NEEDS AND REQUIREMENTS DRIVING THE IMPLEMENTATION OF NONDESTRUCTIVE INSPECTION TECHNOLOGIES IN AUTOMOTIVE APPLICATIONS

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Abstract: This paper will address the development and use of nondestructive inspection (NDI) technologies in automotive applications by providing an overview of the needs, requirements and constraints that guide the development and implementation of nondestructive evaluation (NDE) methods that comprise these NDI technologies. The conditions and constraints that define the limitations imposed on their selection, development and implementation in high-volume, mass-production applications will be explored and examined.

A brief discussion of some examples of successful NDI implementations will be provided as examples in which the requirements and constraints were met. Conversely, a few examples will be given of effective NDE technologies, with demonstrated laboratory feasibility, which failed to meet either cost constraints or manufacturing feasibility requirements and therefore were not implemented in production.

Introduction: The need for improving automotive energy efficiency is intensifying as public awareness of our need to conserve energy and environmental resources creates market, societal and political pressures for more fuel-efficient, environmentally friendly vehicles, with the capacity, performance, appearance and affordability to which we North Americans have become accustomed. The motivating factors driving the industry to champion the development and implementation of low-cost, lightweight materials and processes, as well as designs, to support significant improvements in fuel efficiency are discussed in references 1, 2 and 3, where approaches to meeting the energy-efficiency needs of the industry are also proposed.

One approach to meeting this need is the reduction of weight in automotive body and chassis components, without the unacceptable concomitant reduction in the size, capacity, performance, reliability and appearance: qualities long considered to be customer requirements to which we have become accustomed. Meeting this five-fold challenge, within the unrelenting cost constraints of the industry, depends on the well-optimized, innovative implementation of new materials, processes and designs.

Whenever new materials, processes or designs are implemented in a previously established, high-volume production system, quality issues are generally expected and must be addressed during each phase of the new product development and manufacturing process. Otherwise, a marginal process will produce a significant number of inferior parts with poor quality. Quality, the conformance to requirements, is here being used to include the appropriateness of the design and materials for their required functions and appearance, and the capability of the manufacturing and assembly processes to produce products that fully meet requirements, or design intent. Hence, subsequent to assuring the quality of the design, it is essential to monitor the material and the output of the manufacturing process quickly and cost effectively, in order to assure a well-controlled and capable process during each production phase. Cost-effective inspection technologies must therefore be available to assure the quality of the materials, the processes and the assembly, at each step along the value-adding manufacturing process, in order to achieve and assure process capability and maintain process control. Such inspection technologies are required until the establishment of a reliable process is demonstrated. NDE technologies for these NDI methodologies have historically demonstrated significant advantages in meeting this manufacturing need.

An overview of the need, requirements and constraints that guide the development of those NDE methods that comprise these NDI technologies will be provided. The conditions and constraints that define the limitations imposed on their selection and implementation in high-volume, mass-production applications will be discussed. The development and use of several NDI technologies that have proven useful in automotive applications will be presented. A brief discussion of these examples of successful NDI implementations will provide examples in which the requirements and constraints were met. Conversely, a few examples of effective NDE technologies, with demonstrated laboratory feasibility, which failed to meet either cost constraints or manufacturing feasibility requirements, will be given.

The focus of the information presented herein is on the NDE and NDI needs and requirements of the automotive industry, not on the technology. The purpose is to give the NDE research and development community better insight into the inspection needs, requirements and constraints that shape those technologies that are implemented there to improve quality, cost and productivity. The inspection method must be reasonably low in cost, rapid, reliable, robust in a manufacturing environment, operationally simple, without adverse impact on the process or the product and provide a quick, reliable indicator of component integrity for each specific application. These requirements and constraints imposed on automotive NDI technologies are captured by the often cited "Three Rs" of the industry: (1) rapid enough for synchronous production in high-volume manufacturing by using automated or user-friendly methodologies, (2) robust enough to operate in a non-ideal automotive manufacturing environment and provide consistently reliable results under varying inspection conditions, and (3) reasonable cost, meaning low marginal, material and operating costs, as well as yielding a high value-to-cost ratio.

Additional challenges that must be overcome whenever new materials, processes, designs or technologies invade a long-established manufacturing methodology are implementation strategies, NDI development costs and funding, capital investment costs, operational costs and customer acceptance.

Results and Discussion: Several material and process quality issues encountered in automotive manufacturing are addressed in this section. The NDE technology suitable for the inspection process needed to address and resolve each quality issue is then identified and its development and implementation discussed, along with the results of the application to that quality issue.
The first of these quality issues is an anomaly often encountered in the compression molding and injection molding of fiber-reinforced polymer composites. These materials are commonly called fiber-reinforced plastics (FRP). The anomaly is called a flow line. An x-radiograph of such an anomaly is shown in figure 1. These flow lines occur in regions where the polymer matrix flows in a prevailing direction, thereby aligning the reinforcement fibers in the direction of flow. Although low-energy x-rays (25 kV through the Be window) can be used to nondestructively detect these anomalies, as was done in the figure shown, such NDI technology is not the optimum approach in a high-volume, cost-constrained manufacturing environment where human exposure to x-ray scatter is a highly sensitive issue. Nevertheless, a rapid, low-cost, effective NDI method is needed because the strength and modulus of FRP materials are strongly dependent on fiber concentration and orientation. Obviously, the strength in these flow-line regions is anisotropic and this material anisotropy also causes anisotropy in the coefficient of linear thermal expansion (CLTE), and hence results in non-uniform contraction of the material upon post-mold cooling, yielding geometric or "potato chip" distortion.

Figure 1 – *X-radiograph of a "flow line" showing aligned fiber orientation in a molded FRP automotive component, with electron micrographs inserts showing random and aligned 10-micrometer-diameter fibers.*

The impact that these fiber-orientation flow lines have on strength is shown in figure 2, which also shows the high degree with which fiber orientation, and consequently strength and modulus, correlates with acoustic velocity, as expected, because acoustic velocity is modulus-dependent.

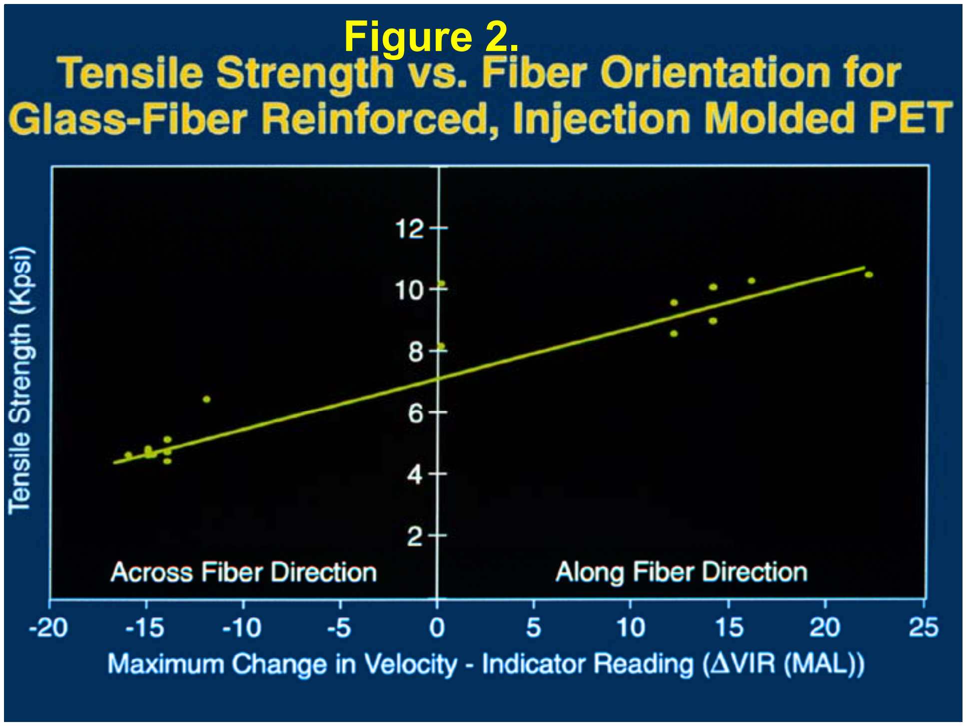

Figure 2 shows the correlation of tensile strength with the maximum change in the velocity of a 25kHz Lamb wave propagated along and then across the flow line. The values along the abscissa are arbitrary and are derived from a measurement of the phase shift of the received wave train. The maximum phase shift is observed while the send-receive, dual-transducer probe is rotated through 100 degrees. They approximate deviations from 800 m/s, the nominal velocity of propagation in the material. The data plotted in figure 2 supports the laboratory feasibility of this technical approach to inspecting for this anomaly. The low-cost, rapid, robust operational simplicity of the instrumentation and inspection methodology in a manufacturing environment, however, are the characteristics that qualify the NDI technology for implementation in a production application. Moreover, the acoustic approach is preferred because acoustic perturbations are fundamentally more responsive to mechanical properties than thermal or x-ray interrogation of the material. Therefore, this low-frequency ultrasonic inspection has been selected as the primary inspection approach. Other approaches can and may be used to compliment and/or confirm the result, but the acoustic approach has the highest potential for yielding fast, reliable results. The low frequency is recommended to avoid adding a liquid couplant to the surface.

This NDI method is a practical example of inspection technology that meets the criteria put forth in the introduction. It utilizes a commercially available, 25k Hz bond tester that can also be used to rapidly inspect adhesive bond joints without liquid coupling. After calibration with reference specimens selected by a statistically based procedure discussed in references x and y, this bond NDI method can detect unbonded areas as small as one centimeter along their major dimension. The development and implementation of this bond NDI methodology has provided a low-cost, rapid, operationally simple inspection method for quality assurance of adhesive bonds during process development, prototype development and testing, and in high-volume automotive manufacturing environments. This bond-joint inspection method is more fully described in references 4 and 7.

The reason there is an unmitigated need for an NDT method for adhesive bonds is clear from the wide coefficients of variation seen in data from adhesive bond testing. An example of such can be seen in typical mechanical test data from six different adhesive-substrate combinations shown in figure 3. Of the six groups, one meets the performance requirements, but not the cost constraints. Further development was therefore warranted.

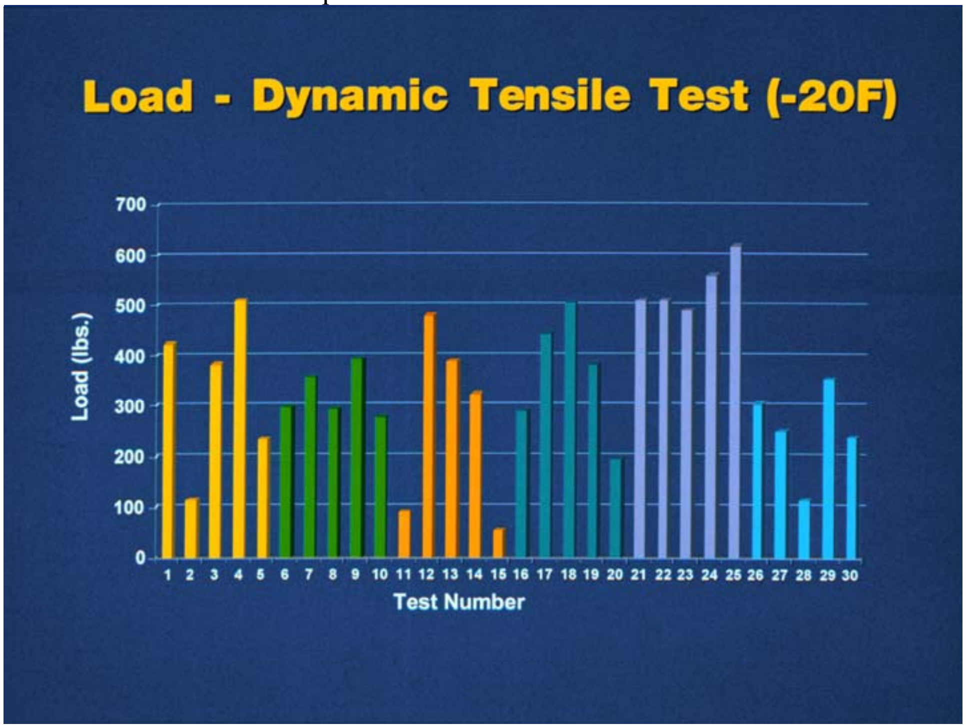

Figure 3. *Early experimental data showing the wide variations in adhesive bond performance during initial testing and therefore supporting the need for NDT during early development and evaluation of designs, materials and processes in new vehicle programs*.

Because of the wide variations in adhesion, testing the adhesive bond joint integrity must be performed to assure reliability. These tests should be designed and selected to assure that the bond joints consistently and reliably meet or exceed the performance requirements. These tests should be selected from well-established or newly developed test procedures that utilize test technology proven to be pertinent to the application in which the bond joint is to perform. The test methods must also meet the criteria put forth in the introduction. An effective method must provide inspection for adhesion within the bond joint, rather than for the mere presence of adhesive material. Moreover, the prevailing interest here is in a method of inspecting for adhesion rather than for the cohesive strength of the adhesive layer, because less than an insignificant fraction of the failures observed in typical automotive bond joints are cohesive.

Mechanical test data must be used to establish correlation with nondestructive test (NDT) results. Depending on appropriate bond-joint design, applying a reliable adhesive bond NDT during manufacturing will assure reliable bond joints, even when the statistical distribution of bond strength data shows that as much as 30 percent of the bonds are substandard. The NDT can assure that the sub-standard bond segments are not contiguous over more than maximum allowed bond lengths. The basis for this is explained in reference 4.

Adhesive bonding has been used to provide joining for the assembly of a wide variety of materials for many years. Body materials such as aluminum, steel, polymer composites and plastics have been adhesively bonded for both automotive and aerospace applications. In many of these applications, the integrity of the adhesive bond must be assured in order to assure the reliable performance of the assembly or component. In many advanced materials applications, adhesive bonding is being evaluated as the leading joining candidate.

The development and implementation of this bond NDI methodology has provided a rapid, operationally simple inspection method for quality assurance of adhesive bonds during process development, prototype development and testing, product evaluation and during the early launch and prove-out phases of the assembly process in high-volume automotive manufacturing.

Ultrasonic friction welding was used in several joining applications for automotive thermoplastic components. Achieving process capability and maintaining process control posed a significant challenge when welding was done in an environment where humidity and temperature fluctuated widely. Therefore wide variations in weld joint consistency were observed during the initial launch of the manufacturing assembly process for both a small under-hood component and a large chassis part. Because high reliability in the weld joints of both these parts was required, the search for an NDT method of inspecting these welds was launched with high priority. Several techniques were investigated for application to the small part, which had a one-millimeter wide circular weld around the circumference of a 25-mm diameter disk. Infrared (IR) monitoring proved to be the NDT method of choice, because it stood out as meeting all the criteria stipulated in the introduction and it could be implemented at very low investment cost, with no interference to the welding process. Data showing the necessity of this process monitoring NDI method are shown in figure 4, along with data supporting the validity of the NDI methodology. Note the wide variations of failure loads exhibited by the four data points produced within minutes at constant weld parameters. Fortunately, the IR surface temperatures developed 11 seconds after weld completion showed excellent correlation with weld strength.

This inspection technology was useful in establishing process control and "hardening" the process so that it produced weld joints four times stronger than the initial minimum requirement of 50 pounds. Subsequently, the NDI was no longer useful and was abandoned, as all NDI systems should be after they have served their noble purpose of helping to bring about a reliable process that produces consistent quality.

This next NDI application is an example of an inspection need arising from the unrelenting drive to reduce vehicle weight and part manufacturing complexity, while improving design flexibility, style and appearance, without compromising cost or quality objectives. To meet this need, another IR NDI technology was subsequently developed and implemented in production to assure the quality of friction welded joints in the aforementioned large thermoplastic chassis part. This part is a safety item and is illustrated in figure 5, with a cross-section showing the weld joints between the "I" section and the "C" section, forming a "D" section. The high reliability required and the large production volume for this part helped make the implementation of an expensive, sophisticated NDI system happen with full support from all participants and stake holder. An experienced engineer was placed on site to provide highly competent technical and operational support.

The earlier experience with inconsistent weld quality in the small part, the lack of reliable adhesive bonding technology for this application, the importance of reliable joint performance and the lack of other known NDI technology for the application, contributed to smoothing the way for this NDI implementation. The IR NDI system installation became a sterling example of an automated system that remained in its essential role as a process control and quality monitoring system throughout the production model lifetime of the product. It also stands out as a lesson on what processes and products make attractive candidates for successful NDI implementations.

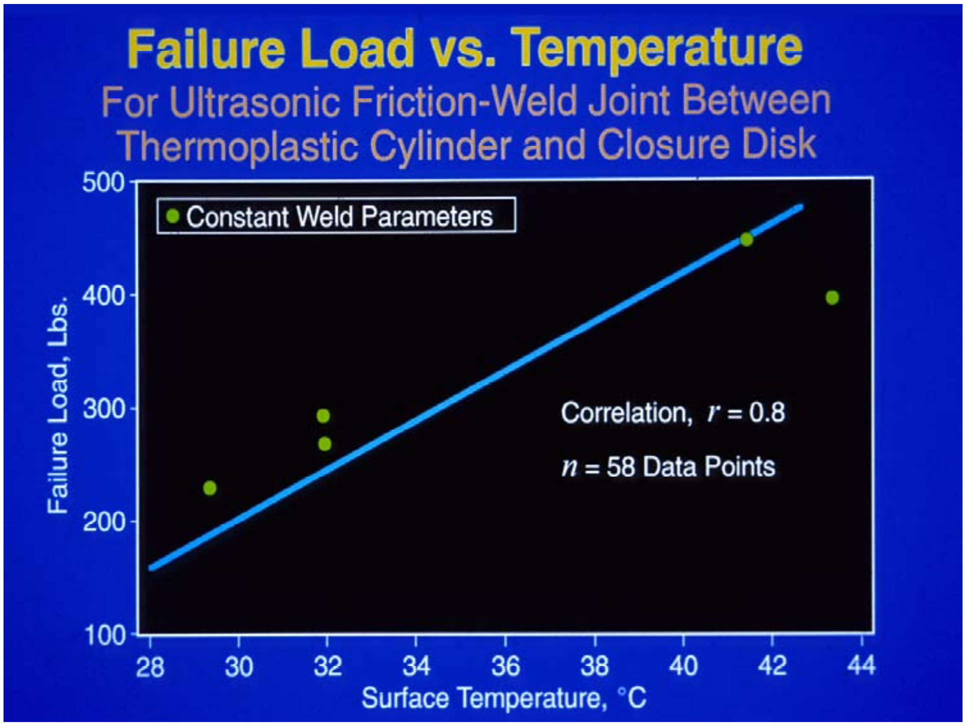

Figure 4. Failure load vs. surface temperature for a friction-welded joint between thermoplastic components.

Figure 5. A friction-welded chassis part inspected by an automated IR NDI system in production.

A very effective NDE technology that uses thermal excitation and infrared detection of thermal diffusivity of the material under interrogation has met with great success in aerospace applications and has been applied in several automotive product development applications and in automotive manufacturing environments. Results of these applications are in references 5, 6 and 7. A comparison of adhesive bond testing results from this thermal diffusivity technology, with results from the 25 kHz bond NDT method, showed great agreement, but the infrared method provided no advantage in investment cost, operational simplicity or labor intensity. Consequently, the simpler, low-cost acoustic NDT remained the primary testing tool. This is one of many examples where a new, more technologically advanced NDT method, with demonstrated laboratory feasibility and success in aerospace applications, failed to be readily implemented in an automotive application because of the cost, speed and simplicity barriers mentioned in the introduction. In this case, the required investment cost would not provide sufficient savings in inspection cost or labor intensity to justify the expenditure for occasional use during vehicle development and prototype testing.

Another such example is the implementation of x-ray computed tomography (CT) in a powertrain components casting plant. The rapid, high-resolution system was difficult to justify because casting plants can rapidly cut castings into thin slices to find interior anomalies and quickly adjust the parameters of the casting process to try to eliminate flaws, then repeat the cycle until success is realized. Nevertheless, plant quality management was eventually “sold” on the procurement of a state-of-the-art CT system that advertised rapid, high-resolution measurement capability and part-to-art interface with the CAD coordinate data for the casting. The CT system was installed and met with several challenges in operation. The only significant challenges are the barriers mentioned earlier: cost (compared to sawing the casting into slices), reliable or robust high-resolution dimensional data (compared to the previously installed coordinate measuring machine), robust maintenance and enhancement, speed (expectation elevated during lengthy purchasing decision making) and operational simplicity.

This example shows how state-of-the-art NDI technology can face several severe challenges when implementation is attempted or accomplished in an environment where its advantages over more robust and familiar methods are seen as marginal, and where the human resources on site may be unavailable or unable to provide the technical and operational support often needed, or where management commitment to the success of the new technology is not widely evident. On the other hand, rapid, operationally simple, automated, robust, reliable eddy-current and ultrasonic NDT systems, currently operating in many facilities, are excellent examples of time-tested NDI technologies that are at home in automotive manufacturing environments.

Conclusions: It is noteworthy that those NDT methods implemented in most automotive applications have

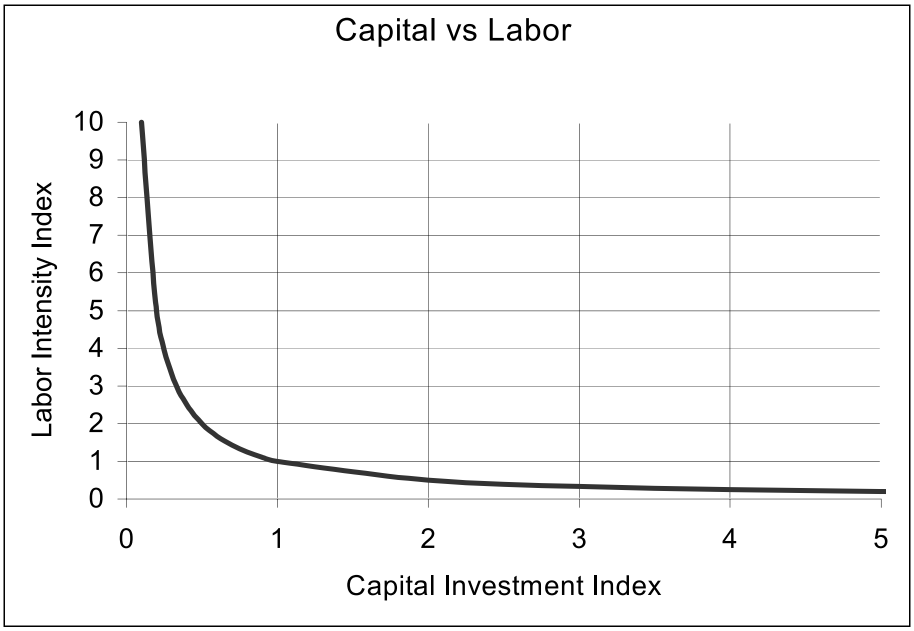

Figure 6. *A schematic showing the reciprocal relationship between test equipment costs the expected or required reduction in labor intensity. Corporate cost-reduction efforts push this curve ever closer to the origin.*

some obvious characteristics of labor costs and investment costs in common. The higher the test-equipment investment cost, the lower the labor intensity or operator cost and/or complexity is required to be, as shown in figure 6. The curve in figure 6 is one of a family of many such curves that graphically shows a nearly constant value for the product of labor intensity (LI) and capital investment (CI): LI x CI = K, a constant. The goal is to find or develop and implement the NDI technology that has LI, CI values along a curve that provides a minimum value of K and an effective yet rapid NDT methodology.

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