DIGITAL INDUSTRIES SOFTWARE

Print durable products faster

Using Simcenter 3D to accurately predict fatigue life for additive manufacturing

Executive summary

Additive manufacturing (AM) will become a massive game changer in production. It offers designers almost unlimited flexibility and paves the way to distributed manufacturing. But are printed parts durable and safe? Lack of expertise in that area keeps AM from being used for structurally loaded, safety-critical components. In this white paper, we describe a unique, validated durability simulation method that has been added to Simcenter™ 3D software. Using Simcenter 3D, engineers can characterize local material conditions introduced by the printing process, use them in a machine learning (ML) algorithm to create an accurate material model for durability and study the fatigue life of the part. With these tools, Siemens Digital Industries Software engineers have designed a novel strategy that will allow manufacturers to print durable parts much faster and cheaper.

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Introduction

Globalization is making us vulnerable to disruptive events

In today's economy, we're all increasingly connected worldwide. This creates a highly dynamic business climate as it allows companies to distribute work as well as deploy just-in-time (JIT) delivery anywhere. At the same time, this thorough intertwining of business activities around the globe makes the entire system vulnerable to disruptive events.

As an example, think of the incident that happened in March 2021 in the Suez Canal, where a single blocked container ship paralyzed an entire global supply chain of materials and goods, causing massive trade losses and delays across the most diverse markets.

The global nature of our businesses is also catalyzing the current sequence of crises caused by the COVID-19 pandemic. First, because it involves the travel that caused the initial spread of the virus and that makes it difficult for authorities to isolate and eradicate it. And secondly, because it causes local virus flareups to have economic consequences that extend far beyond the affected region. All this results in a seemingly endless downward spiral that can only be reversed by either powerful vaccines or antiviral treatment, or if the virus loses potency over time.

Luckily, events on a scale similar to the COVID-19 pandemic don't come often. But if they do, the impact on the globalized economy and society is enormous. Due to COVID-19, McKinsey found that over 90 percent of executives expect fundamental changes to the business in the next five years and 85 percent predict a lasting impact on consumer needs.[1]

Additive manufacturing: the emerging technology that comes just-in-time

Companies that want to arm themselves against the negative consequences of such disruptive events must focus on innovation and look for proportionate disruptive technologies to let them remain operational, or even take the lead. For manufacturing industries, advancements are primarily happening in the areas of materials, production processes and digitalization. We can expect that new breakthrough technologies will come from a combination of those elements.[2] In this context, new applications based on additive manufacturing, also known as 3D printing, are very promising.[3]

AM is the collective name for a variety of production processes that help manufacturers fabricate complex parts by printing them layer-by-layer. These methodologies allow them to generate shapes that were seemingly impossible previously, as well as to be more efficient when it comes to material use compared to traditional subtractive production techniques. The roots of AM lie in the field of prototype creation, where the aim is typically to only produce a limited number of samples. However, thanks to advancements in digital technologies, the method is rapidly gaining ground in serial production where it is becoming a massive game changer.

To understand what AM can mean for businesses, think of a vehicle repair shop that currently either requires a large stock of spare parts or must be backed by an utterly efficient and robust supply. With AM, the stock could be limited to the base material only (for example, metal powder) and a 3D printer and spare parts could be produced on the spot. AM has the capacity to democratize manufacturing, lifting production out of the factory into local part printing shops. In summary, AM offers a clear path to distributed manufacturing, which will increase global resilience of manufacturing capacity and protect supply chain logistics against disruptive events.

Further, AM offers product designers and engineers almost unlimited freedom, allowing them to manufacture (close to) what comes out of an optimization;[4] for example, topology optimization (TO).[5]

Are printed products safe?

Unlimited flexibility, both as to what can be manufactured and where, sounds almost too good to be true. But are these products durable and safe? That question is important because fatigue life performance is among the key requirements across industries and applications. Many real-life structures are subject to cyclic loads, hence sensitive to fatigue failure. Cars and trucks are continuously exposed to road and powertrain loads. Planes experience aerodynamic loads, repeated takeoff and landing events and aero-engine loads. The wind induces cyclic loads on a wind turbine's blades and structure. And machines often have rotating parts that produce loads in repeated cycles. These are just a few examples.

To illustrate how important this is even after releasing a product to the market, manufacturers continue testing components and characterizing materials. In this way, they can study how properties can use impact fatigue life and lessons learned for future repairs or next-generation products. So without proper performance in this area, AM usage will never ramp up to its full potential.[6] And whereas the origin of fatigue analysis is in metal fatigue, an area that was studied since the 19th century, we know now that most other materials experience fatigue-related failure as well, including composites, plastics and ceramics.[7] But let there be no doubt: AM materials are no exception.

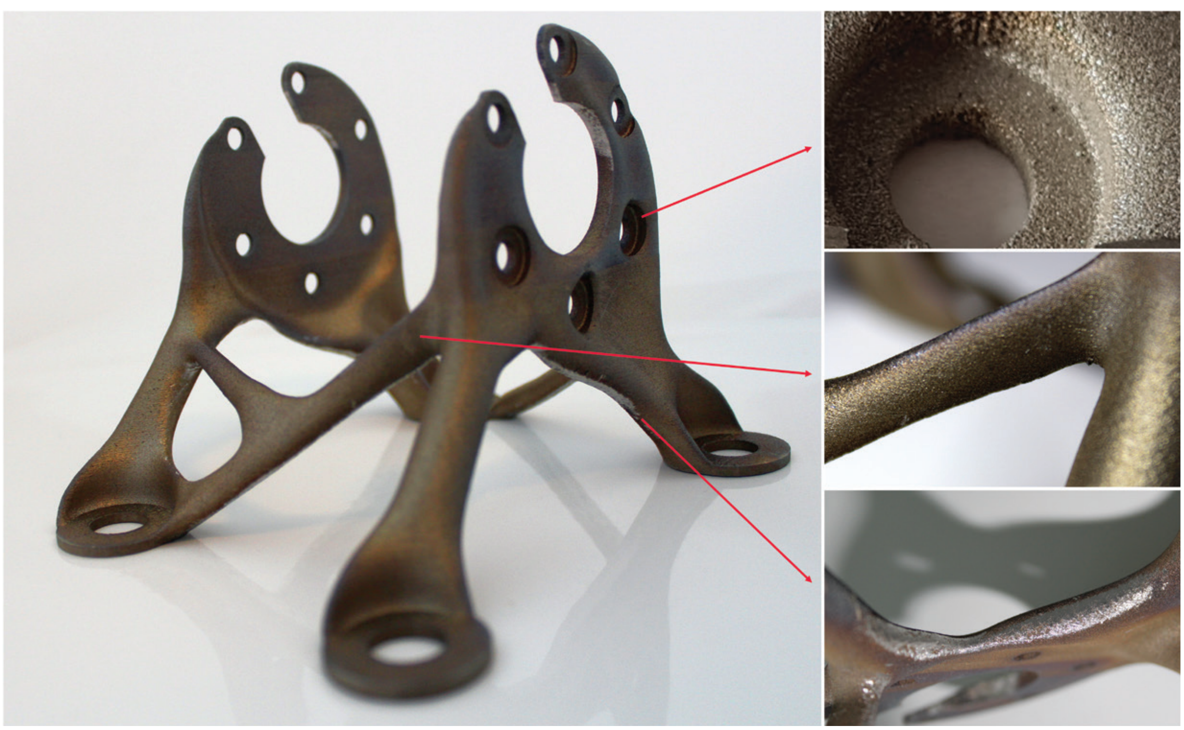

Figure 1. The fatigue challenge for AM: The AM process leads to variable local conditions such as variable surface roughness as presented in this picture, which impacts fatigue performance.

To make sure printed parts will be high quality and safe to use, it is necessary to simulate and optimize their durability performance during design, but that requires dedicated technology. The fatigue performance largely depends on local artifacts on the structure that are due to the printing process, such as variable surface conditions (see figure 1). Specifically targeting them during design can lead to spectacular improvements. For example, by reorienting a component within the build, you can make sure fatigue hot spots get more favorable local properties to better protect them against failure.[8] However, a traditional simulation process doesn't include these manufacturing details. Here is where we can help. In this white paper, we describe some dedicated simulation methods the Simcenter solutions portfolio offers for fatigue analysis of printed structures. Simcenter is part of the Xcelerator portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

An additional challenge for fatigue analysis

The early days of fatigue analysis

Fatigue was already a well-known concept in the 19th century. Wilhelm Albert studied iron mine hoist chains in 1829. He found that failure was dependent on both the load and the number of cycles and invented the twisted steel cable, leading to improved fatigue performance.[9,10]

Very soon after, German railway engineer August Wöhler started to describe fatigue performance in the typical SN-curves, or Wöhler curves (see figure 2). These show the cyclic stress (S) as a function of the cycles to failure (N) on a logarithmic scale. A key insight by Wöhler was the cyclic stress range can be more important than the peak stress, hence fatigue failure can result from low cyclic loads.[11,12]

Later, fatigue life became increasingly important as the number of metal machines and transport vehicles started to grow exponentially and some high-publicity incidents drew public attention. One example happened in 1843 in Versailles, France, where fatigue failure in the axle made a train derail, killing over 50 people. Such incidents raised awareness and put the topic high on the agenda of product design and manufacturing across industries.

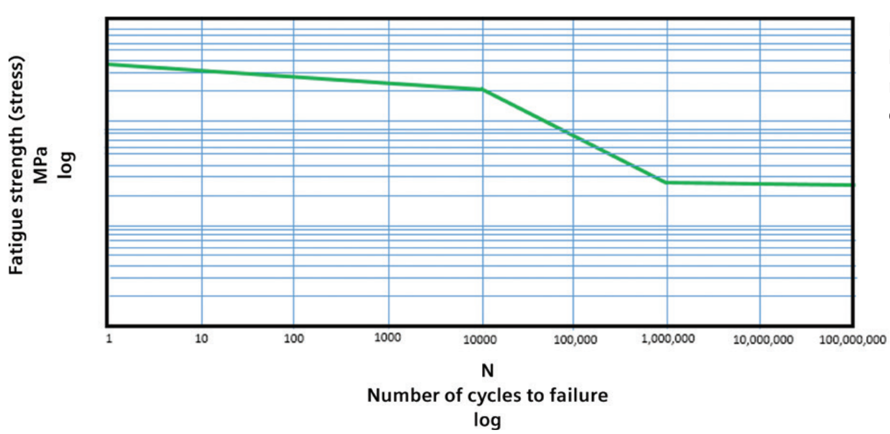

Figure 2. SN-curve for material: higher amplitude stress cycles resulting in lower number of cycles to failure.

A major driver for further research has been the automotive industry, where most manufacturers started to develop their own dedicated test tracks. In practice, the fatigue issue was often overcome by systematic overdesign. Only starting in the 1980s were more meticulous approaches followed, typically to achieve weight reduction while maintaining durability performance. It's obvious that the latter has become even more important today, with the ever-increasing pressure on efficiency. Fatigue is therefore now one of the critical aspects that is considered during design. An increasing amount of simulation is necessary to deal with the complexity of today's vehicles and materials, as well as to properly analyze and optimize the balance between fatigue and other performance requirements.

AM complicates fatigue simulation

With more established materials such as metals and even composites, manufacturers have ample experience. They know which simulation methods and tools to use to properly include fatigue analysis in their engineering processes.[13]

However, with AM it's different. In the introduction, we highlighted its advantages and depicted its potential. But at the same time, the reality is that for structurally loaded safety-critical components, today's manufacturers are still reluctant to apply the technology. One of the main reasons is because they have not fully mastered fatigue behavior.

That's because AM leads to a nonuniform distribution of certain local properties such as porosity and surface roughness (see figure 3). The formation of those depends on both the geometry and its manufacturing process.[14] The fact these artifacts appear local but have an impact at a system level obviously complicates the setup of the simulation process. A multi-scale simulation technique that captures information from micro-scale and leverages this to accurately predict the macro-level behavior is necessary. If this can be achieved, a design can be optimized for fatigue life.[15,16]

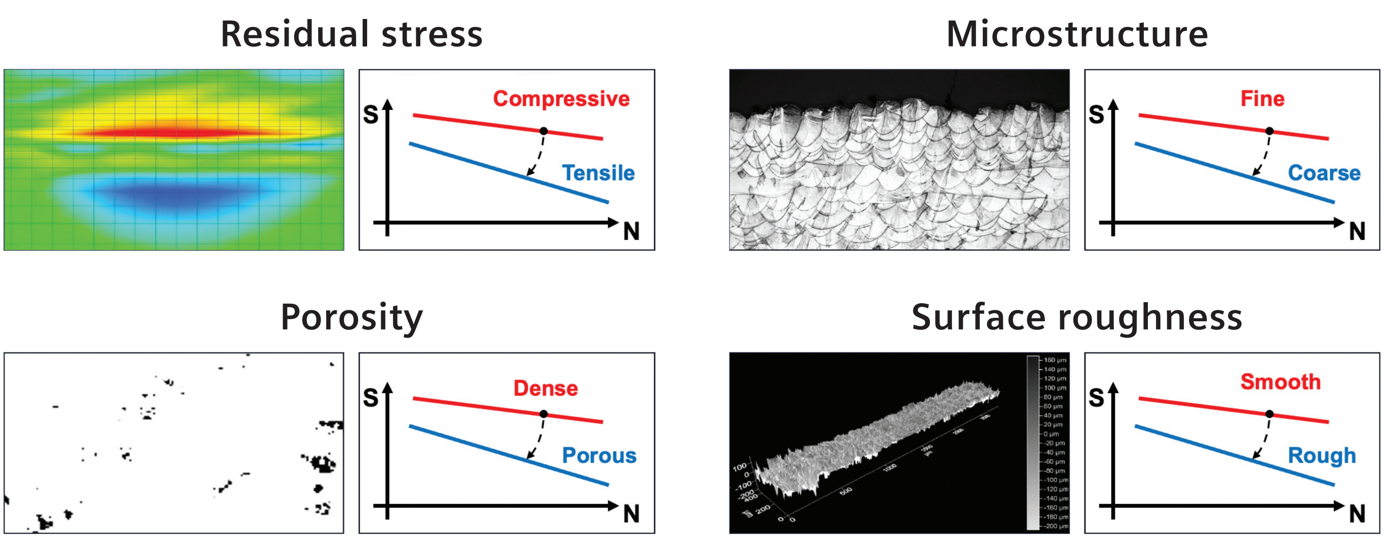

Figure 3. The AM-induced variable local conditions in a 3D printed component leads to variable local fatigue properties.

The fatigue failure mechanism of printed components

To determine how the simulation process for AM fatigue failure prediction should look, it's important to understand the mechanisms that play a role in this phenomenon. They fall into three categories:

First, there is **geometry**. Using AM is a great opportunity to exploit the capabilities of generative engineering thanks to the tight links between AM and TO. The goal of TO is to use only the amount of material that is strictly necessary. In theory that should even lead to reduced stress concentrations. However, at the same time, the increased complexity might give rise to some local artifacts and geometrical features that have an adverse effect and lead to deterioration of fatigue performance.

Secondly, there is **loading**, which is obviously independent from whether AM is being used or not. However, for a more accurate prediction, simulation will need to take all the AM-induced local conditions into consideration.

Finally, there is **material**. Conventionally manufactured materials are well described in vast literature, where their behavior is described based on decades, if not centuries, of research. For AM materials, literature is obviously much scarcer since the industry only started to consider it for safety-critical applications during the last decade. Also, the reported fatigue curves still miss consistency.

A major challenge are the endless possible combinations of material conditions. As a result, it is useless to rely on databases because there is no formula that can predict SN-curves for a random set of material conditions. To illustrate this, consider metal laser power bed fusion (LPBF), which is one of the most mature and widely used AM technologies. It uses a laser to melt the deposited metal powder scan track by scan track until the component is ready.[17]

The typical size of a component is on the order of magnitude of tens of centimeters. But it can consist of kilometers of weld lines. The LPBF process by itself already has numerous parameters, many of which significantly influence the creation of exactly the features that are important, such as porosity and roughness. But on top of that, the geometry as well as the orientation of the component in the build play a role. So, for example, when you print two specimens of the same component with the same machine in the same build, but one is oriented and supported differently than the other, you can still end up with completely different fatigue behavior. All these aspects lead to a huge variation in the reported fatigue properties of AM metal samples (coupons).

It becomes even more difficult on the component level because we also need to consider a multitude of such AM-induced local fatigue-influencing factors. We must evaluate their impact on fatigue performance of the material and then consider all these variable conditions in a durability calculation for the given application.

To deal with all these challenges and ultimately achieve an efficient simulation-based approach for AM products with high durability performance, we need to focus on the following areas:

1. Gain insight into AM-induced local material conditions (or fatigue-influencing factors) and quantify them.
2. Describe how these local material conditions influence the fatigue life. The aim should be to do that by predicting the fatigue properties, thereby avoiding hundreds of tests for all the combinations of conditions.
3. Realize an efficient yet accurate durability analysis approach that considers these local fatigue properties in the product fatigue design.

Below, we describe how this can be achieved in Simcenter 3D.

AM-capable durability analysis in Simcenter 3D

In Simcenter 3D, engineers can create a digital twin of a printed product in its build environment, including thermal loading. As a result, they can optimize both the design and the manufacturing process and ultimately achieve a reliable AM-based product. The solution is based on the following three pillars:

- Predict the AM-induced local material conditions
- Predict the influence of the AM-induced local material conditions on fatigue properties with machine learning
- Perform efficient durability analysis taking into account the AM-induced local conditions

Predict the AM-induced local material conditions

As described above, the local properties that influence fatigue are not evenly distributed over the printed component. Capturing knowledge about that is the first requirement, as in the end fatigue is a failure phenomenon that starts locally.

A tangible example is unevenly distributed surface roughness. In metal LPBF, that is related to certain process parameters as well as to the local overhang angle: the angle of the 3D printed surface with respect to the build direction. This means reorienting the component in the build chamber leads to a redistribution of the varying surface roughness.

In Simcenter 3D, we have included a tool engineers can use to calculate and map the varying surface roughness on the 3D printed component based on the type of LPBF system and the chosen orientation. If the engineer decides to reorient the component, the surface roughness can be re-evaluated and mapped back on the part.[18]

Simcenter 3D can also be used to consider the residual stress that results from the AM process. Linking to available AM process simulation capabilities, engineers can predict the residual stress that builds up during the layer-by-layer production of the component. They can consider such residual stress as mean stress in subsequent durability calculations.

Finally, we're currently also extending the capabilities of Simcenter 3D to predicting porosities and material microstructure due to the AM process.

The ultimate objective of all those tools is to optimize the AM process to obtain desired material conditions in vulnerable locations (finding the orientation of the part in the build chamber so the structure is best quality in the region that is most stressed).

Introduce machine learning to predict fatigue properties

How a material performs in terms of fatigue always depends on the combination of all local influencing factors. They are traditionally separately characterized in tests on coupons. But in the case of LPBF, it's not easy to separate the influence of those individual factors (if that would be possible at all).

As an example, think of surface roughness. That depends on the overhang angle. To study its influence, you could print samples in different build orientations and then test them. But given the layer-by-layer approach, you will also affect the underlying material microstructure as well as the built-up residual stress. Consequently, you cannot evaluate the isolated effect of surface roughness. Similar complexities pop up when you want to study other fatigue-influencing factors.

On top of that, LPBF machines from different vendors with different process settings will also likely produce material with different properties, even when using the same base material. Therefore, literature studies report a wide scatter in fatigue behavior. See also figure 4, which shows a study performed by Catholic University of Leuven, Belgium (KU Leuven) on LPBF of a titanium alloy (Ti6Al4).

To resolve this, we propose to use machine learning to generate a material model. ML can reveal hidden relationships between the different fatigue-influencing factors. The outcome of this can then be used to accurately predict the fatigue property for any given combination of parameters.[19,20]

Using the ML fatigue model, you can predict the SN-curve that corresponds to any combination of LPBF process conditions based on a Gaussian Process approach.[21]

To train the ML model, a dedicated test campaign has been designed and executed in the framework of the M3-FATAM project for different build and postprocessing conditions. This solution supports making meaningful predictions based on available test data. Key advantages are that it can work on relatively scarce data sets and that it does not require a priori assumptions on how different artifacts affect the fatigue life. This allows extrapolation beyond the datasets encountered in the training.[19]

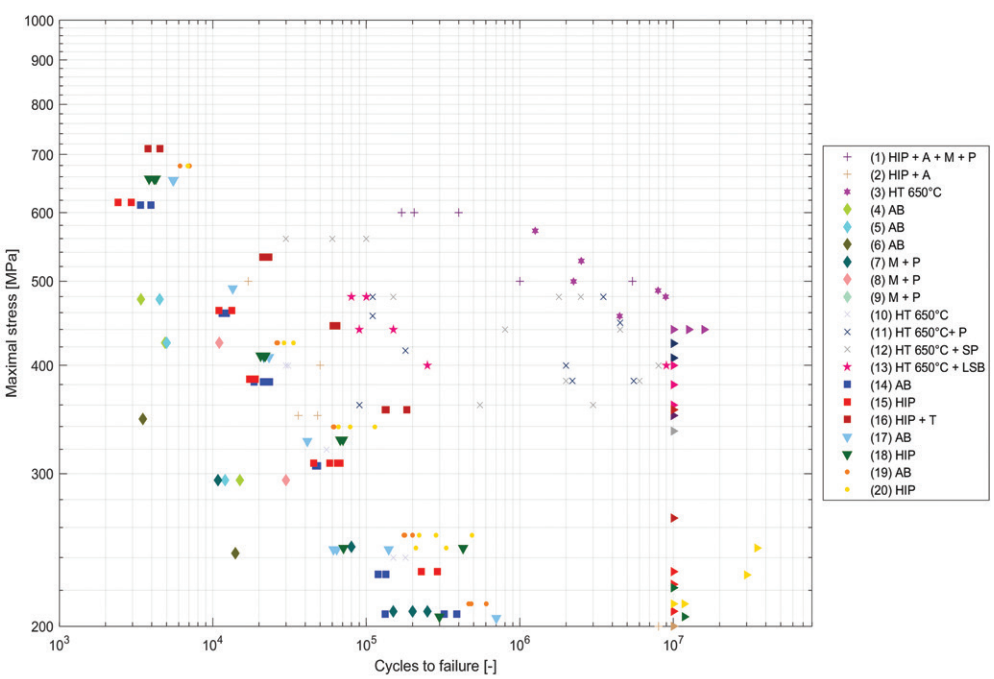

Figure 4. Fatigue behavior of Ti6Al4V from LPBF process for various combinations of local conditions, as described in a study by KU Leuven.

Perform efficient durability analysis by considering the AM-induced local conditions

The final step is to add these material properties to a durability simulation analysis that is conducted on the part level. The capabilities that are necessary to do so are now part of Simcenter 3D Specialist Durability.[22] Using the Simcenter 3D Open Solver framework, the software can include the above-mentioned ML material model for predicting fatigue properties. It can start from either experimental or simulated data. By using the model, you can adequately compensate mean stresses and take the necessary local fatigue-influencing factors into consideration, including surface roughness, void-rich areas, residual stress from the AM process and stress concentrations.

By enabling this three-step approach, Simcenter 3D offers manufacturers a complete durability solution for AM. Engineers can follow the entire design flow, from material, process and product data to fatigue life prediction and subsequent optimization of product design and performance. It will help them create and certify more durable 3D printed parts. The proposed solution has been validated using industrial components that were built with an LPBF process. Next we present the result of this exercise.

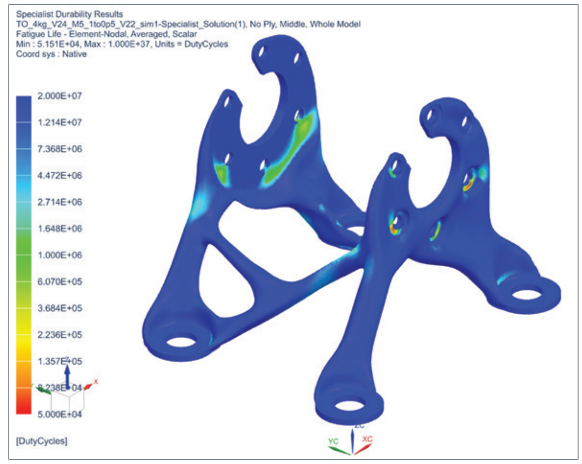

Figure 5. Simcenter 3D Specialist Durability offers the only fatigue solver capable of considering AM-process-induced local properties in part scale durability analysis.

Validation case: a turbine blade made of stainless steel

Case description

In this section, we'll illustrate and validate the Simcenter 3D solution using a turbine blade example (see figure 6). The study was part of the M3-FATAM (Fatigue of Additive Manufactured components) project.

The blade was printed in LPBF 316L stainless steel and electropolished afterwards. The component was tested at the first resonance frequency and then monitored to identify the initiation of cracks. At the same time, a simulation-based analysis of resonance modes was done, followed by a fatigue analysis to predict failure locations on the blade using the AM enhancements in the Simcenter 3D Specialist Durability solver. Based on this analysis, it could be predicted that failure would start at the root of the blade near the edge after a number of cycles, which would depend on the load amplitude according to the simulated component SN-curve.

ML was used to define the material models. Miniature sample geometries were used for the turbine blade. They were printed by 3D Systems, taking into consideration a fixed set of process parameters. The fatigue testing and analysis was carried out using an Instron ElectroPuls E10000[23] by the additive manufacturing team of KU Leuven Department of Mechanical Engineering.

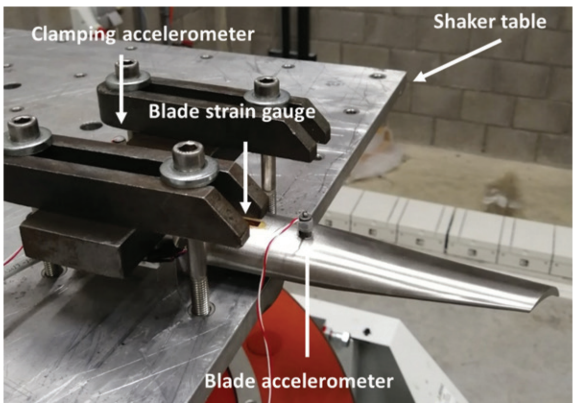

Figure 6. Validation case of simulation method with experimental data on turbine blade (picture by KU Leuven).

Validation results

As you can see in figure 7 on the right, there is a good fidelity between the experimental results and the outcome of the simulation solution in Simcenter 3D. The similar slopes of the curves suggest the behavior could be well predicted. The simulated failure location also matched with where the cracks were found on the tested specimen.

Here is how this comparison was done. The test consisted of a shaker setup and a strain gauge mounted on the blade and acting as a feedback loop for the shaker load. Strain gauge readings for each load level were then transferred to simulation for replicating the load conditions. The simulation model was subsequently used to determine the equivalent stress for each strain gauge value in the test campaign.

This new durability solution can also help manufacturers increase printing efficiency. In the next section, we explain how.

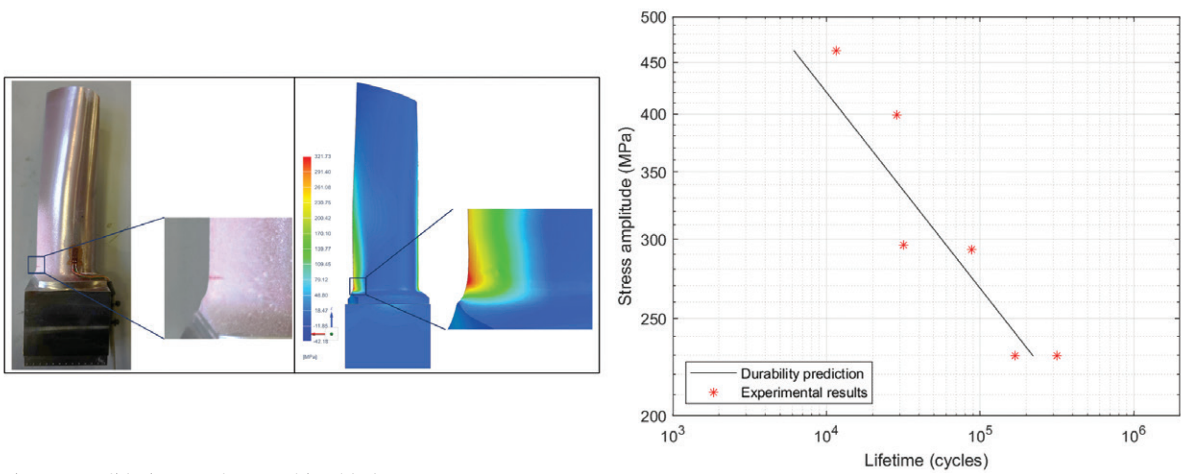

Figure 7. Validation result on turbine blade.

Printing durable parts faster

Even though metal LPBF is the most mature AM technology and presents some clear advantages, there are still some challenges. The scrap rate is relatively high for certain metals and applications and it can be challenging to find the optimal support strategy. Still, the major drawback is speed. Creating a component can take many hours, or even days. Attempting to gain time by applying multiple lasers are largely undone by the ongoing tendency to enlarge the build chambers.

The technology itself is at the heart of the problem. LPBF creates kilometers of weld tracks. They are on the order of magnitude of 100 microns thick. Process parameters such as laser power, speed and layer thickness are specifically chosen to achieve the highest possible density to minimize porosity. Manipulating these parameters to increase throughput will lead to less dense material, probably a rougher surface and worse fatigue performance.

Still, there is another option to gain time. Till now, the approach has always been safety first and print optimal quality everywhere. That was because there were no tools available to predict AM part failure in function of the AM process and related fatigue-influencing factors. However, with the methods and the tools that are presented in this paper and demonstrated in the validation case, it is different. We can now precisely predict the point of failure and we also accurately relate fatigue life to local material conditions. That makes a new approach possible: Print the highest quality material where you need it and speed up the process everywhere else.

The next section introduces new LPBF methods to achieve this. These have been developed by Siemens Technology (Siemens T) and combines test and simulation with process and production insights. Siemens T is the central corporate research unit of Siemens.

Combine faster AM with optimized fatigue life and cost

Siemens T engineers in Berlin have developed a digital twin of the manufacturing process to virtually represent the metal powder bed fusion case.[24,25] This allows them to predict and reduce overheating. Correction strategies, such as introducing waiting times or jumping to a different region during the build, can help in that respect. But they can also lower the need for support. Current printing techniques can allow overhang angles up to 30 degrees without support for LPBF SS316L (316L) stainless steel material. The capability to allow larger overhang angles without support leads to better quality of down-skin surfaces, which enhances fatigue performance.

By combining lessons learned from simulations, including material characterization input and part experiments, Siemens T came to an important insight. When switching from a nominal printing strategy to a novel one that is much faster, Siemens T achieved triple the building speed at the cost of only 1 percent of density. The lower density was due to a higher void content, which slightly increases the likelihood of a fatigue crack initiation.

To mitigate any risk to performance, they could use the previously described durability simulation solution and predict the impact of the 1 percent loss of structural integrity and fatigue life. The outcome of that analysis could allow them to balance the printing productivity with product quality and performance. As such, it makes it possible to optimize the AM process.

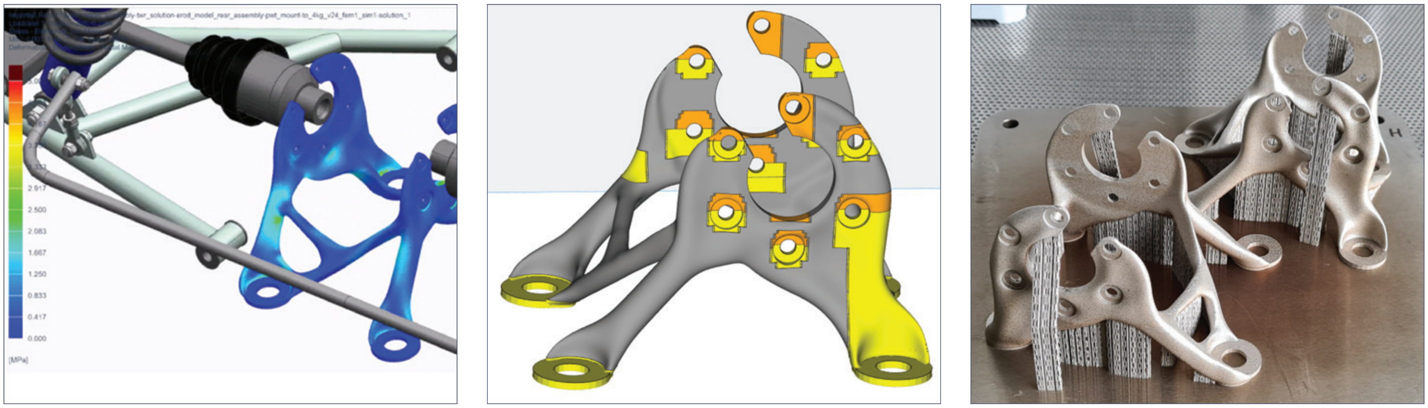

Figure 8. Bracket for SimRod vehicle, printed with strategy based on the outcome of predictions in Simcenter 3D Specialist Durability.

In another approach, Siemens T has tried out exactly what has been suggested above: only printing in high quality on locations that are critical to increase fatigue life performance. In areas that have less impact, such as regions that experience less stress, a faster and cheaper printing process is applied. This can only be done safely with the Simcenter 3D durability simulation solution, which enables the user to find the key regions where high-quality material should come and to predict the effect of using lower grade material on the overall fatigue life. Validation studies have demonstrated that 316L can have up to 4 percent porosity and still provide acceptable fatigue properties.

Results in a validation case

This novel print strategy that increases productivity while reducing cost and keeping fatigue life performance has been applied to a bracket that was designed with TO. The part, manufactured with LPBF in stainless steel 316L, is used to mount a gearbox in the SimRod vehicle, an electric sports car.[26,27] The result was reducing the time needed to manufacture by 35 percent while keeping fatigue life steady.

Additionally, some advanced correction strategies for reducing overheating were applied. If you compare the nominal print strategy (figure 9) with the novel print strategy by Siemens T (figure 10), you can see the latter requires less support.

Figure 9. Bracket printed with nominal print strategy and supports (as reference).

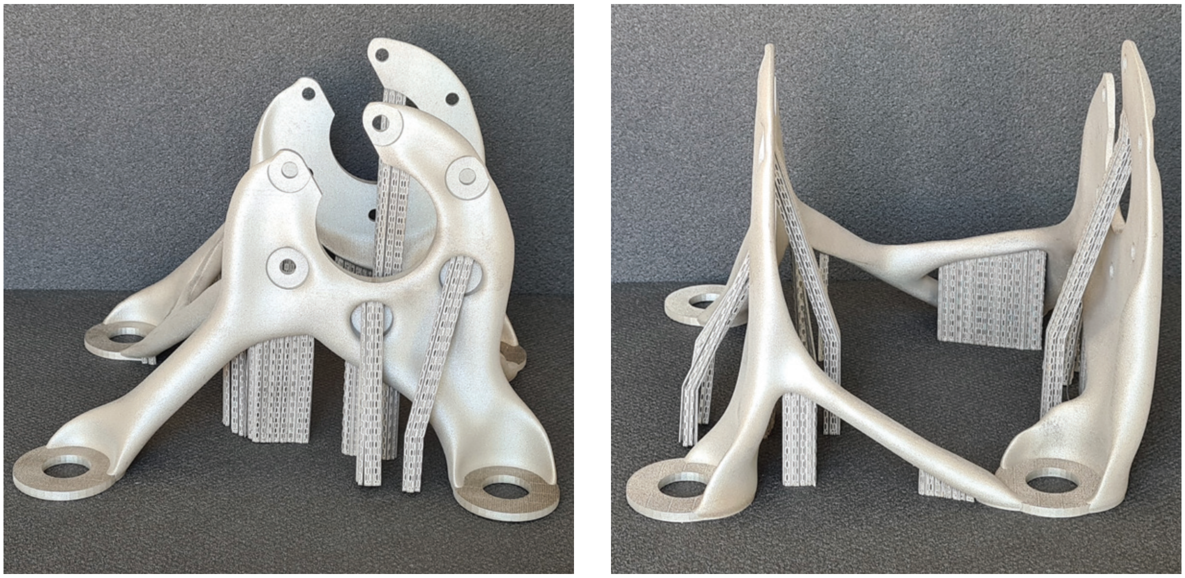

Figure 10. Bracket printed with novel print strategy – fewer supports.

To put it in numbers, the novel print strategy reduces 17 percent of the total volume and 63 percent of the support volume. Further, the novel print strategy results in better quality of the downskin surfaces, while keeping a similar build time compared to the supported part without overheating corrections.

You can also apply both strategies simultaneously. The zone-wise quality assignment based on the Simcenter 3D durability prediction can easily be combined with advanced support reduction. The combination of both strategies will result in the most ambitious speedup of the LPBF process.

Conclusion

AM is undeniably a very promising production method that presents numerous advantages. But lack of confidence in the durability performance of 3D printed components keeps the method from being used with sufficient confidence for structurally loaded, safety-critical components.

In this white paper we have presented some new tools in Simcenter 3D that can end this uncertainty. Engineers can now characterize the local material conditions introduced by the AM process, then use an ML algorithm to create a material model for fatigue that takes into consideration the local conditions. This enables them to finally study the global durability behavior of the printed part based on accurate predictions.

The accurate durability predictions in Simcenter 3D allow engineers to achieve enormous productivity gains by limiting time-consuming, high-quality printing to critical locations only.

Next, advancements have been made to reduce the necessary amount of support structures and increase productivity. This novel strategy that speeds up the printing while keeping the performance for fatigue life has been developed by combining the new durability solution in Simcenter 3D with the AM process knowledge of the people of Siemens T.

Acknowledgements

Siemens Digital Industries Software gratefully acknowledges Strategic Initiative Materials in Flanders (SIM) and the Flemish government agency Flanders Innovation & Entrepreneurship (VLAIO) for their support of the ICON project M3-FATAM, which is part of the research program MacroModelMat (M3), coordinated by Siemens Digital Industries Software, Belgium. See http://www.sim-flanders.be/research-program/m3. Furthermore, we kindly acknowledge Dr. Darya Kastsian, Dr. Frank Heinrichsdorff and Dr. Daniel Reznik from Siemens Technology for their collaboration in the Solutions for Industrial Metal Additive Manufacturing (SoFIA) project.

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