Section - I

INVITED PAPERS

NDE Tools for process and product monitoring in manufacturing

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ABSTRACT

In this paper, a brief overview of some of the recent developments and future trends in the area on NDE is discussed as it pertains to applications in the area of Manufacturing. The NDE sensors may make the Manufacturing of various types of components and products more efficient, economical, and reliable.

Need for NDE Sensors in Manufacturing

Unlike traditional process parameter measurements such as temperature, pressure, etc., NDE technologies offer a means to quantitatively measure the product parameters directly. Such measurements include hardness, toughness, percent-remnant-austenite, degree of cure, bond quality, etc. In many situations, the process parameters sensors and the product parameter sensors can be integrated into an intelligent algorithm for improved productivity and cost-efficient manufacturing.

New NDE sensors finds many applications in Manufacturing where, in addition to measuring process parameters, the product parameters are also measured as illustrated in Figure 1. Eventually, the optimal use of process and product measurements will lead to efficient process. The implementation of product and process measurement methods in the manufacturing feedback control may have the following benefits:

1. Quantitatively 100% monitor the state of the material/product during manufacturing.
2. Real-time feedback control can be implemented to reduce rejects, avoids reprocessing and hence reduces cost.
3. Improved reliability of products reduces product liability costs. (Quality Control Engineer, a friend of the Production Manager)
4. Micro-electronic sensors, High temperature sensors, Non-contact methods are now becoming reality, thus enabling Integrated Product and Process Monitoring

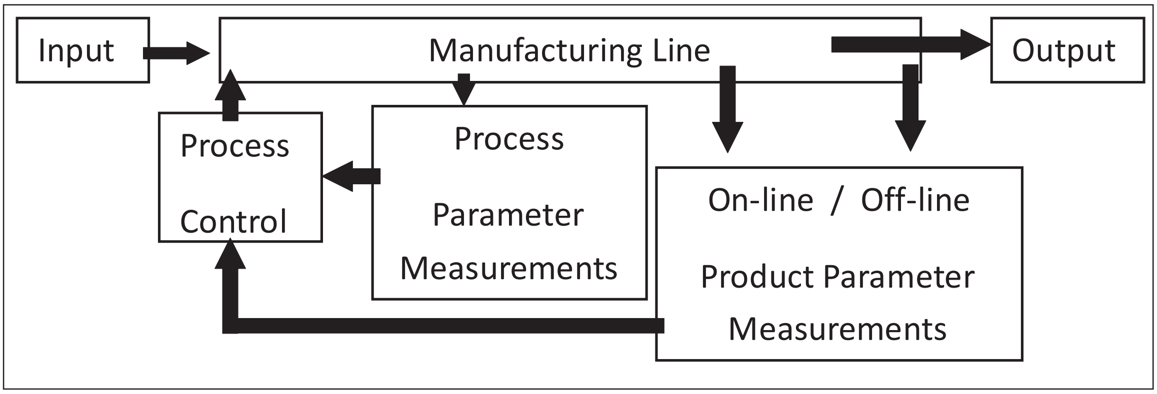

Fig. 1: Product and Process Measurement concepts in Feedback Control of Manufacturing Process

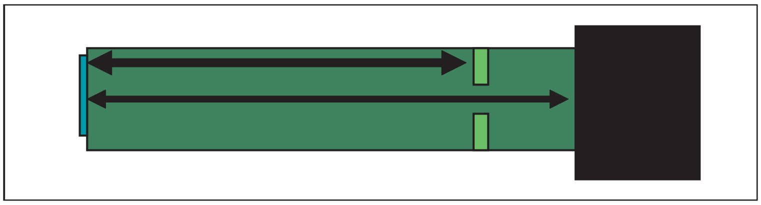

Fig. 2: The simultaneous measurement of viscosity and temperature for high temperature process monitoring.

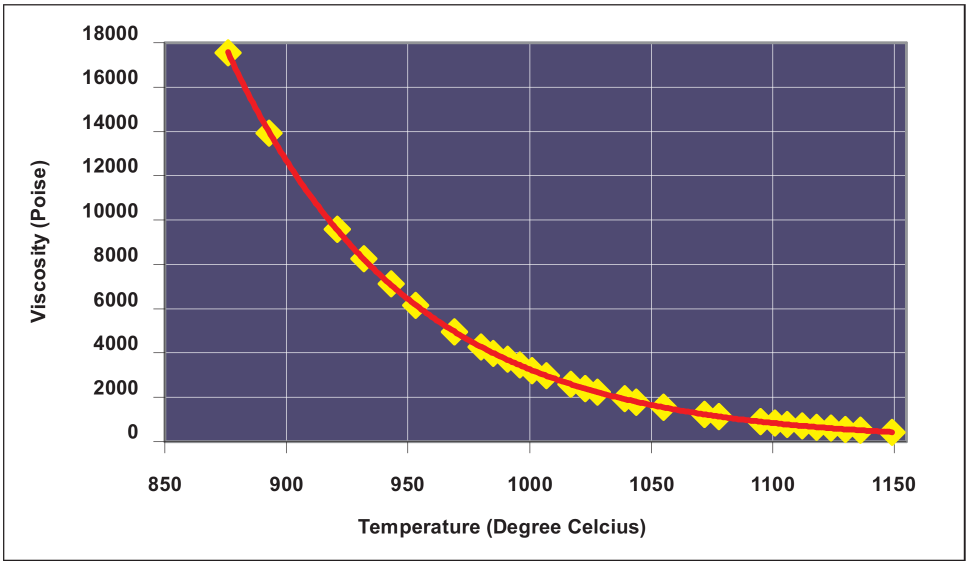

Fig. 3: Typical result from process monitoring of glass melting process using ultrasonic delay line technique.

High Temperature Process Measurements

Using NDE sensors, it has been shown that temperature and viscosity can be simultaneously measured at a local region in a molten melt furnace. This information assist in the feedback control on the quality of molten material manufacturing such as glass where the viscosity plays a key role in the final product quality. At a solid-fluid interface, the amount of ultrasonic shear wave energy reflected back into the solid is independent of the attenuation, but depends on the operating frequency, properties of the fluid (viscosity and density) and the solid (density, shear modulus). It has been demonstrated that viscosity and density of fluids can be quantitatively measured using a combination of longitudinal and shear wave reflection coefficients and wave velocities. It has also been demonstrated that a shear wave delay line technique can be used for temperature and viscosity measurements at high temperatures such as molten glass. The sensor is schematically illustrated in Figure 2 and a typical result obtained from a glass sample that was melted is shown in Figure 3. It can be observed that ultrasonic methods can be effectively used in the process monitoring applications at elevated temperatures.

The application of this rheology measurements were explored as a possibility of measuring high temperature properties of mould powder slags (viscosity, break temperature, liquidus temperature) during heating as well as solidification start and solidification end temperatures during cooing. These powders are used in continuous casting of steel and the abnormality in their properties can impact the productivity and quality of the steel products. The role of the mould powder slag in continuous casting is to:

- Protect the meniscus of the steel from oxidation
- Provide thermal insulation to prevent the steel surface from freezing
- Provide liquid slag to lubricate the strand
- Provide the optimum level of horizontal heat transfer for the steel grade being cast
- Absorb inclusions from the steel.

These properties are in general measured by High Temperature Rotational Viscometers, Hot Stage Microscopes and DTA instruments. Here, the fundamental ultrasonic flexural guided wave mode F(1,1) in a ceramic buffer rod was employed in experiments. The experimental results show the possibility of measuring all the above properties in single experiment by measuring ultrasonic reflection factors during continuous heating and cooling of the mould powders. The advantage of the ultrasonic system can be installed in the plant for on-line monitoring of these properties. The ultrasonically measured properties of the mould powders supplied by 5 different suppliers were compared with those measured by Rotational Viscometers and estimated by mathematical models.

Based on the experimental results the following conclusions can be drawn:

1. Liquidus temperatures of the mould powders can be possibly measured from the ultrasonic reflection factor vs temperature heating curves. (Fig 4a)
2. The solidification start and solidification end temperatures of mould powders can be measured from the ultrasonic reflection factor vs temperature cooling curves.
3. Viscosities of the mould powder slags can be measured with good accuracy by ultrasonic measurements of reflection factors which are fairly comparable with those measured by Rotational Viscometers. (Fig. 4b)

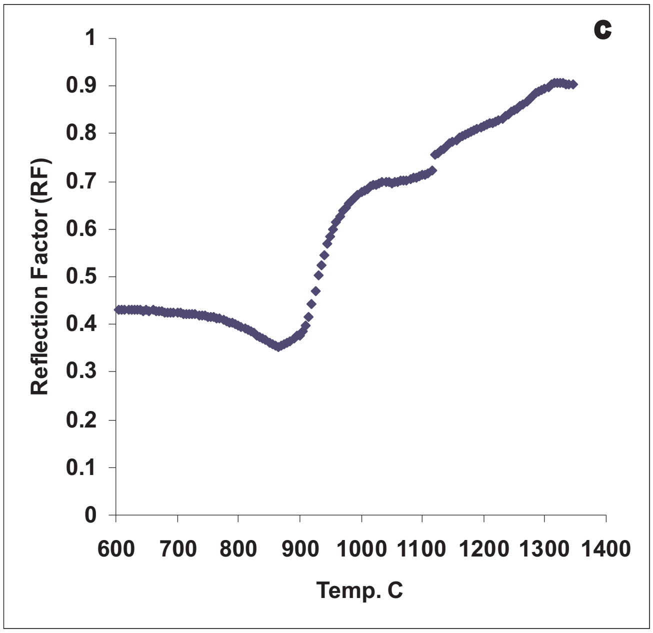

Fig.4a: Cooling curve plotted between Temperature and Reflection Factor (RF) in a typical mold powder slag..

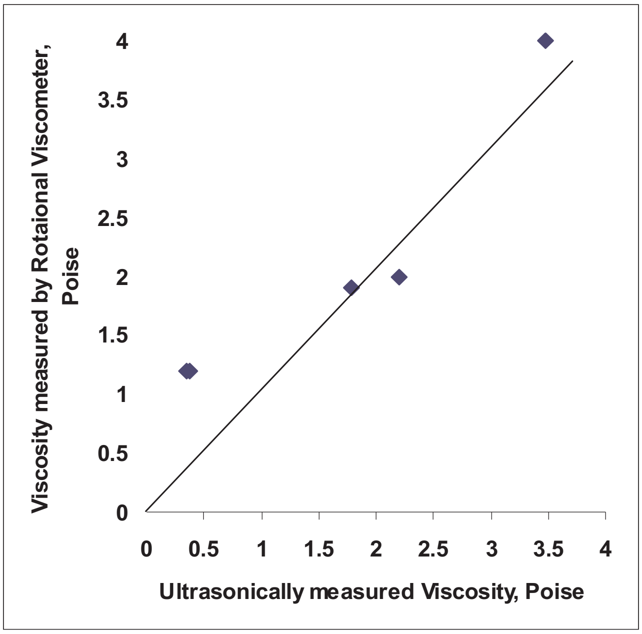

Fig.4b: Graph plot between ultrasonically measured Viscosity and that measured by Rotational Viscometer. The deviation was high for lower viscosity values.

Ultrasonically measured break temperatures from the reflection factors were not found to be fairly matching with those measured by conventional Rotational Viscometers

NDE Methods for Elastic Constant Measurements

The reliability of structures and components are primarily related to assurance of the stiffness and strength during in service use. Even though materials may be "defect-free", the variables in the manufacturing may lead to the production of components that have modulus that are different from the design specifications. This leads to the need for development of rapid and cost-effective techniques that can measure local modulus of the component. The introduction of anisotropic and multi-layered composites into various applications such as aerospace, automobile, and infrastructure further re-iterates this need.

The methods of ultrasonic measurement of modulus of isotropic materials such as metals have long been established. In the case of fiber reinforced composites - which exhibit lower order material symmetries - the interpretation of the ultrasonic data is more involved as result of their anisotropic nature. The behavior of elastic acoustical waves within such anisotropic structures can be predicted using reliable mathematical models for well-characterized material systems.

Reconstruction (or identification) of material properties especially elastic constants (nine for an orthotropic composite) from experimentally measured acoustic data is an essential part of non-destructive ultrasonic material characterization. The idea is that ultrasonic data (usually phase or group velocities) are related to the material properties through a known mathematical model. Normally, the mathematical model relates known material properties to ultrasonic data - the forward problem. Thus, if experimentally measured ultrasonic data are available, computing the required stiffness properties is just a matter of solving the inverse problem i.e. relating known ultrasonic data to material properties using an inverse model. However, even though the forward approach might be relatively easy, the inverse step is often more difficult. Generally, the inverse problems in wave propagation are highly nonlinear and hence, non-unique in nature. Moreover, practical difficulties and the constraint of limited data sets (due to the experimental technique used) further tend to increase the degree of difficulty in the inversion.

As no explicit inverse model can be found, a common and popular approach is to pose the inversion in an optimization form utilizing the forward problem (which is explicit) in an iterative or model-update fashion. Such an inversion is performed on an experimentally measured over-determined ultrasonic data set employing a certain optimization technique.

Two important points are worth noting here. Firstly, the use of an overdetermined set stems from a belief that such an approach helps to reduce the influence of random noise and experimental errors in the measured data and also, brings about uniqueness in the inversion. The effectiveness of the inversion in being stable to noisy data is highly dependent on the sensitivities of the inverted data to the parameters (elastic constants, in this case); and the way the optimization problem is posed ie. the objective function to be extermized. It can be safely stated that using sensitive data is always beneficial from the noise-stability point of view, and hence a sensitivity analysis is strongly recommended. Further, apriori to the actual inversion of experimental data, the reconstruction should be confirmed with noise-free and simulated noisy data from a well-characterized material system, so that the effectiveness of the inversion along with the tolerable noise levels are estimated. Such an effort will aid in deciding the type and accuracy desired of the experimental set-up. Secondly, the choice of the optimization technique is essential in performing a reliable inversion.

Although various classical search methods exist, the gradient-based technique (usually referred to as the nonlinear least squares optimization technique) and the Simplex Algorithm are the most reported in literature. Pertaining to the inversion of bulk wave phase velocity profiles, Chu and co-workers used the least squares optimization approach while others employed the Simplex Algorithm to evaluate the elastic constants of an orthotropic composite material.

Inversion of Lamb wave dispersion data that is more relevant to thin laminated composites, and offers a more convenient single-sided evaluation, has also been reported. Rogers illustrated the inversion process for isotropic materials using a gradient technique. Rokhlin and co-workers applied the nonlinear least squares optimization procedure to invert ultrasonic reflectivity and transmission data associated with the leaky Lamb wave phenomenon of fluid loaded composite plates. Karim et al. used the Simplex Algorithm to invert leaky Lamb wave dispersion curve data.

The main drawback with the vastly utilized gradient methods is that they begin from a single point (initial guess) in the search space and suffer from being local in nature. As a result, they require close initial guesses for searching the complex, multi-modal spaces offered by such nonlinear inverse problems. Their performance is not reliable for initial guesses far off from the global solution and consequently entrapment at local (false) extrema is a common occurrence. Moreover, cumbersome gradient computations are needed.

The Simplex Algorithm begins its search from many points (equal to M+1 for a M-parameter space), requires no gradient computations and is reported to possess a greater convergence zone (more global) than the gradient technique. However, as reported by Karim, convergence to false solutions can result if the algorithm is implemented on non-unique search spaces brought about by the relative insensitivities of some of the parameters to be identified.

On the other hand, pure random search techniques even though, absolutely global in nature, are directionless inefficient searches and hence, practically infeasible due to the huge amount of computational time involved.

Online QA of Brake Pads using Acoustic Impact NDE

The concept of acoustic impact itself is also longstanding, having come to light through the potters of ancient ages and more rigorously automated in recent times for NDE of composites and aerospace components for maintenance applications. [1-9] In this paper, we have attempted to develop an automated process based on the similar principles that can be directly applied to quality assurance of composite parts in a mass production environment. The specimens are excited by an impact actuated by a solenoid, and the acoustic signal is recorded using a microphone and a multimedia PC. Frequency extraction is done on the time domain signal and the frequency spectral data was used as input to a neural network to detect the defects or delaminations in the composites at very high production rates (2-5 parts per second). Usually homogeneous composites are fabricated by compressing the powdered constituents under high temperature and pressure. The composition and dimensions of the lining is normally manipulated to achieve the right values of the control parameters. A typical example is brake linings in which case the usual control parameters are coefficient of friction and thermal conductivity. During the compression process, by product gases are formed, and proper arrangements need to be made to vent them. Occasionally, these gases do not find an escape route and thus form voids within the composite part causing porosity or 'blisters'.

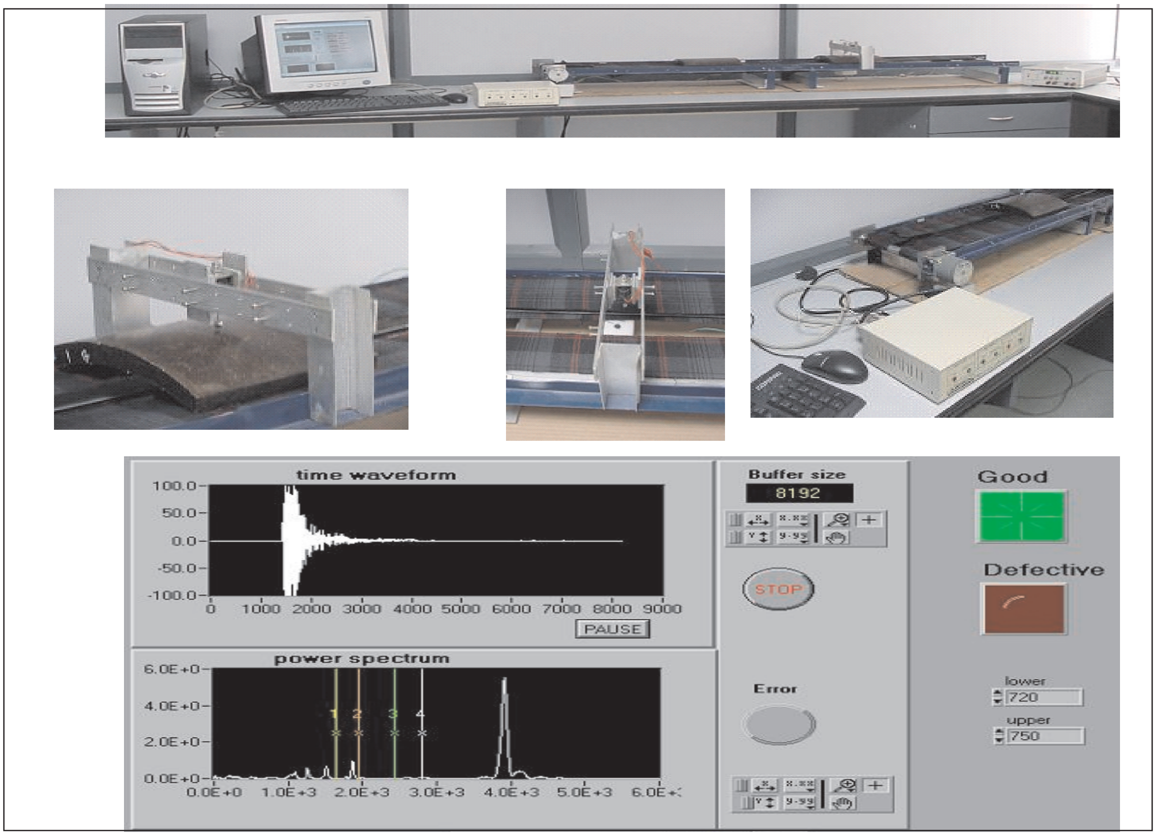

Fig. 5: The brake pad inspection system prototype using the acoustic impact technique with the GUI for ANN implementation.

These voids and 'blisters' adversely affect the performance of the parts. As the part wears out due to repeated use, the voids come to the surface. This has a heavily detrimental effect on the performance of the part. This makes it essential to detect and reject defective parts on the manufacturing line itself. Unless the voids are of significant size (this results in a conspicuous bulge on the surface of the part), they cannot usually be detected by the naked eye.

A prototype of the entire mechanism was designed which can be inserted into a production environment. The conveyer is built using Aluminum L sections for a frame with a cotton belt. A stepper motor given using an MS shaft operates the drive. A computer microphone is used for data acquisition. The setup is designed to fit as the last end of a conveyer belt. The figure of the entire system is shown in Figure 5. Software was developed using the MLP ANN algorithm with lights indicating GO/ NO-GO for each component. The first set of training of the MLP was done with the complete frequency domain data (comprising of 517 data points). This training set was later modified using a data set with the 10 values of frequency appearing with the highest amplitude in the frequency data. Then the data was collected at 9 points on each specimen and all the 90 points were used for training. The training was successful and the time taken was found to be generally proportional to the input vector size since the rest of the architecture was kept unchanged and fully connected at all time. Testing gave best results with the 90-point data with less than 10% error (1 missed call in 13 samples).

Online QA of razor blades

Razor blades are made from special steel that is first rolled into strips that are then slotted and hardened using a heat treatment process. Then the blades are ground to provide the sharpness. The quality of heat treatment will influence the sharpness of the edges and hence must be monitored. Due to variation in the input material from different vendors, the heat treatment process control has limitations that lead to rejection of large quantities of processed blades. The NDE sensors were employed to monitor the three key parameters of the blade during the heat treatment process. This includes (a) Remanant Austenite (%RA) that indicates the degree of phase transformation, (b) Toughness, and (c) Hardness of the blade. Both Eddy Current and Ultrasonic sensors were developed to make these measurements. These sensors had to be designed for on-line implementation and various other process parameters such as temperature, vibration, etc., had to be taken into account. In the Figure 6 a conceptual implementation of the sensors on a 4 line blade manufacturing unit is illustrated.

Ultrasonic On-line Monitoring of Cure and Material State of Pultrusion Process

The pultrusion process is a fully automated process and hence on-line testing of the product is very important from the quality control and reliability point of view. Non-destructive monitoring can play an important role in the pultrusion process through timely information regarding the material state during and after manufacture, especially since 100 % inspection is possible. The primary would be to successfully integrate ultrasonic non-invasive technology into the manufacturing cycle, and establishing algorithms which quantitatively evaluate the actual cure state and the material state of the composite part which is being manufactured. Once this goal has been attained, this cure/ material state information will be made to interact with the intelligent system controlling the overall manufacturing process. In order to easily facilitate this evaluation process, the process and the mold design will provide accessibility for the ultrasonic sensors." The degree of cure is not easy to establish because it cannot be measured directly, but other parameters that experiments and experience have found are related to it, can be" writes Donaldson and Parker. Even though the utilization of sensors such as thermocouples and pressure transducers have now become common manufacturing practices, several other new sensors can be identified which possess an immediate potential for providing enhanced information. This vital data could then be utilized in a feedback mode to actuate the different stages of the manufacturing cycle. One of the best ways of accomplishing total quality is through the effective utilization of sensors and feedback control. The introduction of sensors will have to be anticipated very early in product design and will have direct impact on each step in the overall process. Thus, the technology would involve a concurrent merger of the various disciplines of manufacturing sciences, especially advanced non destructive evaluation(NDE) sensing and monitoring.

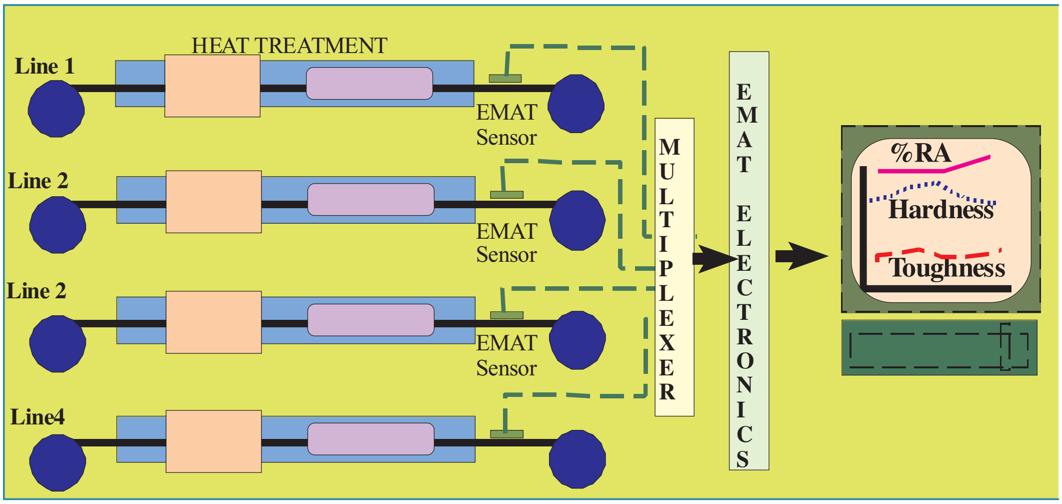

Fig. 6: Online monitoring scheme using NDE Electro Magnetic Acoustic Transducer (EMAT) sensors for steel strip production lines.

The needs for process monitoring go far beyond flaw detection to fundamental quantitative measurements of material and microstructural properties. Such measurements will be needed to provide data on real physical properties that can be evaluated to determine their effects on performance of the material or the structure. The effective strength of the whole structure after manufacture could easily be different from the design strength, often by a considerable amount, some times even by a factor of two. This discrepancy is due to factors such as processing damage, increased likelihood of flaws, incorrect fiber orientation, etc.. For example, in a unidirectional laminate, a variation in overall fiber orientation of 15° can generate up to a 50% reduction in ultimate strength, and can thereby critically effect the desired engineering properties. This leads us to the material characterization aspect of NDE for quantitatively establishing the effective moduli of the whole composite material after manufacture using ultrasonic techniques. The material state data is then added to the common database and used to improve the design process.

Physical principles of ultrasonic wave propagation and wave reflection characteristics can be employed to constantly update the in process fabrication parameters such as degree of cure, rate of mold filling, defects in the part being produced, etc. which are typical in a mold based process. Ultrasonic probes when appropriately placed, will act as sensory organs, which feel and measure the different parameters during fabrication. For example, when the sensor detects an unacceptable degree of cure, a coded signal is fed back to the expert system based process controller, which modifies the process parameters such as feed rate or temperature. Similar control procedures could be adopted to ensure consistent filling, contact of the resin with the mold, the flow patterns, etc., all of which will improve quality and reduce rejects in a manufacturing process.

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