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INTELLIGENT PROCESSING CAPABILITIES OF ASC'S CPC SOFTWARE

The following paper discusses the specific ASC advances in intelligent process control of composites utilizing the industry-standard CPC (Composite Processing Control) control software.

TYPICAL CLOSED-LOOP CONTROL

Closed-loop feedback control of the cure cycle has been used for a number of years. Most composite cure cycles are controlled by this method today. Typically, these systems use thermocouples, pressure transducers, etc. to determine the process states and use them in feedback control loops to control the heaters, coolers, pressure valves, etc. of the process equipment as required to meet a specific time-temperature-pressure profile which was previously determined using laboratory test methods such as Differential Scanning Calorimetry (DSC), and/or Rheometric Dynamic Spectroscopy (RDS). Although changes are not made within a cure cycle, they may be made to subsequent cycles once the composite has been cured and evaluated. These systems can only blindly perform the pre-determined cure cycles and hence are incapable of dealing with variations in a real-world environment.

PROCESS MODELING

Process models have been developed which simulate the cure of a thermosetting material (e.g. Loos and Springer). These models use mass, momentum and energy balances to describe the manufacturing process. Use of these models has the advantage that they can be run repetitively at relatively low cost and can be used to investigate a variety of situations such as variations in processing conditions, part properties and geometry. However, they are generally based on a number of rather crude rheometric and kinetic assumptions and become less accurate at predicting what will occur at points further out in the future.

SELF-DIRECTED CONTROL USING RESIN-STATE SENSORS

More recent approaches have been proposed which employ a number of sensors, coupled to a computer, which can be used to alter the cure in real time based upon observed (e.g. thermal and/or rheological) changes (ie. Cure state) taking place in the resin. These approaches fall into the category of self-directed control. ASC has demonstrated that self directed control (ACCM) is possible using an industrial grade, robust control system.

The system of choice for this work was ASC's CPC system [1] which utilizes ASC's CPC software. Demonstrations were made for the cure of both epoxy and polyimide composites in an autoclave. The effort considered material variations stemming from excessive out time and standard lot-to-lot variations. It was shown that the process times could be substantially reduced while improving the part quality through the use of such a cure-state sensing and feedback system.

SELF-DIRECTED CONTROL FOR FIELD-LEVEL REPAIR

ASC has additionally applied this control strategy to Portable Field Level Repair [2]. Working with Boeing on an Air Force research program ASC designed, manufactured, and demonstrated the first intelligent, portable field level repair unit. ASC additionally designed and demonstrated a novel resin-state sensor that provides full-field monitoring of a composite patch. No other sensor is currently available to monitor the degree-of-cure of the entire patch bond-line. The benefits of ASC's CPC-based mobile repair station coupled with field-level repair include shorter repair times and higher quality composite repairs.

"PROACTIVE" CONTROL SYSTEM FOR COMPOSITES

The work described above uses self-directed functionality that is *reactive* in nature. A reactive system can only respond to real-time data supplied by sensors. These type of systems work well with real-time information, but are therefore incapable of controlling the cure of thick composites due to the inherent thermal lag of these parts and requirement that control actions be made well before time at which a sensor would provide a feedback of an undesirable cure state such as a run-away reaction.

To circumvent this shortcoming, ASC developed a *proactive* control functionality and incorporated it into its standard, industrial CPC software [3]. This proactive system has a predictive model imbedded in its control sequence, allowing the system to make control decisions based on not only real-time sensing, but future modeled expectations. This type of system can now deal with large time lags present in the cure of thick composite parts. Sensor inputs are used to update the cure-state and viscosity model predictions in addition to providing data for short-term/inner-loop feedback control of the process. This has a synergistic effect of minimize modeling error.

In validation cures on sub-scale composite parts, ASC was able to demonstrate the power of its "proactive" algorithms by predicting and controlling the future exotherm of the composite part more than 60 minutes in advance. No other system currently has this capability or feature. A major helicopter manufacturer is now investigating the feasibility of applying this proactive system for control of production presses curing thick composite yokes.

INTELLIGENT PROCESSING USING CPC

ASC’s intelligent processing research and work has always been based on our Composite Process Control software (CPC)[4]. CPC is a modular, PC-based, user programmable control package which readily accommodates incorporation of advanced control functionality and virtually any sensor. CPC is the most widely used software for composite process control in autoclaves, ovens, and presses. Over 500 systems are currently in operation throughout the world.

CPC is capable of multi-loop "cascade" control which allows for regulating one control parameter (e.g. autoclave air temperature) by measuring another (e.g. part temperature). The control strategy is expressed as rules in CPC's "curefile". These rules in the curefile are programmed in "segments" where specific criteria ("watch variables") must be met before control is passed to the next segment. For example, it is possible to specify that a dielectric loss factor must reach a predetermined value or trend before moving to the next segment. The watch variables also make it possible to revert back to a conventional time-based control scheme in the event of sensor failure. In addition, the software has a number of built-in features such as temperature-rate-correction control. The temperature-rate-correction control forces all part temperatures to be within a specified limit by automatically adjusting the heat-up and cool-down rates. This allows for optimal heat-up and cool-down rates in a process while avoiding unacceptable thermal gradients. CPC also has built-in features which force the system to recover and/or sound alarms when any specified variable's value is exceeded at any point in the process. The option to turn on or off data filters can be used on all of the input channels. Sensor data and equipment status information are saved to an output file at user defined intervals.

ASC’S INTELLIGENT CONTROL PHILOSOPHY

All of the previously mentioned *Intelligent Control* features are available in today’s CPC software. ASC has made the decision to keep these features transparent as not to over encumber or confuse the traditional equipment user. However, when invoked, CPC becomes a very powerful *Intelligent Control* system with un-matched advanced capabilities. ASC additionally believes that the best combination of sensors is a minimum set of highly reliably obtains the information needed. Although CPC can interface with virtually any sensor type, it has been our experience that the simpler ones will be the ones which are actually used by the “real world” users. ASC’s successes in this field reflect this mentality.

CONTRACTS AND PAPERS

The following table lists several contractual efforts which ASC has been a party to in the development of Intelligent Process Control of Composites.

Please find attached some of the final papers which present the findings of these contracts.

PROJECT	TECHNOLOGY
ADAPTIVE COMPOSITE CONTROL & MONITORING Buczek, Mason & Saunders DAAJ02-96-C-0052 (Subcontractor to Bell) Completed: May 1999 Contacts: Ed Lee (Bell) 817-280-2942 & Jon Schuck (US Army AATD)	Model-based corrective control (1) Advanced sensor selections & minimization
INTELLIGENT PROCESSING OF FIELD LEVEL REPAIRS Buczek, Mason, Westerman & Rutherford F33165-95-C-5618 (Subcontractor to Boeing) Completed: 1997 Contacts: Paul Rutherford (Boeing) 206-662-1949 & Francis Abrams (AFRL)	• Full-Field Resin State Sensing • Self-directed field level control • Demanding Application
RTM PROCESS MONITORING & CONTROL Buczek, Mason, Et-Al F33615-96-C-5054 & F33615-97-C-5018 Completed: 1997 & 1998 Contacts: John Russell & Francis Abrams (AFRL)	• Zonal heating/control • Multi-port (valve) control • Flow Front monitoring & control • High temp/pressure environment
SELF DIRECTED PROCESS CONTROL Buczek, Lee & Mason, 1995 Contact: Bill Lee (UDRI/AFRL)	• Advanced sensor based control • Trending, event based logic/control
COMPOSITE PROCESSING CONTROL (CPC) ASC's Primary Product, 1990-Current Contacts: e.g. Bill Lee (UDRI/AFRL) A detailed list will be made available on request.	• Autoclave, Press, RTM, CVD Control • 100s of Systems Installed • Alarms, checks, etc. (industrial use) • Almost always a custom installation

References

1. Buczek, M.B., and Lee, C.W., "Self-Directed Process Control of Epoxy Matrix Composites," Proc. of the 40th International SAMPE Symposium, 1995, pp. 337-351.

2. Buczek, M., Mason, D., and Rutherford, P., "Self Directed Cure Control of Composite Material Field Level Repairs," Proc. Of 30th International SAMPE Technical Conference, San Antonio, TX, October 1998.

3. Buczek, M.B., Mason, D., Lee, C.W., and Saunders, A., "Proactive Control of Curing Composites," Proc. Of 44th International SAMPE Symposium, Long Beach, CA, May 1999.

4. www.aschome.com