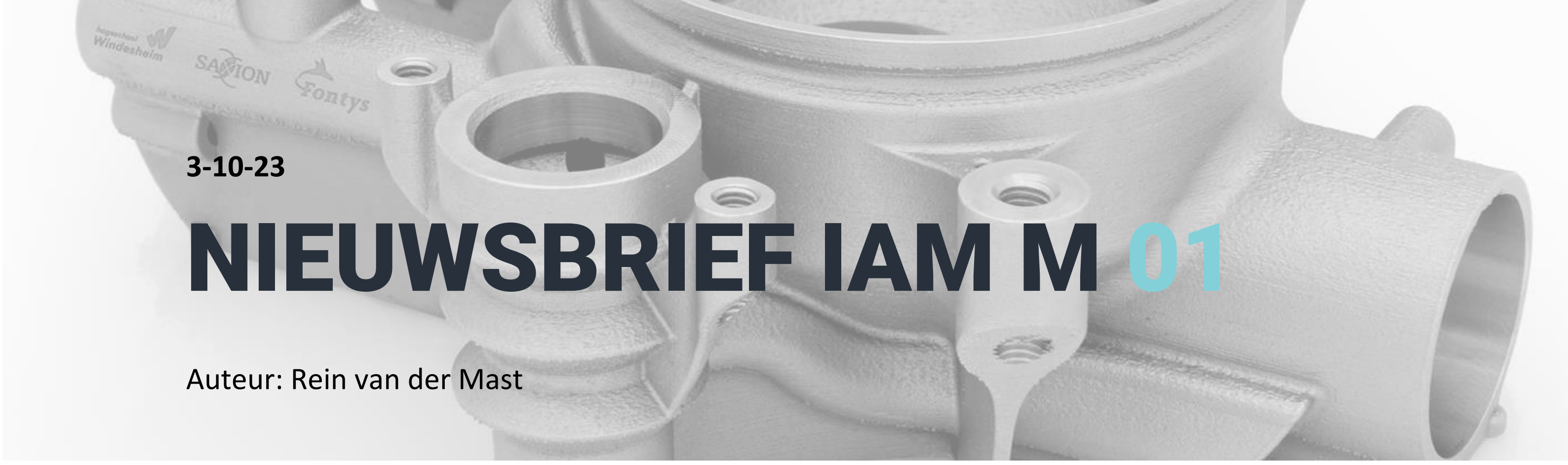

3-10-23

NIEUWSBRIEF IAM M 01

Auteur: Rein van der Mast

Introductie:

Dit is de eerste nieuwsbrief van IAMM waarmee de SPRONG groep intern en extern een kennisstroom op gang hoopt te brengen.

Inherent Strain Method

Auteurs: Stef Rijkers en Rein van der Mast, Fontys University of Applied Sciences Eindhoven, input from Siemens Digital

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Introduction

In LPBF, a high-energy laser selectively melts and fuses metal powder, building up 3D shapes layer by layer. The intense local heat input and subsequent rapid cooling create thermal gradients, leading to differential thermal expansion and contraction of the material. This non-uniform cooling process can introduce undesired tensions and distortions in the final part, compromising its dimensional accuracy and mechanical properties (Figure 1).
Thermal deformations due to transient temperature changes during LPBF pose a significant challenge for creating highprecision components. The thermal cycles create stresses and strains within the material, leading to warpage and residual stresses. The accumulation of these can result in significant inaccuracies in the final printed part, affecting its functionality and performance.

At Fontys, students learn how to work with simulation tools such as Siemens NX. The Engineering department implemented 3D printing in metals in 2014 and today operates a modern Renishaw RenAM 500S metal printer at its facility on the Brainport Industries Campus in Eindhoven (NL), led by Rein van der Mast.

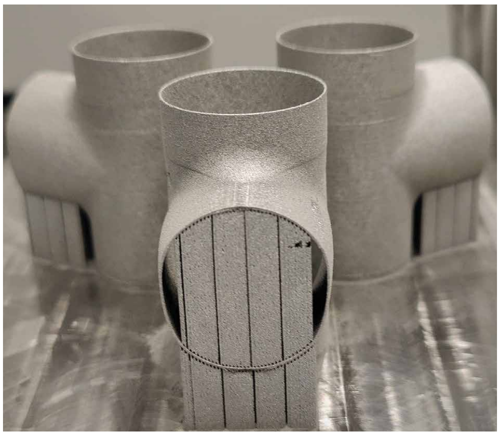
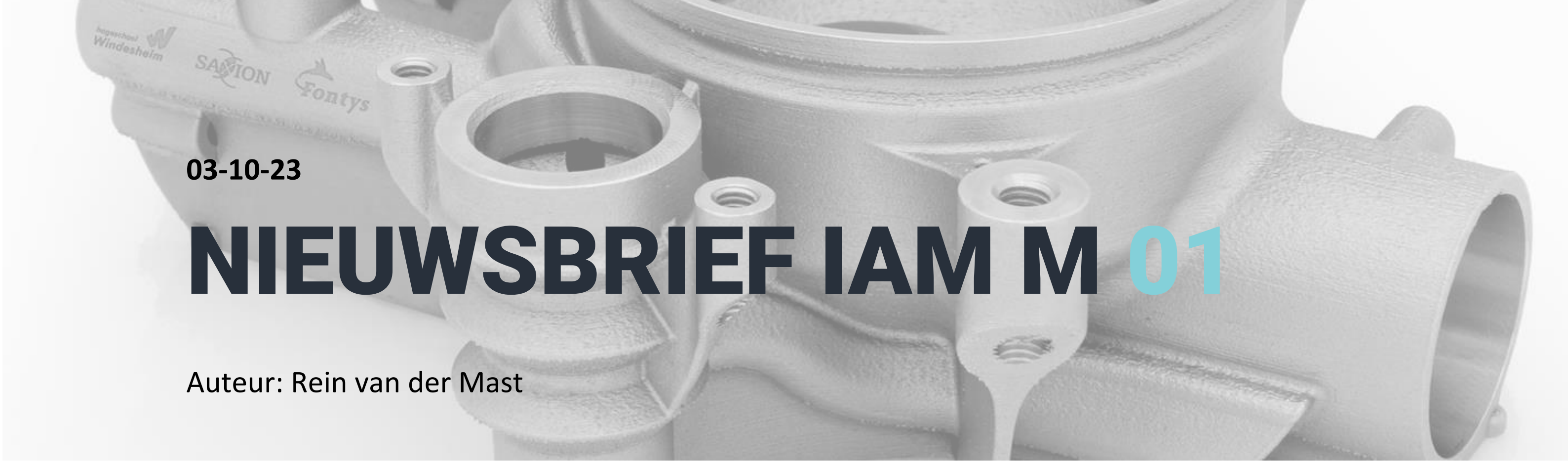


Figure 1. The deviations are clearly visible if the print is carried out without prior correction: out-of-roundness of the cylinder and effects at significant transitions in the construction direction.



Van der Mast has a long track record in 3D printing and was the manager Design & Engineering of Additive Industries before joining Fontys in 2016. Today, he is also a Ph.D. candidate at KULeuven University in Belgium, aiming at better quality levels in small LPBF prints through more direct control for the designer over how the laser scans each layer.

LPBF design paradigm

While professor Erik Puik (with a history at Océ and TNO) is in charge of the overarching domain Smart Manufacturing, last year’s bachelor student Stef Rijkers focused his graduation project on evaluating the effectiveness of what modern simulation tools can offer in terms of optimising LPBF prints prior to their physical printing.
Van der Mast: “LPBF involves many interdependencies, which I call the LPBF design paradigm. If the designer optimises one of the aspects, it will most likely degrade other aspects. As a result, the best possible outcome is, by definition, a compromise. A higher density can be achieved, for example, by sending more power to the powder bed. However, more power also results in more local heat concentrations, which leads to higher stresses and distortions.” He continues: “Without a full digital twin encompassing the manufacturing process, there is often a need for optimisation in the physical domain to achieve the best possible result. That approach involves a lot of costly trial and error. Having a digital representation of such a process available is much faster and less costly.”

Rijkers investigated the practical value of digital twins with regard to their predictive qualities in LPBF. Several reference parts were printed in 316L stainless steel and measured. With the results, including some Siemens reference geometries, he was able to calibrate the system and improve the quality of the virtual representation of the print and the LBBF process. He was assisted by several people, including Tom van Eekelen of Siemens and Cameron Riley of Dunlee (a Philips brand) for precise wire cutting some of the reference parts before measuring the resulting deformations.

Creating spareparts

Van der Mast: “Stef ’s project proved useful in one of the European projects we participate in: Castlab Proeftuin, initiated by Melis Gieterijen in Tilburg. That project is about producing spare parts for assets on and aside railroad tracks as quickly as possible, even if it means making them from scratch.

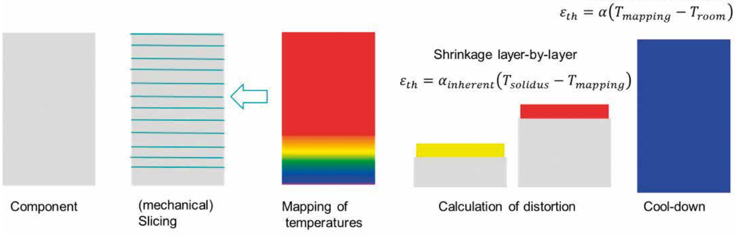
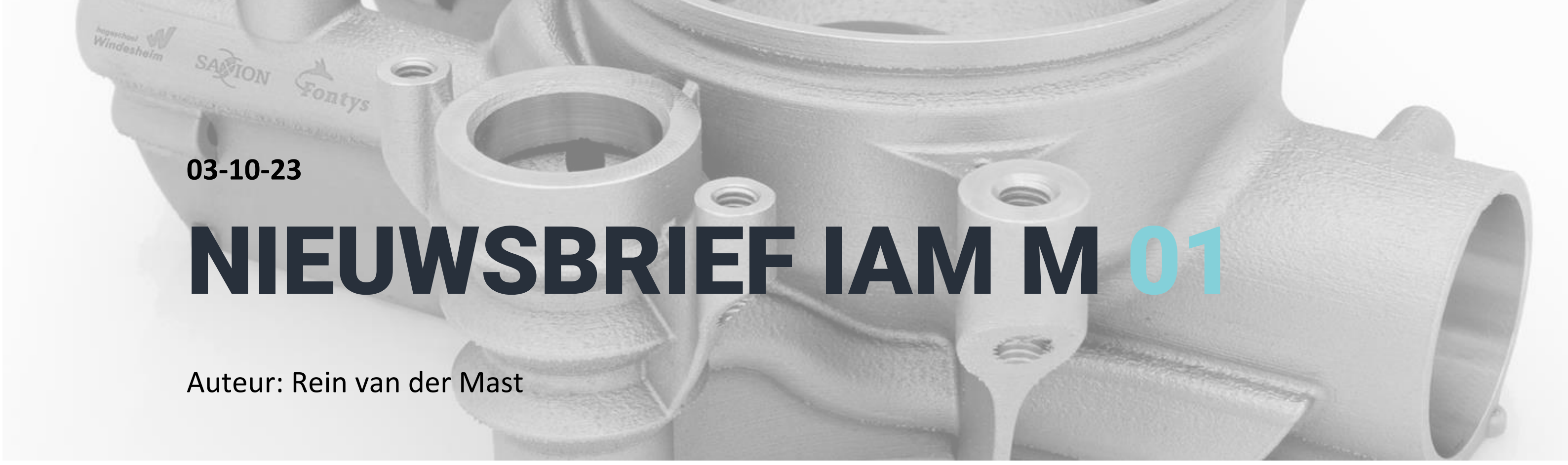


Figure 2. A simplified overview of the inherent strain on the complete object.



Recreating small and medium-sized metal parts by printing them has proven to be an appropriate approach, at least in some cases. A print must be right the first time with the least possible amount of post-processing. LPBF is about rather compact components. Ultimately, we want to have the same tools available for wire-arc AM and even for 3D printing in composites.”

Last year, Van der Mast initiated a long-term partnership with the Windesheim (Zwolle) and Saxion (Enschede) universities of applied sciences: Industrial Additive Manufacturing in Metals (IAMM). “Windesheim, for example, owns a brand-new GE M2 Dual Laser Series 5 LPBF metal printer, has a Meltio metal printer on a Haas Automation milling centre and soon will have a (mediumpressure) cold-spray production cell. These solutions represent different metal-printing concepts for which this piece of software might prove beneficial. We would like to find out to what extent.” Organisations supporting the collaboration include the universities of Enschede (Twente) and Delft, Mikrocentrum, Aeronamic, ASML, and others.

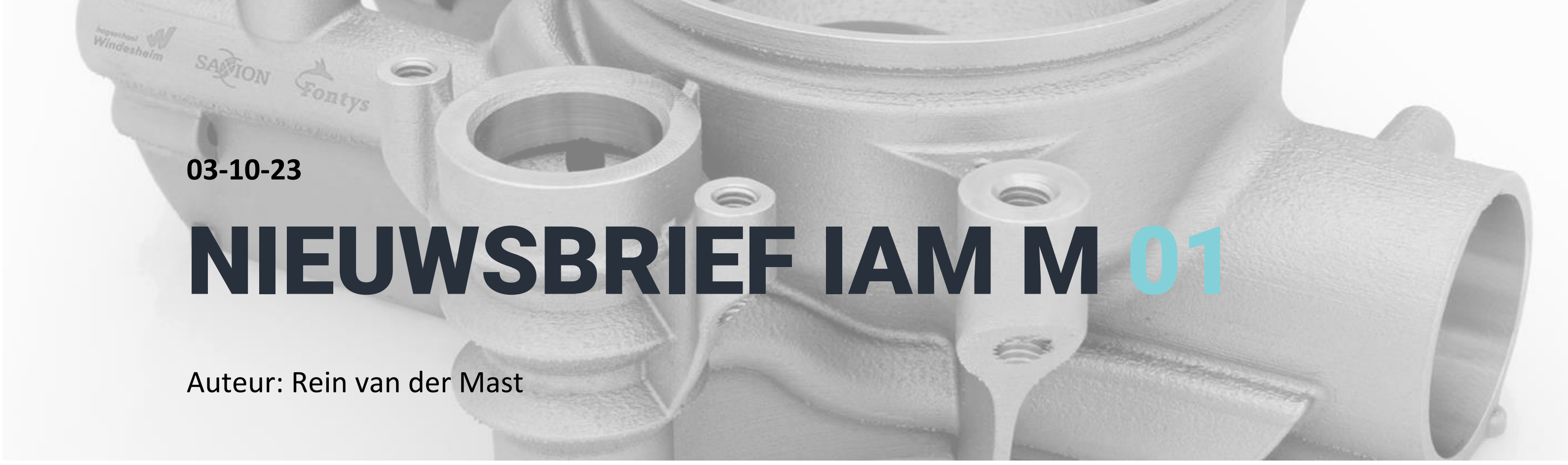
Rijkers, with over 15 years of practical experience gained during his employment at the Ministry of Defence, today as an engineer within the Materiel & IT Command, has proven to be able to combine his practical expertise with his passion for pushing boundaries and exploring unknown technological areas. “My heart beats for building custom AM systems and designing electronics. I strongly believe that we all, including myself, play a part in shaping the future of the manufacturing industry.” Last year his path led him to Fontys, where he started a fascinating graduation project. The focus was on LPBF process simulation and finding ways to improve efficiency and precision.

Inherent Strain Method

Siemens NX offers an advanced simulation platform for LPBF processes, enabling engineers and researchers to delve into the intricacies of thermal behaviour. The software employs the Inherent Strain Method (ISM), initially developed to predict welding distortions, to simulate thermal deformations in LPBF effectively. During the computation cycle, results from ISM are projected onto the finite-element model (FEM) to incorporate the effect on the complete object. The method significantly reduces the computational effort compared to traditional thermal elastoplastic analysis, enabling efficient simulation of large-scale LPBF projects.

ISM is a computational approach used to predict and find deformations and residual stresses introduced during the LPBF process. It is based on the concept that a pre-existing or “inherent” stress exists in a part as a result of the manufacturing process, even before any external loads are applied.

When a layer of powder is melted by the laser in the LPBF process, rapid cooling and solidification occurs.



Due to the layer-by-layer nature of the process, the previously solidified material restricts the free expansion and contraction of the new layer, leading to residual stresses. ISM postulates that if these strains were known in advance, one could predict the accumulated distortions and stresses by simply applying these strains to the finished, stress-free geometry of the part.

Unlike traditional FEM methods that require simulation of the entire layer-by-layer process with associated temperature fields, phase changes, and mechanical behaviours, ISM simplifies the problem into elastic deformation. This reduces computational costs and time. The determination of inherent strains is not trivial. It depends on various factors including material properties, process parameters, and part geometry. Accurately determining these strains often requires a combination of experimental calibration and computational techniques. ISM quantifies non-elastic strains, encompassing thermal strain, phase-transformation strain, plastic strain, and creep strain. In LPBF, the total strain is the sum of elastic and inherent strains:

Total strain = Elastic strain + Inherent strain

The inherent strain values are determined from experimental data and applied to the activated (macro-) layers in the digital model. Using these values, the software constructs a stress distribution model within the FEM analysis to predict thermal deformations accurately.

To achieve precise simulations, parameter calibration based on material properties and process characteristics is needed. The software calculates the inherent strain as a materialdependent thermal expansion coefficient (α) and its variation with stiffness (C). These α(C) curves are essential for accurately capturing thermal deformations during cooling. The calibration process involves printing multiple calibration bridges with various stiffness levels and measuring the resulting deformations. By comparing the measured and simulated deformations, engineers can refine the α(C) curves to match the actual behaviour of the material. This method provides a series of α values ranging from the stiffest printed bridge up to the most deformed one, and interpolates everything in between. The inherent strain as used within the Siemens NX simulation provides an insight in the relationship between the thermal expansion coefficient and the corresponding stiffness:

$$\alpha(C) = \begin{cases} \alpha_{\max} & \text{for} \quad C \le C_{\min} \\ d \cdot (\log(C) - b)^n + \alpha_{\max} & \text{for} \quad C_{\min} < C < C_{\max} \\ \alpha_{\min} & \text{for} \quad C \ge C_{\max} \end{cases}$$

The adoption of ISM is a key feature in predicting thermal deformations in LPBF. So far, the method has proven to be efficient with accurate results. Its foundation lies in its ability to determine non-elastic strains, which encompass factors such as thermal strain, phase-transformation strain, plastic strain, and creep strain.

By incorporating these non-elastic strains into the simulation, engineers can gain valuable insights into the material’s behaviour during the printing process.
By continuously fine-tuning the simulation parameters, engineers can tailor the LPBF process to minimise thermal deformations and enhance material bonding. This feedback loop empowers researchers to optimise their LPBF workflows, leading to improved part quality and reduced production costs.

Digital twins continuously evolving
The research of Rijkers into the simulation of LPBF prints revealed an intriguing anomaly: asymmetric and orientation-dependent deformations. This observation underscored the intricate complexities at play, encompassing thermal dynamics, metallurgical changes, and mechanical interactions. Such findings are precisely why the digital-twin simulations are never stagnant. Rijkers: “Our understanding of LPBF is evolving, and with every new insight, such as the observed asymmetric behaviour, the digital twin must recalibrate and adapt.”

“Moreover, with computational capacities expanding exponentially, the ever-improving simulation software is allowing for a more granular and nuanced digital reflection of LPBF processes. As we feed more real-world data, especially anomalies such as asymmetric deformations, into these systems, our digital twins become sharper, offering enhanced accuracy and foresight. The continuous evolution of digital-twin simulations in LPBF is driven by both the intricate subtleties of the process and the broader technological landscape. Discoveries such as deformations that are depending on the part placement not only enrich our understanding but also highlight the necessity for adaptive and ever-evolving digital tools to navigate the future of LPBF effectively.”

Later releases of the simulation tool overcame the mismatch between the isotropic assumptions and the real-world process by implementing a new calibration method that incorporated orthotropic behaviour within the calibrated datasets.

Using these datasets, the simulation showed a significant increase in accuracy and match with the actual prints. Siemens has integrated a different approach to its AM simulation with ‘voxel-based modelling’.

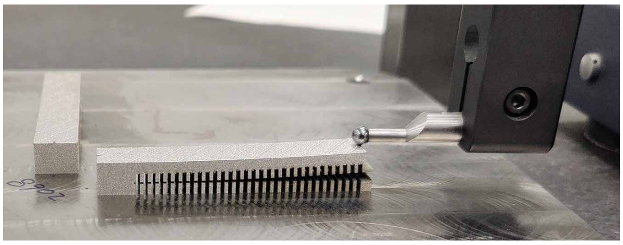


Figure 3. X,Y-beam calibration method provides insight in orthotropic behaviour.

Unlike the conventional mesh-based systems, the voxel-based methodology breaks down the model into threedimensional ‘voxels’, comparable to pixels in a 2D image. The voxel-based mesh sidesteps the intricacies and potential pitfalls of traditional meshing, and allows meshing of highly complex geometries, without any user interaction. An additional advantage is that support-structure properties are automatically approximated, based on material volume fractions inside every voxel.

Optimising LPBF processes

ISM and the iterative refinement approach form a powerful combination for optimising LPBF processes. Through iterative refinement, researchers can explore various scenarios to understand how changes in material properties, laser parameters, and build strategies affect the final part quality. This valuable information enables engineers to design more efficient and cost-effective LPBF workflows, while trading off active machine hours against computing time.

By harnessing the power of advanced simulation tools, engineers can proactively identify and address anomalies within a part. This not only allows them to precisely pinpoint areas of concern within the build but also enables them to accurately calculate compensations for any deformations. The outcomes achieved through these measures are undeniably worth the investment in time and effort. In initial tests, T-shaped connector tubes with thin walls exhibited significant displacements (Figure 4), measuring as much as 0.7 mm – a value well beyond acceptable specifications. However, thanks to the compensation calculations from the simulation tool, these deformations were dramatically reduced to a mere 0.025 mm in the final product.

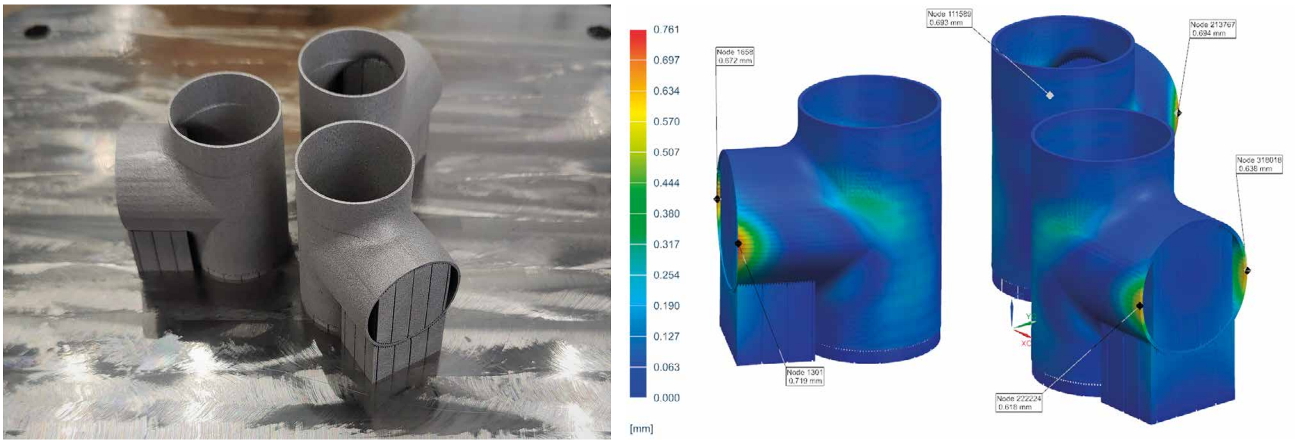
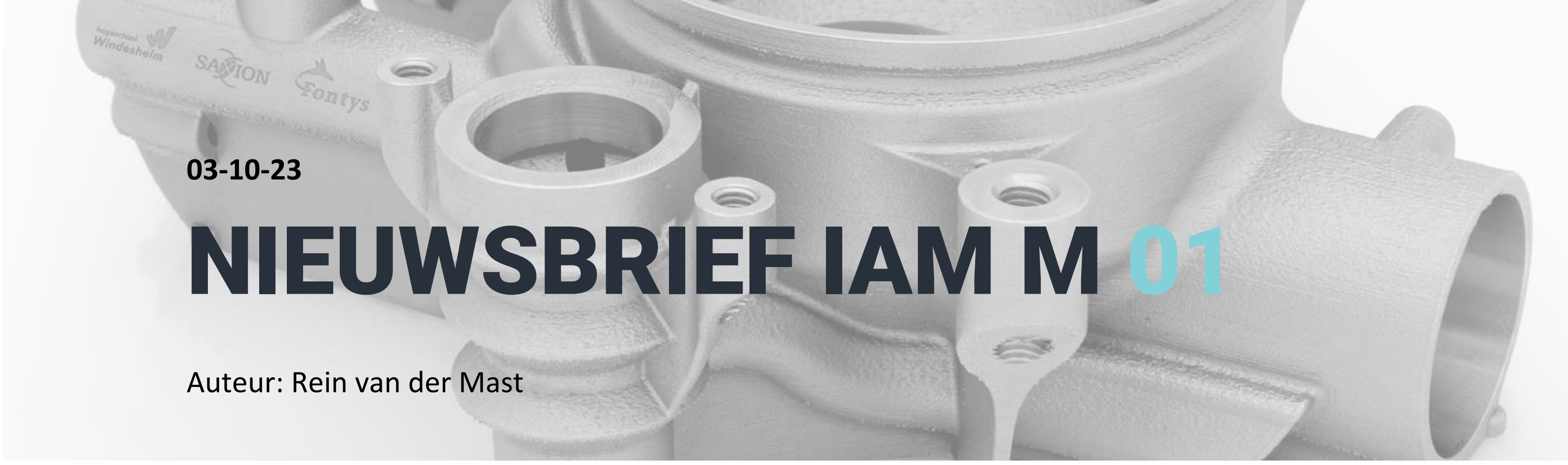


Figure 4. Distortion results from tests with T-shaped connector tubes.



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Room for Improvement

LPBF simulation, while a valuable tool in its domain, still presents areas demanding attention and improvement. One of its primary challenges lies in the computational requirements. Simulating intricate designs or large builds requires significant RAM and processing capabilities. However, the hurdle is not merely computational.

The learning curve of tools like Siemens NX, given its multifaceted capabilities, is notably steep. To navigate and leverage its vast LPBF simulation suite, an engineer must not only understand the different preparation and computation options of the software but also possess a broad understanding of the LPBF process. This includes knowledge of melt-pool dynamics, thermal stresses, and the interaction of the laser with various materials. The software's sophistication, while a strength, demands users to possess a dual mastery: the tool itself and the underlying principles of LPBF.

This expertise requirement is further magnified by the software's speed. Highly detailed simulations, while comprehensive, can often be time-consuming, potentially slowing down the iterative design process. And while the built-in material database includes the most common alloys, it may not always be an absolute match with the preferred real-world material, necessitating user-specific material data sets or a more community-driven update mechanism.

Cost also stands out as a potential barrier. The licensing expenses associated with these kinds of software could deter smaller entities or independent researchers from accessing its profound LPBF capabilities, and is therefore mainly adopted by the larger manufacturing companies.

Conclusion

In sum, LPBF simulation tools, with their undeniable strengths, also highlight areas ripe for refinement. By addressing these nuances, the software can pave the way for even broader, more efficient applications in the realm of LPBF simulations.

Siemens NX has emerged as an indispensable tool for tackling thermal deformations in Laser Powder Bed Fusion. Leveraging the Inherent Strain Method and an iterative refinement approach, engineers can optimise the LPBF process and produce high-quality parts with minimal deformations. As AM continues to revolutionise industries, digital twins will undoubtedly be at the forefront, empowering researchers and manufacturers to push the boundaries of innovation.