Vertically-integrated manufacturing chain optimization in a connected laboratory

Gariepy, Alexandre; Nadeau, François; Idriss, Mohamad; Gagnon, Marie-Christine; Simard, Stéphan

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Manufacturing of modern structural aluminium components in the automotive sector involves a series of interrelated operations that each contribute to the quality of the products. The industry keeps pushing the envelope of individual processes through dedicated research and development (R&D) and introducing new processes to meet the continuing challenges of lightweighting and the new ones of electromobility and sustainability. While such isolated optimization of each step can certainly provide a robust chain, there may be missed opportunities or unexpected issues arising when one step changes. Looking at the manufacturing chain as one entity can shed light on interrelations between processes.

Over the last five years, experts from the National Research Council of Canada's (NRC) Aluminium Technology Centre (ATC), located in Saguenay, Canada, carried out increasingly intricate projects which involved two or more processing steps to develop methods suitable to handle the increasing complexity of process chain optimization. These large-scale, long-term projects are part of the NRC's Advanced Manufacturing program and led by the METALTec industrial R&D group, with funding from the *Centre Québécois de la Recherche et Développement de l'Aluminium*, Natural Resources Canada, and through the contribution of the METALTec industrial partners.

The NRC's METALTec industrial R&D group

The METALTec industrial R&D group was established in June 2020 with the objective of building a research community that catalyzes innovation in the metal fabrication sector in the digital era. The group has 32 active participating companies and 22 partners and academic collaborators who share the cost, risks and benefits of pre-competitive research projects. The pre-competitive R&D activities are focused on the participating companies' common priorities to:

- improve manufacturing processes to increase productivity and agility,
- create smarter, more complex and functional, and higher value-added products by advancing materials, processes and enabling digital technologies, and
- reduce the environmental footprint associated with the manufacture of metal products.

METALTec catalyzes innovation by creating a research community with participants from across the value chain, from raw material suppliers, equipment suppliers, secondary transformation as well as tier 1 and tier 2 producers to major vehicle manufacturers. The intellectual property (IP) generated in the group's research projects enhance the innovation capacity, productivity, and help create sustainable value-added products of partner companies in the manufacturing, assembly and durability assessment of advanced components. All participating companies get access to confidential results, and a non-exclusive license on the IP developed on an ongoing basis and also at the group's annual technology transfer meetings and projects specific technical sessions.

Digital laboratory infrastructure

Activities conducted at the NRC's Aluminium Technology Centre rely on a growing supervisory control and data acquisition (SCADA) architecture progressively deployed throughout the laboratories (Figure 1) for process monitoring and to ensure traceability of data and specimens across manufacturing and characterization. The inherent challenges of Industry 4.0 were also a development track in their own right as the expertise gained by implementing systems across a range of processes can enable the NRC to support the industry in their digital transition. This began in 2018 by implementing conventional data acquisition on existing stamping and die casting cells to generate part-by-part data, and leveraging native outputs from equipment such as the die-casting machine and welding systems. Data analysis was then conducted on an offline, after-the-fact basis. As Industry 4.0-compatible programmable logic controllers and equipment were upgraded or added, direct data collection to a facility-wide relational database was incrementally implemented through Open Platform Communications (OPC) and other industrial ethernet connectivity, which brought an online analysis capability. Monitoring of process nominal parameters as well as actual responses is controlled through the Ignition® platform, which also allows design of user interfaces to handle labour-intensive, difficult-to-automate tasks such as materials tracking or visual inspections. At this time, the implementation is deliberately limited to read-only operations, but it is worth noting that many commercial devices natively support writing capabilities.

Figure 1: Industrial-grade process cells at the NRC: high-pressure vacuum die casting (left) and robotized gas-metal arc welding (right)

Recent completed projects

The NRC's first effort into a cyber-physical production system (CPPS) in 2020 focused on the manufacturing chain optimization for tailor-welded, hot-stamped AA7075 aluminium alloy. This combination of high-strength alloy and forming process enable complex, lightweight and structural automotive components [1]. On the other hand, this alloy is well known to be prone to stress-corrosion cracking (SCC), especially in its highest-strength T6 temper. The purpose of the project was therefore to identify the most important process characteristics that would impact the part quality at each production step, with a focus on corrosion resistance, and evaluate how accurately process measurements could predict the service performance of a given part, or even a region of a given part. The NRC rallied a multidisciplinary team of experts in data analytics, welding, forming, corrosion and project management with the support of METALTec participating companies involved in each step of this process chain. To minimize the breadth of experimental testing, individual steps of friction stir welding (FSW), hot stamping, and heat treatment were first investigated on their own in incremental trials to isolate critical parameters. This included expert-driven feature engineering from machine outputs to calculate statistical indicators that simplified the subsequent analysis [2]. Tests then continued based on the lessons learned by addressing potential interactions between each step. Throughout the project, specimen performance was quantified with visual inspections in accelerated degradation tests in the NRC's environmental chambers as well as real-life exposure. From a relatively small set of 2,000 specimens tested from 220 prototype parts, process windows to produce defect-free components were defined. Selection and tuning of machine learning models allowed refinement to maximize the SCC resistance, minimize distortion, and maximize the yield strength of the component.

Nevertheless, optimization of a process chain as a whole, leads to a very high-dimensional design space when potential interactions between steps are to be addressed. While expert knowledge and theoretical background can help to identify relevant interactions *a priori*, optimization models and methods designed for small datasets remain relevant tools for process chain commissioning as conducting extensive design of experiments can become expensive. The NRC and the Fraunhofer-Gesellschaft (IWU) research institute in Chemnitz-Germany recently began a collaborative project to apply the Institute's numerical expertise in leveraging small datasets [3,4] to the NRC's rich database to investigate the efficiency gain of more complex predictive models.

In parallel, another three-year METALTec initiative focused specifically on an Industry 4.0 toolbox for structural aluminium die casting. Thin-walled, high-integrity high-pressure vacuum die casting (HPVDC) is a lightweighting enabler and is continuously gaining market share in more affordable segments in the automotive industry [5]. Large-scale die casting, often referred to as mega/giga-casting, is now adopted by many vehicle manufacturers, especially in the EV market, to produce functionally-integrated components that minimize assembly operations. While the NRC's 530-ton die casting machine cannot rival with 4000-ton-range structural or 8000-ton-plus giga-casting facilities, its connected cell enables focused small-scale R&D without interrupting companies' time-sensitive production activities when they wish to validate the potential of a technology before implementing it in their large-scale industrial facilities. Structural die casting is by itself a process chain with multiple sequential operations [6] that were quantified with a growing data collection framework. The transition from a 1990s-era controller to a modern, OPC-compatible controller first enabled tracking of process parameters ("recipes"), and more recently machine behaviour, to streamline experimental activities by reducing the manual documentation burden. Basic scripting paved the way to implement an older engraver to facilitate part tracking at the fast pace of the process. The connected cell was fitted with a range of sensors, both commercial and experimental, to minimize the unknowns in this complex process. The R&D cell proved to be a valuable asset to test the potential benefits, measurement challenges, and durability of possible sensor solutions in a representative environment. As this process is highly reliant on robotics for peripheral operations, data collection was also implemented on the robot controllers. This infrastructure enabled research activities spanning the process lifecycle. The first focus was the design stage, in which simulations are a critical tool for the industry to get the expensive tooling right the first time. Microstructural and process (e.g., heat transfer, die spray, etc.) models were calibrated and validated based on the experimental data, including extensive optical and scanning electron microscopy [7]. The second field was process monitoring and correlations between process, microstructure and properties for an Aural™-2 alloy. In this case, the characteristic of interest was the mechanical properties, especially the ductility, as this is a common requirement for structural castings. In addition to performance variations as a function of deliberate process changes, the project was interested in the within-part and between-part variations in nominally stable production, which takes up most of the process lifecycle. The latter proved to be a challenge to predict from process data alone, as it appears there are inherent stochastic factors in this net-shape process where a complex die cavity is filled in a few tens of milliseconds before the material rapidly solidifies as a heterogeneous media. This brought non-destructive testing, especially ultrasound-based methods intended for high-integrity components, as the third aspect of the project towards a feedback loop on the process.

Ongoing effort: durability of multi-alloy assemblies

Building on these activities, the NRC is now integrating a different chain of manufacturing processes and refining the hardware and software tools that make up cyber-physical production systems through another significant METALTec project initiated in 2023. This project focuses on welding of Aural™-5 structural high-pressure vacuum die castings to high-strength wrought and extruded (AA6082) aluminum alloys, examining again their response in terms of environmental durability (Figure 2). This material combination is typical in many vehicle designs, especially for large components such as battery enclosures to best use the advantages of each material form. The project explores a range of candidate welding processes under one roof (Figure 3), including robotic gas metal arc welding (GMAW), laser cold-wire welding, and friction stir welding (FSW), providing the convenience of a one-stop-shop for direct comparability.

Process variations typical of a production environment for each manufacturing step are replicated to generate a comprehensive dataset. As HPVDC or extrusion operations are not very conducive to efficient, single-digit specimen production batches, the strategy adopted in this project is to group focused trials based on available experience, and batch-process characterization activities to extract important lessons. For HPVDC, this can include, for instance, the die lubricant type or concentration, vacuum level, or melt quality [8]. For welding, heat input was identified as the most critical factor aside from the welding processes themselves. A few abnormal, extreme cases are also deliberately included for the sake of modelling: one example is the first few warm-up shots with a colder die, low injection velocity and reduced pressure. Given the part-to-part variations observed in HPVDC, individual specimens were carefully dispatched to each welding variant, based both on measured process responses and non-destructive testing, to enable as much as possible apple-to-apple comparisons. These comparisons start on a short-term basis, with quantification of the post-weld porosity or defects in the assemblies. As one key objective is to measure long-term durability of selected specimens in a short-term process optimization framework, laboratory-scale environmental durability procedures are developed to accelerate product and process design for the aluminium industry to keep up with the shorter vehicle development cycles (Figure 4). This lab-based characterization will be complemented by real-life exposure on the road based on the NRC's extensive experience to provide a validated toolset for fast durability optimization. With this information, NRC researchers can develop artificial intelligence (AI) based models that predict the expected environmental durability quality from production data. By controlling each process step in-house and seizing opportunities to quantify relevant features such as the cleaning operations between casting and welding, unknowns and uncertainties are minimized and the global chain of manufacturing steps can be optimized together to maximize the expected environmental durability, potentially reducing the risk of corrosion-related recalls which have been a significant challenge in the automotive industry for many years.

As a cyber-physical production system’s purpose spans into the “production” phase which should represent most of the process lifecycle, a key deliverable in this project is the development of sensor and numerical tools that can contribute to autonomous process monitoring, to facilitate operators’ tasks and let them focus on high-value activities in the plant. For instance, for the GMAW process, robust traceability between and even within assemblies enables local correlations between process parameters, as-cast porosity, welding signals, and measured post-weld porosity to develop machine-learning-based anomaly detection routines. In HPVDC, small-scale production signals provide the basis to explore similar anomaly detection models at a limited scale, and the connected equipment allows for dedicated trials to evaluate specific questions submitted by industrial clients, such as excessive moisture detection solutions. Finally, the variety of experimental platforms also opens the opportunity to evaluate the transferability of methods between process configurations, or even between processes, so that shared underpinnings of a cyber-physical production system can be identified to accelerate practical deployment.

Figure 2: Example of aluminium transformation processes operated at the NRC: high-pressure vacuum die casting (left), gas-metal arc welding (middle) and laser welding (right)

Figure 3: Simple welded assembly specimens from first phase of the project focusing on durability of welded structural castings

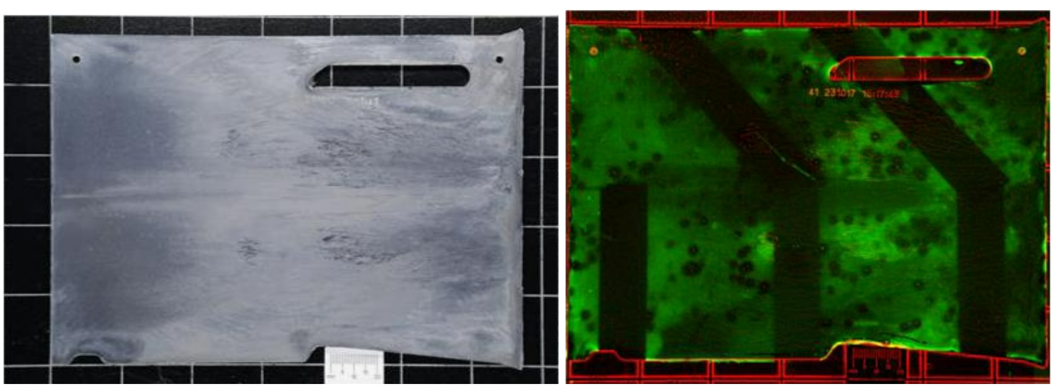

Figure 4: Early attempt at identifying corrosion-prone sites on a simple Aural™-5 die-cast specimen

Scaling up the data analytics

A recurring theme in the last five years has been the generation of robust, reliable, and traceable process data, a prerequisite for any data science initiative. Without this process data environment, these projects would be much more difficult, if not impossible, to conduct. The production-oriented data infrastructure has given the NRC an advantage in industry-relevant topics such as real-time quality control, for example to study early anomaly detection capabilities from various sensors in welding to reduce defect rates and improve part quality. While production and data volumes remain small in the NRC's R&D environment, the basic methods developed on a small scale could be extended to larger industrial facilities to deliver impactful solutions to a range of manufacturing sectors.

The data collection and analysis activities have led to a variety of off-line optimization and monitoring algorithms. The next logical step is to bring these to real-time, on-line deployment, or, in other words, to start giving more control to the machines. The development needed to achieve the autonomy and robustness characteristics of a cyber-physical production system represents new engineering challenges to ensure safe and predictable behaviour. The system must be able to handle the real-life noise, occasional outliers, and unexpected events of a production floor. This is a strategic research track at the NRC on a range of processes from robotized welding to HPVDC. Small-scale, focused initiatives have already started laying critical technical foundations, such as running increasingly complex Python® codes from the Ignition® SCADA architecture. Another important technical step will certainly be to assess the stability of remote OPC write capabilities to commercial equipment, where collaboration with suppliers is paramount.

Future outlook

The NRC's Aluminium Technology Centre (Figure 5) is currently upgrading its welding, foundry, and characterization laboratories to introduce 4.0-ready machines as well as advanced process monitoring equipment to continue its path towards demonstration of safe, robust automated process feedback. Data represents considerable value for advanced analytics. One area of focus is to replace tried-and-true but labour-intensive or subjective solutions, such as the Reduced Pressure Test or K-mold test for hydrogen and inclusions in aluminium die casting or visual inspection and compliance with some facets of relevant codes (CSA, AWS, ISO) in welding, with quantified, preferably real-time, metrics. The goal is to be ready to help the industry addresses the new challenges of, for instance, maximization of secondary aluminium in structural die casting or real-time assessment of defective welds at the welding cell preventing service failures on battery components. In addition to the quality aspects that are key for scrap reduction, process data could also become a key piece of information supporting quantification of the carbon footprint of a given product that is becoming a common commercial requirement [9].

Figure 5: The multidisciplinary R&D staff at the NRC collaborating to support the aluminium transformation industry's process innovation and digital transformation

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Links:

The NRC’s METALTec industrial R&D group: nrc.canada.ca/en/research-development/research-collaboration/industrial-rd-groups/metaltec-industrial-rd-group

The NRC’S Advanced Manufacturing program: nrc.canada.ca/en/research-development/research-collaboration/programs/advanced-manufacturing-program

The NRC’s Aluminium Technology Centre - National Research Council of Canada: https://nrc.canada.ca/en/research-development/nrc-facilities/aluminium-technology-centre