METAL ADDITIVE MANUFACTURING – NEW CHALLENGES FOR SOFTWARE SUPPLIERS

Michael Wohlmuth[1*], Dr. Hendrik Schafstall[2], Arjaan Buijk[3]

[1,2] Hamburg, [3] Ann Arbor

ABSTRACT: This paper describes the status of Metal Additive Manufacturing in an industrial environment. The problems to achieve an economic, robust production are addressed as well as the challenges arising from this situation – to optimize 3D printing processes by means of CAE. An approach of Simufact Additive is presented, which allows industrial users to predict the distortion of AM parts during the build process and to analyze the reasons for its cause. The three-level concept of Simufact Additive is introduced, as well as the methodology to simulate the entire process chain of an AM workflow. Several application examples are presented.

Keywords: Metal Additive Manufacturing, Metal 3D Print, AM Simulation, Simufact Additive, AM Process Optimization

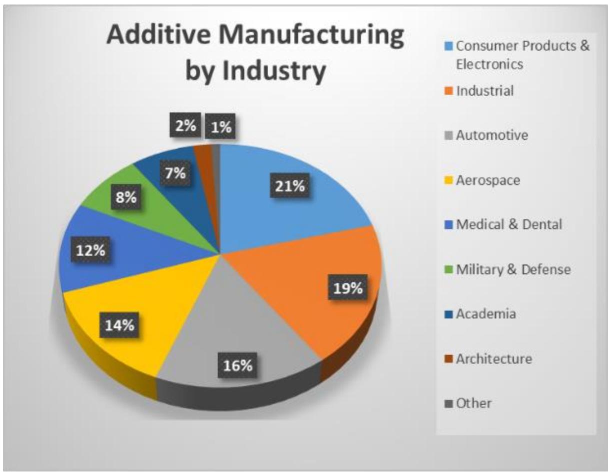
1 INTRODUCTION

Additive Manufacturing began in the mid 1980's as so called Rapid Prototyping but has accelerated in usage after 2010. The technology has been significantly improved with a greater choice of hardware, larger build platforms, more materials and faster build rates. It is anticipated that there will be continued and accelerated improvement in the hardware (machines) over the next few years.
From today's perspective, it can be stated that we are watching the transition from "just another technology hype" to the next industrial revolution.
The advantages of Additive Manufacturing are evident:

- Increased role in Rapid Prototyping
- Production of small and medium lot sizes
- Design of optimized parts that would otherwise be impossible to manufacture
- Light components with integrated functions and high stiffness
- Lower material usage
- Lower Energy Usage, due to elimination of production steps
- Light weighting
- No need for expensive tooling
- Manufacture products from fewer parts, thus reducing part inventory
- Manufacture parts anywhere / Print on Demand / Customization
- Repair of parts
- Make functionally graded materials (FGM)

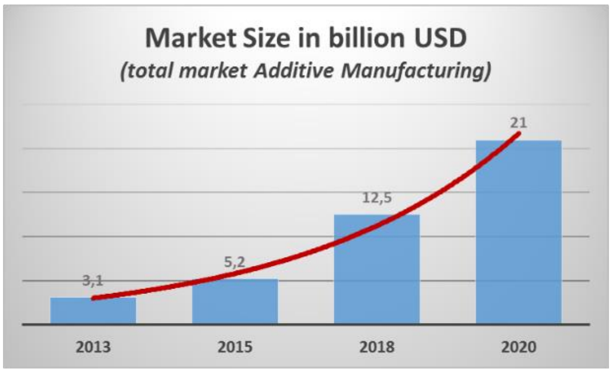
Based on this significant potential in terms of manufacturing effectiveness there is no industry which does not have a close look at Additive Manufacturing Technology, also known as 3D printing. Typical Industries are automotive, aerospace, consumer products & electronics, medical, military & defense and many others.

* Corresponding Author: Simufact Engineering GmbH, Tempowerkring 19, 21079 Hamburg (Germany), Phone +49 40 790128000, email: michael.wohlmuth@simufact.de



Picture 1: Additive Manufacturing distribution along industries 2014 [1]

The total Additive Manufacturing market is projected to grow four times in the next five years from today's over 5 billion US dollars [2], [2].



Picture 2: Projected market size of Additive Manufacturing from 2013 to 20120 [1], [2]

Improved machine concepts will be developed, additional materials created, faster throughput and larger part sizes will be feasible and finally many new start-ups will drive this emerging business.
One of the most significant steps will be the transition from purely rapid prototyping to industrial serial production.
In this paper, we will address metal additive manufacturing aspects only. Many of the statements are probably true also for plastics or composites, but this is not the subject of this article.

2 CURRENT INDUSTRIAL SITUATION

Even though Additive Manufacturing (AM) is a very exciting technology, it is likewise extremely challenging. The general situation in the industry can be described as: budgets are available but no practical experience – yet. AM cannot be compared with traditional manufacturing processes such as casting, forging, machining or welding, where the engineers and shop floor people have decades of experience and can manage the processes based on their deep knowledge of the technology. In AM the industrial managers together with the designers and the operators have to answer questions like [4]:

- What kind of machines to buy?
- What is the best plant layout?
- What are "AM friendly parts" considering parameters like lot size, material, complexity, dimensions, assembly, tolerances, cost & tooling time – also considering the subsequent manufacturing steps in a total process chain?

- Can part counts in sub-assemblies be reduced?
- Can weight be saved without compromising part performance?

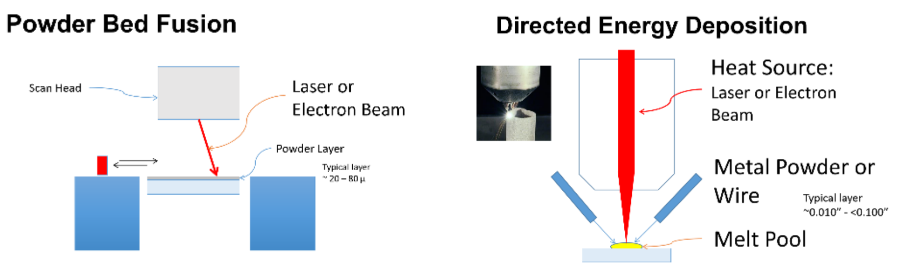
These are general strategic questions that each company must answer before a decision can be made to go for a strategic initiative that will influence the future competitiveness of the enterprise.
When introducing AM as a new production technology, major challenges arise on the shop floor when the parts are actually printed. Some of the challenges are [5]:

- Achieving the final net shape – reducing the part distortion
- Dealing with the effects of residual stresses which lead to distortion and sometimes even cracking, not just during the build process, but also during support removal, HIP, heat-treatment and subsequent machining
- What about the structural quality in terms of part performance, such as
  - Homogeneity and density
  - Microstructure evolution
  - Fracture and fatigue behavior
  - Surface roughness
- Issues with quality control of complex parts
- Higher material costs – specialized and expensive materials, few material vendors
- Size limitations due to build space
- Low machine utilization rates due to job abortion
- Build speed as one of the significant cost drivers – low production rates

Having a closer look at the last item: assuming a hourly machine rate of 80 € and typical build times between 10 to 40 hours, and one part per built would lead to basic part expenses between 800 and 3.200 € without consideration of the material, development overhead, HR expenses etc. Not to mention, how many AM machines a company would need to produce 50, 100 or a thousand different products with lot sizes between 100 to 10,000 parts?
It’s evident that beside the improvements of the technology itself – machine, material, process – there is a need for complementary tools to drive the engineering process. So, many software vendors are focused on developing solutions to support the AM process design. To mention a few of these, topology optimization systems to find an AM suited part design, software to optimize the support structure, tools which analyzes the melt bath, and software that simulate the structural behavior of the built during the AM process, amongst several other software products.
Simufact Engineering is offering solutions for the structural behavior during the AM process chain, and late 2016 released a brand new product, Simufact Additive 1.0.

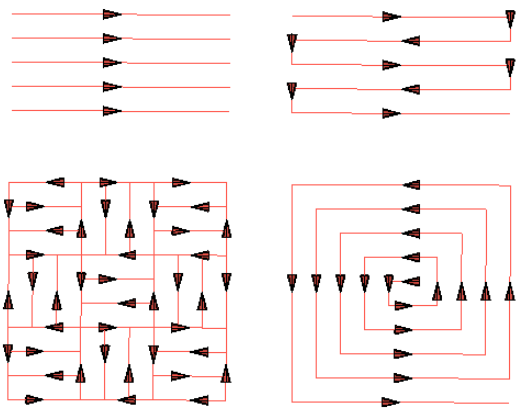
3 CHALLENGES FOR SOFTWARE PROVIDERS

The first question is: which general process should be supported? For metal AM, it is basically segmented into two main categories: Metal Deposition and Powder Bed Fusion.



Picture 3: Principle Differences between powder bed fusion and deposition method [1]

Both come with several variants, often dedicated technologies of machine vendors and often known by their respective trade names. The next question is about the energy source used to melt the material. This can be a laser or an electron beam, both with different characteristics and from different suppliers. The third challenge is the material. For powder bed, the material is provided as a powder with different characteristics and conditions, either new powder or recycled. Typical metals for AM are steel, stainless steel, Titanium alloys, NiCo based superalloys and Aluminum.



Picture 4: Several scan pattern – unidirectional (upper left), bidirectional (upper right), checker board hatch pattern (lower left), spiral hatch pattern (lower right)

Furthermore, the kinematics of the AM process is a critical issue for a successful built. The way the laser (or electron beam) scans along the powder bed is strongly influencing the results. This is called the hatching strategy. Many different hatching patterns are available to drive the AM process (picture 4). There are over 200 parameters to control the printing process in the machine.
In addition to these parameters many other conditions determine the physics and thus the outcome of an AM built. These can be the gravity, the flow conditions in the inert gas flooded build chamber and the huge temperature gradients in the part, just to mention a few.
And finally, very challenging for modeling AM processes with the Finite Element Method, is the AM-specific transition between bulky regions to very thin walled and lattice type regions.
Running AM process simulations on complex parts using a "moving heat source" approach and including the complete, detailed, micro-level physics is feasible in principle, but leads to impractical run times of days, weeks or months, even on the most powerful computer hardware available. This is definitely contrary with the requirement to provide a software solution which should run in an industrial environment, used by process engineers (not dedicated CAE experts!) and should produce quick turn-around times. This is a practical requirement in order to influence design decision and improve the engineering process to get to "First Time Right".
It is obvious that smart, purposeful and acceptable simplifications and assumptions have to be made to achieve this objective.

4 APPROACH WITH SIMUFACT ADDITIVE

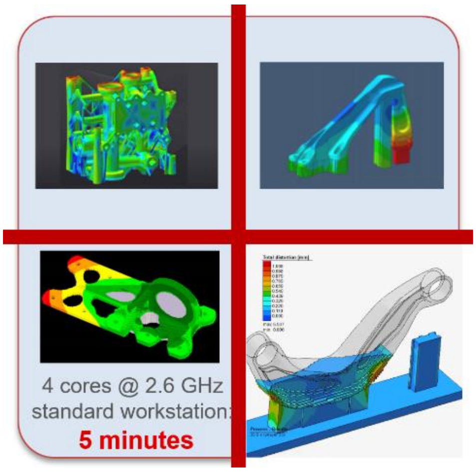
4.1 SCALED APPROACH

Simufact Additive is using a three level concept to meet all requirement of both industrial and scientific users. The three levels are:

- Macroscopic Scale
- Mesoscopic Scale
- Microscopic Scale

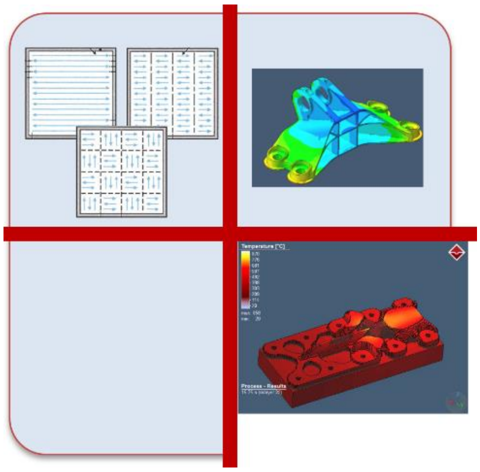
The **Macroscopic Scale** allows the mechanical analysis of single layers in one step, delivering distortions and stresses in the structure. The method is based on the inherent strain approach, which is a known and accepted methodology used for many years in other applications like weld simulation. The method assumes that there is an inelastic strain that is representative of the material when subjected to a thermal load. This would include plastic, creep and phase transformation if available. This approach is also known as "eigenstrain" method.

The advantage of this macroscopic scale as it is implemented in Simufact Additive is the extremely fast simulation time, which allows the study of several manufacturing strategies in a short term. Simulation times range, depending on the model, from a few minutes to a few hours.



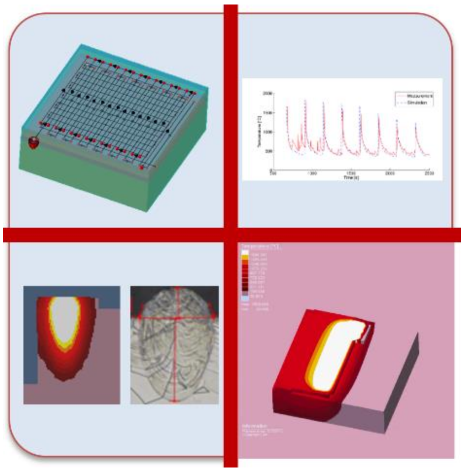
Picture 5: Macroscopic Scale Approach

The prediction of part distortion is proven to be extremely precise. With this approach, one the main pains of industrial users can be eliminated.
The **Mesoscopic Scale** provides either a mechanical, thermal or fully coupled thermo-mechanical simulation. This can be applied on entire layers or single segments of the hatching pattern. The additional results are e. g. the thermal history and thus allows to analyze thermal dependencies of parameters and material behavior. The thermal history will allow the prediction of the final microstructure in the part when analyzed from material specialists.



Picture 6: Mesoscopic Scale Approach

Finally, the **Microscopic Scale** dives even more into the detailed physics of the microstructure. This requires a simulation of the real scanning path of the laser and the utilization of microstructure models. It delivers the time-temperature history, the distribution of the mechanical properties and the microstructure.
It is evident, that this third scale requires much more computer resources as well as a higher understanding of material behavior. It is currently seen more as a tool for an R&D and scientific community. The good news are that the results which are provided by this high sophisticated approach is not required for a realistic and high quality distortion analysis – which is the dominating pain in the industrial environment. However the microscopic scale allows answering questions towards final physical properties of the 3D printed structure.



Picture 7: Microscopic Scale Approach

The Microscopic Scale approach is also utilized to run a brief partial simulation for the purpose of examining parameters that would feed the quicker mesoscale simulation. Altogether, the three levels of physical representation are not intended to be isolated implementations, but complementing solutions affording varying level of analysis based on optimized parameter sets.

4.2 PROCESS CHAIN

For each level of modeling (Macro, Meso, Micro), the implementation in Simufact Additive is designed to cover the whole process chain. There is an "external loop" and there are "internal steps" of the process chain.

Picture 8: Process chain at AM processes

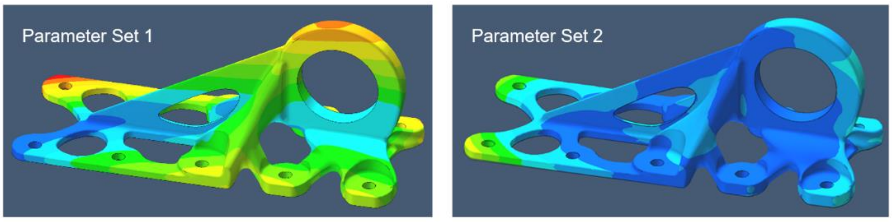
The external loop, like topology or design optimization at the front end, or machining, stress and fatigue analysis at the back end, is covered by additional software products from MSC Software. Data exchange interfaces also allow a coupling with third party software.

The internal steps within the AM process, which are entirely covered by Simufact Additive, are the build process itself, but additionally a subsequent heat treatment process, the removal of the base plate and the support structure and HIP (Hot Isostatic Pressure). The purpose of simulating these sub-tasks is evident: it allows to predict the final distortion of the printed parts right after the entire AM process including post-processing. This assures a high level of accuracy even when utilizing the Macroscopic Level approach.

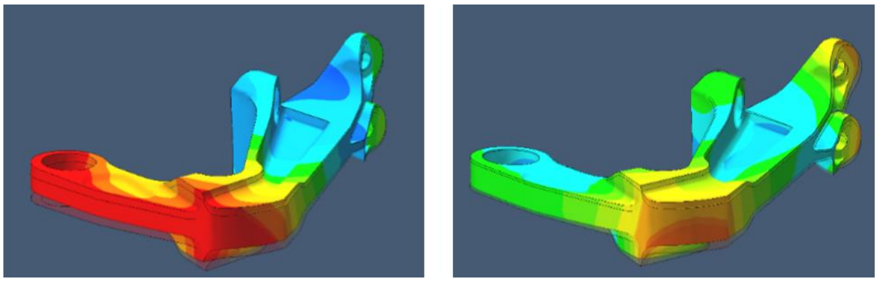
5 APPLICATION OF VIRTUAL AM OPTIMIZATION

The following pictures depict the utilization of structural analysis for AM processes. Several process parameters were studied, such as build orientation, support structure placement, directional cutting off the base plate, and removal of the support structure.

Picture 10 shows that it makes a substantial difference, in terms of part distortion, from which direction a baseplate and the support structures will be removed. The manner with which residual stress influences the strain – and thus global distortion of the part – will be visible, and the user can refine the strategy to attain part conformance.

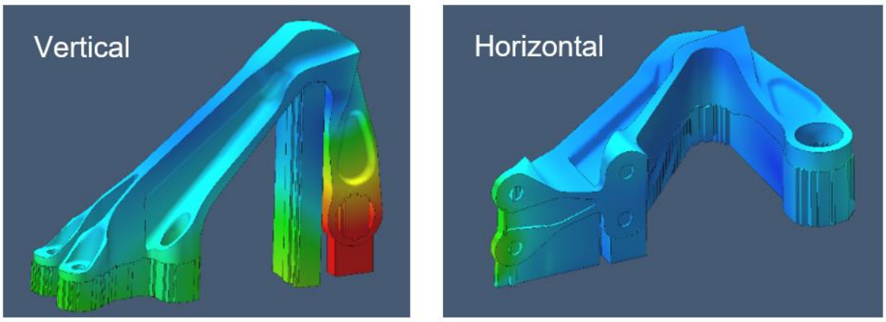


Picture 9: Influence of process parameters on final part distortion

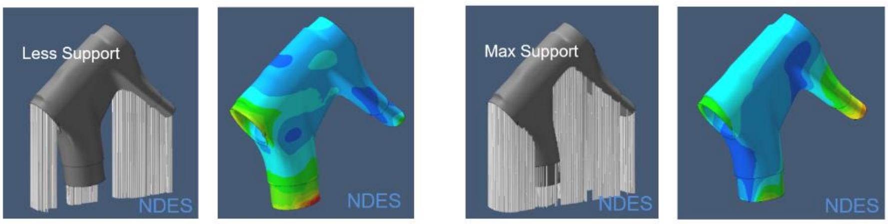


Picture 10: Effect of different strategies to remove the base plate and support structure

In pictures 11 and 12, the influence of build orientation and effect of support structure placement can be seen. Specifically with regards to build orientation, it's not just a matter of reducing the distortion – this parameter typically has a significant impact on the build time and total cost of the AM part. As stated previously, machine costs are often some of the most severe expenses of a metal AM process [7].

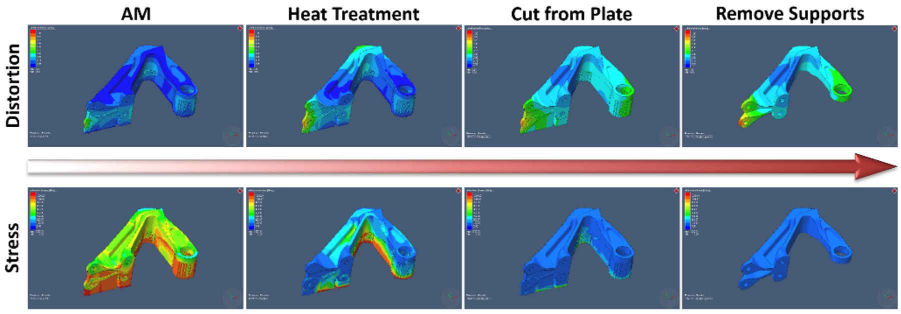


Picture 11: Different build orientations result in distinct part distortion



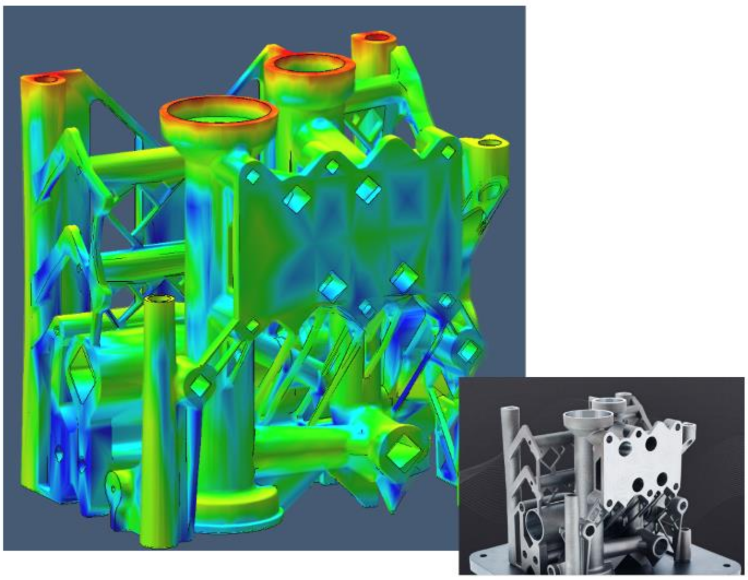
Picture 12: Study of varying support structures

With that consideration, this type of study is not just to optimize the quality of the part – meeting the technical specification – but also to optimize the AM process from an economic and business perspective.
Picture 13 shows an example of simulating the entire process chain, including: the actual build process, heat treatment, base plate and support structure removal, as well as the HIP process. Traditionally, the same tried-and-true sequence has been utilized on the shop-floor; but now, innovators are in search of restructured workflows to achieve process improvements and Simufact Additive is designed to support this flexibility. It's up to the user to define a process chain to understand the influence of AM strategies.



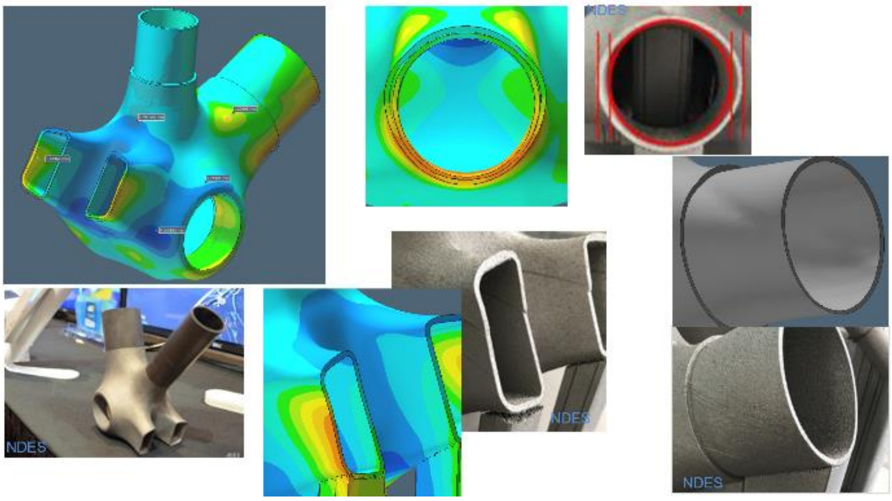
Picture 13: Simulation of an entire process chain

As shown in picture 14, the structural FE analysis of 3D printed metal parts can depict notable insight for highly complex parts. This is essential in the industrial movement to grasp the benefits of AM technology – producing parts with complexity previously thought to be unattainable. The simulation displayed in picture 14 required approximately 2.5 hours of solve time.



Picture 14: Simulation of **c**omplex part

Picture 15 shows the deformation behavior from an analysis of a TiAl6V4 bicycle part. Historically, producing AM qualified parts within tolerance (such as circularity) would require many expensive trial and error iterations. In this example, the shop-floor tests could be reduced significantly by virtually prototyping within Simufact Additive. The simulation was used to optimize the support structure placement, achieve the proper stiffness during printing, and to minimize the final distortion for functionality.



Picture 15: Deformation studies of a bicycle part

6 CONCLUSION

Metal Additive Manufacturing is considered to be the next industrial revolution. It comes with many challenges – not just for the manufacturing enterprises, but also for the software suppliers that support the engineering process. Simufact Engineering and MSC Software have released a software solution to predict the most critical pain in metal AM, the part distortion. The objective is to provide a solution for industrial process engineers to shorten their process development time and to produce high quality parts with this revolutionary manufacturing methodology, reaching the objective "first time right".

LITERATURE

[1] Chausovsky, A.: The Impact of 3D Printing on Industrial Manufacturing, IHS Engineering 360, Englewood, 2014
[2] Wohlers Report 2016, Fort Collins 2016.
[3] www.statista.com, Statista Inc., New York 2017
[4] Gallello, D.: Additive Manufacturing – From Trial and Error to a true revolution, Make Parts Fast, WTWH Media LLC, Cleveland, 2016.
[5] Wertheimer, T.: MSC Software internal White Paper, Newport Beach, 2016
[6] Crandall, J.: Metal Additive Technology 101: Technology Choices and Applications, Manufacturing 4 The Future, 2016
[7] Cotteleer, M.: 3D opportunity: Additive manufacturing paths to performance, innovation, and growth, SIMT Symposium, 2014

Published and presented at:

XXXVI. Verformungkundliches Kolloquium
18.03. to 22.03.2017
Zauchensee, Austria

Department Product Enginering, University of Leoben, Prof. Bruno Buchmayr