Additive Manufacturing

Revolutionizing How Products Are Made

The global Additive Manufacturing (AM) market reached 4.1 billion USD in 2014 with an impressive 30% year on year growth[1]. Market analysts expect double-digit growth in the coming years also, as industrial sectors including aerospace, automotive and medical all seek to use and benefit from the advantages of AM technologies. Nevertheless, Additive Manufacturing — commonly referred to as 3D printing — does come with challenges! Adopters of AM are struggling to achieve the production volumes and quality required to compete effectively with conventional manufacturing processes. On its part, ESI recognizes the huge potential of Additive Manufacturing and, in the framework of several large collaborative projects, has developed a suite of tools addressing design challenges and process optimization. Our objective: to enable designers and manufacturers to benefit fully from the potential that AM offers in many applications.

Metal Additive Manufacturing – an overview

Additive Manufacturing enables digital 3D design data to be physically created by building up layers of deposited material. Metal feed stock is fused to form layers using different heat sources, including lasers, electron beams and arc discharges, to build solid objects.

Metal AM technologies include powder bed, blown powder and wire feed processes. Powder bed systems melt a deposited metal powder using a laser, or an electron beam. In blown powder technologies, a metal powder is blown coaxially with a heat source, which melts the particles so that they adhere to a base metal to form a metallurgical bond when cooled. Wire feed systems allow for the highest deposition rates and are usually used for very large components. Here we focus on powder bed and blown powder technologies, but the underlying considerations are universal.

What advantages does AM bring to manufacturers?

Additive Manufacturing offers unrivalled design freedom and customization, as manufacturers can produce parts of virtually any shape.

Objects with new levels of geometric complexity can be created, delivering the opportunity to achieve functional designs that are impossible, impractical or very costly using conventional manufacturing methods.

Used in the production of metal parts, AM offers manufacturers the ability to create novel, lightweight designs, potentially with fewer number of parts. Tooling can be reduced and there is the potential to move to one step production, even of very complex parts.

And what are the associated challenges?

Application of AM technology is hampered by slow build rates, high production costs, and the need for post-build treatments to address dimensional inaccuracies, residual stresses, metallurgical properties and the quality of surface finish. Management of feed stock quality, recycling and energy consumption are some of many other challenges.

> *"The lack of standardization, design rules, repeatability, production speed, and quality control significantly hinder the expansion of 3D printing. Computer simulations can be a great asset in overcoming these challenges."*
>
> **Dr Mustafa Megahed,**
> Manager of the CFD & Multiphysics Center of Excellence,
> ESI Group

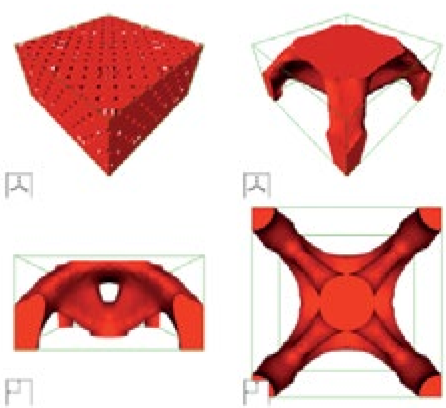
Advanced Topology Optimization Tools

As discussed, AM enables the manufacture of parts with large level of geometrical complexity. To realize the full benefit of that important attribute, ESI Group has developed advanced topology optimization tools that take into account both functional and manufacturing constraints.

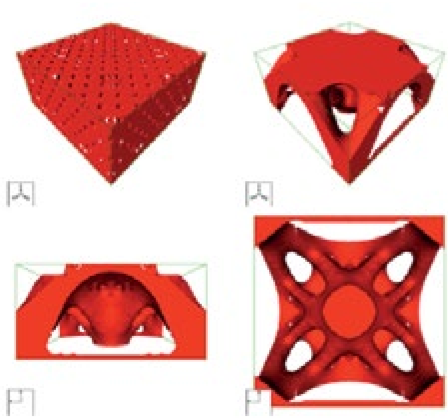
Let's take the example of a designer who wants to create a product with minimum weight, while sustaining certain functional loads. ESI's tool will create an optimal design that fulfills both functional and other requirements while additionally addressing manufacturing constraints such as minimum wall thickness.

ESI's solution is based on tracking surfaces – not material densities – and thereby enables users to define manufacturing constraints and cost functions, in addition to the functional constraints for the final product. Understanding such constraints is vital to obtain producible structures using the AM process.

Also, ESI has successfully demonstrated the ability to transfer the optimized topology back to CAD for geometry processing.



This example shows a topologically optimized component. The difference between the design here and the one below is driven by wall thickness constraints (maximum thickness 0.6 units). The results provide smooth surfaces, directly prepared for CAD return, fulfilling load constraints and cost function within the manufacturing wall thickness limitation.



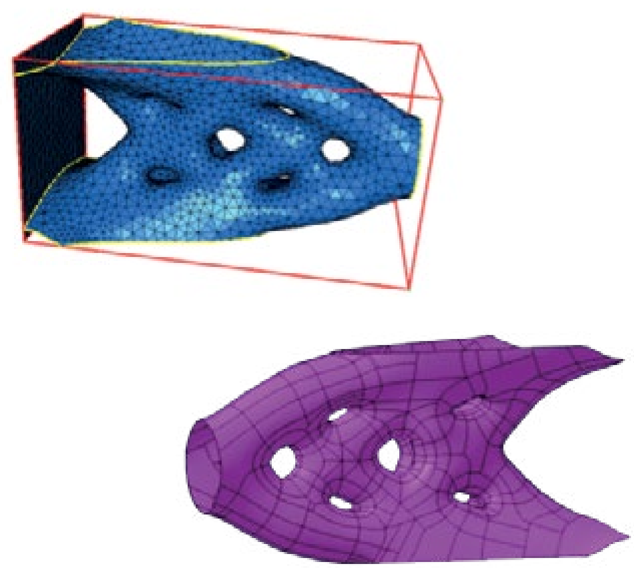
Assuming a change was made in the machine or the AM process, limiting the maximum thickness to 0.4 units, the optimization tool would take this change into account by creating a similar geometry, with each leg replaced by 2 ribs. Return to CAD would be again directly possible for further validation and certification of the design.

Additive Manufacturing Process Modeling

All AM technologies involve the use of a heat source to interact with a feed stock of material particles.

The heat source only interacts with the powder particles for a few microseconds, but the total build time can last several days. Powder particles are in the order of a few microns, whereas the total deposition track can be hundreds or even thousands of meter long. Such multi-scale problems can be a challenge to simulate! Addressing that challenge, ESI has developed a multi-scale, multiphysics solution to characterize the physics associated with AM technologies.

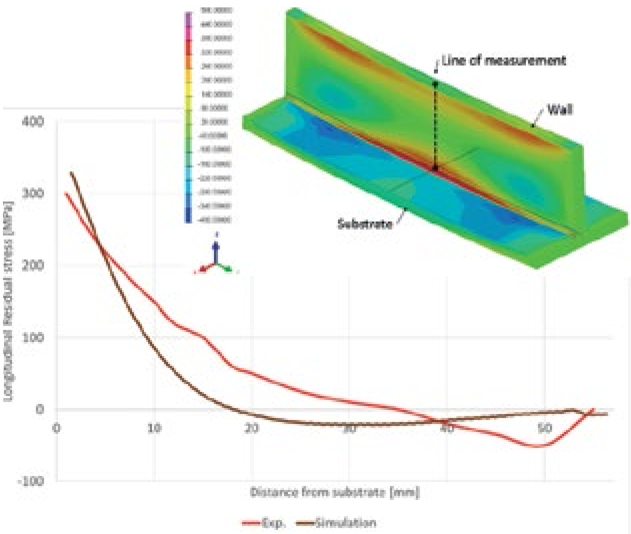
Mustafa Megahed, comments: "*In particular, when simulating AM processes, you are dealing with particles in the order of 10 microns in diameter, a work piece several centimeters long, and a laser path that could be as long as a kilometer. If you were to simulate that all at once at the same level of detail, it would take more computing power than current high performance computing can handle.*"



Up: Topologically optimized beam. Down: CAD return of topologically optimized geometry.

Another major challenge of all Additive Manufacturing processes is to produce parts to specification in spite of porosity and residual stresses accumulated throughout the build process.

Quick models, which calculate the thermal history of the work piece, are key to produce accurate thermo-mechanical predictions. However, ESI has taken the next steps by validating state of the art thermo-mechanical models that are sensitive to the deposition strategy.



Residual stress predictions compared with neutron defraction results (ESA, ESI, Irepa Laser, AMAZE - FP7 project).

Powder Bed / Direct Metal Laser Melting (DMLM)

The DMLM process involves layer-by-layer shaping and consolidation of a powder feed stock to arbitrary configurations.

To improve Additive Manufacturing production rates, the laser power is increased to enable faster scanning. Thicker powder layers are also preferred to increase deposition and, at the same time, reduce the number of deposition layers. Laser beams with a large diameter are also used to melt wider tracks. However, these control parameters interact in a very complex manner. For example, increasing the laser power may lead to a significant evaporation of the molten metal, while increasing the scan speed reduces the interaction time between laser and powder particles, which may in turn lead to reduced melting and lack of fusion.

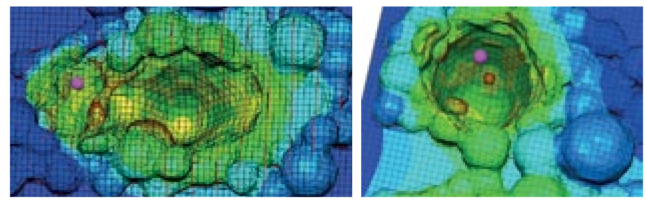
Furthermore, energy densities required for DMLM lead to a significant accumulation of residual stresses and distortions during the build process. Unfortunately, today these complex interactions are not mapped or understood in detail and therefore require cumbersome trial and error research to ensure high quality production.

Addressing these complexities directly, ESI has developed high fidelity models that account for powder feed stock coating and heat interaction with the powder particles. These models enable manufacturers to identify optimal process parameters to achieve high material density.

ESI also delivers simulation results related to the thermal cycles applied to the material, and the corresponding evolution of residual stresses during the build process.

Within the framework of the European project AMAZE, ESI studied the characteristics of a titanium alloy, as processed by a commercial machine that modulates the laser with specific exposure times.

The images below show the impact of different process parameters on material densities and the underlying simulation provides explanation for the gaseous enclosures observed in experimental specimens.



Powder Bed Fusion melt pool analysis
Left: Example for process parameters leading to high material density.
Right: Example for process parameters leading to gas enclosures in melt pool and high porosity (AMAZE - FP7 project).

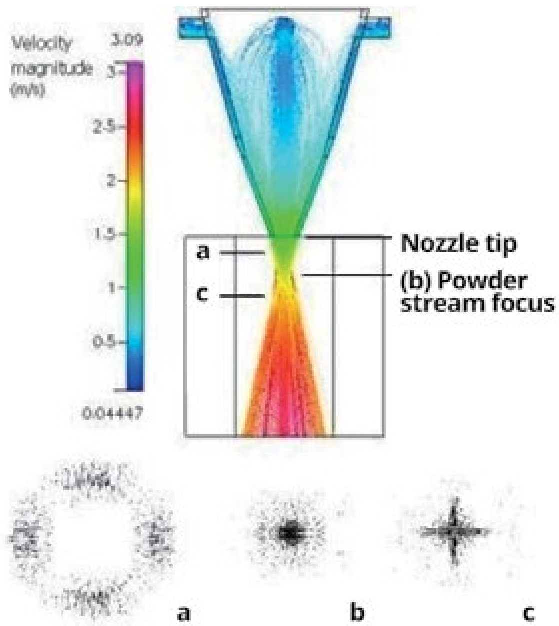
In addition, ESI has collaborated with 3D Systems, originators of 3D printing and leaders in 3D design and digital fabrication, to extend knowledge about coating processes and how they affect the powder bed distribution prior to processing.

This joint research is aimed at defining processes that deliver fully dense metal parts that can be used for the most demanding applications and perform at levels equal to or greater than traditionally manufactured parts. The collaboration with 3D Systems leverages the company's line of ProX Direct Metal Printers (DMP) and has demonstrated how tandem innovations in software and hardware are needed to take Metal Additive Manufacturing to the next level. Taking a very practical example, 3D Systems' DMP line offers a unique compacting roller system that provides greater precision for coating each layer. Combined with ESI's simulation solutions, that capability has the potential to provide a level of control and accuracy in metal AM that has not been achievable before.

Such advances will, in turn, enable the emergence of new applications and accelerate adoption of these technologies.

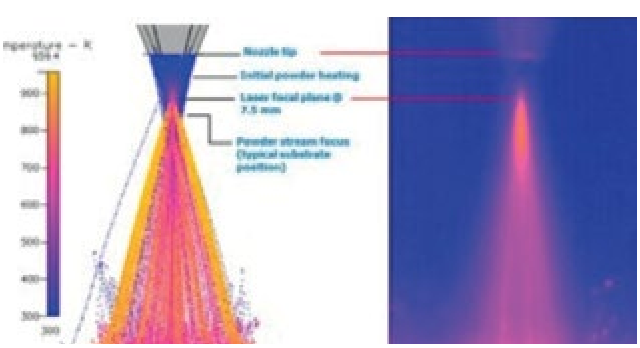
Blown Powder / Laser Direct Metal Deposition (LDMD)[2]

LDMD printers have a nozzle with two functions: to deliver powder particles and to direct the heat source melting the particles so that they adhere to the substrate. The nozzle-to-substrate distance needs to be optimized to control the particle deposition pattern, and the laser's speed must be optimized to control the melt pool dimensions and material properties.



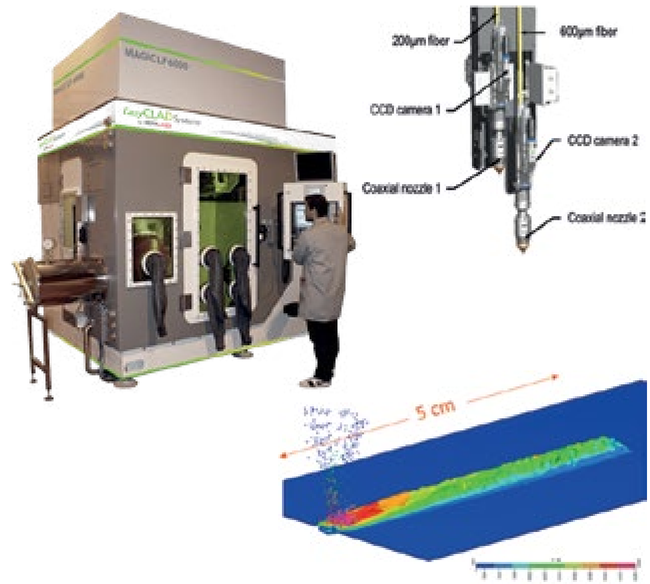
Powder Stream simulation and deposition patterns based on nozzle substrate distance ("a" close, "b" focused, "c" far). Courtesy of ESI and University of Manchester.

Within the framework of the European project INLADE, ESI developed and validated models, in collaboration with the University of Manchester, to describe how powder particles absorb and scatter the laser energy.



Comparison of thermal distribution and powder in-flight. Simulation has good correlation to reality. Courtesy of ESI and University of Manchester.

"*The micro scale models of the LDMD simulation deal with the powder trajectory and the thermal cycle of the melt pool,"* explains Megahed. *"The micro scale simulation is used to optimize the nozzle and process parameters to influence the melt pool shape, avoiding porosities or built defects. The thermal cycle is obtained as a by-product and is utilized in macro-models to determine the corresponding residual stresses,*" Megahed continues.



Laser Direct Metal Deposition Machine – Courtesy of IREPA LASER – and Ti-Al6-V4 bead shape for certain powder feed rate, nozzle translation velocity and laser power.

Conclusion

Many challenges must be addressed before the great potential of Additive Manufacturing can be fully exploited by manufacturers. The range of benefits is huge: "*Companies benefit from the flexibility that Additive Manufacturing brings to their manufacturing line,*" comments Dominique Lefebvre, Product Management Director at ESI Group. "*Indeed, a factory can switch or relocate its production overnight as 3D printers allow for the manufacture of infinite types of parts and require minimal tooling. The benefit is not only for the initial production but also for repair of parts.*"

ESI's software is improving the design processes and process control technologies behind AM. It's not a case of *if* AM will achieve the total production volume targets that the machine tool industry demands, but *when*. Lefebvre adds: "*To ensure a robust process and parts that meet the manufacturer's specifications, Virtual Manufacturing simulation is needed. While AM is in many aspects more complex, numerical simulation can deliver the right answers, just as it does for many other manufacturing processes.*"

Article produced in collaboration with

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[1] 2015 Wohlers report. Available on: www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/9908/The-2015-Wohlers-Report-Is-Out.aspx

[2] Shawn Wasserman (May 28, 2015). In collaboration with www.engineering.com. Metal Additive Manufacturing Optimized Via Simulation Solution. Available on: www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/10176/Metal-Additive-Manufacturing-Optimized-Via-Simulation-Solution.aspx

3 Questions for...

Dr. Alonso Peralta

Principal Investigator, Honeywell
In charge of the DARPA Open Manufacturing Program

Could you give us some insights into the research projects you are working on in relation to Additive Manufacturing?

I work on several Additive Manufacturing (AM) programs; the majority of them dealing with technology development. The biggest current program is related to the DARPA Open Manufacturing (OM) initiative. Its goal is to develop Integrated Computational Materials Engineering (ICME) tools and methodologies supporting the application and acceptance of AM technologies in the aerospace market. The end goal for ICME is the certification or qualification of components by regulatory agencies. This drives us to work on AM process modeling (including melting and solidification), material property models (predicting properties such as yield and ultimate strength), and experimental techniques (for example, recording the thermal response of the melt pool). We also need to quantify uncertainty as we apply the ICME tools.

Why have you chosen to collaborate with ESI on the DARPA Open Manufacturing program?

ESI brings expertise in manufacturing process modeling. For many years now, ESI has offered a suite of manufacturing process simulation tools. In fact, the company was already working on modeling Additive Manufacturing processes before we joined forces for the DARPA OM program. Modeling AM processes requires a broad range of simulation capabilities, addressing heat transfer, fluid flow, phase changes, residual stress modeling, and more. ESI had already made essential developments before we started working together and now applies these to AM.

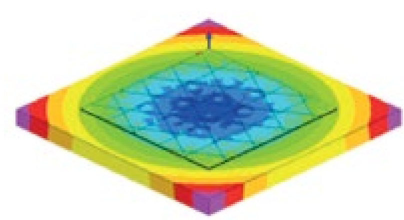
How do you simulate AM processes?

Three important models are at the heart of AM processes simulation:

- First, the powder spreading model that is used to gain insight into why powders can be difficult to spread on a fresh build plate and also to acquire an understanding of the powder packing density upon recoating. Such insights could not have been gained easily without Additive Manufacturing simulation tools. We believe these tools help us understand the powder particle size distributions needed for enhanced spreadability of the powder and to achieve better packing density in the powder bed. We are also looking forward to understanding the build thickness needed to prevent recoater arm crashes and to minimize vibration caused by interaction of the rough surface of the new build with the powder during the spreading process.

- Second, the micro model for melting and solidification, used to identify the conditions under which the three different types of porosity found in metal Additive Manufacturing can occur. It is also used to confirm the occurrence of gas porosity, which would be very difficult to confirm experimentally. We are currently analyzing a large amount of modeling data that matches experimental observations but doesn't always confirm our expectations. The models are now explaining many of the observations we obtained and are on the verge of guiding process window identification.

- Finally, the macro model to predict the residual stresses of the 'as built' component. This is very useful as we have been able to show that residual stress and deformation are a function of the build conditions and also of the build pattern. For example, we have learned that the residual stresses are not equi-biaxial, which may prove to be important when building slender structures as excessive deformation from layer to layer could lead to unacceptable departure from the intended geometry.



As-built distortion simulation using ESI software.

About Honeywell

With more than 127,000 employees worldwide, including more than 22,000 engineers and scientists, Honeywell invents and manufactures technologies to address some of the world's toughest challenges initiated by revolutionary macro-trends in science, technology and society.

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