PBF式Additive Manufacturing装置 NXG 600Eの開発

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Development of PBF Additive Manufacturing Machine NXG 600E

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レーザー粉末床溶融（L-PBF）などの積層造形(AM)技術は，長い間プロトタイピングや研究用途での使用にのみ適しているという評判を乗り越えてきた．現在，Nikon SLM Solutionsは，これまでに製造された中で最も複雑な金属部品の連続生産に注力する世界中の高度な目利きの顧客にAMソリューションを提供している．NXG 600Eマシンの開発により，Nikon SLM Solutionsは，最大600 mm × 600 mm × 1500 mmの寸法の部品を製造できる，最も生産性と信頼性の高いL-PBFプロセスの提供に努めており，多くの技術的課題に直面してきた．本稿では，これらの個々の課題を詳細に説明し，金属AMの分野で革新的な機能を導入することで，これらの課題をどのように克服したかについて説明する．

Additive Manufacturing (AM) technologies such as Laser Powder Bed Fusion (L-PBF) have long surpassed the reputation of only being suitable for use in the context of prototyping or research applications. Today, Nikon SLM Solutions already provides AM solutions to highly discerning customers around the world, who are focused on serial production of the most complex metal components that have ever been manufactured. With the development of the NXG 600E machine, Nikon SLM Solutions faced many technical challenges while striving to provide the most productive and reliable L-PBF process, capable of producing parts with a dimension of up to 600 mm x 600 mm x 1500 mm. This paper describes these individual challenges in detail and how they were successfully overcome by introducing innovative features which are novel in the realm of metal AM.

Key words レーザー粉末床溶融（L-PBF），積層造形(AM)，SLM Solutions，NXG 600E
laser powder bed fusion (L-PBF), additive manufacturing (AM), SLM Solutions, NXG 600E

1 Introduction

Laser Powder Bed Fusion (L-PBF) is a cutting-edge metal additive manufacturing technology revolutionizing industries like aerospace, automotive, and healthcare. Nikon SLM Solutions is a market leading manufacturer of metal L-PBF machines for serial production and prototyping applications, seeking to drive the mass adoption of this manufacturing technique forward and enabling the creation of previously impossible components. Additionally, L-PBF allows for customization and on-demand production, making it ideal for small- to medium-batch manufacturing and customized products.

Since its very inception as “SLM Solutions GmbH” in 2011, Nikon SLM Solutions has been focused on pushing metal additive manufacturing towards commercial and serial production maturity by implementing innovative technology solutions to boost productivity, stability, and part quality. In 2013, the German company launched the SLM®500, which was the first system to feature 4 lasers that could generate a single part simultaneously. The patented multi-laser approach quickly became an industry defining standard for highest productivity, shaping the forefront of metal additive manufacturing capabilities.

In 2020, the company reshaped the market by launching the NXG XII 600, a revolutionary machine which at the time tripled the industry adopted maximum number of lasers from 4 to 12 in a single step, as well as increasing each laser’s maximum output power from 700 W to 1000 W. This machine’s capabilities in a build envelope of 600 mm x 600 mm x 600 mm (XYZ) are still unmatched by the rest of the market in terms of productivity and robustness. Now, with the launch of the NXG 600E (shown as Fig. 1), the NXG system platform has been expanded to allow for

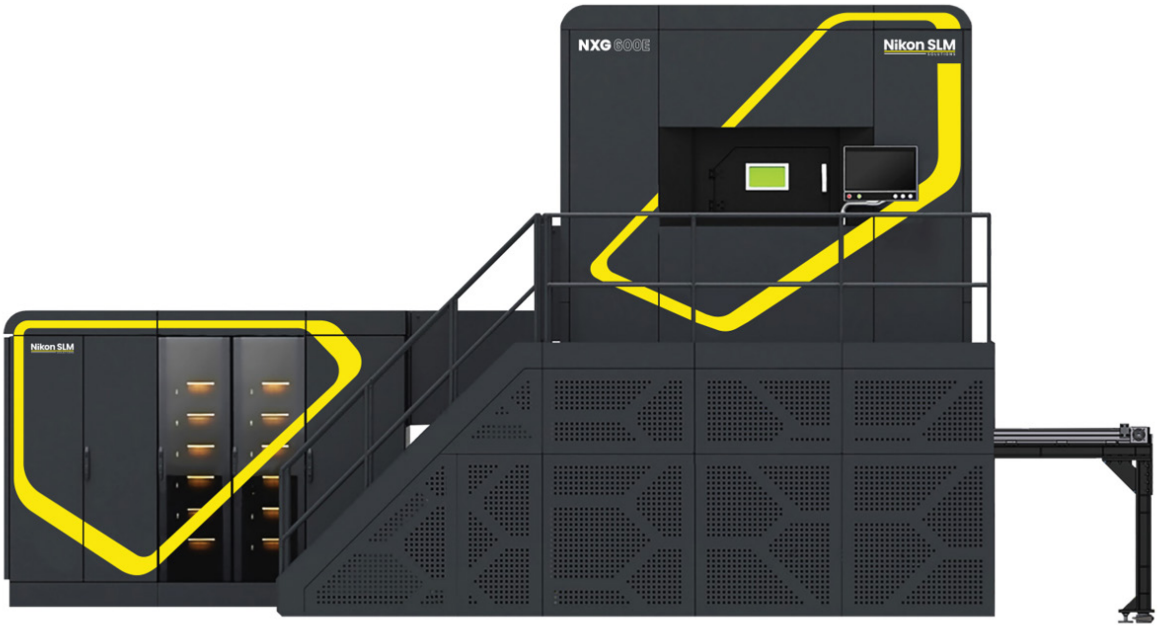

Fig. 1　Picture of the NXG 600E machine

the manufacture of components with a z-height of up to 1500 mm. This endeavor came with several technical obstacles that may seem small to the uninitiated, nevertheless posed significant challenges during the development and qualification phase.

2 Technology Background

The process of metal Laser Powder Bed Fusion (L-PBF) begins with a digital 3D model (as Fig. 2) of the desired part, which must be prepared accordingly to make it compatible with the generative process within the L-PBF machine. The 3D model is placed inside of a virtual representation of the machine's build envelope, while proper orientation and support structures are already considered. Next, a software processor slices this model, along with its orientation data and support structures into thousands of individual layers. These thin layers contain the cross-sectional data for a specific section of the part which is to be created. The thickness of each layer typically ranges from between 30 μm and 90 μm, depending on whether the focus lies on part quality or process speed. However, as even more productivity is desired in the future, layer thicknesses of beyond 120 μm are already used.

The finalized data is transferred to the L-PBF machine, where the selective melting procedure occurs in a controlled inert gas environment, preventing oxidation (Fig. 3). This procedure begins with the spreading of a fine metal powder layer onto a build platform (Substrate Plate) by the Recoater. Afterwards, one or multiple high-powered lasers, guided by

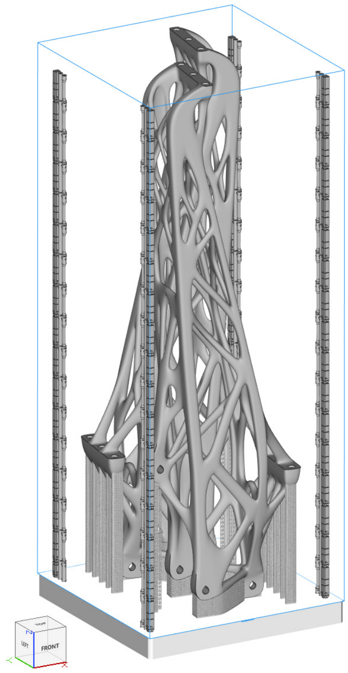

Fig. 2　A 3D model being prepared for layer generation

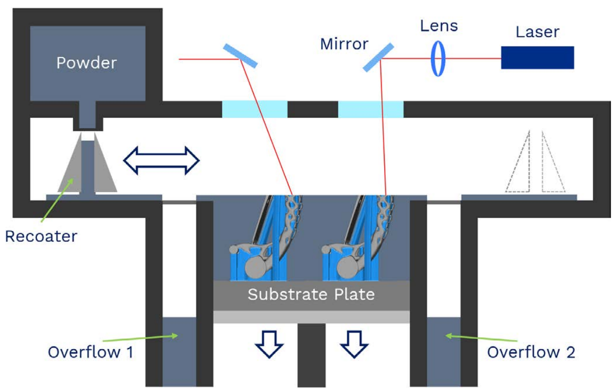

Fig. 3　Layout of a typical L-PBF machine process chamber

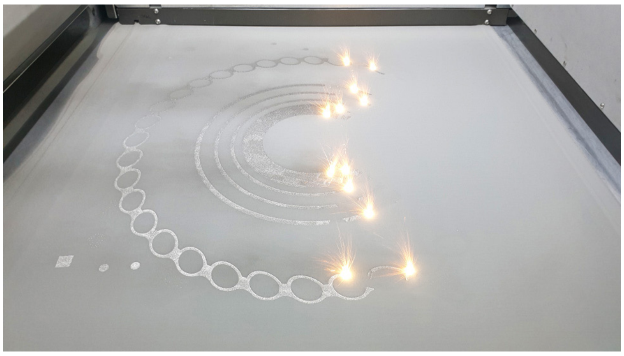

Fig. 4　Active laser exposure of metal powder within the NXG 600E machine process chamber

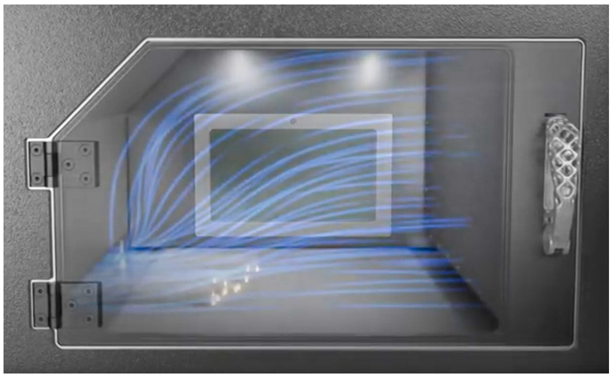

Fig. 5　Laminar shield gas flow within the sealed process chamber

individually controlled mirrors, selectively melt the powder according to the individual cross sections of the digital model. As the lasers move across the powder on the build platform, they fuse melted metal particles together, forming a solid cross-section of the part. Powder which is not melted remains loose and can be reclaimed later for a future process. The build platform then descends by the thickness of one layer and new metal powder is spread on top. Laser exposure of powder material again occurs as in the previous sequence, now guided by the data from the next part cross-section. Each new cross-section is solidified and fused with the solidified sections from previous layers, allowing the metal part to grow vertically as the L-PBF process continues.

Figure 4 shows active laser exposure of metal powder within the NXG 600E machine process chamber. This layer-by-layer procedure is repeated until the entire part is fabricated. Any required support structures are generated simultaneously to prevent the deformation of complex geometries. After completion, the part is removed from the L-PBF machine and undergoes post-processing steps such as unpacking, support removal, and heat treatment. Machining for dimensional accuracy, as well as surface finishing for desired surface qualities can also be completed separately. The result is a high-precision, complex metal part ready for use in various industries like aerospace, automotive, medical, and more. The concept of additive part generation sounds simple but each step along the process chain poses unique technical challenges, all of which had to be approached in a new way for the large-scale printer NXG 600E.

3 Challenges to Overcome for Large-scale Metal AM

3.1. Multi-laser Segmentation and Alignment

For Data preparation, new algorithms needed to be developed and validated to handle the complex task of assigning segments of the individual part cross sections to one or more of the 12 lasers. The goal here was to find the fastest melting strategy to satisfy the highest demands for part quality properties. Another factor that plays into these quality characteristics is the ability to accurately align each of the 12 lasers to one another so that they melt the powder at precisely the location which they are being instructed to travel to. For this purpose, a novel alignment method was developed which guarantees flawless build quality and reduces risks from optical drifts. The result is that each position of the process chamber's build area can be reached by accurately aligned lasers, enabling a laser utilization of up to 100%.

3.2. Process Stability within Each Layer

Another technological feat to achieve was designing a large process chamber that would be able to contain a stable shield gas environment in which 12 lasers could melt the powder material consistently. Figure 5 shows laminar shield gas flow within the sealed process chamber. Build chamber sizes are not infinitely scalable; lower gas flow stability will require a reduction in laser power and thus productivity. During melting, a large amount of soot and sparks are generated which need to be ejected from the process chamber via a steady gas flow. The way the lasers move to melt the powder is calculated very precisely so that none of the soot from one active laser exposure travels into the region of another. For these calculations to be feasible and predictable, the gas flow must be laminar and persistent during the entire run-time of multiple days or even weeks. Generating a laminar flow is very difficult to ensure over such a large build area of 600 mm x 600 mm. Nikon SLM Solutions already began developing new shield gas flow principles for their smaller machines, incorporating a patented sintered wall technology which was enhanced and further optimized for the NXG XII 600 platform.

Fig. 6 Two 1500 mm tall jet engine pylons, made of nickel alloy In718, produced within 169 hours

Fig. 7 Seventeen vertically stacked sample part levels from a single NXG 600E L-PBF process

3.3. Process Stability across 25.000 Layers

A controlled melting procedure within each individual layer is not enough. An industrial scale metal additive manufacturing machine must also deliver a stable process which can be kept consistent over tens of thousands of layers. For a standard NXG XII 600 with a build envelope of 600 mm x 600 mm x 600 mm this was already very challenging, as the extracted build job after production includes a finished part and loose powder with a combined weight of over 2000 kg. Figure 6 is a photo of built parts. When extending the z-height for the NXG 600E to 1500 mm, the maximum weight could exceed 5000 kg. This has severe implications for both the accuracy level within each layer, as well as the structural integrity requirements for the entire system as a whole unit. Typically, extending the z-height of a metal additive manufacturing system is simple to achieve because the process chamber and optical components do not need to be changed. However, at this scale, the z-drive robustness and overall machine architecture also required additional consideration.

3.4. Part Characteristics Consistency

The result of the previously elaborated process and machine characteristics combined is a solidified metal part which needs to perform as desired in a variety of different scenarios. These applications can vary widely in their needs for alloy composition and geometrical complexity, resulting in increased capability needs for the AM system. Depending on how well factors like laser alignment, gas flow stability, process stability are fine-tuned to one another, the solidified part may display varied levels of mechanical strength, elongation at break or surface quality. Such a variability is undesired, as the expectation is that the part will feature a level of homogeneity across its entire z-height. To ensure customer expectations are met, Nikon SLM Solutions carried out rigorous material parameter and process validations during the development of the NXG 600E using stacked sample parts as Fig. 7. This approach will be elaborated in the following chapter.

4 Testing and Validation of Process Stability

4.1. Laser Allocation Strategies

Wherever any laser melts powder material, large amounts of soot and spatter ejections will form. These pose a risk to the overall process stability, as well as part characteristics and therefore need to be removed by the shield gas flow. Naturally, any soot and spatter travelling downstream towards the gas flow outlet may also interact with exposure areas from other lasers. To prevent this, characteristics of soot and spatter creation need to be predicted, as well as the travel trajectory towards the gas flow outlet. This is a general problem of the metal L-PBF technology that Nikon SLM Solutions overcame with optimized machine design experience, accrued over the last 3 decades.

During the NXG XII 600 early development phase, testing with only 6 lasers was performed to understand the complex interactions between fume and spatter, which increase tremendously with every added laser. The following study was divided into a first setup where all 6 lasers were exposing a

(a)

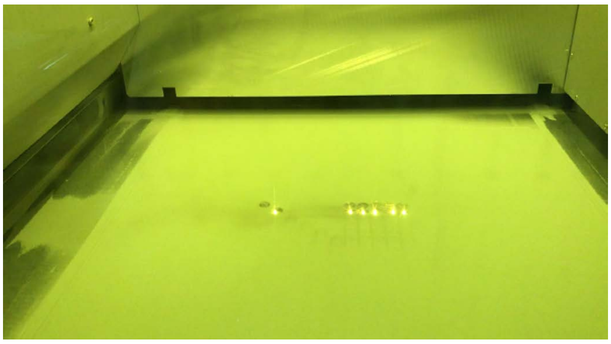

Fig. 8a　Six lasers exposing synchronously with maximum soot and spatter interaction

(b)

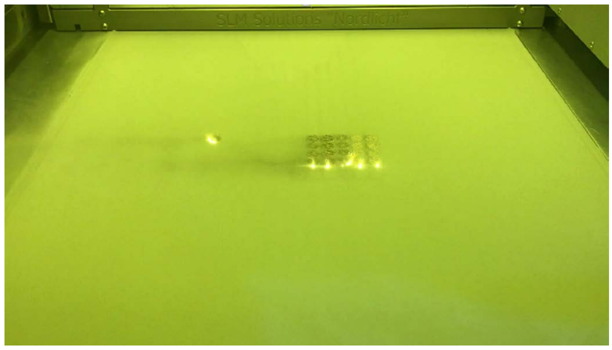

Fig. 8b　Asynchronous exposure leading to less soot and spatter interaction for

(a) (b) (c)

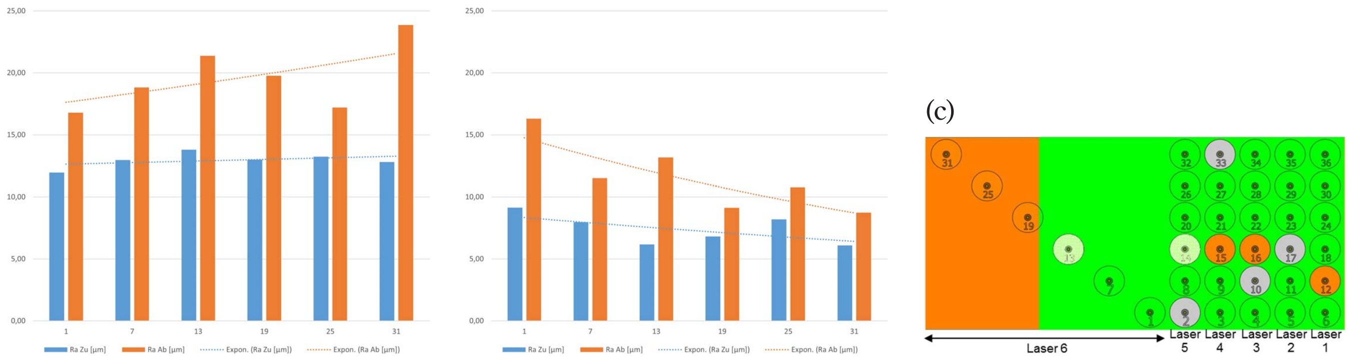

Fig. 9　Roughness (a) increases/(b) decreases with the distance for (a) synchronous/(b) asynchronous exposure and (c) Sample distribution for the test setup

secluded area of powder synchronously (Fig. 8a) and into a second setup which features asynchronous exposure (Fig. 8b). In both cases, the performance characteristics of the laser furthest to the left were observed. During the first setup, the exposure from the laser on the left side is heavily influenced by soot and spatter ejections from the remaining lasers on the right side. As shown in the figure below, the distance of the 5 lasers further to the right side was then increased significantly for the second test setup. The left laser was subsequently only influenced by spatter on the powder bed and no longer by any foreign soot ejections.

The results of a detailed sample analysis show that surface roughness on the part which was exposed by the laser on the left side increases significantly for synchronous exposure (Fig. 9a and Fig. 9b). Figure 9c is a sample distribution. When the distance between laser exposure areas is increased (asynchronous approach), surface roughness decreases to a level which users of the L-PBF technology are familiar with.

However, in a real production scenario, the highest possible level of quality needs to be achieved on all parts and samples. The assessment of multiple individual part cross-sections for each layer and how to allocate the 12 lasers is a complex task which only very advanced software algorithms can solve. For use in serial production scenarios, the goal was not only to achieve best part quality but also to minimize overall exposure time. Lower exposure times result in lower cost per part and make the entire process viable. As emphasized by the test setup above, a maximized utilization rate for all 12 lasers is desired. A high amount of additional test scenarios were conducted to acquire more data which could be used to derive the best laser allocation algorithms.

The result is a variety of strategies that can be chosen during the data preparation phase. Different scanner allocation strategy options need to be made available, due to the high amount of unique cross-section characteristics that differ from one application to the next. The outcome of maximizing either productivity or part quality will vary greatly, even for the same part.

- Maximized productivity and less quality (fastest scanning time)
- Mixture of high productivity and high quality (+35% scanning time)
- Maximized quality and low productivity (+90% scanning time)

Ultimately, the goal was to offer users of the L-PBF technology a spectrum of scanner allocation approaches, eliminating the need for compromises.

4.2. Gas Flow Optimization for Laminar Flow

The task of managing up to 12 individual lasers and their interactions could only be achieved if the underlying process conditions were managed in a consistent and repeatable way. Therefore, it was crucial to supply the process chamber with a highly laminar shield gas flow across the entire powder bed. An active shield gas flow within a metal L-PBF machine' s process chamber has been used since the technology was first developed. However, as the number of lasers increased steadily, new approaches had to be found to prevent the need for sacrificing part quality for higher productivity.

Initially, the shield gas was introduced from one side of the process chamber via two separate inlets. One inlet was located at the bottom of the chamber, to produce a stable flow across the powder bed, while the second inlet was located towards the top of the chamber, to prevent soot ejections from reaching the area where the laser enters the chamber. Both gas streams exit the chamber through an outlet located at the bottom of the opposite side, carrying soot and spatter ejections with them. This setup however contains flaws that become more apparent when the number of lasers increases. The two separate streams do not cover the entire z-height of the chamber and a turbulent zone with considerable back flow starts to form in the center of the chamber. A simulation of this inlet setup can be seen in Fig. 10a, where gas enters the chamber on the right and exits at the left.

With multiple active exposure areas, soot will have the opportunity to accumulate in this turbulent zone before it is ejected. The result is a temporary 'soot cloud' formation which lasers will have to pass through before reaching the powder bed. This effectively causes a decreased amount of laser power to arrive where it is needed for melting, leading to an unstable exposure process and inconsistent part properties.

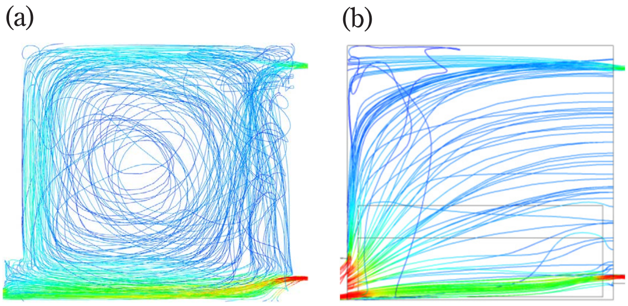

Fig. 10 (a)Turbulent gas flow resulting from two separate inlets, (b) Laminar gas flow resulting from sintered wall inlet approach

Nikon SLM Solutions already tackled the investigation into alternative shield gas flow principles prior to the development of the NXG XII 600. The solution was to ensure a steady gas flow via the entire z-height, as opposed to only at the very top and bottom. This was achieved by incorporating a patented sintered wall technology, where the gas flow inlet itself comprises a major part of one process chamber wall. Figure 10b shows a gas flow simulation which includes only a reduced amount of additional inlet points in the middle of the right wall. The difference in process chamber environment quality is obvious. The turbulent zone in the middle can be eliminated effectively.

Even though this approach was already implemented on smaller L-PBF machines such as the SLM®280 and SLM®500, an identical setup could not be adapted without major modifications. Previously, the distance which the laminar gas stream covered was only around 280 mm. With the increased size of the NXG XII 600 process chamber, a highly laminar flow had to be ensured over a distance of 600 mm.

The chosen approach was to iteratively design, simulate, build, and test various process chamber configurations in virtual and real-life environments. This process contained multiple stages, comprised of complex design adaptations, individual unit and system tests. In summation, the targeted performance characteristics to optimize revolved around three aspects:

- Achieving a highly homogenous flow profile in y-direction (process chamber front to back)
- Minimizing the gas flow speed reduction above the powder in x-direction (as it travels from inlet to outlet)
- Eliminating the risk for laser inlet contamination at the top of the process chamber

Multiple variables for each property needed to be assessed individually and in combination. These variables included but were not limited to gas inlet geometry, gas outlet geometry, process chamber design, gas volume flow rate, background gas flow design, as well as distribution between background flow and lower jet flow. One additional design guideline was the need to remove all unnecessary obstacles to the gas, for the purpose of isolating dead cavities. The result was a highly symmetric chamber where even the streamlined powder Recoater has a hidden parking position in both back and front positions, so as not to disturb the overall flow.

Figure 11a-c demonstrates the iterative process, where

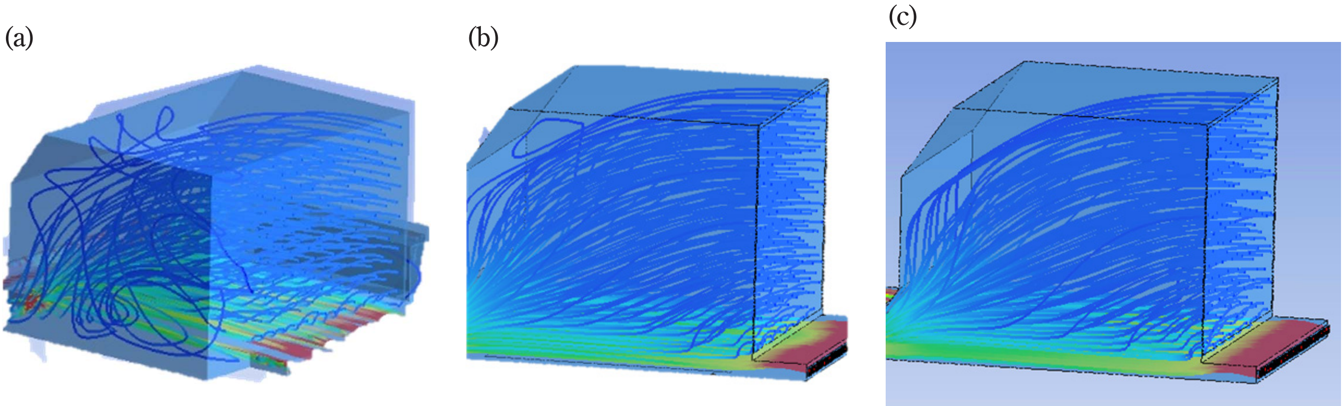

Fig. 11　(a) Simulation results of the unchanged inlet concept applied to a large process chamber, (b) Redesigned gas flow inlet leads to significant improvements in laminar flow (c) Redesigned gas flow outlet further reduces drop in speed and backpressure effects

different development stages can be compared. Initially, the existing sintered wall technology from smaller L-PBF systems was applied to the enlarged process chamber of the NXG XII 600, with less-than-optimal results (Fig. 11a). After continuously improving the inlet geometry, gas flow homogeneity in y-direction was greatly improved and the risk for laser inlet contamination was reduced (Fig. 11b). However, the overall backflow characteristics and decreasing gas flow speed profile were not yet satisfactory. To achieve the desired state, several modifications needed to be made to both the gas flow outlet, as well as the process chamber wall located closest to the outlet. Testing was conducted over a period of several years, with the result being a homogenous gas flow profile in x- and y-direction (Fig. 11c).

4.3. Z-Drive Accuracy and Structural Integrity

In addition to overcoming technical challenges influencing stability and productivity within a single cross-section exposure, consistent performance and part quality over thousands of layers had to be achieved. With the development of the even larger NXG 600E, the total z-height of the build envelope was increased from 600 mm to 1500 mm, resulting in an increase from 10.000 to 25.000 individual layers for a slice thickness of 60 µm. To make this feasible, two separate aspects were investigated:

- Z-Drive accuracy during substrate plate movement from one layer to the next
- Structural integrity of the NXG system frame for increased total load

For the investigation of the first aspect, clear requirements had to be established to what level of accuracy repeated substrate plate movements needed to be achieved. Ultimately, the desired precision had to be reflected in the additively manufactured metal part, as opposed to just the L-PBF machine itself. The expectation from users of this technology is that the 3D part model can be replicated to a specific tolerance level that is defined within an ISO standard. Therefore, part accuracy in terms of permissible length deviation was defined according to class F of DIN ISO 2768-1. With regards to straightness, this was specified in accordance with class H of DIN ISO 2768-2. The main influencing factor here was the Z-Drive responsible for moving the substrate plate. To verify that the chosen Z-Drive could achieve high demands for movement accuracy under complex loads, a laser interferometer was used to measure incremental movements in all positions along the z-axis (Fig. 12, 13).

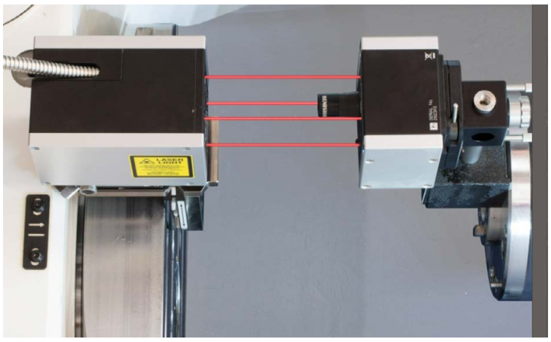

Fig. 12　XM-60 laser interferometer

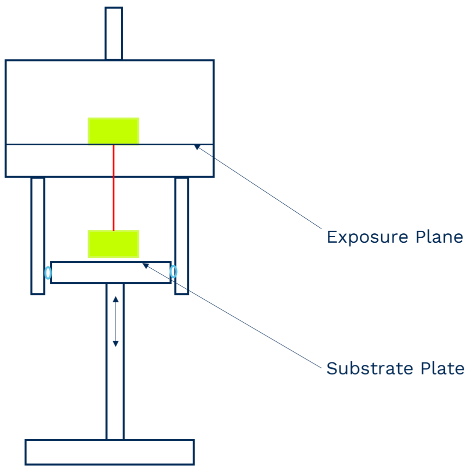

Fig. 13　Schematic representation of the test setup with laser interferometer

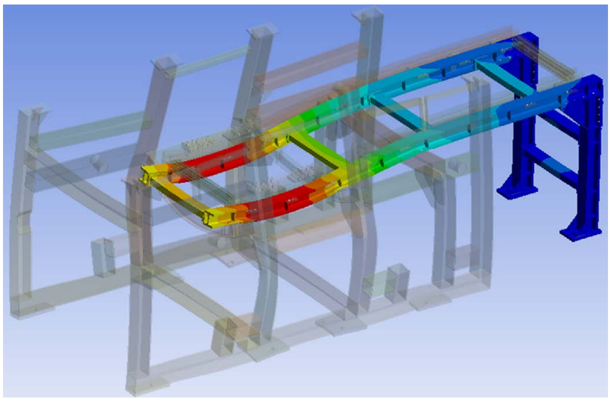

Fig. 14 Structural deformation calculation results from finite element method

Additionally, the accuracy measurements were also carried out for both the x-axis and y-axis along the full stroke of 1500 mm.

The measurements confirmed that Z-Drive accuracy was well within class F and H specifications, in accordance with DIN ISO 2678. One remaining influence on final part accuracy is the resulting material shrinkage after cool-down occurs towards the end of the L-PBF process. Luckily, this factor can be mitigated by rescaling the 3D model before it is sliced into individual layers, thus decoupling shrinkage compensation from the actual machine hardware.

For the investigation of the second aspect, structural integrity, ample use was made of finite element analysis tools shown as Fig. 14 to perform calculations on key structural components within the NXG 600E. This was crucial, as many components are affected by the increased build envelope, including those which had to be moved into and out of the system regularly, such as the build cylinder and plate package. Overall, the total load to be handled safely could reach 52,3 kN or 5334 kg, while the maximum allowed deformation for continuous and safe operation should not surpass 0.5 mm. As an example, the simulation results for the track are shown in Fig. 15. This track is needed to transport the build cylinder (containing the finished part) from inside of the machine to the external extraction location.

4.4. Analysis of Part Consistency

As previously demonstrated, a variety of technical innovations were developed to increase productivity, reliability, and repeatability within the metal L-PBF process. The final step was to validate that all innovations were operating in tandem to not only allow for the entire process to run in a stable manner for weeks without interruption, but also to guarantee that the solidified metal parts met the high expectations regarding part characteristics. A rigorous procedure to

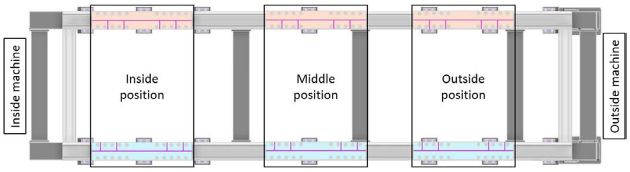

Fig. 15 Deformation positions along the linear track from inside to outside position

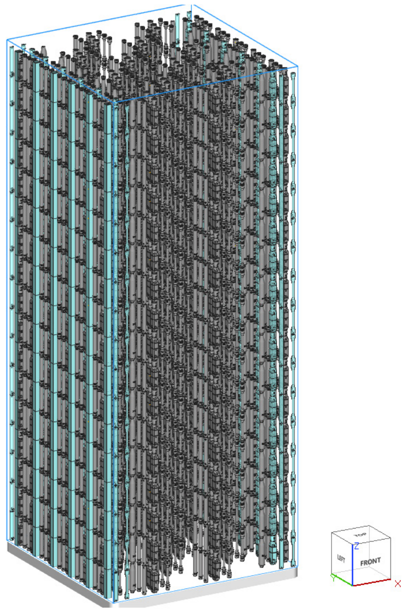

Fig. 16 Seventeen vertically stacked sample part levels, over 1800 individual samples in total

develop, test and validate unique part generation parameters had to be carried out within each alloy category, that either focused on part quality or productivity. For the sake of simplification, the following descriptions and tables will only showcase the approach and results for Inconel 718 and a single parameter variant which features a balance between highest part characteristics and productivity. Furthermore, sample parts were subjected to three different heat treatment profiles:

- No heat treatment, machined surface
- Solution annealing + aging, machined surface
- Hot isostatic pressing + solution annealing + aging, machined surface

The showcased sample results are those which were solution annealed and aged as per AMS 2774 S1750DP. Emphasis was placed on ensuring that the entire NXG 600E build envelope across its full height of 1500 mm was assessed. For this purpose, the sample generation was repeated over 17 individual levels, which each feature the same specimen geometries and layout in x and y directions. These layers can be seen in Fig. 16 (corresponding to Fig. 7).

In this process, the main focus was placed mainly on part density, hardness, and tensile properties. These characteris-

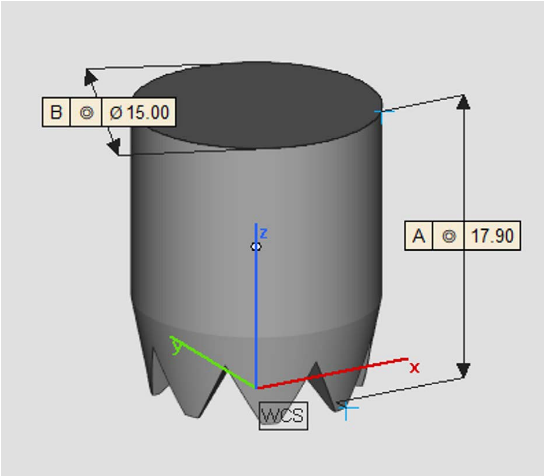

Fig. 17　3D models of a standardized CT specimen

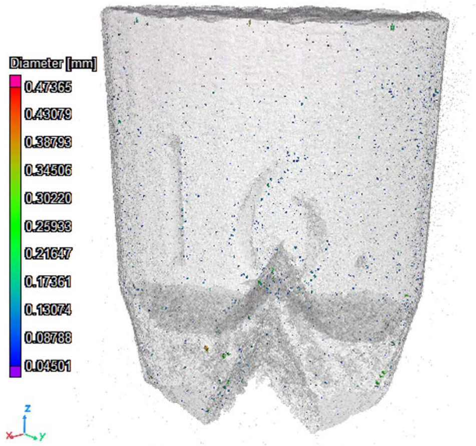

Fig. 18　Visual representation of Micro-CT results for a single specimen

tics are crucial to ensure the highest quality of additional secondary properties, which could be investigated at a later stage.

For density investigations, ample use was made of non-destructive material testing, in which information on external and internal defects was acquired. Potential defects include porosities and inclusions, among others. One such technology is Micro-CT, for which hundreds of CT-specimens (Fig. 17, 18) were scrutinized down to a voxel size of just 15 μm, enabling the detectability of anomalies down to 45 μm. This is sufficient to identify defects or inclusions with serious implications for a solidified part's long-term stability. To accelerate the analysis of hundreds of specimens, an automatic sample changer was utilized, which allowed up to 63 samples to be run in one single batch. For each sample, the result was an elaborate report offering insights into the total number of pores, pore sizes, pore distribution, sphericity characteristics of individual pores, and pore distance to the part surface. Additionally, localized porosity hotspots were visualized, in which a pre-defined porosity threshold is exceeded. This was then assessed to enable further fine tuning of L-PBF process parameters for either maximized productivity or part density. Figure 19 shows a histogram of density distributions for one sample level, where a MEAN value of 99.97% was achieved. This corresponds very well to

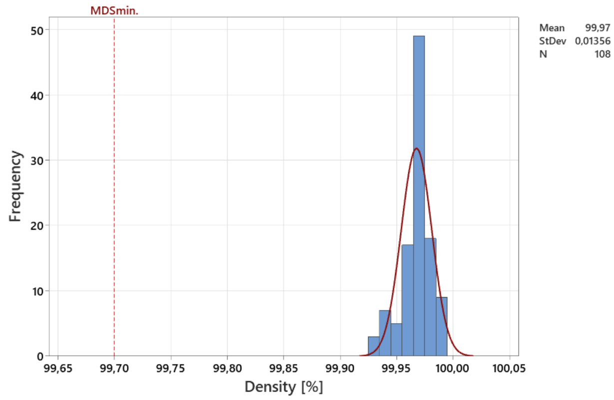

Fig. 19　Histogram of Density [%]

the sample analysis of all remaining levels from the same L-PBF process.

For the validation of tensile properties and hardness, each level within the previous layout features over 60 dedicated samples that can be subjected to multiple tests. The main characteristics of interest were Ultimate Tensile Strength (UTS), Yield Strength (YLD), Elongation at Break, and Hardness. As can be seen from the results in Fig. 20a-d, the L-PBF process within the NXG 600E delivers highly stable properties over the full build height in each level, especially for UTS and Elongation. Within the narrow distribution of mechanical properties, there is no upwards trend visible, the standard deviation also behaves consistently from one level

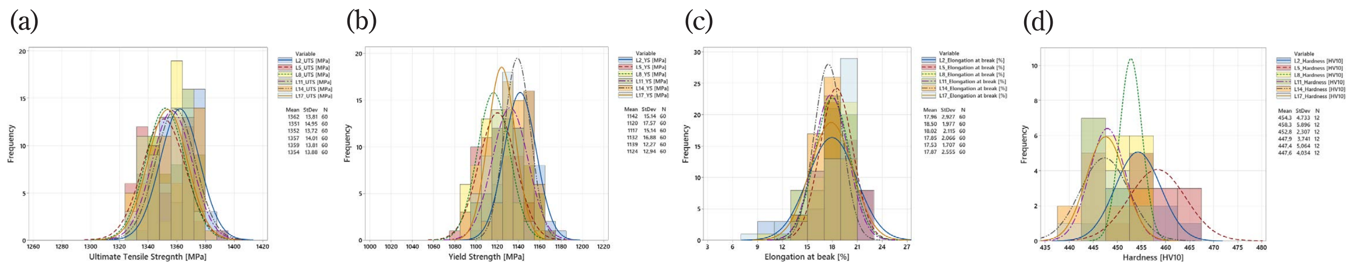

Fig. 20　Histograms of (a) Ultimate Tensile Strength, (b) Yield Strength, (c) Elongation, (d) Hardness

to the next. Furthermore, Vickers testing across all sample levels reveals a high degree of overlap in hardness with low anisotropy characteristics. This is a testament to the overall homogeneity within the machine's technological capabilities, resulting from years of testing and iterative improvements.

5 Conclusion

The NXG 600E expands on the initial capabilities of the NXG XII 600 system to deliver state-of-the-art productivity, reliability, output quality and will accelerate the adoption of L-PBF technologies across a variety of industries such as aerospace, automotive, defense, energy and healthcare. Through rigorous testing and design validation procedures, innovative solutions for multi-laser alignment, laminar gas flow generation and part consistency management were incorporated without sacrificing process performance or part characteristics. By pushing the boundaries of existing technology approaches within the L-PBF process, Nikon SLM Solutions will continue to develop products which exceed customer expectations and enable the use of AM technologies for novel applications in entirely new industries.

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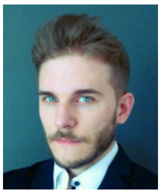

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