Manufacturing Challenges for Smart Processing

David Crawford

The following is an edited transcript of the plenary talk presented by David Crawford at the Smart Processing of Materials session of the 27th International SAMPE (Society for the Advancement of Materials and Process Engineering) Technical Conference in Albuquerque, New Mexico, October 10, 1995.

My assignment is to provide some industrial insight and examples into how smart processing is being applied to solve actual manufacturing problems. As our product and technology development efforts wind their way into production, the old paradigms *higher*, *faster* and *farther* are still in place, but a new paradigm, *cost*, is forcing tradeoffs to be made, especially in manufacturing.

In response, Pratt & Whitney has set three major goals which impact *speed*, *cost* and *quality*. Not long ago we were targeting 18–24 months to actually get an engine out. We now target about four months. Spare parts used to take 30 days; we're talking hours now. Development of hardware used to take 36 months; now it takes less than 12 months. The idea of smart processing primarily relates to achieving certified processes which consistently produce defect-free parts at a high rate of speed. It means one-piece flow through the processing steps which is the key to being the low-cost producer. So, how does smart processing help us achieve certified processes?

Smart processing relates to understanding the physics and behavior of the processing elements which include the material, tooling, and equipment. This understanding can be gained via expensive and time-consuming experimental work; however, today's computer simulation tools enable us to gain a deeper understanding than time and money would not permit if we relied only on trial-and-error. To give an example, we recently used computation approved dynamics modeling to redesign a high compressor, P&W 4084 engine that powers the Boeing 777. This was done in preparation for the 90,000 lb. plus version of the engine which would normally have taken about three years to build the necessary hardware and test rigs. However, computer simulation reduced the time to 12 months.

Within Pratt & Whitney, we view process simulation as a strategic technology. In many cases, our manufacturing engineers can understand the science which underpins our processes. We use computer-aided-design (CAD) tools to model the geometry of a workpiece and tooling, then we use finite-element computer-aided-engineering (CAE) tools to simulate process behavior as a function of time, temperature, and pressure.

In summary, smart processing by using process simulation offers numerous benefits. It helps us develop innovative new manufacturing processes and to optimize current processes. Our speed is improved both in terms of faster production throughput and quicker introduction of new designs. The best way to understand the strategic value of this technology is by reviewing a few examples of our applications.

During the past 10 years, we applied process simulation to all of these applications and developed a small team of specialists who worked closely with manufacturing engineers and with materials engineers. In a few instances, such as for disk forging, we trained manufacturing engineers to do their own process simulation. Some of our materials engineers are beginning to use this technology to predict process metallurgy and to help them design more effective alloys.

The disk forging application from the mid-1980s was widely publicized and involves simulating metal flow for simple two-dimensional axisymmetric forging. The technology is used throughout the U.S. forging industry including our factory in Georgia. Today, our forging engineers routinely perform the process analysis work, manage the first piece production, and frequently make a perfect part on the first try. Previously, disk forging was troubled by excessive cost and lead time due to development by trial-and-error. Computer simulation of metal flow to predict cavity fuel, laps, and optimum shapes provided a solution.

During the early 1990s, we performed U.S. Air Force-funded contract work to help a small software company develop a tool for simulating ring rolling. This is a two-and-a-half-dimensional problem in which metal is being squeezed thinner as it flows laterally into the shape of the rollers. Today, the capability is fairly robust but not widely used. We occasionally assist our ring suppliers when they have a problem like die breakage. We are slowly moving toward more net-shape-rolled rings for both thin sheet and for thick cross sections.

Blade forging involves both three-dimensional metal flow and behavior relating to thermal distortion during the cool down phase. We forge compressor blades to net-shape which requires us to account for thermal distortion in our die design. We can do the thermal analysis for distortion but the metal flow analysis is not affordable or timely. The solution to the problem of thermal distortion during postforge cool-down is to simulate heat transfer, predict distortion, and redesign dies to compensate for distortion. Several commercial software products are on the verge of offering a combination of three-dimensional automated mesh generation and metal flow analysis but none are currently adequate.

We improved the curing of a composite engine vane by using simple two-dimensional thermal analysis to optimize the die design. We used process analysis in combination with other technologies to achieve adaptive process control. The result was to reduce a curing cycle time from an hour-and-a-half to one-half hour which approaches the chemical cure limit of the composite material which is a graphite epoxy. The problem of excessive curing time due to nonoptimal heat transfer was resolved by simulating transient thermal response to a complex current cycle to optimize tooling design.

A more challenging three-dimensional thermal process analysis relates to stimulating behavior during solidification to produce a single-crystal turbine blade. We began developing the capability in

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the late 1980s with a general-purpose finite-element code. We were able to do this type of analysis but with excessively high labor cost and time. Today, commercially available software is emerging which is specific to this application and our casting suppliers are working hard to take advantage of this capability. The problem is single-crystal blades require complex molds and gatings to avoid metallurgical defects, premature nucleation, unwanted grains, and voids. Simulation of molten metal, solidification, shrinkage, and thermal behavior in ceramic mold offers a solution.

Welding represents one of the grand challenges for process analysis. Since the early 1990s, we have been working closely with scientists in the Department of Energy to develop this capability. Among the challenges are a small area of metal and solidification, modeling of material properties, and the effects of local geometric features and tooling, plus the requirement for affordable parallel processing to perform the complex thermomechanical analyses. Solutions are found in simulating the manufacturing process during molding, melting, resolidification, and subsequent distortion.

Process simulation has been an essential technology to develop new manufacturing processes for our hollow fan blades on the Boeing 777 and the military F-22 Advanced Tactical Fighter. On the Boeing 777, these titanium blades are four feet long with intricate cavities inside, and they must be robust enough to handle birds and large balls of hail.

Manufacturing process simulation begins with the cavity design in the blade. Through simulation, researchers can follow how blade cavities will deform during superplastic forming to the final shape.

The manufacturing process begins with large, thick plates of titanium which are machined to contoured shapes that are then diffusion bonded to create a flat blade. Creep forming is used to twist the blade before a final forming operation at superplastic temperatures. Since 1987, we have been applying process simulation to support process development which involves a variety of thermal and metal flow analyses as well as modeling of the equipment used to perform these processes.

Process analysis was used to understand the complex interaction of the press, the bonding dies, and the workpiece as the material is squeezed and plasticity occurs during a lengthy bond cycle.

The superplastic final forming occurs in a vacuum furnace press. Process simulation was used to understand metal flow and cool down distortion. The result of this processing step is a near-net-shape blade. Process simulation capabilities enabled us to develop processes for hollow fan blades used in the Boeing 777.

As we analyze and apply analytical models to manufacturing processes, we are truly engaged in a transition from art to science. Our workforce is slowly evolving as we learn to rely more on process simulations that require fewer costly experiments.

*In the mid-1980s our process simula*tion engineers learned a valuable lesson. Their simulations could target the ideal process variable and design optimal tooling but if process variation was not controlled and thoroughly understood, the simulation effort was a waste. One of our major efforts is called process variability so that first piece quality is high with no tailgate inspection. Today, our process certification work initially focuses on controlling variation, then seeks deeper knowledge of the process physics to redesign the process.

Our experience has also told us that we have only begun to fully exploit this technology. To date, most of our focus has been on understanding process physics. We are now beginning to use this technology to predict resultant metallurgy and to have an impact on upstream design decisions which must be matched to process capability. The impact of this technology on part and process quality cannot be understated. Our latest data has shown that the cost of poor quality is anywhere from 25 to 40% of the part cost which is a long way from the "old" perception of only a 5% penalty.

Our experience has shown us how to acquire, develop, and deploy the technology of process simulation. In general, this must be tailored to the nature of our manufacturing processes and our organizational design.

***David Crawford** is the director of manufacturing technology at Pratt & Whitney. He received an MS degree in science management from Rensselaer Polytechnic Institute.*

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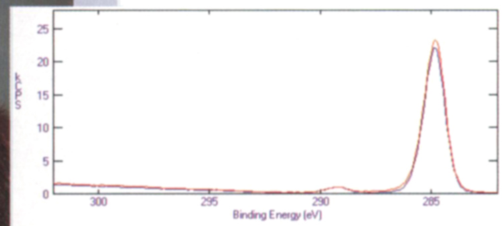

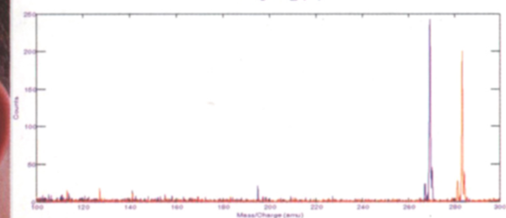

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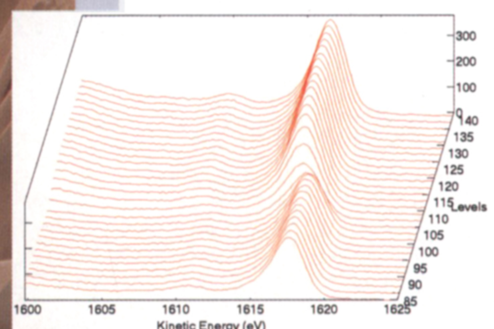

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Tel. +44 1342 327211, Fax. +44 1342 324613
e-mail: sales@surface.fisons.co.uk

AUSTRALIA. Rydalmere. Tel. (2) 898 1244
AUSTRIA. Vienna. Tel. (43) 1 52326110.
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