Simulation and integration of a DED repair pipeline into the machine tool control environment

by Daniele Calsolaro, Livio Airaudi
EnginSoft

The terms "3D printing" or "Additive Manufacturing" (AM) refer to the creation of solid three-dimensional objects from a digital file by depositing successive layers of a material until the object is created. Each deposited layer can be viewed as a narrow cross-section of the final object. There are several types of material deposition process, such as powder bed fusion, binder jetting, material extrusion, material jetting, vat polymerization, and direct energy deposition.

Directed energy deposition (DED), more commonly called metal DED, is an AM technology related to metals, in which a metal in powder or wire form is melted using a high-density energy source and is simultaneously deposited locally to form the object in question.

DED technology can be used to repair existing components or to manufacture large new components. While it can be used to manufacture parts from scratch, the technology is mostly used in industry to repair large costly components like turbine blades or propellers that have been damaged during use. As a result of the benefits accruing from its use, including cost and scrap reduction, shorter repair times, and minimization of inventories, and the related substantial environmental benefits, this technology is rapidly gaining in importance.

The EU EIT Manufacturing's OScaR project, which lasted from January to December 2022, was a collaborative undertaking to define a technological solution for repairing metal components using DED AM. Industrial manufacturers require an automated or semi-automated solution that enables them to mount a part that has a partially unknown shape on a machine, measure the relevant part of its surface in 3D, and automatically generate an AM repair program to return the part to the desired shape.

The OScaR project

A typical DED machine consists of a multi-axis instrument with a nozzle that deposits molten material onto the work surface – a base or component – that has been firmly clamped. The metallic material is fed to the nozzle as a powder or wire. This material is melted during deposition by a concentrated heat source - usually a laser electron beam or plasma arc.

In principle all weldable metals such as titanium and its alloys, Inconel, tungsten, stainless steel, and aluminium can be 3D printed with DED. The size of the wire used typically ranges from 1-3mm in diameter, while the powder particle sizes are similar to those used in powder metallurgy processes, i.e. between 50 and 150 microns.

Obviously, such a process generates temperatures with very high thermal gradients that can lead to significant overheating, deformation, and accumulation of residual stresses during the layer deposition phase; the deformation effects can be so great that they can affect the proper functioning of the technology and cause fracture or breaking.

Therefore, it is extremely important to be able to accurately predict, specifically by using finite element simulation, the effects of DED printing related to deposition, with the aim of optimizing the printing process in terms of time and to reduce the residual stress.

End users need an automated or semi-automated solution to mount a part with a partially unknown shape onto a machine, measure the relevant part of its surface in 3D, and automatically generate a repair program to restore it to the desired shape. The generated part must be automatically analysed to ensure inline quality control. Furthermore, since the repair process does not allow for failures, the use of a simulation tool is mandatory to pre-assess the results that can be obtained.

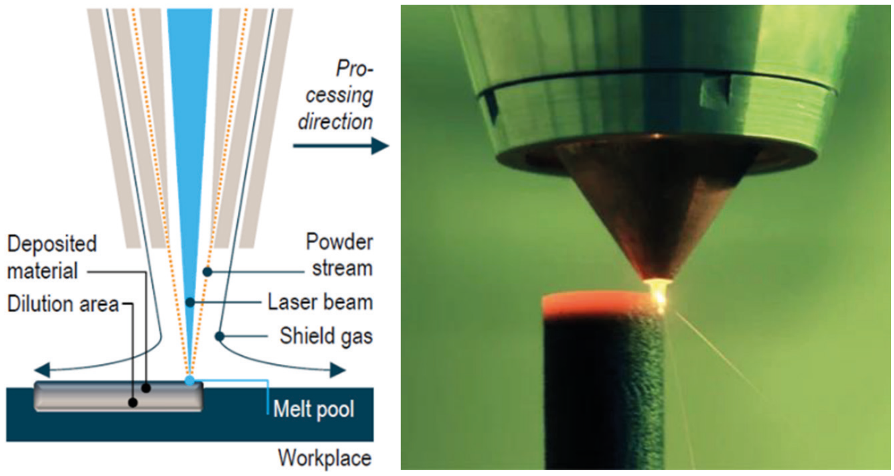

Fig. 1. Direct energy deposition (DED).

In many modern manufacturing environments, in-situ reconstruction of a damaged or faulty part's geometry is a highly desired function in the production pipeline, for example, damaged parts can be repaired/reworked to extend their life cycle. However, working on a damaged part requires applying the preferred remanufacturing or repair technology to a surface with a partly unknown shape.

Parts, especially those prefabricated externally, that have to move through multiple machines during production, also have this requirement for repair or remanufacture. Many industries would benefit from the ability to easily modify multi-process parts and repair damaged parts, but lack an established technology to 1) easily work on existing parts that have a far from nominal geometry, and 2) automatically generate an AM-DED repair toolpath for a damaged segment. Furthermore, quality control of the generated part must be performed entirely off-machine, requiring additional production time.

The OScaR (Optical SCAn-and-Repair solution for machine tools) project, co-funded by the EU's EIT Manufacturing, focused on the use of DED technology; in particular, the project's ultimate goal was to define a technological solution to repair metal components. OScaR enables the repair of complex metal parts for high quality applications using an AM-DED machine, in-situ 3D scanning, DED simulation and toolpath generation to achieve the next level of flexible manufacturing.

The project's most important impacts on the manufacture-and-repair industry worldwide are to enable:

- Environmentally sustainable production
- Lower energy consumption
- Reduced consumption of raw materials
- Reduced engineering time through automation
- Inline quality control of processed parts

Simulating the DED repair process

EnginSoft's role was to develop a suitable simulation method and configuration to virtually replicate the DED process for repair applications, smoothing the path for new potential customers. The model to simulate the DED repair process is based on Ansys Additive Suite and enables the effects of the repair process on the reference part to be predicted and optimized. The Ansys DED simulation module imports a scanned baseline geometry and an externally generated G-Code. The main materials and process configurations relevant to the use cases are entered into the simulation parameters. The final simulation of the deposition process and its thermo-mechanical deformation was developed and tested on two principal use cases, which included validation of the results against real measurements.

Ansys Additive Suite is a powerful collection of tools from Ansys specifically for additive manufacturing simulation. Workbench Add-itive is one of the tools designed for use within

Fig 2. A-frame test case.

the Workbench platform and Mechanical application. The DED Process Simulation functionality in Workbench Additive is implemented as an ACT extension that must be loaded into Workbench. The objective of DED Process Simulation in Workbench Additive is to predict temperature-induced deformations and stresses in the various components on a macroscopic level during the production phase to prevent failures, while simultaneously providing trend data to enable improvements during the design phase of the additive process, including the orientation of the parts and their build order.

To simulate the DED manufacturing process, the analysis must follow the actual printing process as it is deposited and solidifies, so-called "track-by-weld" solidification. In this type of simulation, the thermal analysis and structural physics (stress and distortion) tend to be decoupled which allows the full thermal process to be simulated prior to the structural simulation. In a DED process simulation, the model evolves over time with elements being added during the process.

To begin, the full initial part is meshed using Cartesian or tetrahedral elements and then a "birth and death" technique is applied, which allows the sequential activation of element clusters to simulate the progression of the print job (where the term "cluster" defines a part of the weld path). In addition, the associated boundary conditions for each stage also develop as thermal convection surfaces. The build phase is complete when all the elements have been activated (brought to life).

Analysis times and time steps are controlled by the process parameters and are not known in advance; these aspects are verified internally during the simulation phase. The DED process requires a very detailed level of simulation using real weld lines and an abstraction known as element grouping.

This grouping is used to sub-divide the weld lines into smaller portions of mesh, called clusters, to which the thermal conditions are sequentially applied at each time step. Each cluster is thus a portion of a weld line that is created sequentially by activating that section through the birth-and-death technique and assigning to each newly activated piece the thermal conditions resulting from the thermal simulation performed on the previous piece.

The project involved an initial configuration phase using an example case (A-frame) after which the optimized method was applied to repair a turbine blade.

Simulation setup is guided by a wizard to ensure that all the necessary steps are followed to discretize the model and for the subsequent simulation. In particular, the wizard guides the user through the following steps:

- **Import Geometry:** defining the bodies to be printed;
- **Mesh Creation** (a hexahedral mesh is recommended): the DED Process does not require a strictly layered mesh of identical layer heights, but the weld trace must be represented in the mesh. A slightly coarser mesh is acceptable for the base plate because it simply serves as a heat sink and fixed support in the simulation. Mesh types to consider include Cartesian, tetrahedral, and sweep meshes. A hexagonal (i.e. Cartesian) mesh should be preferred to a tetrahedral mesh if manual clustering is to be used because some tetrahedra may be excluded from element clusters for some geometries. We also recommend using linear rather than quadratic elements;
- **Clustering:** it is possible to create a cluster manually or to use a G-Code file, as in our case. The cluster volume (in mm^3) is used to control the cluster size and therefore has a direct influence on the simulation time. This value determines how many elements are activated per loading step; the time for this loading step is then determined by volume/deposition rate. A smaller cluster volume tends to give a more accurate result. Depending on the overall size of the build geometry, this value should be determined by balancing the computing effort with the desired accuracy. Set the cluster volume according to the total volume of your part;
- **Material assignment:** in this window, you can assign the material to be printed and the basic components;
- **Define build settings:** in this step the user defines the machine and process settings and conditions, grouped according to three categories:
  - Machine Settings: The process parameters, which vary for each DED machine and according to the material used in the deposition process;
  - Material Deposition Rate: The feed rate of the molten material, in mm^3/sec. This value can be determined by multiplying layer thickness (mm) x weld width (mm) x deposition speed (mm/sec); and
  - Build Conditions: The settings for the environment in the build chamber that surrounds the part during printing, including the preheating temperature;
- **Boundary conditions:** in this last step the user defines the constraints of the

model in detail and, more specifically, the bottom of the base is fixed to the ground;

- **Generate clusters:** before generating the clusters, the position of the G-code can be checked using the "Show path" option in the multifunction bar (green line for laser on, blue line for laser off).

The two DED case studies

Following the setup described above, the transient thermal simulation was performed for the two case studies. Typical significant results are temperatures in the transient thermal solution, and displacements and equivalent stresses in the static structural solution.

The results obtained in terms of temperatures and equivalent Von Mises stress for the "A Frame" case study are shown in Fig. 3; the temperature and residual strain values were compared with the actual results obtained by one of the partners, SUPSI, using Prima Additive's DED machine, thus validating the Ansys results.

The full procedure was then repeated on an Inconel718 blade (the second case study) in order to verify that the method would work for an industrial case. In fact, this second structure is a perfect example of a major potential application for this method.

Conclusions

The solution for repairing complex metal parts was developed, tested, and validated as part of the OScaR project. This complete part-repair method combines an AM-DED (directed energy deposition) machine, in-situ 3D scanning, DED simulation and toolpath generation to achieve the next level of flexible manufacturing.

The simulation tool pre-assesses the results that can be obtained by using additive manufacturing processes in the repair pipeline to get the part right the first time.

In summary, OScaR automates metal part repair through an advanced inspection and toolpath generation platform. The advantages for manufacturers and users are:

- An enormous reduction in the engineering time required to develop such repair strategies;
- The ability to repair a wider range of complex parts;
- Increased ease of repair compared to manufacturing parts from scratch; and
- Consequently, cost reduction throughout the production chain.

The results achieved are important for society because of:

- Environmentally friendly production (several large parts were repaired instead of replaced, as is currently common practice);
- Reduced energy consumption;
- In-line quality control of the processed parts.

In addition, the OScaR project

- Supported the development of a dedicated ecosystem for new services and value chains;
- Created a robust solution to enable the provision of high-quality manufacturing services for research and consultancy
- Enabled increased competitiveness.

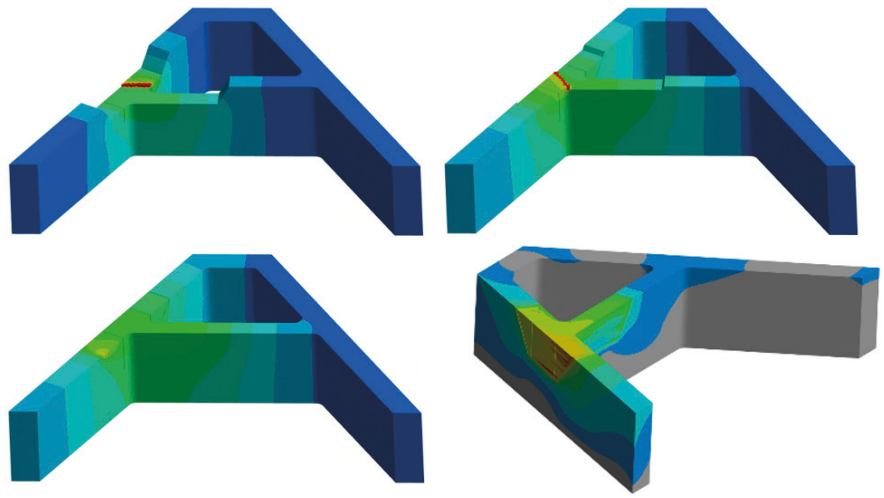

Fig 2. A-frame test case.

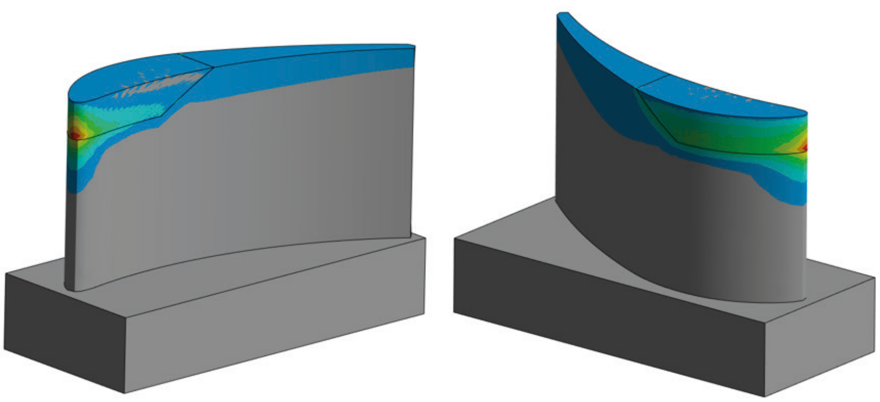

Fig. 4. Simulation and results of the DED repair process applied to the tip of a turbine blade.

Acknowledgements

The OScaR project was co-funded by the 2022 EIT Manufacturing Call for Proposals for "Flexible production systems for competitive manufacturing". We would like to thank all project partners (Prima Additive, SUPSI, inspire, AIDIMME, POZZO, and EnginSoft) for their cooperation and contribution to the success of the project.

For more information:
Daniele Calsolaro – EnginSoft
d.calsolaro@enginsoft.com

Article from: *Futurities* Special Issue 2023 - Additive Manufacturing