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ADDITIVE MANUFACTURING FOR HOT GAS PATH PARTS

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ABSTRACT

Additive Manufacturing (AM) offers a vast potential for the manufacturing of gas turbine components. Especially the powder bed based method utilizing a laser beam called Direct Metal Laser Melting (DMLM) is an enabling technology for production and repair of gas turbine components.

The benefits are evident since it allows the production of novel part and component designs with a high degree complexity or even upgrades of existing parts. Today's gas turbine component production features multiple process steps until engine ready status has been accomplished. As a consequence, the introduction of a new manufacturing method to replace conventional methods requires the careful assessment and validation of the entire process chain from design to production as well as associated processes like material properties generation.

A recently conducted engine validation in a heavy duty gas turbine was targeted to assess the technology readiness of a monolithic and a hybrid turbine component generated by DMLM. During the production, advanced inspection technologies have been applied such as X-Ray Computer Tomography (CT) to confirm the targeted part quality. The engine validation was completed successfully and the executed metallurgical investigations confirmed the previous made assessment.

INTRODUCTION AND BACKGROUND

Rapidly changing market environments across the globe require a fast response to provide new solutions to the customer. In order to cope with the situation AM and in particular DMLM is capable to effectively support delivering new solutions to the customers. This is being realized at various stages of the product development and production process. One example is the technology and part validation with functional prototypes produced by AM which allows faster design iterations by cutting lead time for test hardware. As a consequence, the time to market for new and upgrade products can be significantly reduced.

Focus for new products and components is put on efficiency improvements of gas turbine power plant. This can be realized by higher firing temperatures and/or by the reduction of cooling air consumption. Opportunities to support these targets by additively made parts can be found mainly in the combustion and turbine section, refer Figure 1. AM produced combustion parts feature intricate design features to facilitate low emissions even at elevated firing temperatures. Turbine parts could benefit from conformal cooling features realized by AM in order to deal with elevated firing temperatures or cooling air consumptions can be reduced for highly thermal loaded components.

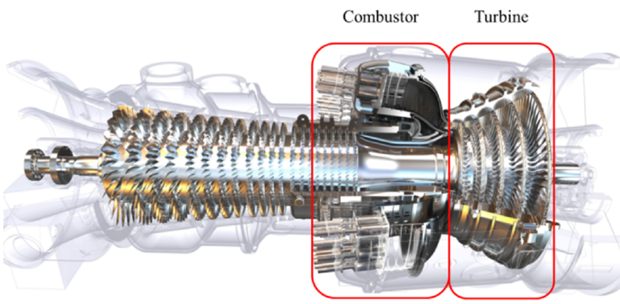

Figure 1 Schematic view of GE GT 13E2

Beside the already highlighted technology advancements, DMLM can help to reduce manufacturing costs by leveraging the opportunities of integral designs leading to a substitution of conventional manufactured parts. Through integration of functionalities certain process steps for complex assemblies like machining, joining and associated quality controls become obsolete, recently reported by Kellner (2014) [1]. This enables allows costs and lead time reduction.

NOMENCLATURE

AM	Additive Manufacturing

CT	Computer Tomography
DMLM	Direct Metal Laser Melting
DT	Destructive Testing
GT	Gas Turbine
IR	Infra-Red
NDT	Non Destructive Testing
SX	Singe Crystal

DESIGN FOR ADDITIVE MANUFACTURING

Additive Manufacturing enables the production of metal parts and components without the need to invest in molds or tools. A sliced 3D model of the desired part serves As input for the DMLM machine. Each slice, with a thickness usually in the range of 20-50 µm, contains an individual set of tool paths, called scan tracks, which represents the part geometry and where the powder bed is being exposed by a focused Laser beam. The interaction of the focused laser beam and the metal powder particles leads to the formation of a melt pool along the scan tracks. The subsequently solidified melt pool in connection with the previously exposed layers forms a dense micro structure representing the part geometry. After the completion of the last layer, the desired part shape has been generated and powder and part can be separated, refer to Figure 2.

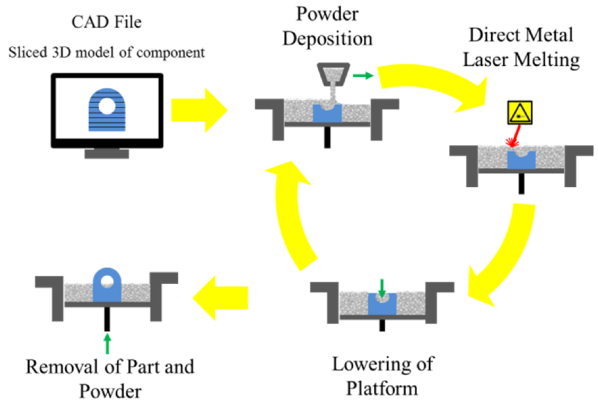

FIGURE 2: PRINCIPLE OF DMLM PROCESS

The layer wise build up principle allows for the generation of parts with unseen level of complexity since the Laser beam exposes only the relevant cross sections whereas other areas remain untreated. It can be concluded that this is paradigm change since the technology offers design complexity for free which is in contrast to established manufacturing methods.

Along with the above mentioned process, certain boundary conditions must be taken into account during the part design phase. Based on the orientation, which indicates the part position and orientation inside the DMLM build chamber, the so called overhang surfaces must be considered, see Figure 3. If the angle between the xy-plane represented by a substrate plate and the part surface drops below 45°, then thermal boundary conditions are also changing dramatically. Since the induced energy is unable to dissipate through the solid material of previous layers, the excessive heat is directed into the loose powder material which leads to unwanted powder adhesion.

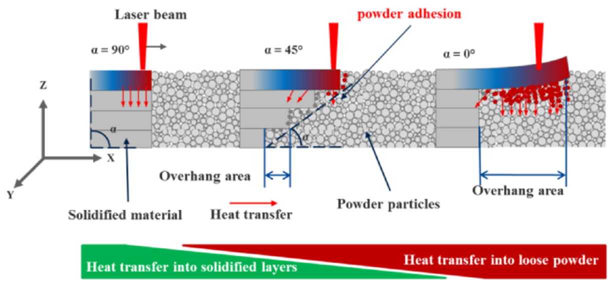

FIGURE 3: PRINCIPLE SKETCH OVERHANG AREA

Cross discipline collaborations and specific materials processing know-how is required to unlock the potential of AM for gas turbine components. As an example DMLM offers unique opportunities like topology optimizations where part features can be tailored based on thermal and mechanical load conditions to increase part performance, part lifetime or costs.

MATERIAL PROPERTIES

The availability of material properties and their corresponding material curves are essential for the application of DMLM made parts in a heavy duty gas turbine. They ensure the safe operation during the validation campaign and enable potential product application. The data serve as inputs for various predictions on part performance and lifetime.

Not only the availability of sound material properties is required, moreover an understanding about the history of such data sets is essential. As high level overview the material properties are an aggregate of the utilized powder, the applied process parameters and the subsequent heat treatment, see Figure 4. The selection and control of raw powder is crucial to the final quality. As described by Tomus et al. (2013) [2] and Engeli et al. (2016) [3] minor changes of the chemical compositions lead to significant changes in the metallurgical quality. For the γ' hardened Nickel-base turbine alloy Inconel 738 LC, a varying amounts of Silicone lead to an increased amount of micro cracking.

Another key input factor is the set of processing parameters and the scanning strategies that is being used to melt the powder particles and forming the part. Beside often reported anisotropy along the z-axis in the as-built condition, the grain structure can be modified by the applied scanning strategy for the as-built and heat treated condition as recently reported by Meidani et al. (2016) [4].

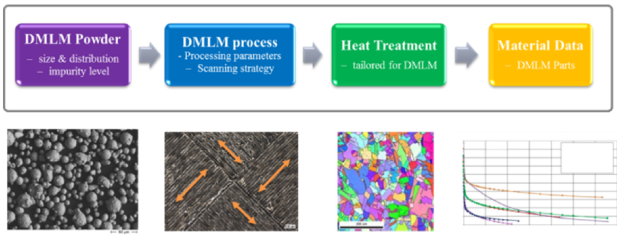

FIGURE 4: MATERIAL DATA GENERATION PROCESS

Compared to investment casting, the heat treatment for DMLM made parts has to be adjusted for the unique micro-structure caused by the rapid cooling rates during the layer-wise build. In order to balance the anisotropy in the as built condition, recent work by Etter et al. (2015) [5] indicated a transformation from anisotropic as-built conditions into isotropic properties for the Nickel-base alloy Hastelloy X realized by an appropriate heat treatment.

For the described part validation and the associated material properties generation the previous highlighted influence factors and correlations were taken into account.

MANUFACTURING AND VALIDATION

Two different parts have been manufactured by DMLM, a monolithic stage 1 heat shield with two different cooling configurations. Another approach was selected for a turbine blade, where DMLM was used to create a tip cab on top of a single crystal (SX) cast body.

The scheduled manufacturing process sequence for the shroud design from DMLM to engine ready condition is illustrated in Figure 5. A focus was put on the implications that the change of manufacturing technology from investment casting to DMLM induced. For example, the ability of DMLM to produce near net shape components offers the potential to reduce post-machining efforts and associated cost and lead time. During the manufacturing complementary NDT technologies have been used to asses and mitigate potential risks. To leverage the near net shape, potential 3D scanning was performed at various manufacturing steps to determine the geometric deviations. In order to cope with the thermal load during operation the airflow testing of the part has been performed at various stages during the development phase. The complementary qualitative heat transfer tests were done by IR thermography and indicated potential issues. The quick feedback into design allowed corresponding modifications to the final validation parts to be made.

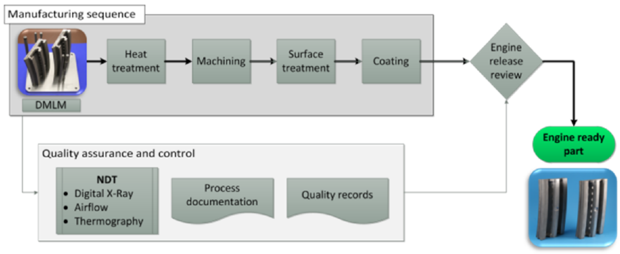

FIGURE 5: MANUFACTURING FOR SHROUD

For the hybrid blade concept, the process chain was changed based on the different approach. Instead of starting the DMLM process on top of a so called substrate plate, the precise machined cast blade served as substrate. In order to ensure a proper metallurgical bonding and alignment the laser beam and the blade airfoil cross section had to be aligned prior the DMLM process, see Figure 6.

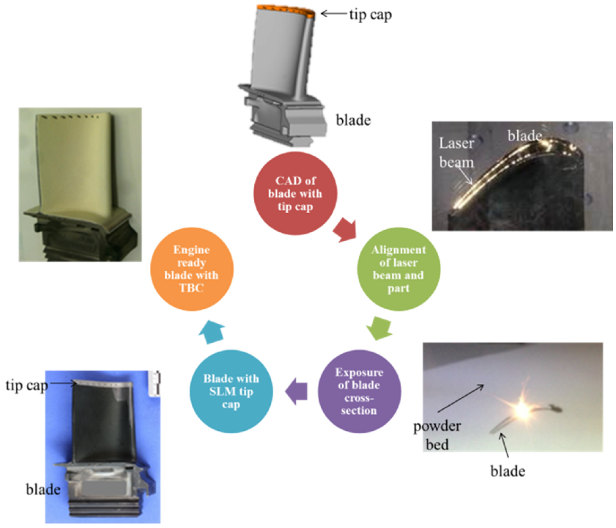

FIGURE 6: PROCESS CHAIN HYBRID BLADE

After the process step completion the blade was covered in powder hereafter the laser beam fused the metallic powder onto the airfoil cross section and created a metallurgical bonding, compare Figure 7. For the further post processing a tailored strategy was applied based on the described sequence by the recent work of Kissel et.al. (2012).

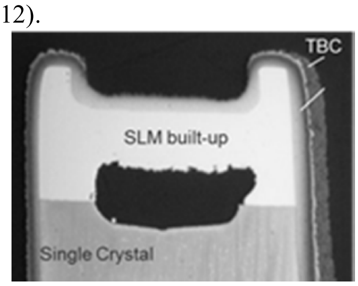

FIGURE 7: METALLURGICAL CROSS SECTION OF ENGINE READY HYBRID TIP CAP

Prior to installation, a technical review assessed the collected quality records and documentation and reviewed them against the specified requirements. All parts were released and tested under heavy duty gas turbine conditions. During the campaign, the condition of the parts has been monitored and regularly inspected by borescope, see FIGURE 8.

Heat Shield at Wedge Face   Hybrid Turbine Tip

FIGURE 8: INSPECTION OF COMPONENTS DURING CAMPAIGN

After the validation campaign, the parts were disassembled and a careful, in-depth examination utilizing latest NDT and DT technologies was conducted. The findings were in line with the previously made calculations and predictions, and furthermore the results serve as input for future technology developments.

SUMMARY AND CONCLUSION

The driver for Additive Manufacturing and in particular for DMLM is evident since it facilitates to cut the time to market and to design more advanced designs compared to conventional manufactured methods. Nevertheless, certain criteria for highly loaded turbine parts such as lifetime, competitive costs and performance have to be ensured.

The validation for the described components from design, manufacturing by DMLM and testing in the GT was completed successful. In addition, associated processes such as material properties generation linked with a deep process understanding ensured the safe validation. Based on the experience gained the manufacturing method DMLM has proven its capability and strengths for the manufacture of gas turbine components. Through Additive Manufacturing GE will be able to offer competitive solutions for today's and future challenges meeting customer expectations.

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