INFRARED MONITORING OF FRICTION WELDS AND ADHESIVE BOND CURING IN AUTOMOTIVE MANUFACTURING

G. B. Chapman, University of Windsor, Department of Physics, DaimlerChrysler NSERC Industrial Research Center, Windsor, ON, Canada

Abstract: The need for improving automotive assembly, energy-efficiency, performance, durability and quality is intensifying as customer demands and competitive pressures drive the industry toward unrelenting improvements in energy conservation, cost, quality and speed to market, without compromising the vehicle capacity, performance, appearance and affordability to which North Americans have become accustomed.

This presentation describes the need for and the development and use of infrared detection methods to assure the joint quality of friction welds in thermoplastic assemblies and to monitor adhesive bond-joint curing in metal assemblies. Some remaining barriers to the wider applications of this technology in the quality assurance of joints in automotive body structures will also be presented as indicators of further research and development opportunities.

Introduction: The use of infrared (IR) detection to monitor surface temperatures in order to determine the progress and state of thermally dependent processes is a well-known nondestructive inspection (NDI) technology in the automotive industry. It was an easy and short technology "leap" from the use of thermography for preventative-maintenance health monitoring of industrial machinery to use of thermographic NDI for process monitoring of manufacturing processes. The financial incentives for health monitoring industrial machinery for preventative maintenance are derived from two factors: (1) preventative maintenance can save repair time and cost and (2) it can also reduce or eliminate unscheduled production down time. Such clear financial incentives are worth noting when looking for opportunities to implement new or emerging technologies in cost-sensitive manufacturing environments. So, like health monitoring of industrial machinery, passive monitoring of thermally dependent processes was a "solution waiting for a problem".

A longer technology leap was required to move the technology from process monitoring to the post-manufactured interrogation of materials, parts and assemblies for flaws produced during manufacturing or service. This leap required a more sophisticated technological approach to thermal excitation of the specimen and analysis of the resulting signals in order to determine the nature, geometry and location of the anomaly. This information is needed to determine whether the anomaly or indication is an insignificant deviation in properties or a super-critical flaw that is expected to impact the performance or appearance of the component in service.

There are many applications of thermography and other forms of IR monitoring for NDI in industry. Examples of those that have been made a part of the public record appear in references 1, 2 and 3. Many other automotive applications exist that have not been published, but they are known by those working in the IR NDI community. Some of these have had a significant impact on the assurance of consistent quality and reliability in the welding and adhesive bonding processes. The significant impact of the NDI is indicated by the often-unfulfilled need for high reliability during the launch of new products and concomitant processes.

The need for the application of this non-contact inspection technology was made evident when friction welds used in the joining of a thermoplastic part were found to have inconsistent strength and were therefore unreliable during the early phases of initial production, or vehicle production launch. Because friction welding was used in several joining applications for automotive thermoplastic components, achieving process capability and maintaining process control was very important and posed a significant challenge when welding was done in an environment where humidity and temperature fluctuated widely. Therefore when 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, there was high-level interest, because high reliability in the weld joints of both these parts was required. Consequently, 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, shown in figure 1. This part 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 well-known automotive NDT criteria. These criteria imposed on automotive NDI technologies are captured by the often-cited “Three Rs” of the industry: (1) rapid enough to support 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 enough in cost to support the quality and value requirements of the industry. This means low marginal, material and operating costs and yielding a high value-to-cost ratio. A more complete discussion of NDT needs and requirements for the automotive industry are discussed in reference 4 and in paper 132 of these Proceedings.

This paper will report on IR NDI systems used for nondestructive testing of the aforementioned friction welds in thermoplastic assemblies, as well as the NDI for adhesive bond integrity in a composite body assembly and induction-heating-induced adhesive bond curing in sheet-metal assemblies.

Results and Discussion: The IR NDI system application shown in figure 1 could be implemented at low investment cost, with no interference to the welding process. Moreover, the system was passive, robust and operational simple. These characteristics fit the automotive NDT requirements well. Data showing the necessity of this process monitoring NDI method are shown in figure 2, 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 in adding value and was abandoned, as all NDI systems can be, after they have served their noble purpose of helping to quickly and cost-effectively bring about a reliable process that produce 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 3, with a cross-section showing the weld joints between the “I” section and the “C” section, forming a “D” section.

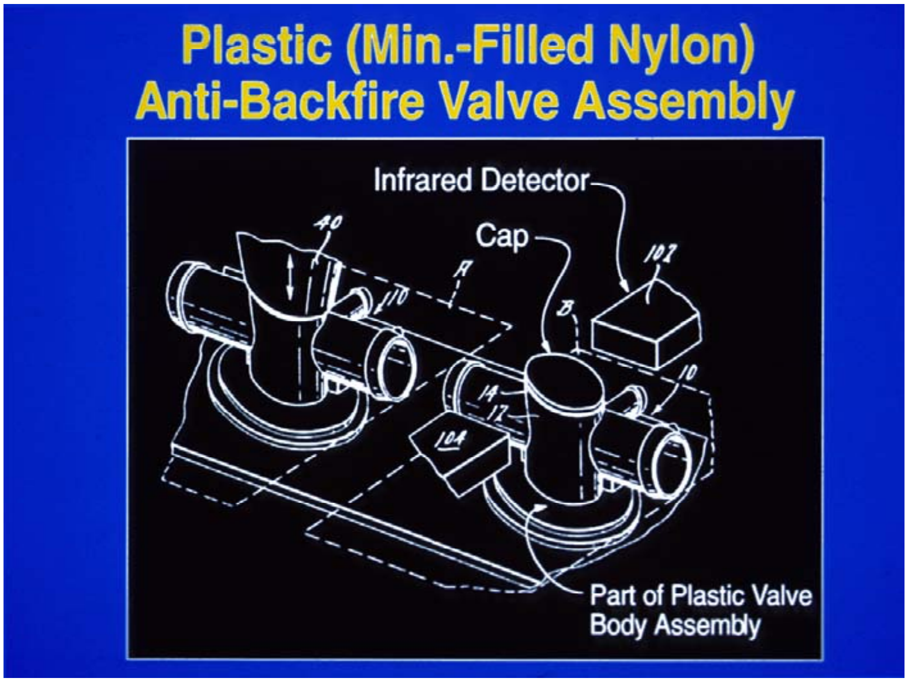

Figure 1. *A thermoplastic component being vibration welded at left and monitored for IR emission at right. Note vertical arrow indicating the motion of the 20 kHz ultrasonic horn pressed atop the assembly at left and the detectors to monitor the welded region of the assembly at right.*

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, all contributed to urging the pursuit of this NDI implementation, as

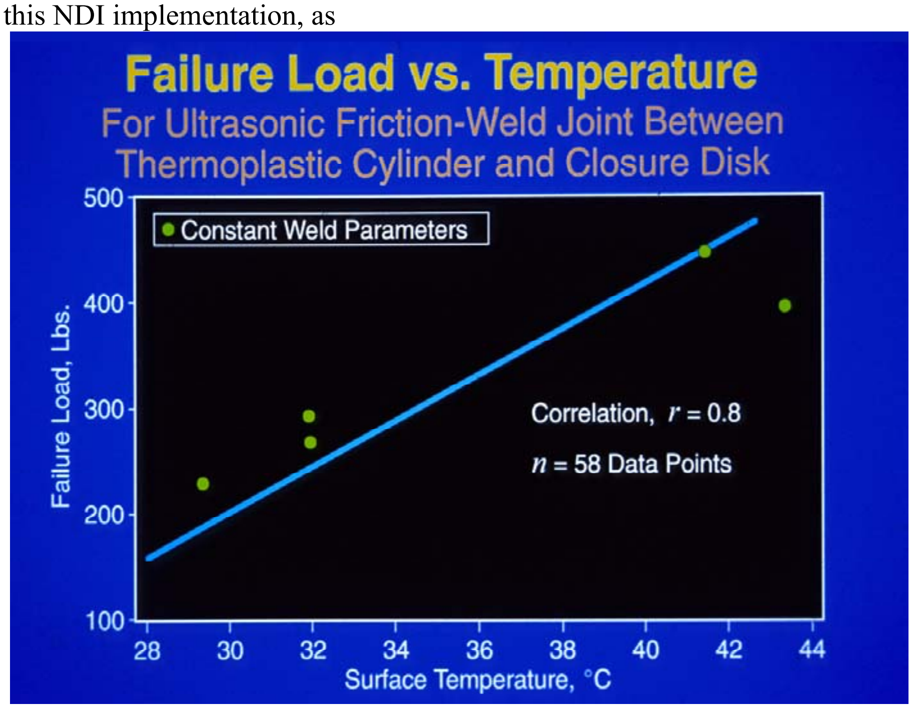

Figure 2. *Correlation of disk weld-joint failure load with surface temperature measured by IR 11 seconds after weld completion. Note the scatter among the four data points, shown as green dots,*

among the 58 data points represented by the regression line, thus indicating a need for an inspection method.

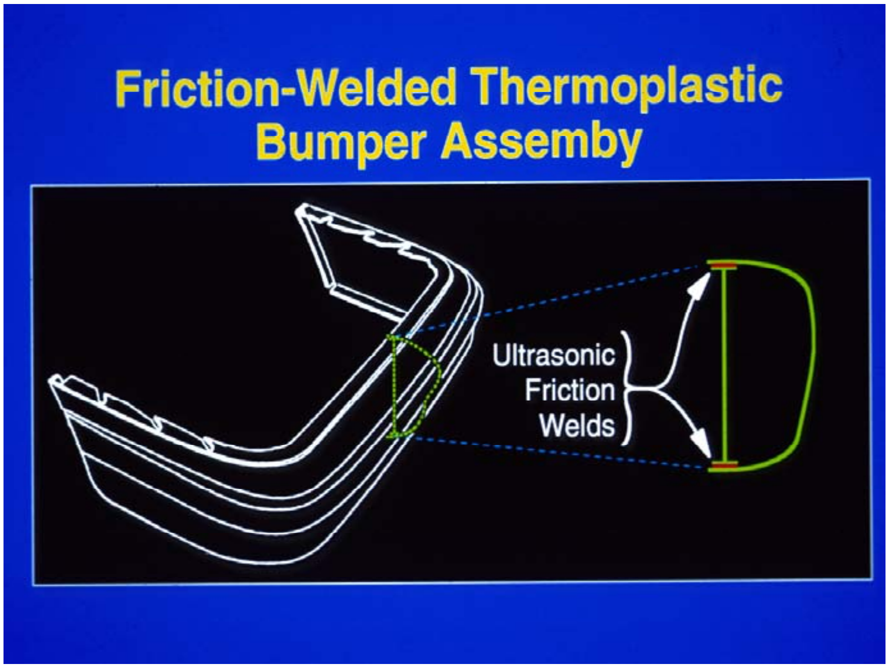

Figure 3. *A friction-welded chassis part inspected by an automated IR NDI system in production.*

well as to its eager support from management and the manufacturing sector. The high reliability requirement and
the large production volume planned for this part helped to justify the implementation of an expensive, sophisticated NDI system that monitored each region of the weld on each part and displayed the results, with critical criteria established for each region, in order to provide for quick process adjustment. Thus preventing the deterioration of the welding process beyond design limits. An experienced engineer was assigned on site to provide readily available, competent technical support and operational expertise. 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, with full support from all participants and stakeholder.

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 provided in references 1, 2 and 3. This thermal-wave imaging (TWI) NDE technology is effective as a materials characterization tool as well for finding flaws resulting from manufacturing processes or in-service stresses and exposures.

An automotive vehicle development project on which this thermal-wave imaging technology was applied was the Chrysler Composite Vehicle (CCV) shown in figure 4. This functional concept vehicle has a glass-fiber reinforced, injection-molded thermoplastic body on a metal frame. The four main body components shown in figure 5 are assembled and joined by adhesive bonding, then the assembled body is adhesively bonded to the metal frame, shown in figure 6. Mechanical fasteners are also added at critical locations along the approximately12 meters of body-to-frame bond lines. A TWI team of research scientists from Wayne State University inspected the adhesive bonds between body and frame. The graphic record resulting from their inspection was in good agreement with the data obtained from bond NDI by a 25 kHz acoustic method described in reference 5, and therefore supported a high level of confidence in both methods.

Although the comparison of the adhesive bond testing results with results from the 25 kHz bond NDT method showed great agreement, 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 field implementation success in aerospace applications, was not readily accepted for implementation 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.

Figure 4. The Chrysler Composite Vehicle (CCV)

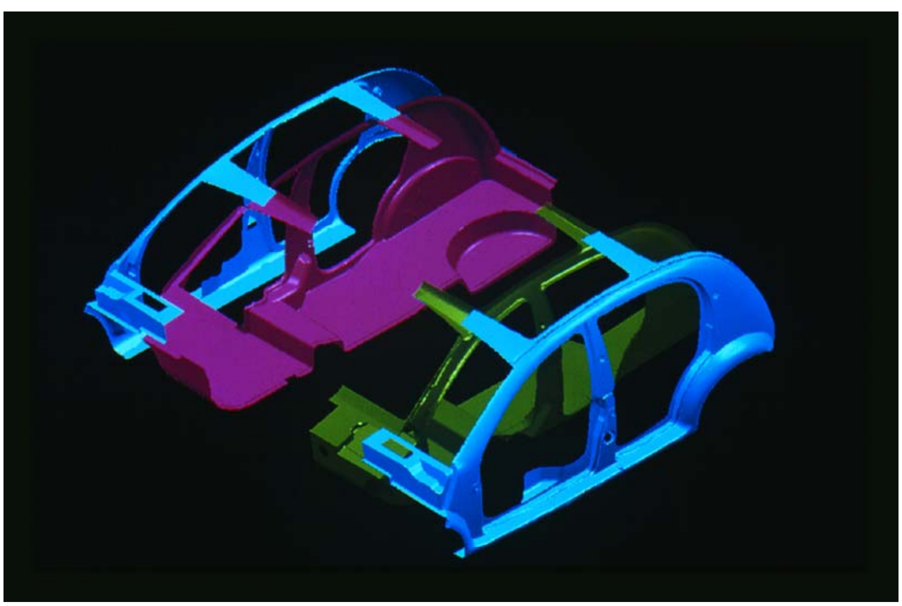

Figure 5. The four major injection-molded, thermoplastic CCV body parts before assembly

The use of an IR NDI system to monitor the curing of adhesive bonds was investigated when an inductive heating process that was used in a stamping plant to provide a "green-state" degree of cure to adhesive in adhesively bonded hem flanges of a large vehicle door. The door sub-assemblies were then shipped to an assembly plant nearly 200 miles away, where they were mounted onto vehicle bodies. The final vehicle assemblies were then painted and processed through hot paint curing ovens where the adhesive bonding the door hem flanges was cured to its final state. The design of this process for curing the adhesive was indeed clever, so long as the critical, inductively heated "green-state" cure part of the process was consistently uniform, robust and reliable.

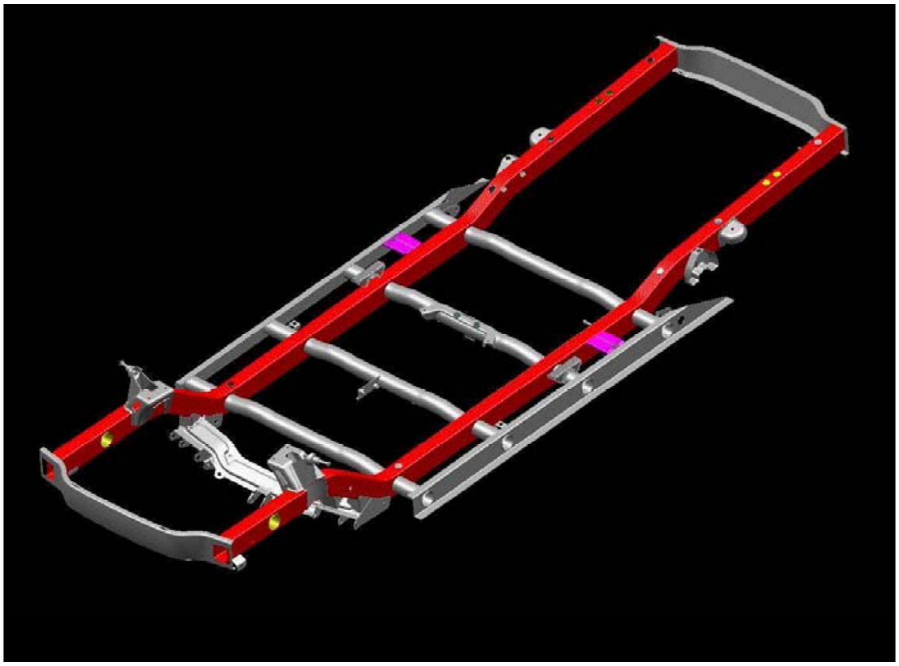

Figure 6. *The all metal CCV frame to which the body is bonded and mechanically fastened*

The high door-sag warranty on this vehicle was a clear indication that the "green-state" cure may not have provided the adhesive bond in the door hem flange joint with enough "green strength" to maintain the geometric integrity of the large door during subsequent handling, packing, shipping, unpacking and assembly of the doors before the adhesive was cured to its final state in the paint oven. The thermal image shown in figure 7 reveals a wide distribution of hem-flange temperatures that are provided for the green-state cure of the adhesive by the induction-heating process. The wide temperature variations were observed from door to door and within the doors that were monitored. Significant day-to-day and week-to-week variations were indicated by these observations, although not observed because of the limited time over which the study was undertaken.

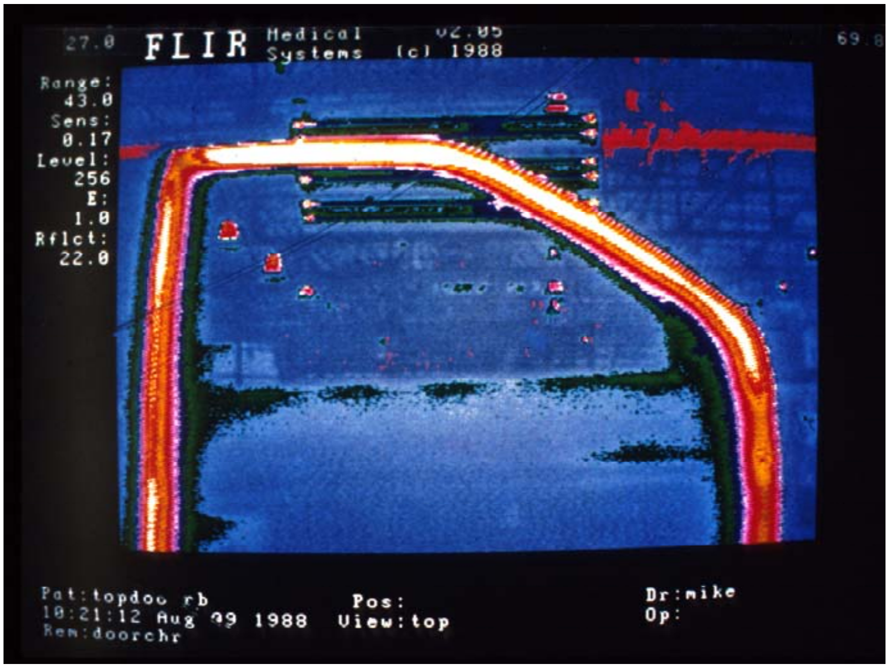

Figure 7. *The thermal image of a vehicle front door after the adhesively bonded hem flange has been thermally cured to a partially cured "green state" by inductive heating*

Conclusions: This final example, from a vehicle no longer produced, explains how windows of opportunity for the implementation of NDI systems can be identified when non-robust processes contribute to significant warrant costs and customer dissatisfaction. These can negatively impact, customer loyalty, future sales and profits. Whether unfortunately or not, it is often the job of the NDE-NDT-NDI technologist to demonstrate how the implementation of the technology can solve the quality problem at an early point in the process, before much more value is added. The technologist, or an ally, must also convince cost-sensitive management of the value of the implementation to their profit center. At the time the door hem-flange work was done, door-sag warranty cost was charged to the assembly plant, not to the stamping plant where the implementation was needed. Naturally, under the old "chimney" system of organizational operation, the stamping plant had little or no motivation to spend money from their tight budget to solve a problem that was not being charged to them, and the solution thereof would show no benefit to their profit center.

Thankfully, things have chanced and there are now quality management systems in place that bring more global resolution to what was incorrectly seen as a local quality issue. This underscores the obvious conclusion that quality issues must be addressed by the senior management of the corporation and quality management systems put in place that reward all levels of the company for quality improvements upon which profits and employment must ultimately depend. These obvious insights may help the technologist maneuver around, over or through the business barriers often encountered between the demonstration of the laboratory feasibility of the NDE technology and the implementation of the NDT or the NDI system in a manufacturing system. These insights will also help the technologist select the NDE research and development projects that are the most likely candidates for implementation.

There are other opportunities for IR NDI systems to be implemented for process and produce quality assurance. The attractive advantages of IR NDI systems are their ability to do passive non-contact sensing immediately after the heat-dependant process, with virtually no interference with the process layout. Some of these potential applications, however, still face technical barriers such as uniform and constant surface emissivity, reliable and affordable pattern recognition, and robust IR sensory systems. Continuous improvements in these and other areas of the technology will bring about increased opportunities for implementation in other manufacturing quality assurance applications such as casting, welding, injection molding and exothermal curing.

References:

1. Robert L. Thomas, Xiaoyan Han and L. D. Favro; "Thermal Wave Imaging of Aircraft for Evaluation of Disbonding and Corrosion" NDT.net, December 1998, vol.3, No.12; ECNDT'98
2. Xiaoyan Han, L. D. Favro. T. Ahmed, Zhong Ouyang, Li Wang, Xun Wang, Feng Zhang, P. K. Kuo and Robert L. Thomas; "Thermal Wave Imaging of Aircraft for Evaluation of Disbonding and Corrosion", Review of Progress in Quantitative NDE, Vol. 16, edited by D. O. Thompson and D. Chimenti, Plenum, New York, pp. 353-356 (1997)
3. Robert L. Thomas, L. D. Favro and P. K. Kuo; "Mechanical Properties of Materials by Thermal Wave Imaging", 24 July 1995. Storming Media Report Number A087003.
4. Gilbert B. Chapman II; "Polymer Composites for Improved Automotive Energy Efficiency", Symposium on Physical Sciences and Advanced Vehicle Technologies at the Annual Congress of the Canadian Association of Physicists; Toronto, Ontario, Canada, 8 June 20, 2000; Physical Sciences and Advanced Vehicle Technologies, Roman Gr. Maev.
5. Gilbert B. Chapman II; "Quality Systems for Automotive Plastics"; Chapter 10 of Composites Materials Technology – Processes and Properties , edited by P. K. Mallick and S. Newman; Hanser Publishers 90-38921, 1990