Non-destructive Testing and Evaluation at CSIR-National Metallurgical Laboratory, Jamshedpur for Iron and Steel Industry: an Overview

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ABSTRACT

In the area of iron and steel, the NDE centre at CSIR- National Metallurgical Laboratory has not only developed different NDE based methodologies for characterisation of microstructure and assessment of different kinds of damage (creep, fatigue, corrosion etc) in various grades of steel; but also developing methodologies for blast furnace lining thickness measurement and assessment of High Speed Steel (HSS) rolls. This paper will highlight some of the above activities particularly related to steel and allied industries.

Introduction

Research and developments at CSIR-National Metallurgical Laboratory (CSIR-NML) focuses on Minerals, Metals and Materials. Through an arsenal of state of the art facilities and infrastructure, and on the strength of its expertise, CSIR-NML has evolved into a premier Indian organization in the stated areas. Its materials evaluation and characterization facilities compare with the best in the world. CSIR-NML has been active for the last two decades on structural health monitoring and remaining life assessment of materials in the power plant, petrochemicals and steel industries both through microstructure and mechanical property evaluation as well as non-destructive evaluation (NDE).

Over the years, NDE activities for component integrity assessment augmented by way of equipment and personnel too. In 2003, with a partial funding from Department of Science & Technology (DST), Govt. of India, a non-destructive evaluation centre for excellence has been established at CSIR-NML. The Centre supported by a wide range of NDE techniques, encompassing ultrasonic, non-linear ultrasonic, acoustic emission, magnetic and electromagnetic and experience in developing NDE protocols for diverse components from aerospace, defence, power and steel sector is pursuing focused application oriented research. Need based development of NDE sensors and techniques for specialised applications are also the integral part of Centre activities. The centre over the years has developed different NDE based methodologies for characterisation of microstructure and assessment of different kinds of damage (creep, fatigue, corrosion etc) in various grades of steel. Presently one of the main activities of the centre is to develop methodologies for blast furnace lining thickness measurement and assessment of HSS rolls. This paper will highlight some of the above activities particularly related to steel and allied industries.

Blast Furnace Lining Thickness Measurement by Low Frequency Ultrasonic Technique (LFUT)

Blast furnace (BF), a high-efficiency counter-current packed bed reactor is being successfully used in all integrated Iron & Steel plants of the world to produce pig iron. Throughout the years, large efforts have been put on finding ways to increase the productivity and extend the campaign length of the plants. The state of the hearth has by many been identified as the most important factor for a long campaign length. This lower region of the furnace is exposed to liquid iron and slag at high temperatures that could be in direct contact with the lining, causing erosion and corrosion of the lining material. The most aggressive environment is found in the region closest to the tap hole. It is exposed to thermal stresses and liquid iron and slag at high flow rates. An increased productivity results in higher load on the furnace, which potentially can shorten the campaign length. To strive to optimize both these goals, it is important to carefully control the state of the hearth. As the refractory lining of the hearth gradually worn out during operation, the lining thickness distribution is an important factor that limits the remaining life of the blast furnace and is taken as a major check point for evaluating repair quality. Many methods have been employed to measure blast furnace lining thickness, including radioisotopes, thermal measurement and core-drilling. Temperature measurement is among the most widely used method for on-line monitoring the profile of the blast furnace inner surface, which is based on numerically solving inverse problem using heat transfer models and readings from thermocouple [1-3]. Optimization methods are applied to obtain the boundary of the domain iteratively, and hence the computation is very expensive and calculation cannot be very accurate. Radioactive method uses radiation source that emits gamma ray into the wall and the wall thickness can be obtained as a function of scattering intensity [4,5]. Core-drilling is an invasive method to inspect the wall thickness of a particular position on the wall by taking sample of a very small portion. These methods can only give localized information with disadvantages such as radiation safety concerns as well as accuracy issues. Therefore, an effort has been made at NML to develop non-invasive technique based on low frequency ultrasonic to measure the blast furnace lining thickness.

A mock-up facility as shown in figure 1 was set-up at CSIR-National Metallurgical Laboratory to study and optimise the measurement parameters under cool and hot (1250ºC) conditions. As the hearth lining is the most critical area of the blast furnace, a full scale model of 9º sector of hearth zone of designated BF of Bokaro steel plant, SAIL was considered for the mock-up facility.

LFUT was used in bi-static mode to measure the wall thickness of the mock-up facility at room temperature and also at elevated temperature. The results as obtained indicate that low frequency ultrasonic technique in a bi-static mode can be used to monitor the liner profile of blast furnace in empty condition. The developed methodology was used for refractory lining thickness measurements of BF#5 of Bhilai Steel Plant just after the tapping. Measurements were carried out at different positions mainly in the Tuyer layer (T) and the results obtained are very encouraging.

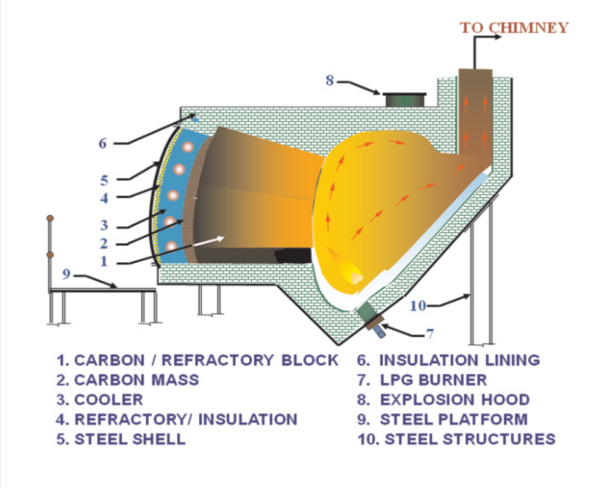

Fig. 1: 9º Sector model of Mock-up facility

Assessment of HSS Rolls by Ultrasonic Technique

The high speed steel (HSS) rolls have high hardness and good wear resistance at high temperatures. This grade is only produced by the horizontal Centrifugal Cast (CC) method and has the core material in spheroidal graphite pearlitic iron. This type of roll is used in finishing applications for increased campaign times and better surface finish. During rolling process of the rolls, micro-cracks often initiate in and proceed along hard carbides distributed in the microstructure [6, 7]. HSS rolls can be fractured unexpectedly by spalling or thermal fatigue caused by the growth of internal cracks or by the roughening of the roll surface. Hence it is highly recommended to eliminate all kinds of surface cracks, whenever these rolls are reground otherwise typical `cats'-tongue band type spalls may occur. Surface crack depth determination by ultrasonic surface wave has been reported by Hetchmann Paul et al. and Takada Hazime et al. [8, 9] have been reported earlier. At Tata Steel, though a regular eddy current and ultrasonic testing are performed after each grinding and before placing the rolls back to the stands, still few rolls failure had taken place in the last few months. CSIR-NML in collaboration with Tata Steel, Jamshedpur has developed a surface wave based ultrasonic technique using 0.5 MHz probe for the surface condition detection of HSS rolls. Calibration for crack echo amplitude with crack depth and back wall echo amplitude with crack depth for fixed gain fixed distance has been established for HSS roll and is shown in figure 2 below. From the calibration curve, optimal grinding condition can be estimated that may reduce the rate of roll failure at Hot Strip Mill of steel plants.

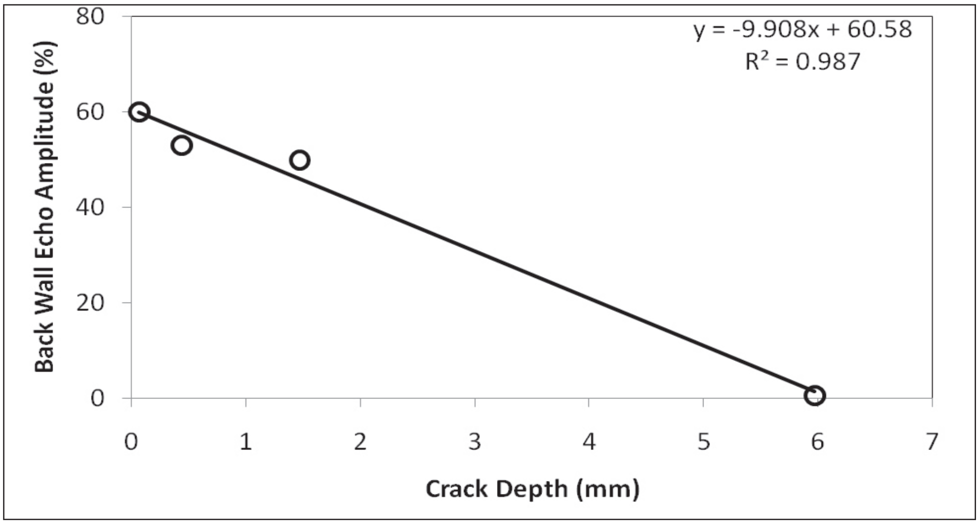

Fig. 2: Back wall echo amplitude Vs. Crack depth profile

Acoustic Emission Technique for Analysis of Splitting Failure of Patented Steel Wire Rods

The investigated wires having final diameter of 4.16 mm, are drawn from wire rods of 12 mm diameter with a nominal composition of C-0.82, Mn-0.7, Si-0.2, S-0.02, and P-0.02. The wire rods are first pickled and baked at 1500C for 15 minutes, followed by coating and are then pre-drawn to 10mm diameter before patenting. A gap of 10hrs is allowed between coating, pre-drawing and patenting. Subsequent to the patenting, the pickled wires are dipped in hot water and drawn through the flux to 6mm size. This is followed by galvanizing and final drawing to 4.16mm diameter. The splitting failures are reported at this stage in addition to failure during spooling and stranding. Splitting failure may occur spontaneously when the material is embrittled along a longitudinal plane or when the residual stress generated during the drawing and handling operations are released through splitting. Cold drawn high carbon wires are amenable to being weaker along longitudinal planes rather than transverse planes due to fibre-like deformation of pearlitic phase in the longitudinal direction [10]. It is also possible that further metallurgical embrittlement may take place due to inter-facial segregation, hydrogen activity etc., which makes delamination/ decohesion easier. Acoustic emission testing was used to confirm embrittlement either due to metallurgical reasons or due to the presence of hydrogen.

Delayed cracking tests were conducted on partially split wire samples, by hanging a dead weight (800gm) to one of the split ends. A 150 kHz resonant piezoelectric sensor was placed on the wire surface to monitor the acoustic emission signals generated during the test. The AE signals were then amplified by a 40dB pre-amplifier and were fed to a Spartan-AT AE system from M/s. Physical Acoustic Corporation, USA to record and analyze the signals. A schematic view of the experimental set-up is shown in figure 3. The longitudinal fractured surfaces were then examined under scanning electron microscope.

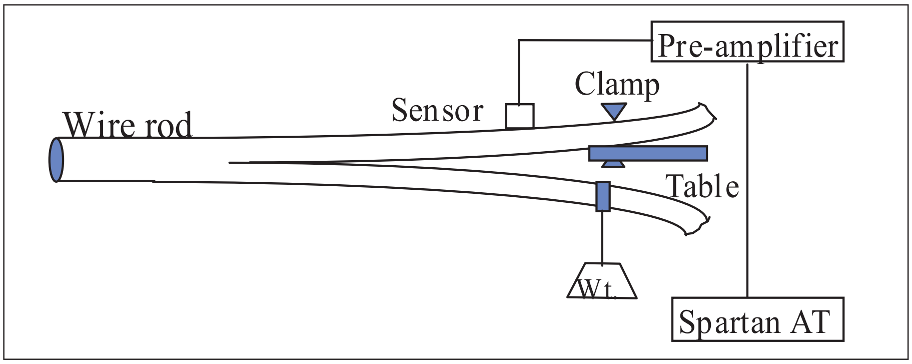

Fig. 3: Schematic view of the experimental set-up.

The acoustic emission signals collected from a wire rod sample that was kept under constant load for a period of five and half an hour are presented in figure 4. It can be seen from this figure that even though the wire rod was under constant load, a number of AE signals (39 AE events) were generated during the test. These signals were not generated continuously but in intervals. This indicates that some dynamic substructural phenomenon is taking place in the material during the test, and the process is time dependent and therefore is diffusion controlled. Signals of this nature may be generated due to hydrogen evolution or due to hydrogen induced microcrack formation by the diffusion of hydrogen to the maximum stressed region. The longitudinal fracture surfaces of the failed wire rods, examined under SEM showed again fibrous appearance with secondary cracks (Figure 5). The presence of secondary cracks suggests hydrogen attack of some form or the other.

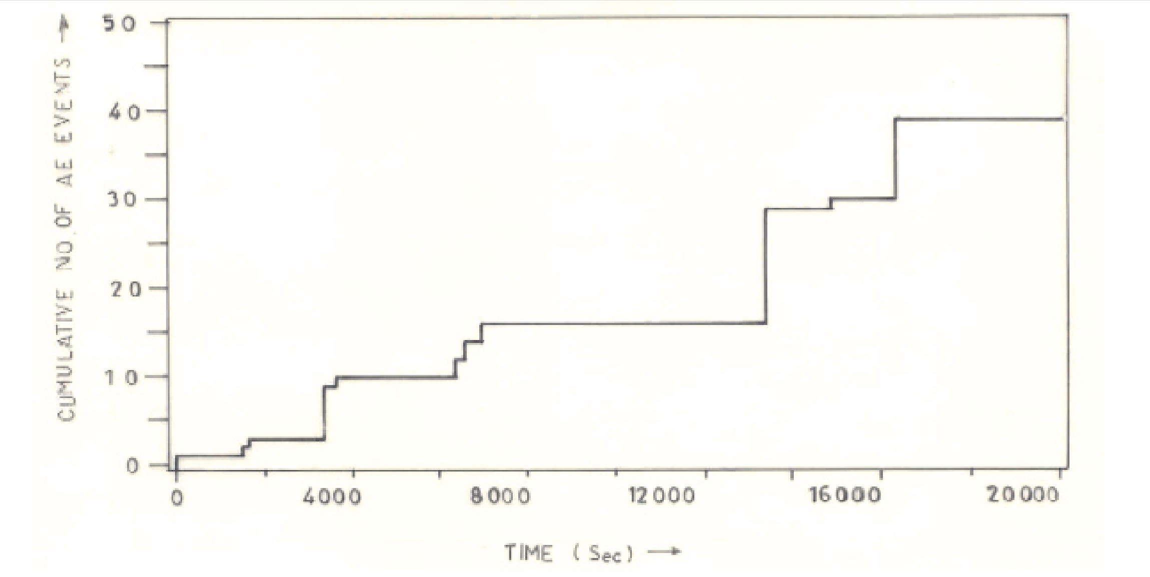

Fig. 4: Cumulative number of AE events generated during delayed cracking test of the wire.

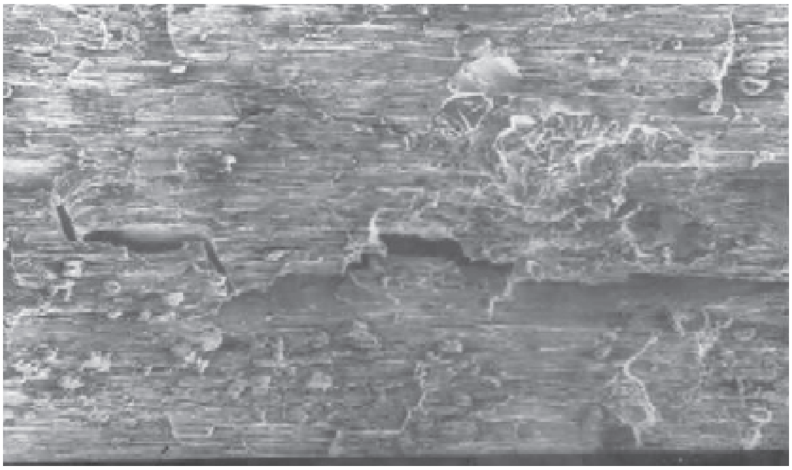

Fig. 5: Fractograph of the failed wire

The results indicate that the cohesive strength of the grain boundaries/ interfaces was reduced by the presence of atomic hydrogen which ultimately leads to sharp splitting because of the presence of high tensile residual stress in the central region of the wires developed during drawing operation.

Listening to the Sound of Steel during Fracture

The results of fracture always leads to catastrophic failure of materials, but the mechanisms involved in the fracture process can vary for different materials and may be different under different circumstances. A number of fracture phenomena, such as ductile, brittle, cleavage, intergranular stress corrosion cracking and creep failure have been identified. The mechanism of each of these is complex often involving simultaneous operation of several physical processes, such as decohesion at the second phase/matrix interface, localised dislocation motion, diffusion, and local chemical changes. It is, therefore, very important to detect and understand the early stages of fracture by non-destructive means for condition monitoring of in-service components/structures. A number of new experimental techniques have emerged which show promise of addressing the measurement needs to detect early stages of fracture and for the fundamental understanding of fracture processes. They include acoustic emission, ultrasonic scattering, electromagnetic NDE, use of synchrotron radiation and small-angle (neutron and x-ray) scattering. The CSIR-National Metallurgical Laboratory at Jamshedpur has been actively involved in the application of acoustic emission technique for studying the fracture process in various grades of steel. Here application of Acoustic Emission technique for the above study particularly on dimple fracture in steel is high-lighted.

For studying ductile fracture, single edge notch bend (SENB) specimens of 25mm thick and 50 mm width with 10mm deep notch were machined from SA333 Gr.6 steel. They were pre-cracked, to a/W = 0.5 under software control. The J-integral tests were then performed on the pre-cracked specimens by single specimen unloading compliance technique as per the guidelines of

ASTM standards [11,12]. AE signals generated during the tests were monitored and analysed by a Spartan-AT acoustic emission test system of M/s. Physical Acoustic Corporation, USA. Two 150 kHz resonant sensors with 40dB pre-amplifiers under linear source location set-up were used to pick up the AE signals. The data obtained from J-integral tests were software-analysed for constructing the J-R curve. A typical load vs. time curve along with AE energy is illustrated in figure 6.

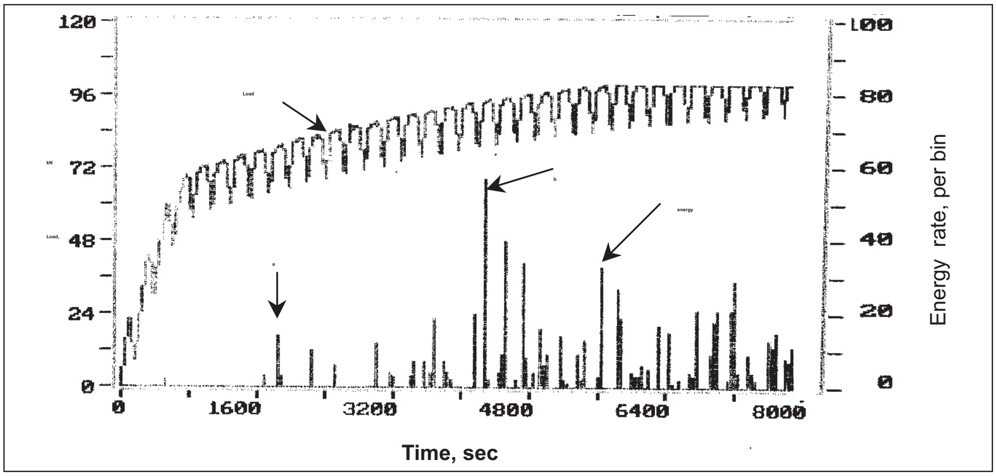

Fig. 6: Load along with AE energy rate vs

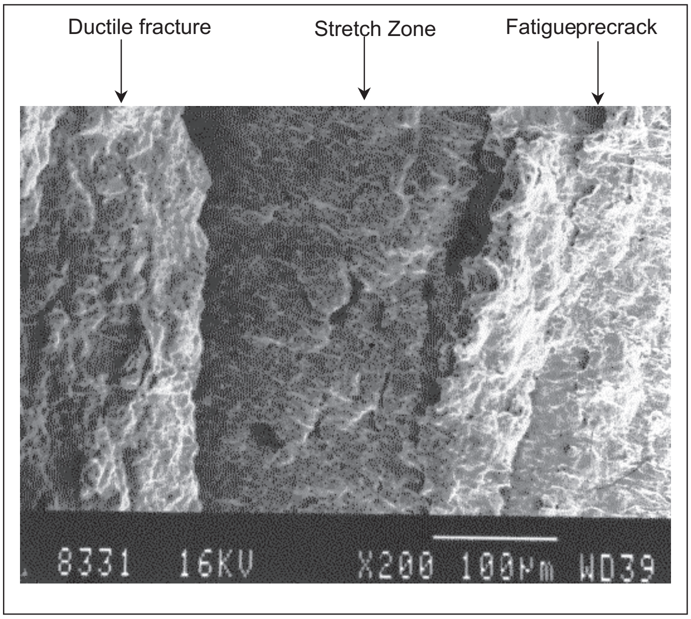

Fig. 7: SEM fractograph depicting the stretch zone.

When a sharp pre-crack contained in a ductile material is loaded; the crack tip first blunts under the influence of tensile pull created by the surrounding material. The blunting of the pre-crack is accompanied by virtual extension of the crack with respect to the original position of the tip due to Poissons' contraction, and a characteristic crack tip opening displacement (CTOD).

On continuation of loading, cracking initiates from blunted pre-crack through ductile tearing. Stable extension of crack takes place subsequently, and in load controlled systems may be followed by unstable crack growth. The virtual extension of the pre-crack prior to ductile crack initiation through crack tip blunting is called stretch zone (SZ). It is a relatively featureless region containing stretch marks parallel to the direction of extension. In ductile material it can have considerable relief, and characteristic stretch zone width (SZW) and stretch zone height (SZH) can be ascribed to its geometry. In ductile tearing process, crack generally forms through the growth and coalescence of micro-voids in steel. This can be seen in SEM fractograph of the fractured surface of the steel (Figure 7). In this figure, the relatively featureless region containing stretch marks parallel to direction of crack extension corresponds to the stretch zone. These fracture processes can also be identified on figure 6. In this figures, point 'a' can be taken as onset of blunting and 'b' as onset of stable crack growth (point of crack initiation). On blunting, plastic deformation at the crack tip occurs and this gives rise to AE signals. This is characterised by low amplitude, low energy, and low count rate signals. As the blunting continues, similar AE signals were generated till the cracking initiated at the blunted pre-crack. On initiation of the crack, AE events with high energy, high amplitude and high count rate were generated, but as the crack further grew, relatively low amplitude and low energy signals were generated. This is because in ductile tearing process crack generally form through the growth and coalescence of microvoids in steel. The absence of AE signals up to point 'a' in figure 6 was due to the Keiser effect. This also indicates that no AE signals were generated during the unloading cycles. It can be concluded that three AE parameters, namely the peak amplitude, the energy rate and the count rate, are required to be used in combination to study the fracture processes in steel. By using these parameters one can find the onset of blunting; and the crack initiation point i.e. the onset of stable crack extension in ductile steel. This could be used as indicative of deterioration of structural integrity during AE monitoring of pressure vessel/piping

Concluding Remarks

There have been consistent attempts by CSIR-NML to apply NDT technique for solving various problems in steel industry such as measurement of blast furnace lining thickness beyond its current state of technical development. The National Metallurgical Laboratory at Jamshedpur over the years has developed different NDE based methodologies for characterisation of microstructure and assessment of different kinds of damage (creep, fatigue, corrosion etc) in various grades of steel. Presently one of the main activities of the NDE centre of CSIR-NML is to develop methodologies for blast furnace lining thickness measurement and assessment of HSS rolls.

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