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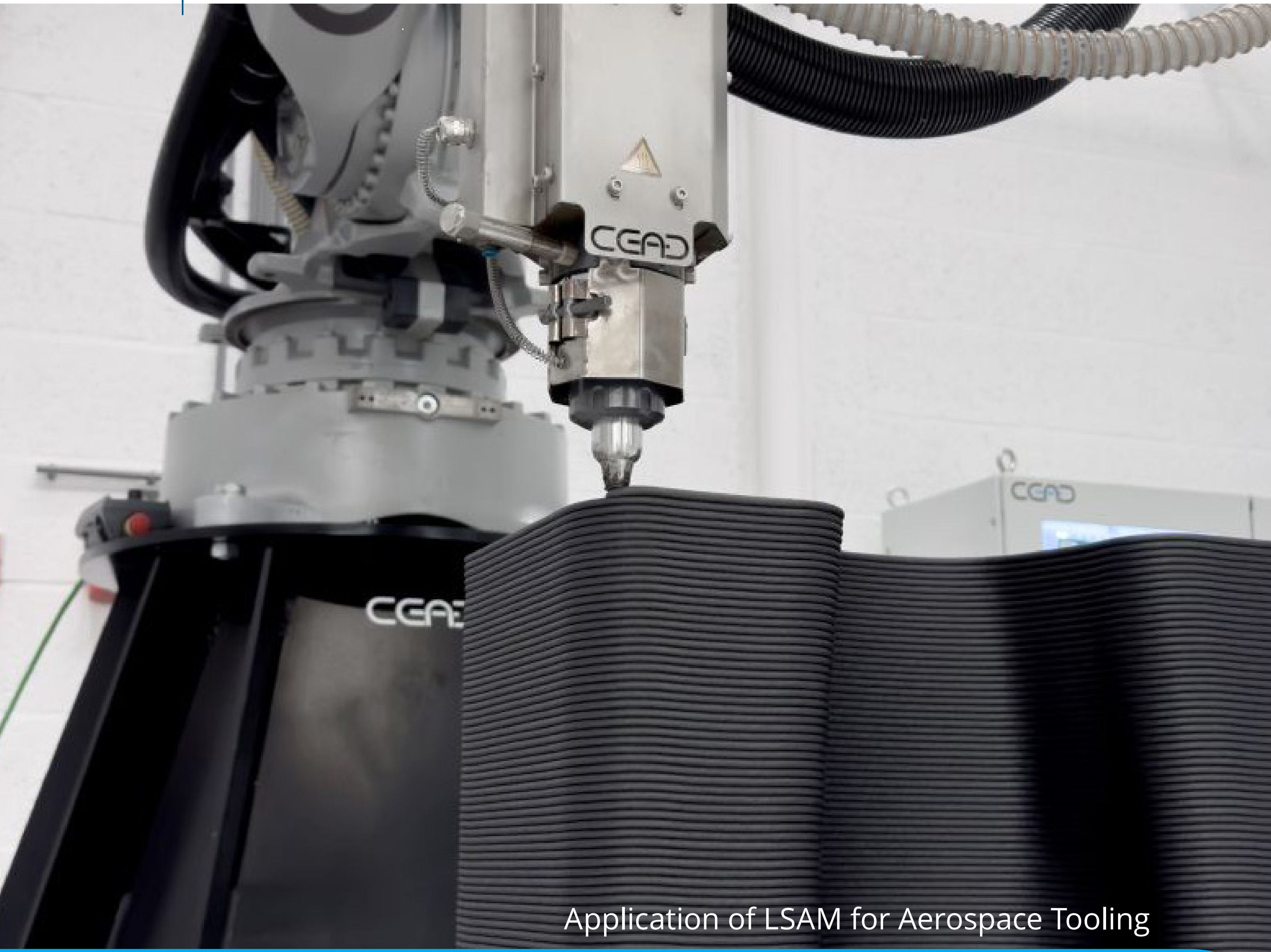
Exploring Large-Scale Additive Manufacturing

AUTHORS
Ana Ramirez de las Heras
Timo Osinga



Application of LSAM for Aerospace Tooling

Innovation has always been the driving force behind advancements in the aerospace industry. The pursuit of excellence in aerospace tooling must not be an exception as it plays a pivotal role in the overall efficiency of aerospace operations. The complexities and challenges inherent in Large-Scale Additive Manufacturing (LSAM) of aerospace tooling demand the collaborative efforts of experts from various disciplines in order to exploit the full potential of this technology.

Royal NLR - Netherlands Aerospace Centre

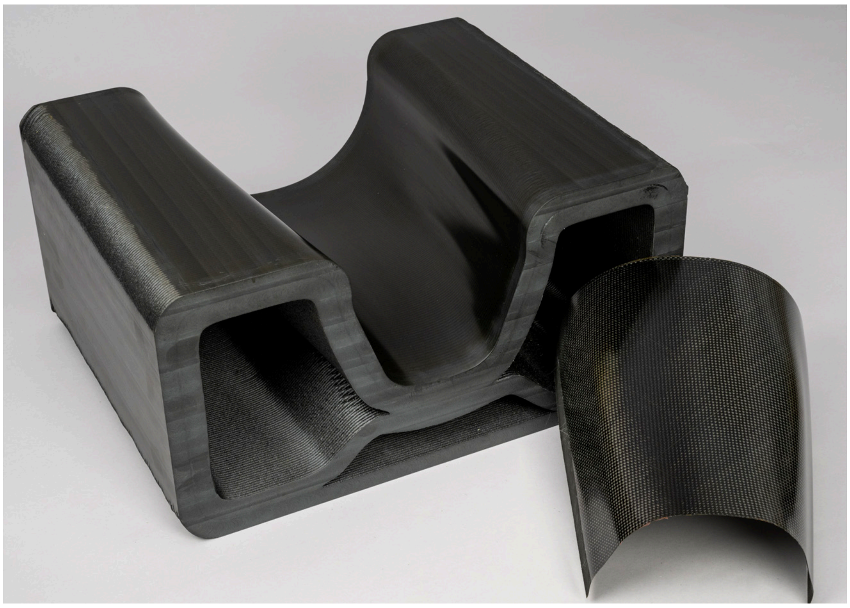
Introduction

The aerospace industry is witnessing unprecedented growth, driven by increasing demand for air travel, advancements in space exploration and the need for more fuel-efficient and environmentally sustainable aircraft. In an industry where safety, performance and reliability are essential, the manufacturing processes play a critical role in achieving excellence. The development and production of aerospace tooling such as moulds is critical for ensuring the accuracy and reliability of aircraft components. Moreover, as the demand for more advanced, lightweight and geometrically intricate aerospace components grows, the industry requires tooling manufacturing equipment and techniques that can evolve and meet these needs.

Aerospace tooling has traditionally relied on conventional materials and manufacturing techniques such as CNC machining of metals and layup of fibre-reinforced composites that often entail time-consuming processes and high costs, and impose limitations on design complexity. Manufacturing techniques are also evolving towards more energy- and cost-efficient options, such as out-of-autoclave (OOA) composite curing, where the high energy consumption and costs of autoclave usage can be avoided. OOA-capable tools might require incorporating complex features such as heating and cooling channels to ensure temperature distribution along the full extent of the composite product. These features represent a good example of the challenges that the conventional manufacturing techniques mentioned are currently facing.

With the advent of **Large-Scale Additive Manufacturing (LSAM)**, the various industries are witnessing a transformative shift in tooling manufacturing processes, as it offers opportunities to revolutionise the production of tooling. This can deliver enhanced efficiency, cost-effectiveness and design flexibility. As in any other additive manufacturing process, material is deposited layer by layer at specific locations until the final product is created. The LSAM process in particular is allowing new horizons to be explored thanks to its implicit orientation to the larger scale – a significant leap with respect to other polymer/composite additive manufacturing methods such as Fused Filament Fabrication.

Royal NLR’s Aerospace Vehicles Structures Department is actively exploring various applications of LSAM technology within the aerospace industry.
The aim is to assess the challenges mentioned above and also to meet **thermoset cure tooling** requirements for superior quality and performance. For the LSAM process, NLR is concentrating its efforts on utilizing **carbon reinforced high-performance thermoplastics**.



Jet engine nacelle section 3D printed mould and final thermoset product

About the LSAM process

LSAM, also referred to as FGF (Fused Granulate Fabrication) or BAAM (Big Area Additive Manufacturing), has revolutionised the industry by facilitating the creation of intricate structures on a much *larger scale than ever before*.

In this process, the raw material is initially in the form of granules or pellets. These granules are fed into a heated extruder, where they melt in several stages or heating zones. The molten material is subsequently deposited layer by layer to create the desired object. The extruder is typically mounted on a robotic arm or a gantry system that performs the movements to achieve the 3D shape.

The process involves various **critical parameters** that influence the outcome, including layer dimensions, printing speed, layer time, extrusion temperature and environmental conditions (printing surface temperature, presence of draughts, etc.).

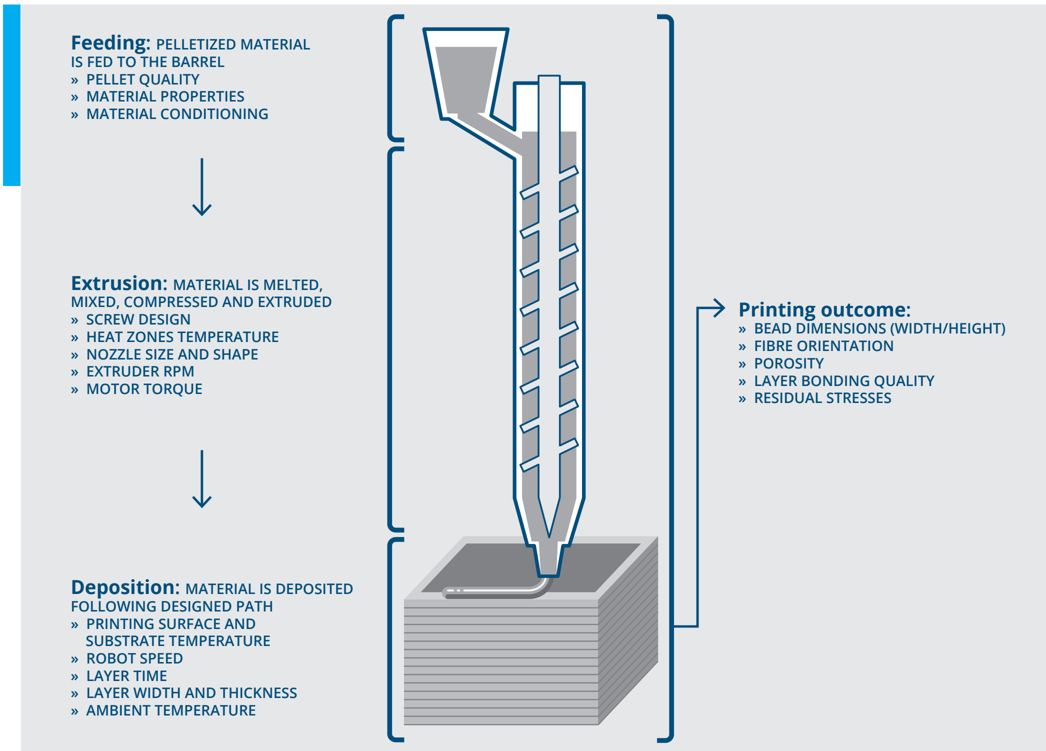
The processed material will also affect the parameter selection, as factors like viscosity and cooling behaviour will influence its processing window.
The material conditions are also important, as the level of moisture absorbed by the material has a significant impact on the print quality in terms of porosity.

LSAM offers several benefits compared to conventional tooling manufacturing methods used in the aerospace industry in terms of design, production and lifecycle of moulds. LSAM can produce complex mould geometries that might be challenging to achieve with traditional CNC machining or extremely costly when applying of high accuracy assembly of billets that conform the final shape. This makes more efficient and **optimized mould designs** possible, improving the overall manufacturing process.

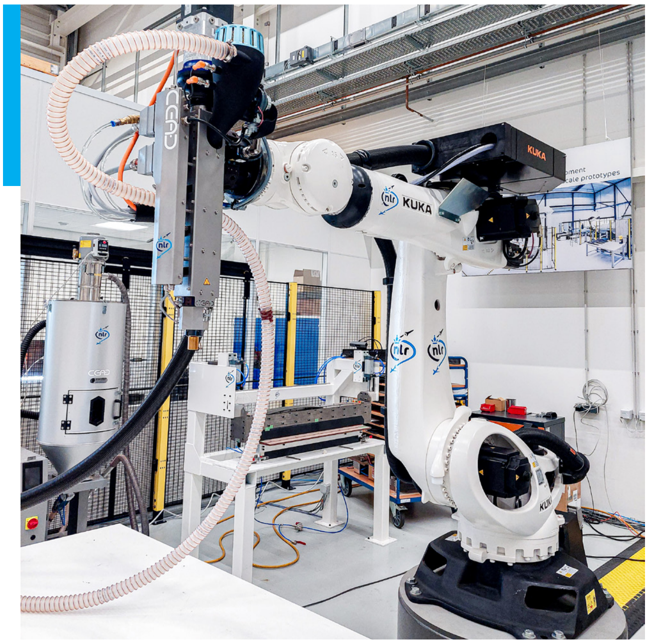
Like other additive manufacturing technologies, the LSAM process **minimizes material waste** by using (roughly) only the necessary material directly in the product fabrication. In contrast, CNC machining produces substantial waste through material removal from a billet.

Moreover, LSAM's capability to process **thermoplastics** not only yields lightweight and durable moulds but also opens up the potential for material recycling [1].

LSAM’s additive nature can significantly reduce mould production **lead times** too, as moulds can be designed, produced and implemented more rapidly than in other traditionally used methods [2]. This makes it also more **cost-effective**, especially for low-volume or custom mould production.



LSAM process variables overview



LSAM setup at the NLR:
CEAD S25 extruder mounted on KUKA KR240 robot

LSAM's advantages in design flexibility, rapid production and cost-effectiveness are making it an attractive and increasingly viable option for aerospace tooling manufacturing, such as large-scale moulds.

LSAM R&D at NLR

NLR has extensive experience in additive manufacturing of metals and polymers and that knowledge is now being expanded to extrusion of composite materials. Laser Powder Bed Fusion (LPBF), Directed Energy Deposition (DED), sinter-based Fused Filament Fabrication (FFF) and high performance thermoplastic Fused Deposition Modelling (FDM) are some of the additive manufacturing technologies that NLR focuses on. And that now includes Large-Scale AM of composite materials.

To assess the capabilities of LSAM for the aerospace industry, NLR is working on several lines of investigation simultaneously. The main focus is on **aerospace-grade mould** manufacturing, which can then be used to produce final parts. These final parts are usually made of thermoset composite materials that require high temperatures to cure the matrix resin, usually around 180°C. Besides being able to withstand the **high temperatures** without undergoing degradation, the mould must be **dimensionally stable** and **vacuum-tight**. To verify compliance with the requirements, the tool is subjected to various tests carried out before and after consecutive heat cycles to ensure material stability.

To demonstrate the dimensional stability, 3D optical inspection is performed on the tool and compared to previous scans. A dimensionally stable mould is one for which the final dimensions do not change even after being heated and cooled down multiple times. This is essential to ensure production repeatability.

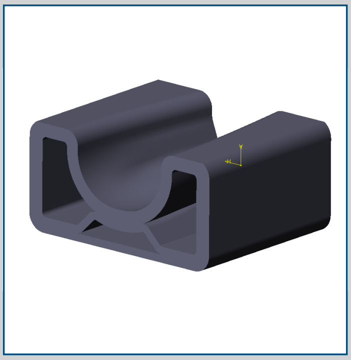
NLR’s experience is that deviations can be kept to within **0.01 millimetres** after six heat cycles. It is expected that a similar outcome will be obtained after >500 cycles, as this has been already demonstrated by the material provider.

Achieving vacuum tightness will depend on various factors because there is a close relationship between the printing parameters and final surface quality. Based on NLR's experience, applying sealants can help achieving vacuum tightness on porous surfaces, as well as improving the final surface quality. A vacuum test is carried out to demonstrate vacuum tightness of the tool. The vacuum requirements can vary, depending on the final application and process.
For use in the vacuum resin infusion process, NLR aims for a **maximum drop of 10 millibars in 10 minutes** after achieving approximately 98% vacuum. This test result was also successful for the tool studied.

Despite the positive outcome of the initial tests, NLR has also come up against the **challenges of the current state of LSAM equipment and technology** when processing high-temperature thermoplastics. Equipment upgrades are essential to improve the thermal stability and extrusion conditions, which influence the layer **bond quality**, the **porosity content** and the coefficient of thermal expansion of the final print.

Production of an aerospace-grade 3D printed tool entails the following phases:

1. Computer Aided Design (CAD) of desired 3D shape
2. Slicing: design is translated into robot language, including movements, speeds and extrusion rates
3. Printing
4. Annealing: mould is brought to high temperature to release residual stresses
5. Machining: remove material excess and achieve final geometry
6. Surface preparation: sealing of the surfaces, filling in any existing void and ensuring good surface quality of the final product
7. Testing: vacuum tightness and dimensional stability checks before and after heat cycles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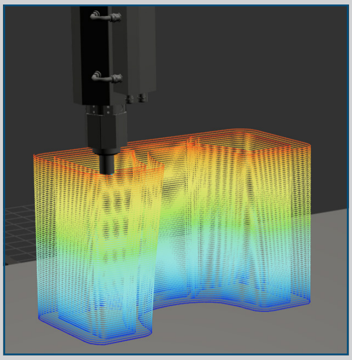
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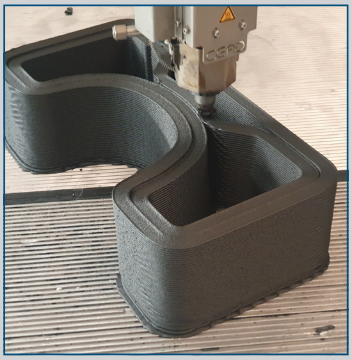
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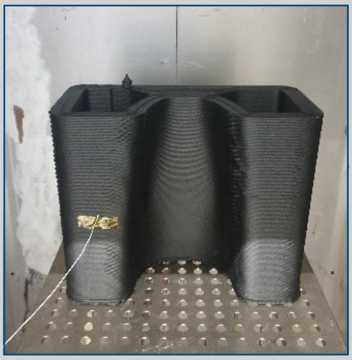
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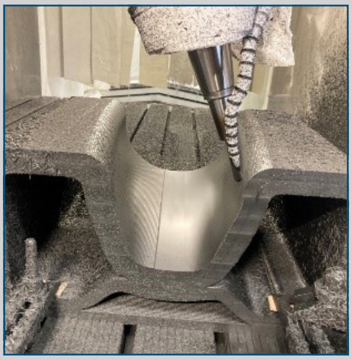
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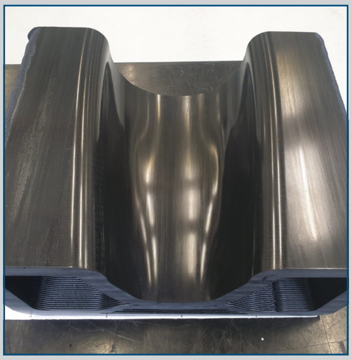
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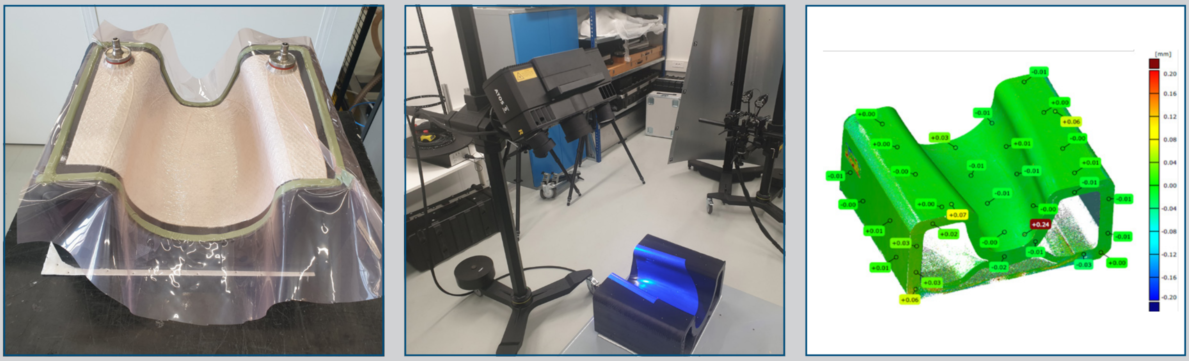

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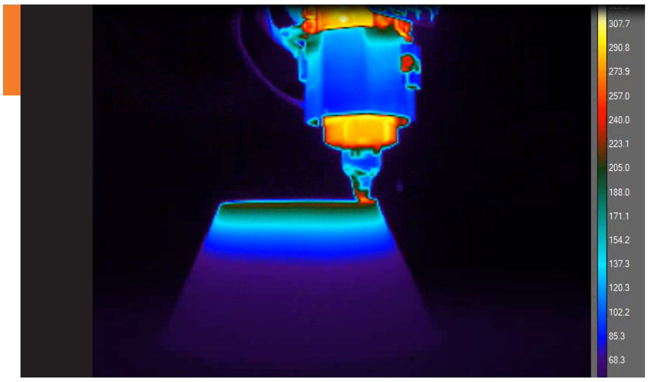
LAYER BOND QUALITY

After a layer is deposited, the material begins to cool rapidly until the next layer is added on top, when it will heat up again slightly. The temperature of the preceding layer plays a crucial role in determining the bond quality. If the substrate temperature is too low, it hinders the formation of polymer chains and generates stresses due to successive temperature fluctuations when new layers are deposited. As result, the performance in the stacking direction will be poorer and **delamination** can occur.



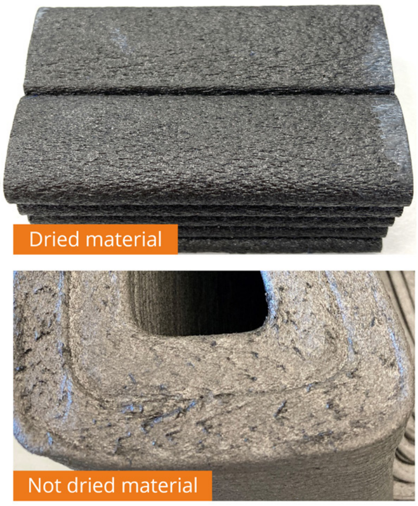
Thermal data tracking during LSAM at NLR

On the other hand, if the substrate is too hot (above the melting temperature, Tm), the viscosity of the substrate remains too low, leading to polymer flow after deposition. This translates into insufficient support for the subsequent printed layers and concomitant print failure. In this sense, maintaining the deposited material between the melting temperature and the glass transition temperature (Tg) is essential for ensuring a good result [3]–[6]. To determine the layer bond quality, infrared cameras are used to track the bead and substrate temperatures.

POROSITY CONTENT

One challenge of this technology is the porosity content: the amount of voids has a direct impact on the mechanical properties, vacuum tightness and overall quality of the final product. The possible sources of this porosity that NLR has examined are pellet quality, improper material conditioning before printing, poor material compression during extrusion and fibre displacement after deposition. LSAM is essentially a pressure-free process, where material is deposited but not forced into shape. Applying pressure during deposition could help counteract the above-mentioned sources of porosity.

Preparation of the material prior to printing is crucial. Most polymers tend to absorb **moisture** from the surrounding air when not stored in ideal conditions, and for some this translates in mechanical performance modification [7]. In addition, printing quality is also affected, as moisture can reduce the flow characteristics and cause uneven extrusion. Visually, a material with high moisture content will look rough when printed, while a properly conditioned material will have a smooth appearance.
The roughness equates to voids when a new layer is deposited on top.
To remove surface moisture from the pelletised material, it is placed in a **dryer**, where it is exposed to a certain temperature for a specific time depending on the material requirements.

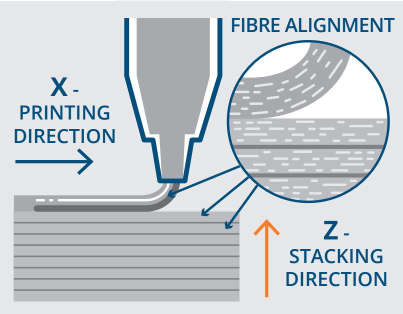


Effect of material conditioning on visual appearance

During printing, the material is passed through the extruder barrel and its consecutive screw phases.
In the initial section or feeding zone, the pellets are driven by gravity through the first heating zones, where the material melts. In the section prior to extrusion (or deposition), the material is compressed and pushed through the nozzle, the final stage of the extruder. The screw design plays an important role in the porosity content of the final print. The optimal design should result in sufficient pressure build-up, ensuring that any air trapped during material heating, mixing and compression is forced out right before material extrusion.

Not every material behaves in the same way, it is therefore sensible to assume that no single extruder will be suitable for all the materials available in the market. When processing fibre-reinforced high-performance polymers, i.e. the ones that are interesting for the aerospace industry, the role of the screw design requires thorough attention.

In the latest phase, once the material is deposited and begins to cool, the polymer shrinks (reduces in volume). When fibres are present, they tend to displace slowly during this phase generating voids that are not filled by the already hardened polymer [8]. As mentioned previously, applying pressure directly after deposition, while the polymer can still flow, could help forcing out the entrapped air.

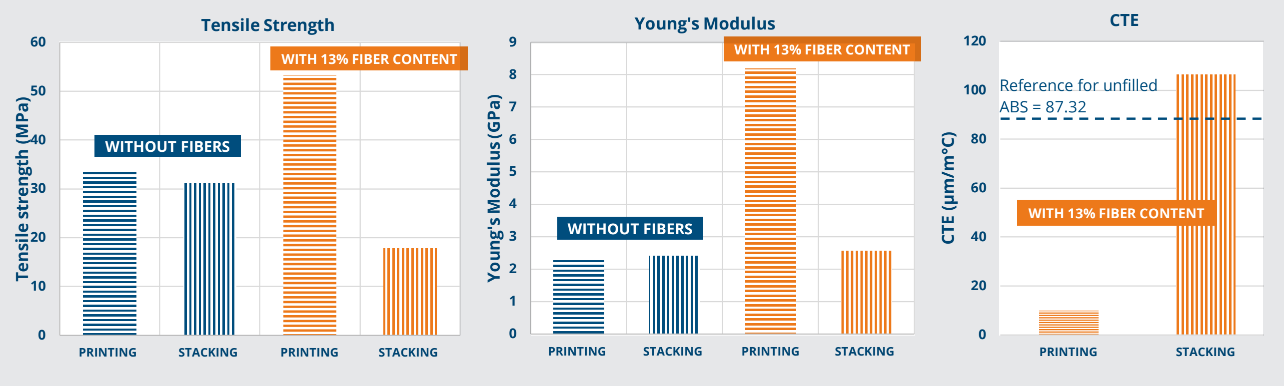


Representation of the fibre alignment in an LSAM print

COEFFICIENT OF THERMAL EXPANSION

Adding fibres to the polymer matrix affects the final material performance positively. Besides the well-known increases in strength and stiffness, it will modify the CTE (Coefficient of Thermal Expansion) reducing the tendency for warping and distortion [9], [10]. The CTE of a material describes how its dimensions change with temperature and it is an essential property to consider in engineering applications, especially when dealing with temperature-sensitive components and structures like an aerospace composites cure tool. The higher the operating temperature (i.e. the curing temperature of common thermoset aerospace parts, which is above 180°C), the greater the dimensional variation that the tool will experience. Furthermore, the absolute deviations will also increase with the size of the tool.

Although adding fibres will have a beneficial effect on the CTE values, it is important to pay attention to the alignment of the fibres in the final print, because they will have a notable impact on its behaviour. Typically, fibres will become aligned in the printing direction, following the material extrusion flow [11]. This will lead to significant variations in properties as a function of the stacking direction; this is an anisotropic behaviour [3]. To correct this variation in CTE, smart printing strategies as well as dimensional compensation during the design phase are crucial for overcoming the anisotropic behaviour.



Anisotropic behaviour of LSAM samples and effect of fibre content on Young's Modulus, tensile strength and CTE values. Data extracted from [10], [12]

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Accelerate LSAM

Through rigorous experimentation and meticulous analysis, NLR aims to advance the understanding of the LSAM process, the materials and their suitability for producing high-performance aerospace tools.

To make use of the full potential of the LSAM technology and promote its use in the aerospace industry, NLR is implementing several equipment upgrades for addressing the above-mentioned challenges:

- Study screw design optimisation for fibre-reinforced high-temperature polymers;
- Add a heated printing surface, improving first layer adhesion and print thermal stability;
- Enhance interlayer bond quality by aincluding a substrate pre-heating device, which will ensure the correct substrate temperature for optimum stacking direction properties. Moreover, this will increase the available processing window, translating in longer layer times and therefore an increase in the maximum layer length and final size of the print;
- Enhance process repeatability and monitoring by extracting printing parameters such as extruder torque, heat zone temperatures, RPMs, nozzle pressure values, etc.;
- Improve the level of printing environment control by enclosing the printing cell, preventing air draughts and other external influencing factors;
- Explore software opportunities for closed loop control (e.g. automatic tuning of parameters such as robot speed, heat zone temperatures or material flow , based on thermal data).

The white paper serves as a testimony to the efforts of the NLR's team of researchers, engineers and scientists, who are dedicated investigating LSAM and its application in aerospace tooling. This way NLR wants to inspire further advancements in LSAM of aerospace tooling while, at the same time, ignite a sense of curiosity and collaboration among industry stakeholders. Together, we can continue pushing the boundaries of what is possible.

The production and testing of the Aerospace tool is part of the Valorisatie 3DXL circular printing project and made possible with contribution by:

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About the co-authors:

Ana Ramírez de las Heras and Timo Osinga are part of the Structures Technology department at Royal NLR. Ana's background in Aerospace & Manufacturing Engineering, coupled with her keen interest in understanding the science behind phenomena, propelled her towards a career dedicated to research. As an R&D engineer, Ana delves into various topics with the aim of contributing to the future of safe, sustainable, and affordable aviation.

Timo, on the other hand, is a fervent aeronautical engineer with extensive experience in both metal and composite additive manufacturing technologies. Serving as a senior project engineer, Timo is deeply committed to advancing and refining additive manufacturing processes to make them more mature and applicable to the industry, ultimately striving to enhance sustainability within the aviation sector.

NLR Amsterdam
Anthony Fokkerweg 2
1059 CM Amsterdam
p) +31 88 511 3113
e) info@nlr.nl i) www.nlr.org

NLR Marknesse
Voorsterweg 31
8316 PR Marknesse
p) +31 88 511 4444
e) info@nlr.nl i) www.nlr.org

If you have any questions or comments, please feel free to contact us: MAMTeC@nlr.nl