A Path to Recovery

Ramping Up the Aviation Industry

sensXPERT

EXPAND your sense of the possible

Global connectivity and technological advancements are defining characteristics of contemporary times, and the aviation industry stands as a testament to that human innovation and transformation.

From the phenomenon of powered flight, as actualized by the Wright brothers, to present-day breakthroughs in aerospace engineering, the aviation industry has reshaped the human perception of distance, time, and opportunity.

The success of the aviation industry is not only evident through its technological advancement, but also through the consumer demand and revenue it has generated. For instance, the global airline industry has an estimated market size of 841.4bn U.S. dollars in 2023 [1]. To put into perspective the size of the industry, the expectation is that, with global aircraft units having been 25,578 in 2022, the number of units will rise to 38,189 by 2032 [2].

While advances in aircraft design and navigation are significant factors in the industry's ongoing development, one considerable contribution is that of plastics and composites manufacturing. By integrating lightweight, durable, and high-performance materials, aviation manufacturers have pushed aircraft efficiency and innovation to new heights.

According to Airbus, "The use of composites provides significant benefits to aircraft operators in the form of fuel savings, weight reduction, fatigue and corrosion resistance and extended in-service life" [3]. Therefore, there has been mounting demand for the manufacturing of plastics and composites for aviation applications such as control panels, structural components, cabin interiors, windows, and more.

Unfortunately, following the outbreak of the COVID-19 pandemic, the entire industry was dealt a handful of challenges.

The COVID-19 pandemic was a period during which the aviation industry was burdened by heavy restrictions – on air travel and factory operations for example - and economic loss. In the case of air freight, on the other hand, there was greater demand for the transportation of goods such as personal protective equipment (PPE), medication, and e-commerce-driven sales during the pandemic [4]. Therefore, while passenger flights faced significant operational decrease on account of flight cancellations, cargo airlines experienced increased use and greater profits [4].

Following the pandemic, easing restrictions resulted in high demand for passenger flights, transporting both cargo shipments and consumers looking to travel. Therefore, to cope with the recovery of global air travel and to satisfy the demand for more aircraft units, aviation manufacturers such as Airbus and Boeing are aiming to ramp up production. Nonetheless, preparing for the large volumes these manufacturers hope to produce means that several considerations regarding material science and processes have been under investigation.

For one, many long-established manufacturing processes have proven to be too labor intensive and time-consuming to keep up with the desired production volumes.

Additionally, these lengthy processes can lead to difficulties in maintaining cost-effective production.

As a means of evading these issues, aviation manufacturers have been discussing the introduction of new processes and materials in their production. Despite that, the aviation industry is tied to a multitude of regulations and qualification requirements that must be adhered to. Thus, introducing new processes and materials also introduce lengthy and difficult qualification processes, which can come in the way of an accelerated production ramp up.

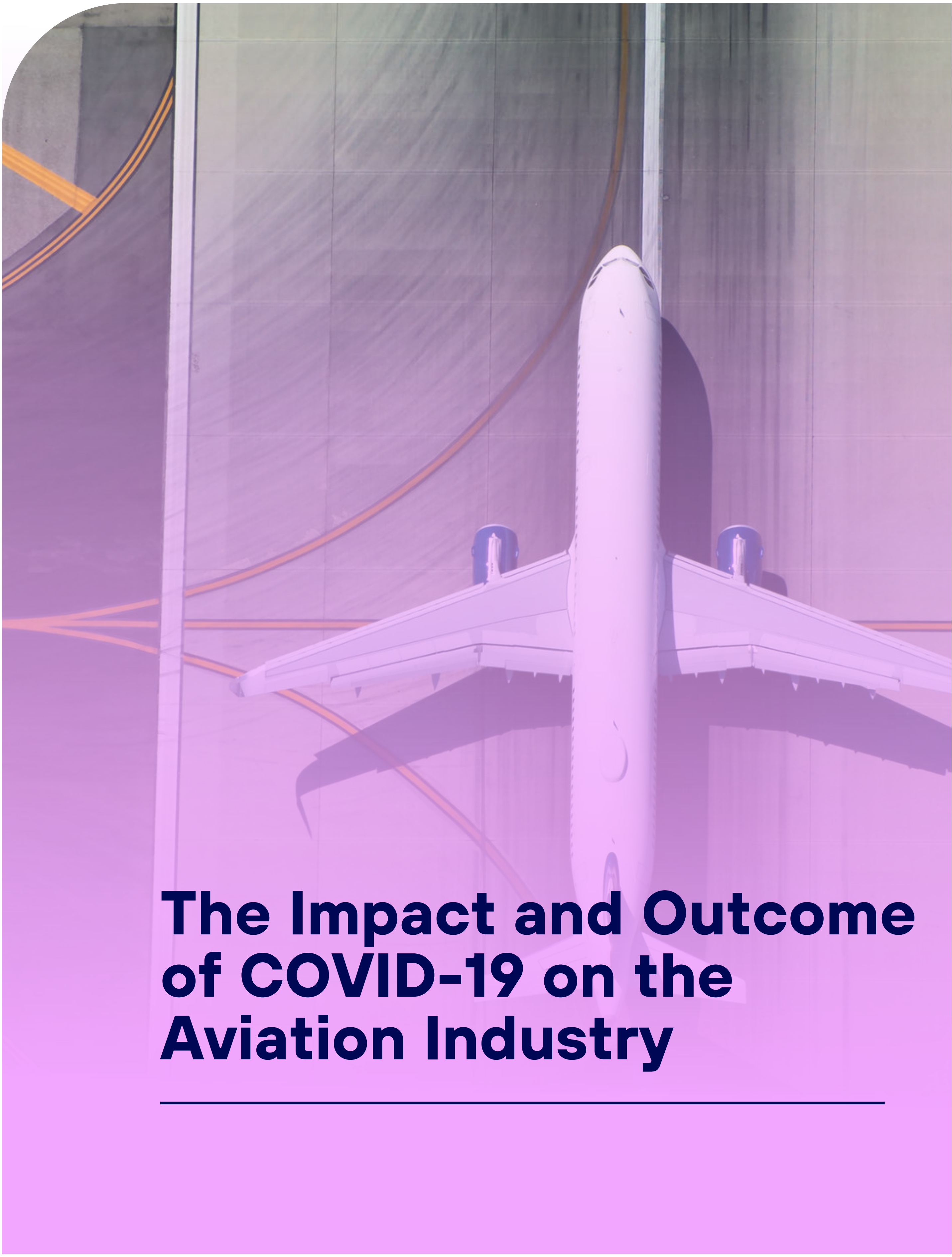
Fortunately, there are existing solutions that can help manufacturers combat these challenges, automation being one of them.

Throughout this white paper, you will find a more in-depth exploration of several challenges encumbering the aerospace manufacturing industry, along with insight on the use of automation technology to address a few of those challenges. More specifically, we will cover the following:

- The impact and outcome of COVID-19 on the aviation industry
- Dealing with heightening demand with a production ramp up
- A historical lens on aviation manufacturing
- The established autoclave process
- The use of automation to enhance pre-existing processes
- Other advantages of automation

Finally, we will present a case study on a leader in aviation manufacturing and how they used sensXPERT Digital Mold to digitize their composites manufacturing.

White Paper Contents



The Impact and Outcome of COVID-19 on the Aviation Industry

Having emerged in early 2020, the COVID-19 pandemic created unprecedented challenges for most industries. Regarding the aviation manufacturing industry, the pandemic temporarily led to a huge decrease in demand, causing supply chain interruptions, financial losses, and workforce detriments.

The onset of the pandemic triggered a sudden and severe decline in global air travel. As a result of lockdowns, travel restrictions, and passenger reluctance to fly, numerous airlines slashed their fleets and cancelled new aircraft orders. All of this led to a cascading effect throughout the aviation manufacturing supply chain, which caused delays, layoffs, and significant revenue losses for manufacturers.

As reported by McKinsey & Company, aviation manufacturers were burdened by a loss of 12 billion U.S. dollars in 2020 [4]. With airlines facing major financial disadvantages, less new orders were placed, and more deliveries were suspended or postponed. McKinsey & Company also recounted that "[orders for commercial aircraft dropped by around 55 percent in 2020 from the previous year's level, while the number of deferred aircraft deliveries increased fivefold" [4].

This financial strain led leading aviation manufacturers to reevaluate their production schedules and workforce numbers. The results were substantial layoffs and voluntary retirements, and many smaller manufacturing companies operating at a significantly reduced capacity or facing temporary closures. Consequently, there were large global supply chain disruptions, causing delays in critical component and material deliveries to aircraft manufacturers. This further exacerbated production challenges.

Following the alleviation of COVID-19 lockdowns and restrictions, demand for air travel began to rise. This can be exemplified through the increased demand for airline tickets, which "was back to around 100% of pre-pandemic levels in May 2023" [8]. Accordingly, airlines resumed orders for new aircraft and production rates increased, thus spurring manufacturers into addressing supply chain disruptions, enhancing production efficiency, and economically recovering.

Heightening Demand and Ramping Up Production

The aviation manufacturing industry is led by a few big players, namely Airbus, Boeing, Embraer, and Bombardier. Following the pandemic, the recovery in air travel and consumer demand added pressure on these market leaders to perform. Overall, industry players are looking to gradually increase the rate at which they manufacture aircraft, as they expect to see a continued rise in demand. In the case of Airbus, the company intends to "increase production to close to 1,000 aircraft per year" by 2025, more than double the amount they produced in 2022 [5]. These ambitious production goals not only intensify pressure on the manufacturers, but also have significant implications for the entire aviation supply chain.

For instance, by placing large orders to adhere to their production goals, OEMs and tier 1 suppliers – such as GKN Aerospace - create a surge in demand for raw materials and various required components. Raw material suppliers, in this case, can face strain in their own supply chains by trying to meet the surplus of orders, potentially leading to delays and shortages if not effectively managed. Additionally, suppliers along the supply chain may also face constraints in the capacity they have to fulfill the high number of orders.

Aviation manufacturers themselves are confronted by many challenges in their goals of ramping up production, a skilled workforce shortage and financial considerations being a couple of them.

Following COVID-19 and the ensuing layoffs, the aviation industry has been dealing with the consequences of a skilled workforce shortage. As will be later explained, manufacturers consistently look to build upon innovative ideas and to advance technologically, which makes their desired workforce a very select, niche few. At the same time, the sector is contending with an aging workforce. In the U.S, for example, "more than one-third of mechanics are between 55 and 64" in the airline industry [6]. Therefore, there is a great number of people approaching retirement and a lack of people with an equivalent skill set looking to work in the aviation industry, thus creating a large skills gap.

Moreover, there are considerable financial resources required to ramp up production efforts. Substantial investments are needed to expand production lines, purchase new equipment, and attempt to hire additional workers. The previously mentioned financial loss during the pandemic made cash flow management crucial for manufacturers.

Beyond the skilled workforce shortage and financial limitations, long-established materials and processes have been under investigation to prepare manufacturers for the large volumes they intend to produce.

A Historical Lens on Aviation Manufacturing

The aviation industry is ripe-full of advancements and transformation. Materials and processes have evolved ever since the development of the first powered flight by the Wright Brothers in 1915, which was built out of wires, canvas, wood, and steel. The 1920s and1930s saw a material transition to metals such as aluminum. This was seen as a metamorphosis into lightweight and durable aircraft manufacturing.

The post-war period saw even more material advancements with the introduction of titanium, a material that is resistant to fatigue, corrosion, and high temperatures. However, titanium quickly proved to be very costly and limited in availability. First used in the 1940s, "[g]lass fibre-reinforced plastic, or fibreglass, was the first lightweight composite material to be found in aircraft" [7]. An evolution towards the use of carbon fibre marked the material landscape of the 1970s to 1980s, and, in our present day, carbon fibre-reinforced composites have become standard in aviation manufacturing, especially due to their lightweight properties.

Advantages of Lightweight Composites

The primary advantage of lightweight composites is that they have a high strength and stiffness to weight ratio. Structures made of composite materials, such as carbon fiber-reinforced polymers, can be designed to be significantly lighter than traditional materials like aluminum or steel. Additionally, a lighter aircraft generally requires less fuel to achieve and maintain flight, which leads to lower operating costs and reduced environmental impact.

Despite their low weight, composite materials are known for their exceptional strength and stiffness, so their structural integrity and performance is not compromised. This means that they can withstand the structural stresses and loads encountered during a flight, as well as increased pressure, compression, and tension. Composites are also corrosion resistant, which increases an aircraft's lifespan and can lower maintenance costs.

Aviation manufacturing processes also have a rich history of technological advancement. During World War I, a time of wood and canvas material usage, skilled woodworkers and experienced sewers created parts – such as wooden frames and skins for wings and fuselages - by hand. When metal became the material of choice, processes adapted accordingly. This included the manual cutting, shaping, bending, and forming of metals, as well as employing processes such as welding and flush riveting. With the rise of composites, the traditional metalworking machinery became overcast by other machinery, such as the autoclave.

Contemporary times see autoclave curing as a nearly indispensable manufacturing process for the production of large polymer composite parts in the aviation industry.

The Autoclave Process

As a long-established manufacturing process, autoclave currently represents a bottleneck in the aviation industry. An autoclave is a sealed chamber in which materials are put under controlled high-temperature and high-pressure conditions. To cure the resin in composite parts for aviation applications, a part is often placed under vacuum in an autoclave, which is then pressurized during a part's temperature-controlled curing cycle. The entire process ensures an even cure, as well as curbs potential voids or imperfections in the resin.

Following a curing cycle, the autoclave slowly cools down. This controlled cooling phase is enacted to prevent thermal stress and maintain the structural integrity of the composite components.

Regarding the current production ramp up goals in the aviation industry, autoclave is a costly, labor-intensive process that is not fast enough to keep up with the demands for an increased rate of aircraft production.

Therefore, aviation manufacturers are looking to break the mold and investigate alternative processes such as resin transfer molding or compression molding to manufacture more components at a faster pace. However, these new introductions bring with them additional challenges, such as long and complex qualification processes, which can hinder the goal of ramping up production.

Alternative Process Considerations

Resin transfer molding (RTM) and compression molding are a couple of process examples that are under consideration as alternatives to autoclave [5]. However, to move away from the autoclave, these alternative process considerations have to be rigorously qualified to ensure their feasibility and reliability.

Resin Transfer Molding (RTM)

RTM is a closed-mold, liquid composite molding process that injects resin into a mold with pre-formed dry reinforcement materials - which could be fiberglass or carbon fiber – to produce composite parts.

This process begins with the preparation of two mold halves designed to create the desired shape and dimensions of the final composite part. The dry reinforcement materials are precisely placed in one of the mold halves and are strategically layered to achieve the desired strength and performance characteristics. The two mold halves are then securely clamped to one another, thus enclosing the dry reinforcement materials within the mold cavity.

A liquid resin system - often composed of a mixture of epoxy or polyester resin and curing agents – is then injected through runners and gates into the mold under controlled pressure. The dry reinforcement material is infiltrated by the resin to create a solid composite structure. To cure the resin, high controlled temperatures are applied to the mold contents. After the curing cycle is complete and the composite is hardened, the mold is opened, and the final composite part is demolded.

With qualification procedures requiring a considerable amount of time, the integration of new manufacturing processes that were not previously used in aviation part manufacturing can come in the way of an accelerated production ramp up.

Therefore, by placing greater emphasis on the development and optimization of pre-existing, qualified processes, manufacturers can begin reaching their production goals faster than they would through the exploration and lengthy qualification of alternative processes.

Fortunately, the advent of Industry 4.0 led to the development of technological solutions that can assist aviation manufacturers in enhancing pre-existing processes and upholding their recovery goals.

Using Automation to Enhance Pre-Existing Processes

Automation is one such development which can enhance the capabilities of pre-existing, qualified processes like autoclave. Additionally, technology that improves process tracking and provides access to material characterization data can further manufacturing transparency and enable manufacturers to optimize their pre-existing processes.

Automation technology can improve data monitoring in pre-existing processes through the use of advanced sensors and real-time data analysis. Advanced sensors can continuously collect real-time data, which can be transmitted to software for data analysis. Algorithms can then be applied to detect anomalies or deviations from desired parameters, thus enabling immediate adjustments or interventions if necessary.

Furthermore, manufacturers can implement automated control systems that adjust machine settings according to the development of each individual process cycle. For instance, automated systems can perform dynamic process adaptation if certain cycles are deviating from desired outcomes.

Other Advantages of Automation

Automation can offer several other advantages in manufacturing. One advantage is increased productivity. Production output can be significantly increased, as automation can operate constantly without a need for breaks. Additionally, tasks that require repetitive, monotonous action can be performed by automated systems, thus reducing production cycle times. Therefore, people that had previously carried out these tasks can gain the time to focus on higher-value tasks.

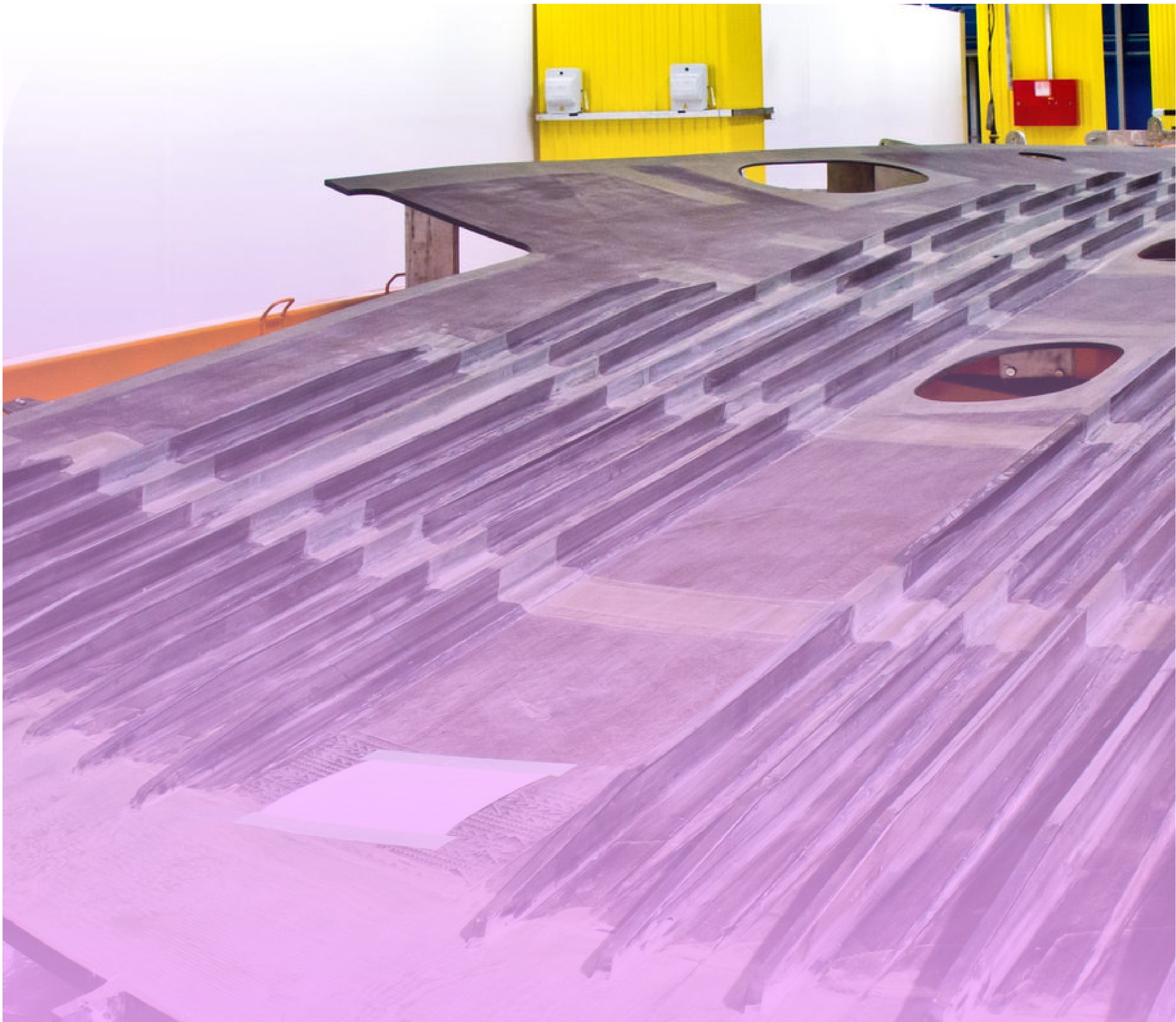
Correspondingly, automation reduces reliance on a specialized, skilled workforce, which is advantageous when manufacturers are facing a shortage of skilled workers.

Automation technologies also aid manufacturers in maintaining consistent production levels even when facing skilled workforce shortages.

Furthermore, automation can lead to improved quality and consistency. Through precise control and accuracy, automation can minimize errors and defects in manufacturing processes, and decrease scrap production. Another advantage is the capability of automation technology to collect vast amounts of data in real-time, which allows for greater process monitoring and analysis.

Beyond reduced labor costs, increased productivity and quality control, automation allows for better resource allocation to ensure that resources like raw materials and energy are efficiently handled. At the same time, such technologies can lead to reduced material waste, as they can measure and utilize materials with precision. Therefore, raw material costs can be lowered.

Automation presents a multitude of other advantages, but on the whole it addresses the challenges of a shortage in skilled workers, financial recovery, and the optimization of pre-existing materials and processes.



Case: Digitizing Composites Manufacturing in the Aviation Industry

With the aim of investigating the impact of automation and digitization on production efficiency, a leader in aerospace manufacturing implemented the in-mold process monitoring system by NETZSCH Process Intelligence GmbH. Otherwise known as sensXPERT Digital Mold, the process monitoring system examined the in-mold material behavior of structural composite aerospace parts to detect potential deviations and avoid part rejection in post-process quality assurance (QA) tests.

Composite Part Specifications

The monitored composite part is used for fuselage support and is composed of woven carbon fibre fabrics infused with RTM6-1 (HexFlow® by Hexcel Corp). RTM6-1 is a type of aerospace-grade epoxy. This material combination is typically used in the aviation industry, specifically in (vacuum-assisted) resin transfer molding, or (VA)RTM for short. This specific part is large and has different thickness-levels throughout its structure. During initial investigations, 45 fuselage support parts were produced using sensXPERT Digital Mold.

Manufacturing Insight

Two major processes are involved in the production of the aerospace parts, namely VARTM and autoclave. To effectively cure the parts, VARTM is conducted with a target Degree of Cure (DoC) of 80%, and the post-mold autoclave process with a 95% secondary DoC target. Between the VARTM and autoclave cycles, a cool-down, or hold, period is carried out.

VARTM is a process in which a vacuum is applied in resin transfer molding. To start, the aviation part manufacturer cuts dry-fiber fabric and manually places them into the molding tool.

After closing the mold, the RTM6-1 - composed out of a premixed epoxy resin and a hardener – is injected into the mold. The average cycle time for VARTM is about 110 minutes (~ 2 hours). As a means of avoiding deformation and stress on the part during demolding, a slow cure at low temperatures is implemented.

When VARTM is completed, the parts are at a temperature of about 150°C and take several hours to reach a safe enough temperature for demolding. Therefore, the cool-down/hold period is a necessary step in the production of these parts. During the cool-down period, the parts continue to cure. When they reach temperatures of about 50°C or lower, they are cool enough to be safely demolded – for the protection of the workers handling the parts – and they will have reached a DoC of at least 80%.

The final process in the molding of these parts is autoclave post-curing. In this part of the process, several parts enter an autoclave. The molding cycle only begins once the autoclave chamber is filled. Once this cycle starts, the parts are exposed to predetermined pressure and temperature levels to attain a target DoC of around 95%.

The Problem

The entire manufacturing process consists of long cycles and hold periods to prevent scrap and defective parts. Generally, manufacturers implement longer cycles to guarantee reaching their desired DoC. A couple of reasons for this are limited insight into in-mold material behavior and a lack of process transparency, which make it difficult to detect deviations in material behavior and process parameters. However, longer cycles result in greater energy expenditure, higher costs, and overall slower production.

Additionally, long cycles can come in the way of abiding by a production ramp up. Furthermore, the VARTM to autoclave process is a labor intensive one in which workers have to manually demold parts and move them into the autoclave.

These difficulties can be countered by implementing process control technologies to increase transparency, optimize processes, and improve production efficiency.

The Solution

The sensXPERT Digital Mold comes into play where digitization and real-time material characterization data can help optimize manufacturing processes.

The Digital Mold solution was developed to reliably predict in-mold material behavior and help manufacturers implement dynamic process adaptation in their production cycles. sensXPERT provides real-time cure monitoring, which can be used to determine the optimal time for demolding.

How it works...

The sensXPERT system is comprised of four main components; material characterization sensors with dielectric analysis capabilities, an accompanying edge device, an edge device interface, and a digital Cloud service.

The material characterization sensors are positioned in the mold and can withstand a range of pressures and temperatures. Compatible with several manufacturing processes – including but not limited to (reaction) injection molding, VARTM and autoclave curing – the sensors can measure the behavior of various materials, such as thermosets, thermoplastics, rubber, fiber-reinforced polymers, and more.

When using sensXPERT, manufacturers gain insight into several in-mold material and process parameters throughout the entire cycle.

Examples include,

- Degree of Cure (DoC),
- Percent polymerization,
- Glass-transition temperature (Tg),
- Viscosity and flow-front position,
- Temperature inside the mold,
- and material deviations – which can be caused by aging, out-of-spec material, the presence of contaminants, pre-molding storage conditions, etc.

The sensors are connected to an edge device that is positioned outside, but nearby, the mold. An all-in-one powerful IPC and dielectric analyzer, the edge device collects all machine data and process parameters. The edge device interface then visualizes all active processes and implements machine learning (ML) and predictive algorithms to provide real-time cure monitoring and determine the optimal point of demolding. In doing so, manufacturers can view and adapt their processes in real-time.

Additionally, all data collected by the edge device is transferred to a manufacturer's sensXPERT Digital Cloud Service account following a completed production cycle. In the Cloud, all collected data is stored, visualized, and compared with historical process data to assess various quality indicators. Cloud data is also used to train ML algorithms and optimize them for process outcome predictions on the edge device.

All in all, the entire sensXPERT system ensures the digitization of and full transparency in molding cycles. Part processors can use sensXPERT to account for optimal curing points and potential in-situ process or material behavior deviations. By moving QA testing upstream, manufacturers gain more process stability and can avoid final part defects.

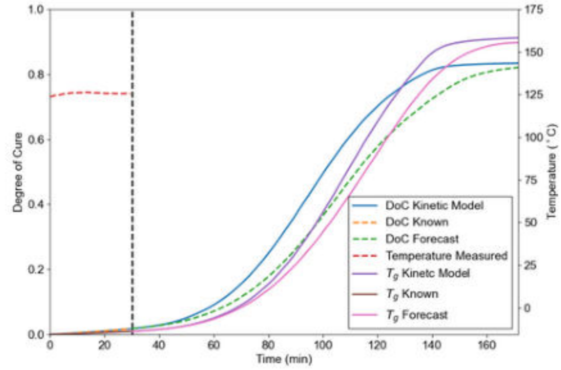
sensXPERT X Aviation Results

To train the predictive algorithm – specific to this aviation part manufacturer's process -, data from 20 VARTM cycles was collected and used to train an ML model. Using the material characterization sensors, sensXPERT collected dielectric analysis data for several minutes to calculate the DoC via kinetics and the ML model.

A way of mathematically describing chemical reactions at specific temperatures, a ***kinetic model*** *presents the speed of cure and is used by sensXPERT to determine the optimal point of cure.*

Correspondingly, the ML model is trained to forecast process curing outcomes. Following a completed cycle, the ML model's forecast was compared to the DoC calculated using a kinetic model. This was done to ensure accuracy and validity in the predictions.

Figure 1 illustrates how the longer a process is measured the more accurate its prediction becomes. In this case, after 20 to 50 minutes of measurements, sensXPERT accurately forecasted the outcome of the cycle. Furthermore, as predictions develop in real-time, new data is promptly fed into the ML model. Thus, the model is constantly updated.



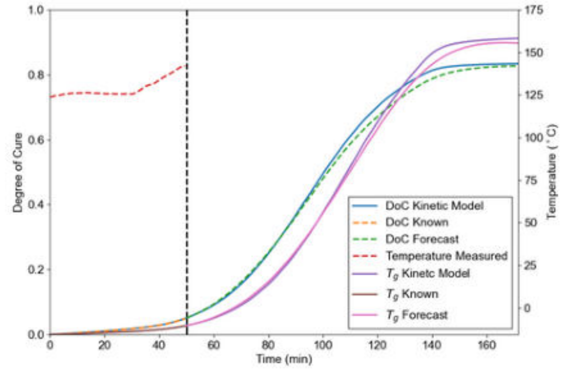


Figure 1 depicts predictions for DoC and Tg. The forecast is compared to the kinetic model. Top: Forecast for DoC and Tg after 30 min. Bottom: Forecast for DoC and Tg after 45 min.

In this production process, DoC and Tg were the outcomes used to predict part performance. For greater prediction accuracy, additional factors, such as temperature and dielectric response were also used to develop the predictive ML algorithm.

Through their collaboration with sensXPERT, the aviation company gained transparency in their processes and, consequently, production data that enabled overall process optimization. By improving their process transparency, the aviation company also came by four major benefits, namely a digital thread per part produced, reduced manual labor, strengthened quality control, and cycle flexibility.

PROCESS TRANSPARENCY	
DIGITAL THREAD	With the sensXPERT Cloud Service, manufacturers have access to all historical data on each part produced using the sensXPERT solution. Data on everything that occurred in-mold, such as temperature and pressure levels, cycle times, DoCs, etc., is recorded on the Cloud. Therefore, should any part defects or issues be detected in downstream quality testing, the responsible process engineers or machine operators are able to provide a digital file illustrating how each part behaved during processing. Furthermore, with the enforcement of the EU Taxonomy Regulation in 2020, companies are generally required to provide documentation on their contribution to the climate and environmental objectives as laid out by the regulation. Therefore, in having a digital file automatically generated for each part produced, companies can more easily adhere to the Taxonomy Regulation and comply with documentation requirements.
REDUCED MANUAL LABOR	Process digitalization and the digital thread are also beneficial in reducing the amount of effort required for manual process tracking and quality control. In other words, those responsible for physically recording cycle times, temperatures, pressure levels, and more, gain more time to perform other tasks.
QUALITY CONTROL	Generally, manufacturers carry out quality sampling on their products, meaning that a sample of an entire batch is tested for defects or issues. With the sensXPERT solution, real-time quality control can be conducted on each part produced rather than a sample, as the system can detect when certain parameters or behaviors are out of the ordinary. Therefore, intensive quality testing, and the high costs associated with them, can be reduced.
FLEXIBILITY & DYNAMIC PROCESS ADAPTATION	Due to the predictive capabilities of the process monitoring solution, manufacturers can dynamically adapt their processes should any deviations occur. Additionally, by accurately predicting when desired DoC targets will be reached, cycles can become more flexible. Based on the DoC predictions, machine operators can decide to decrease or increase cycle times to achieve their DoC targets.

Overall, the sensXPERT process monitoring system allowed for real-time process adaptation, especially with the advantage of only needing up to 50 minutes - which is about 45% of an average VARTM cycle - to forecast the rest of the cycle. sensXPERT created an opportunity for process visualization and the ability to remedy deviated parts before they moved downstream. Flexibility in the cool-down/post-curing period was another added benefit. Furthermore, an advantage of Digital Mold lies in its creation of a digital thread for each part produced, which is beneficial for quality control and general reporting.

The aviation company was able to digitize its manufacturing process, gain real-time process insights, acquire significant potential in cycle time savings, and secure historical data on every part produced in collaboration with sensXPERT. This case revealed that more complicated production cycles with various production stages - such as the ones carried out in aerospace part manufacturing - can be equipped with technology that generates greater process understanding, efficiency, and transparency.

Digitizing manufacturing processes with sensXPERT Digital Mold leads to a number of advantages, some of which are,

- Cycle time reduction
- Scrap Reduction
- Lower energy usage
- In-mold transparency
- Cost control
- Efficient production
- Digital thread that offers traceability on each part produced.

Conclusion

The COVID-19 pandemic impacted a wide range of industries, one of them being aviation. The aviation industry is in the midst of a challenging period of production recovery and ramp up. On the road to recovery, aviation manufacturers are attempting to combat cost pressure, shortages in a skilled workforce, bottleneck processes, and production delays. Therefore, the need for a greater digital transformation, through the implementation of automation technologies in manufacturing processes, to address these challenges has become evident.

Technologies, such as sensXPERT Digital Mold, can play into the industry's goals of ramping up production and delivering a high-volume of aircraft over the next few years. The sensXPERT solution is compatible with multiple composite and plastics manufacturing processes in the aviation industry, including both pre-existing and alternatively considered processes. Therefore, the solution can make processes like autoclave curing and resin transfer molding more efficient and transparent. Additionally, the easy integration of the Digital Mold solution ensures process optimization and productivity from the get-go.

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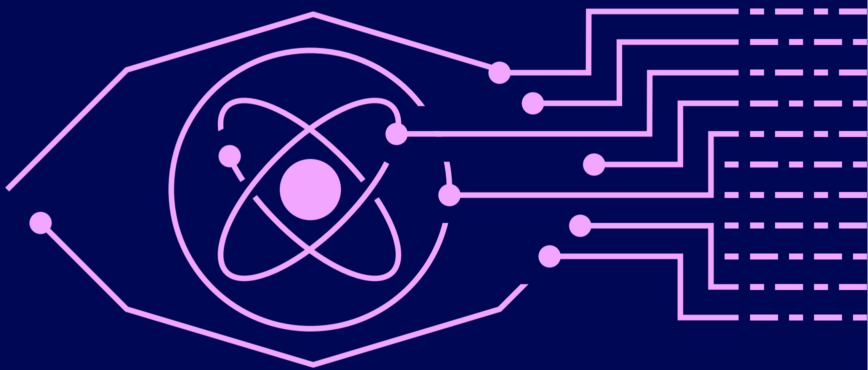

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