Technological and economical consideration for turbine blade tip restoration through metal deposition technologies

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Abstract

In the Oil and Gas industry, repair activities are critical to keep the maintenance costs of turbomachinery equipment down. Several repair technologies can be applied to various components of turbomachines. When dealing with gas turbines, the repair of turbine rotor blades has always been a very sensitive topic, given their critical application and their impact in terms of cost on the whole turbine lifecycle. Specifically, cracking and wearing of blade tips are some of the most common failure modes. Thus, the repair of these failure modes is of paramount importance, both for the original manufacturer as well as its aftermarket competitors. The present paper describes blade tip repair technologies from an Original Equipment Manufacturer (OEM) standpoint. Three different approaches are introduced and described for tip restoration. Laser cladding is presented first, which is one of the most common technologies for this application, and the one the OEM is currently applying. Then, Cold Metal Transfer (CMT) and Direct Metal Laser Melting (DMLM) technologies are investigated. A technologic and financial assessment is made, to drive the technology selection for the turbine blades restoration.

Key words: Cold Metal Transfer, Laser cladding, Direct Metal Laser Melting, repair technology, rotor turbine blades

1. Introduction

The Oil&Gas (O&G) industry includes the global processes of exploration, extraction, refining, transporting and marketing of hydrocarbon products. In this environment, turbomachinery equipment typically represents the core engine that drives most of the plant assets. Therefore, a great effort is put towards reducing the operating expenses resulting from its operation while maintaining equipment availability. In particular, turbomachinery equipment has a high impact in the plant's operating expenses, thus its maintenance is carefully managed and controlled. Turbomachinery equipment usually has a very long lifecycle, in which up-time needs to be maximized. In fact, every time the equipment must be shut-down, owner is highly impacted from a financial perspective. Thus, it is critical to reduce equipment idle time as much as possible [1]. This concept is expressed by the availability parameter, which quantifies the operational time with respect of the total one. Availability shall be maximized by reducing maintenance intervals as much as possible.

Typical availability for turbomachinery equipment in Oil and Gas industry are bigger than 96% [2-4].

From these fundamental concepts, it is clear how much repair technologies are a very attractive option to rotating equipment users, since they allow to keep their maintenance costs down. In fact, the high replacement costs of gas turbine components have led to a fast-growing, highly-specialized segment of repair industry. Components repair allow to reduce the costs that would be higher in the case of purchase of new spare parts, while keeping proper values of equipment availability. Only very rarely a repair process leads to a part that is equivalent in all respects to a new one [5]; yet, the scope of repair activities is to provide sufficient quality for the restored part to perform at least another cycle of operations [6-8]. It is the repair provider's responsibility to determine whether a component that has gone under operation is repairable or not. Thus, only some level of degradation – depending on location and extent – is tolerated for components that are eligible for repair. Although the economic rationale for repair is clear, the metallurgical one is less certain. In order to mitigate technical risk, a repair process must be thoroughly qualified before being offered to the customers. The validation steps of a repair process depend on the OEM requirements, but might also be a result of specific customer requirements. Once the repair procedures and limits are established, they are interpreted and applied by the operator and/or the repair facility.

There are many possible technologies involved when it comes to repair for turbomachinery components. Repair processes may lean on stand-alone technologies or, more frequently, use a combination of many to achieve final repair result. Commonly, certain families of repair strategies are more suited to certain application; in this work we will focus on the metal deposition technologies.

Metal deposition technologies are a repairing family that allows the restoration of a very valuable component for turbomachinery equipment, both from a technical and economic perspective: the rotor blades.

Given their importance of rotor blades within a turbomachine, their repair allows significant savings from the user perspective.

Gas turbine blades experience dimensional and metallurgical degradation during engine operation [9]. A super alloy blade that is to be repaired usually exhibits a combination of the following types of damages [10] [11]:

    a) degenerated base material (DBM). Prolonged service exposure to high temperatures can lead to a degradation in terms of alloy microstructure. For nickel-based super alloys, which are among the most common materials for rotor blades, the material degradation is mainly due to a modification in shape of the γ' precipitate, as well as the solution of some γ' in the γ-phase continuum.

    b) low-cycle fatigue (LCF) and high-cycle fatigue (HCF). LCF is related to the large stress cycles deriving from starting and stopping the turbine. In fact, when the turbine is not operating, both disk and blades are subject to stresses deriving from their self-weight only, in a relatively cold environment. While in operation, though, the same components are subject to large centrifugal forces at a much higher temperature. On the other hand, HCF generally is not a concern for this application, unless specific events (like ingested debris) trigger it. If triggered, HCF can lead to dramatic consequences in a matter of hours.

c) creep and wear. Creep phenomena become more evident at higher temperatures, determining a blade elongation which eventually leads to a contact between blade and external case. Wear of blade tips is often encountered because of this, although wear is also frequent at the interface between blade and disk.

d) mechanical damage and erosion: foreign-object damage (FOD) and domestic-object damage (DOD). Despite the environment around turbine rotor blades usually is debris-free, particles, impurities or small objects may still be present. Sometimes they come from outside (causing FOD), some other times they are detached debris from internal components (causing DOD).

e) corrosion and oxidation. Corrosion may be triggered by the end products of the combustion process, especially in maritime environments with the presence of sodium and chlorine. On the other hand, oxidation is activated by the presence of oxygen at high temperatures. Both these phenomena are amplified by high temperatures, and cause progressive deterioration of the blade surface mechanical and geometrical properties.

Figure 1 shows some of the most common and evident failure mode emerging from a blade that has undergone operations. Letters from "a" to "e" refer to the damage types described in the previous list. On the other hand, Table 1 describes the likelihood of failure location and reparability of each failure mode.

From an OEM standpoint, not all failure modes are eligible for repair. Some failure modes are not addressed because the technical risk is too high (i.e. repair does not guarantee sufficient material properties and thermo-mechanical resistance of the component) and/or because of economic considerations (i.e. too expensive compared to the cost of new). Thus, repair applications are usually limited only to some of the existing failure modes. The likelihood of repair of a specific failure mode is the result of a balance among the maturity level of repair technology, the associated cost/benefit ratio and the level of risk aversity of the specific OEM. Nevertheless, repair offerings are important in driving better customer satisfaction, in terms of costs and/or lead time.

Blade repairs vary depending on blade configuration, but generally include the restoration of blade tips or tip shrouds to desired dimensional criteria. In fact, among the described failure modes, those relative to the blade tip are among the most commonly encountered after turbines' operation.

Therefore, in this work we will develop a cost assessment for the identification of the most efficient tip repair technology both from a technical and economic point of view, focusing only on the repair step itself (in the following it is explained what is intended with repair process and repair step).
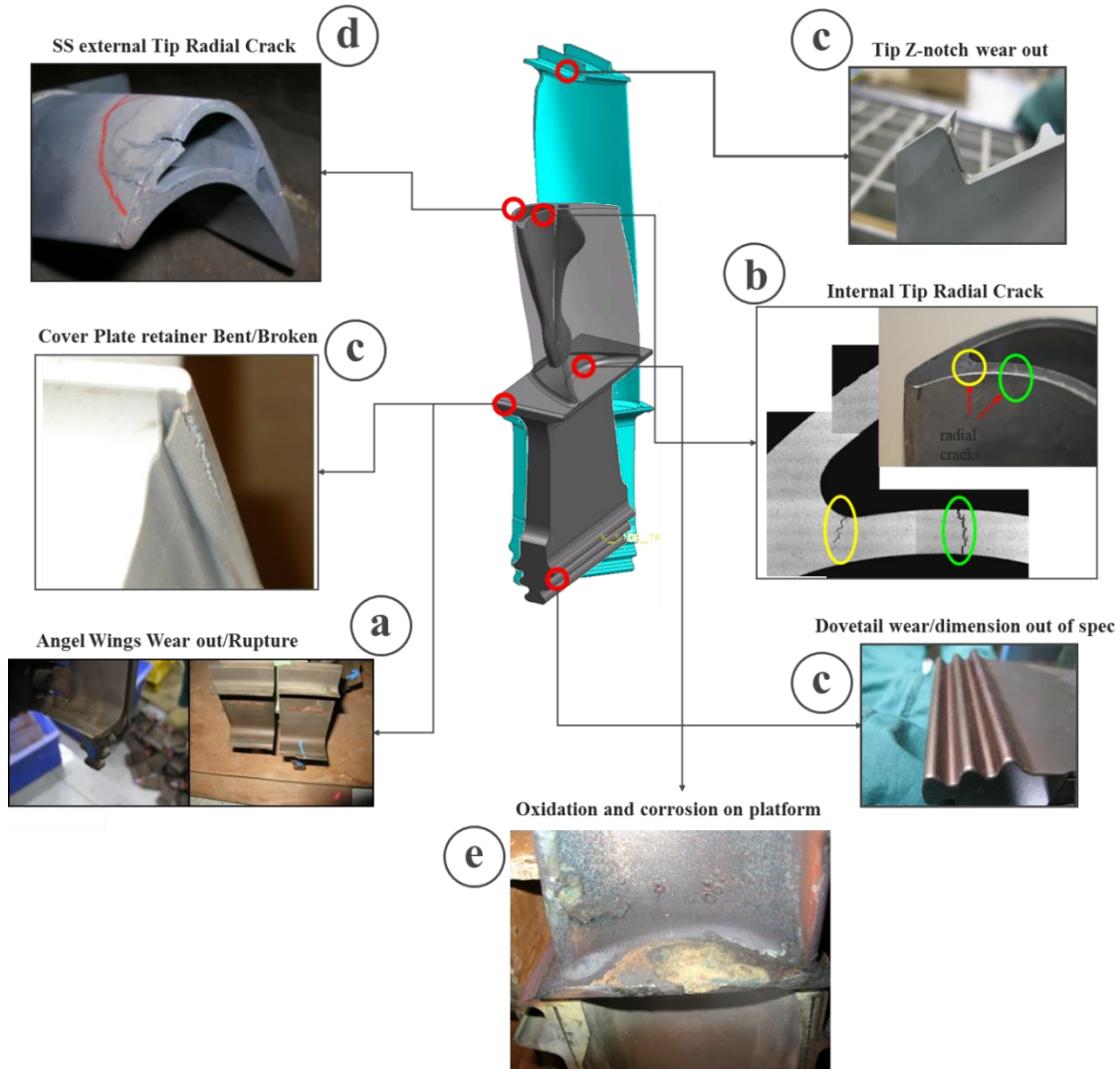
Figure 1. Typical failure modes of first and second stage rotor blades. Image copyright (2011) General Electric Company or its affiliates. Used by permission.

Table 1. Likelihood of failure location and reparability depending on failure mechanisms, based on company experience

Failure mechanism	Likelihood of failure location	Likelihood of reparability
DBM	Blade root	Low
LCF	Blade tip and angel wings	Medium / high
Creep / wear	Blade tip, blade root	Medium / high
FOD / DOD	All blade (from platform up)	None / low
Corrosion / oxidation	All blade (from platform up)	Low / medium

2. Methodology

Ciappi, A., Giorgetti, A., Ceccanti, F., & Canegallo, G. (2021). "Technological and economical consideration for turbine blade tip restoration through metal deposition technologies". Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235(10), 1741-1758. doi:10.1177/0954406219888245

Blade tip restoration generally consists in weld overlays on the top portion of a blade, which is one of the lower-stressed area due to the decrementing centrifugal force moving from the tail to the tip. Thus, dimensional restoration of a blade tip by welding would provide a part which is functionally satisfactory, even though the weld area does not have properties equivalent to the parent material. Blade tips usually get cracks due to either LCF thermal-mechanical stresses, or are worn because of blades' elongation due to creep phenomena. Typical turbine blade wear and corresponding reconditioning steps vary from manufacturer to manufacturer, and even from job to job, depending on the component defects, material composition, service conditions and quality assurance practices [12]. Also, the admissible height of weld overlays depends on the specific blade configuration and the qualification standard the OEM has accomplished. The repair and restoration techniques available, and generally employed, for tip blade repair are [13]:

- manual grinding and polishing;
- welding – manual Gas Tungsten Arc Welding (GTAW) processes are the most commonly used, yet plasma, laser, and electron-beam welding processes are finding increased usage as the trend to automation continues.
- brazing;
- hot isostatic pressing (HIP);
- re-heat treating;
- coating.

These techniques can be used in combination to perform full repair activity, or can be deployed as stand-alone processes on the specific repair to be performed. Conventional airfoils remanufacture steps usually comprehend all (or most of) these activities: Figure 2 describes a typical sequence of activities encountered during a repair activity relative to blades.

Among these activities, the presence (and the number) of stripping, coatings and resulting heat treatments may vary significantly depending on the blade stage. Given the different nature of thermal and mechanical stresses they are subject to, the repair of first stage blades usually involves a higher amount of these repair activities.

Depending on the type of technology used and its level of industrialization, some OEMs perform all these activities manually, while others include some automated steps. Usually, automation is preferred in situations with higher volumes and/or higher needs for repeatability, to improve the efficiency and consistency of the outcome.

This article will focus only on the Step 5, (which is the actual repair step we were referring to in the Introduction section) in which new metal is deposited on the blade tip to restore its functionality. Step 4 and 7 are not directly taken into account. However, since the objective of this work is to assess the overall viability of metal deposition technologies, step 4 and 7 are only considered as long as they are influenced by the technology in step 5. All the other steps are not affected by the technology chosen in Step 5, therefore they need to be carried out regardless the specific process considered and will not be considered in the overall cost calculation.

As above mentioned, to improve repair efficiency and consistency, automation is preferred to manual operations.

1 —
Initial inspection
Careful check of damaged areas

2 —
Cleaning
Degreasing, polishing, etc.

3 —
Stripping
Removal of previous coating, if existing

4 —
Set-up
Tools, jigs and fixtures, machining of damaged surfaces

5 —
Blade(s) Repair
Material deposition, welding, grinding, etc.

6 —
Heat treatment(s)
Restoring material microstructural integrity

7 —
Finishing activities
Machining, blending, etc.

8 —
Coating(s)
Enhancing protection from oxidation and corrosion

9 —
Inspection
Control of repaired areas through non-destructive tests

10 —
Balancing
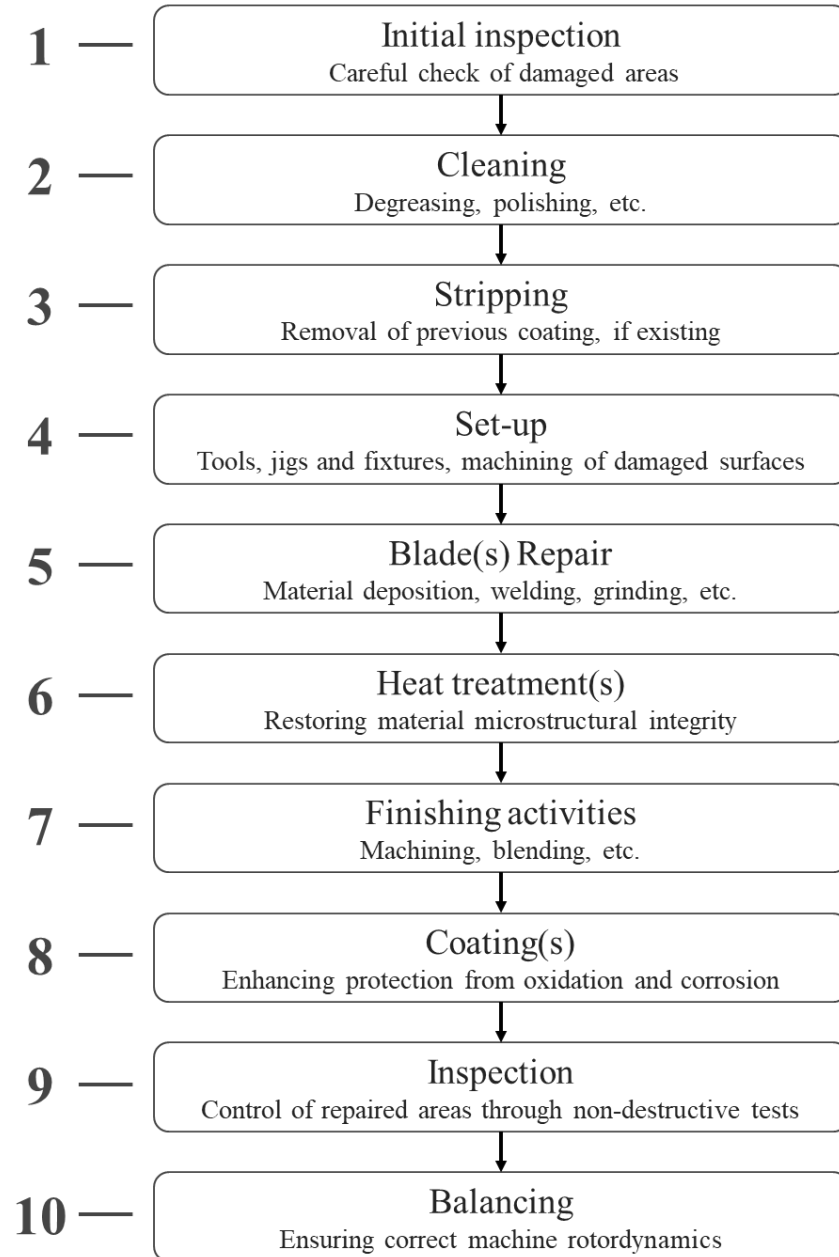Ensuring correct machine rotordynamics

Figure 2. Blade repair process workflow

Industrialization of the tip blade repair process is critical for OEMs to boost productivity and repeatability while controlling costs. A well-established process in the industry to perform tip repair is through thermal spray technologies [13-16] and in particular laser cladding. However, the adoption of new and faster technology could provide additional benefits compared to the already established one. The goal of this paper is to scout among different technologies, and investigate whether their adoption would unlock additional opportunities for further improvement.

The present article deals with repair activities on turbine blades from an OEM standpoint. The OEM already owns laser cladding equipment, which is used to repair the tip of its

blades. However, in a continuous improvement effort, the OEM company's management is scouting for viable alternatives, if existing. Two additional technologies for the repair of turbine blade tips are hereby considered: Cold Metal Transfer, or CMT [17, 18], and Direct Metal Laser Melting, or DMLM [19, 20]. These technologies have been widely established in the industry during the last decade and used in several applications. Table 2 highlights equipment characteristics and typical applications for each technology.

Table 2. Equipment characteristics and typical applications for the mentioned technologies

Technology	Equipment characteristics	Main applications
Laser cladding	Laser-powered system in a closed chamber, with dimensions spanning from 200mm to up to a meter	Repair of used components, hard-facing treatments
CMT	Open environment – equipment footprint depends on robot maximum extension	Join of lightweight materials and/or low thickness elements
DMLM	Laser-powered system in a closed and sealed chamber, with dimensions spanning from 100mm up to 400mm	Rapid prototyping, production of components with high geometrical complexity

The OEM is performing preliminary scouting on these technologies because it is already familiar with them through some test campaigns performed over the years through some qualified suppliers to understand process capabilities. However, the OEM has never moved forward in applying it in a practical situation like the field of repair. This paper represents the framework through which the future decision is driven.

2.1. Laser cladding

Laser powder deposition methods are used to produce high integrity, high-performance welds in a large range of gas turbine components. They have long established in the turbine blade repair environment, allowing for a more repeatable outcome than manual welding, thus a more robust and industrialized process. [13, 14, 19, 21-22]
The first commercial equipment for laser cladding is from 1998, with the LENS (Laser-Engineered Net Shaping) metallic powder system [23], which is part of the more general category of the direct energy deposition (DED) processes. The powder is channeled through a nozzle by the carrier gas, and blown towards the building surface. A laser, often concentric to the deposition head, is utilized to melt the powder as it is sprayed, thus adhering with the surface. Everything happens inside an inert atmosphere, created by both the carrier and the shielding gas; the inert atmosphere is needed to prevent oxidation during the powder melting. This operation (that is the layer deposition) is repeated until the component restoration is completed. Figure 3 illustrates the operating principle of this technology.

Laser

Shielding Gas

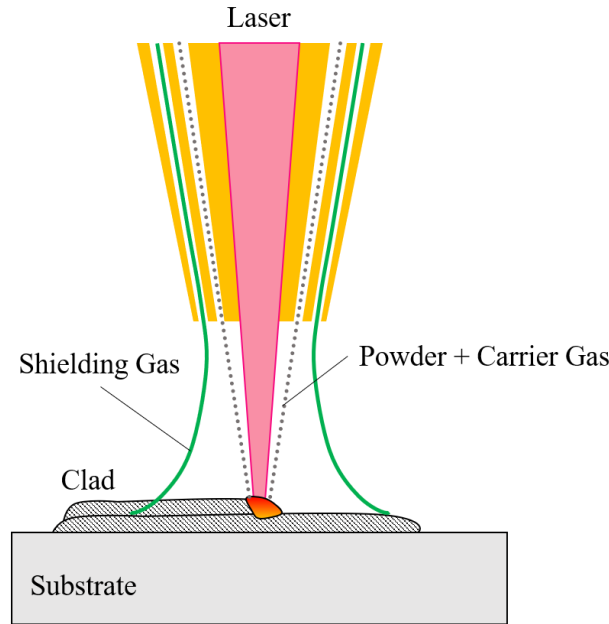Powder + Carrier Gas

Clad

Substrate

Figure 3. Direct energy deposition processes schematization.

Dimensional accuracy and as-built surface roughness depend on various parameters, i.e. powder deposition rate, thermal source power, laser spot dimension, etc. General characteristics of laser cladding processes are a material deposition rate in the range of 0,3-1kg/h, a dimensional accuracy around ±0,3 mm and surface roughness in the range of Rz 40-90 µm [19, 20].

It is important to underline that, for what concern DED processes, surfaces obtained through this technology are badly characterized with conventional roughness parameters, because of the huge surface waviness produced by the process itself; hence, other parameters are more appropriate for their description, such as waviness parameters.

2.2 Cold Metal Transfer technology

Cold Metal Transfer, or CMT [20], is a subset of Gas Metal Arc Welding (GMAW) technologies, developed and patented by Fronius GmbH. The main parts constituting the equipment are: the welding torch, the robot (along with its interface), the power source, the remote control unit, the cooling unit, and the wire feeder. There are several CMT configurations, involving both manual or automatic motion, as well as different power output configurations. In a similar fashion as laser cladding, CMT might be used for bulk material deposition through wire layering [24]. As illustrated in Figure 4, during the deposition process the wire moves forward within the torch and is pulled back again as soon as a short circuit is detected. As a result, the arc generates heat only for a brief period during the arc-burning phase. The short circuit is controlled and the current is kept low, resulting in a drop-by-drop transfer of spatter-free weld material.

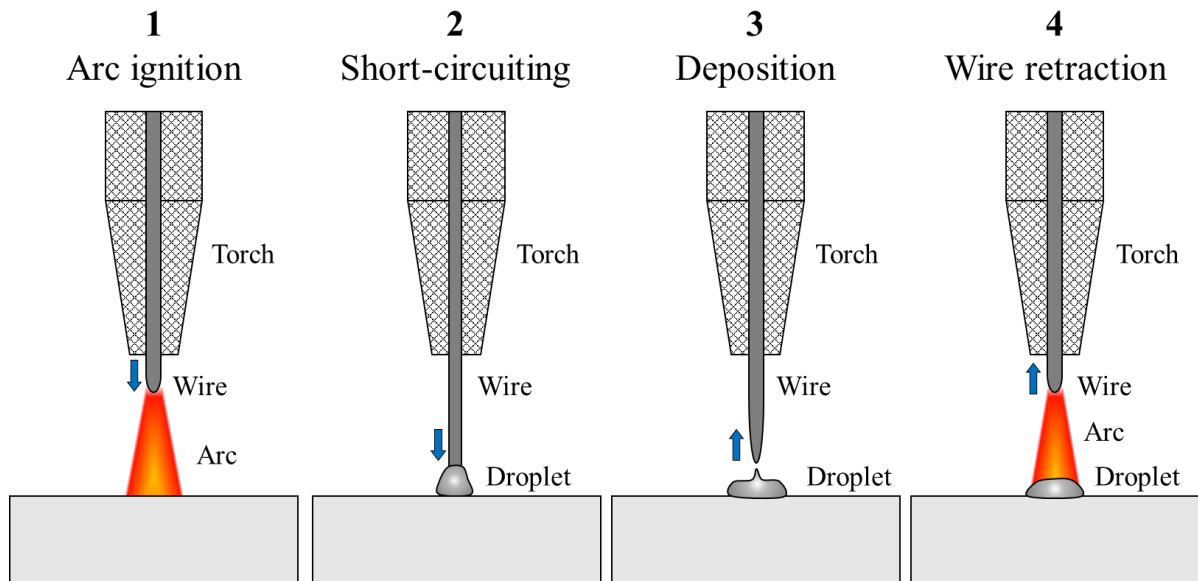|			
1	**2**	**3**	**4**
Arc ignition	Short-circuiting	Deposition	Wire retraction

Figure 4. CMT working principle for material deposition.

Thus, the CMT process is characterized by extremely low heat input and an exceptionally stable arc, compared to other technologies of its same group. It evolved from the continuous adaptation of the MIG/MAG process to resolve the problems posed by the joining of metals [25] like aluminum, magnesium, etc. [26, 27]. Even though CMT application perfectly suits lighter materials, it is possible to apply it also to thicker materials and a wider range of more noble materials. In this case, the advantage lies in the reduction of thermal stresses induced in the part, thanks to the extremely low heat input generated by the process.

This process shows many differences compared to laser cladding systems, especially in terms of type of heat source (pulsing resistance vs. laser), raw material form (wire vs. powder) and material deposition criteria (torch vs. precision nozzle). Since CMT is born as welding process rather than a deposition one, dimensional accuracy and final surface roughness are not available in the case of laser cladding. However, preliminary tests performed by the OEM have shown that the accuracy of the robot is enough for material deposition in this application.

2.3 DMLM technology

DMLM is an additive manufacturing technology belonging to the powder-bed processes. These processes use the heat deriving from an energy source (in this case, laser), which is focused in a spot (with dimensions around 100µm), to selectively melt the deposited layer of material. The chamber in which the layers are deposited is sealed, to maintain the atmosphere inert. The working atmosphere is mainly made of nitrogen or argon, with less than 0.1% of oxygen in volume. This is important to prevent metal oxidation during the melting process.

Once a layer is deposited and selectively melted, a new layer is deposited on top of the previous one. The process continues until a tridimensional solid product is manufactured.

In order to realize overhanging surfaces, support structures need to be taken into account; they are built together with the component and removed in the post-processing phase when the manufacturing process is completed.

Support structures are fundamental in DMLM because they provide many functions and potentially affect the overall technology effectiveness.

For the purpose of this work, two of the most important functions issued from them are:

- The enlargement of geometries feasible though DMLM;
- The dramatic influence that their design has on the post-process time.

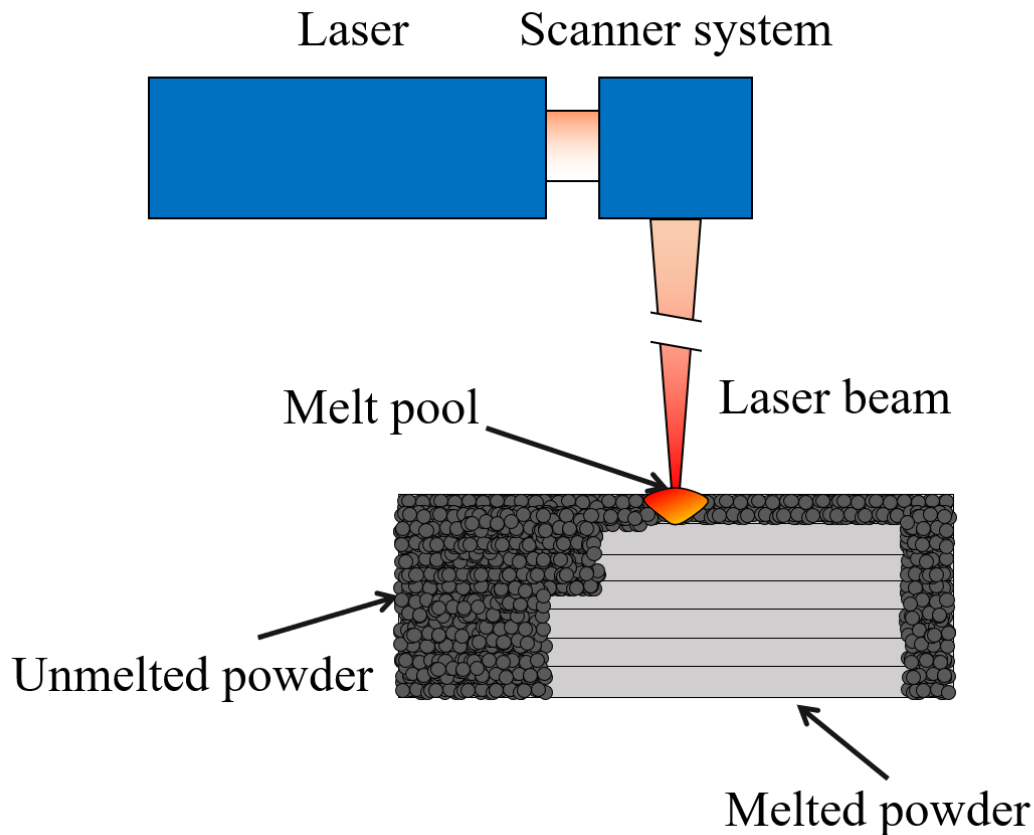Figure 5 schematized the DMLM equipment, and the way the process works within the chamber.

Figure 5. DMLM equipment components, and working principle of the process within the chamber.

In DMLM processes, in a similar way to laser cladding, dimensional accuracy and final surface roughness depend on various parameters, e.g. thermal source power, laser spot dimension, powder layer height. General characteristics of DMLM metal processes are an hourly build up volume around 0,02-0,1kg/h, dimensional accuracy ±0,1 mm and a surface roughness around Ra 3-30 µm.

Ciappi, A., Giorgetti, A., Ceccanti, F., & Canegallo, G. (2021). "Technological and economical consideration for turbine blade tip restoration through metal deposition technologies". Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235(10), 1741-1758. doi:10.1177/0954406219888245

Repair activities with DMLM in the O&G industry have already been performed and industrialized [28, 29]. To do that, the equipment has to be modified accordingly through some additional tooling. In this specific case, the DMLM equipment shall present fiducials to reference the building platform to the machine absolute coordinate system, and simultaneously the components to be repaired shall be referenced to the fiducials. Once this arrangement was done, the machine would be able to start building up material on blade tips, which would be machined accordingly beforehand. Figure 6 shows the necessary steps required in the case of some gas turbine shrouds.
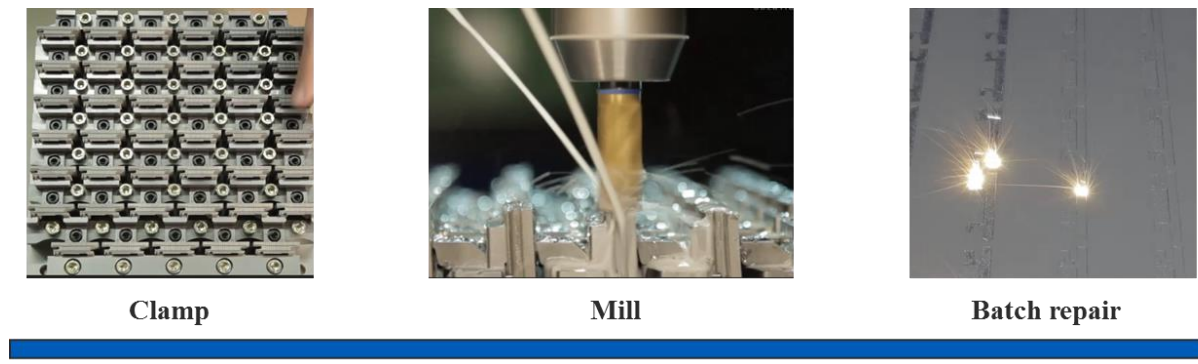

Clamp   **Mill**   **Batch repair**

Figure 6. Required steps for repair through DMLM process [30].

3. Comparative study of metal deposition technologies for blade tip repair

Repair technologies must fulfill desired requirements for the material properties, quality of the junction, and accuracy of results. Accordingly, economic considerations shall be considered as well. From a technical perspective, the chance to invest in either one of the technologies is driven by results found both in literature and in preliminary test campaigns the OEM has already done beforehand. The results found in these test campaigns are fully aligned with the literature findings, which are hereby described briefly. The OEM already has relevant experience on laser cladding. Even if CMT and/or DMLM technologies resulted attractive from a technical standpoint, their full validation consists in the substitution of a mature process with new technology, thus the introduction of new variables and risks.

This framework provides suggestions and indications to guide a thoughtful choice. Even though development risks will still be possible, they will be mitigated from the start.

Once technological capabilities are assessed, also financial evaluations are performed to determine the future return on investments. Cost drivers are highlighted for each technology, and a preliminary business case is illustrated, showing the strengths and weaknesses of each repair optionality.

3.1 Metallurgical and dimensional accuracy considerations

Laser cladding deposition processes have been subject to extensive R&D efforts in recent years to develop and explore their full capabilities. There are several kinds of commercially

available laser cladding equipment today, and the process understanding is highly improved. In general, laser powder deposited items can result in fully dense and metallurgically sound parts with extremely fine microstructures, which convey excellent mechanical properties, similar to or even exceeding those of wrought and cast materials [31]. These properties are achieved because of the rapid cooling conditions the deposited layers are subjected to, caused by the high heat conduction between the small amount of melted powder drove on the component and the cool substrate. As heat conduction to the cooler substrate is generally the dominant heat transfer mechanism by which heat is extracted from the melt pool, cooling of newly deposited material will depend strongly not only on the temperature of the underlying material but also on its geometry [32]. Several empirical mathematical expressions clearly demonstrate that both the material deposition rate and the spatial distribution of the deposited material within the individual material tracks depend on the processing parameters in a complex, non-linear manner, and so are the resulting material mechanical properties.

The OEM subject of this paper has owned laser cladding equipment for the repair of blades with different base materials and geometries. The company has always adopted nickel-based alloys as filler materials for repair through laser cladding, whose characteristics have been analyzed in depth also for aerospace applications [14]. Recognized advantages of laser cladding systems over manual TIG welding for the repair of nickel-based superalloys are: smaller thermal distortion, lower dilution, better fusion bonding, less porosity and higher homogeneity in mechanical properties. A more abrupt change in hardness from clad to substrate is detected, due to a narrower dilution zone; however, this effect can be minimized by applying a successive post-welding heat treatment (PWHT). Going through with the description of both CMT and DMLM technologies, it is important to note that the OEM is meaning to maintain the same repair engineering instructions in terms of filler material deposited during the repair, as well as the maximum height allowed for deposition of filler material on the blade tip. These choices are driven by the necessity to gradually introduce new degrees of change, instead of introducing too many variables altogether that might lead to exceeding development costs.

CMT has accomplished the efficient welding of many similar aluminum alloys [17]. Also, it has been demonstrated how CMT is fully suitable for the welding of Inconel 718, and tests have also shown that no lack of fusion was evident in the microstructural analysis, thus proving the weld quality as good [24]. The Heat Affected Zone (HAZ) of a CMT process is small in size (roughly 0.5 mm) when compared to the same produced by classical MIG welding [18]. The size and geometry of crystallites in the weld zone, i.e. large dendrites, are similar to those obtained in classic MIG process. After performing EDS chemical analysis, no significant variation has been detected in the homogeneity of the weld bead. The residual stresses are found to be minimum. Since the OEM requirements ask for nickel-based alloys as wire feed material, technical experience on welding within the company suggests for a wire diameter in the range 0.8-1.2mm. Test campaigns on CMT performed by the OEM have used nickel alloys for the trials, confirming the same expectation; anticipated results are of a joint with lower HAZ and residual stresses. Figure 7 and 8 show some of the visual results deriving from the test campaign.
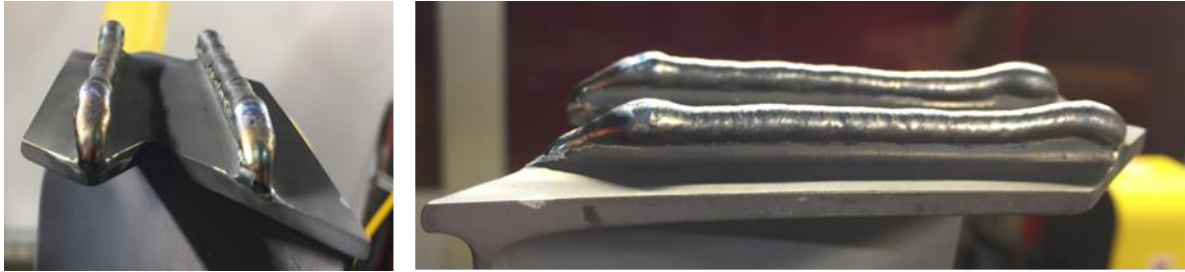
Figure 7. Layer deposition on blade rail tip through CMT technology (front and lateral views). Image copyright (2017) General Electric Company or its affiliates. Used by permission.
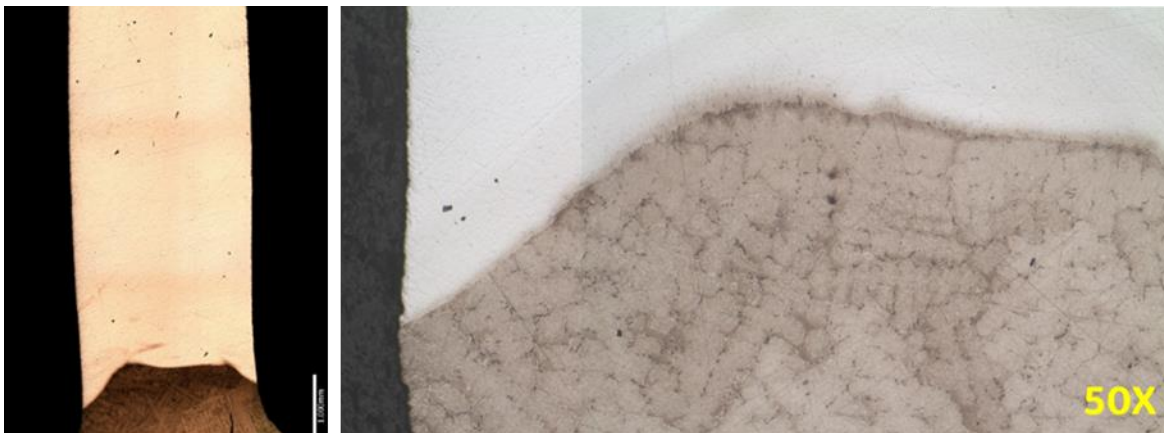

Figure 8. Cut-up image of the welded tip, showing no lack of fusion between base and filler material. Image copyright (2017) General Electric Company or its affiliates. Used by permission.

About DMLM technology, the test campaign has focused on experimenting commercially available nickel-based superalloys [33]. No significant differences have been reported from a material properties perspective. Given the different scope of the specific test campaign, the quality of the joint of the superalloy with the blade base material could not be verified. Material mechanical properties of one of the nickel-based alloy manufactured through DMLM process are reported in Table 3.

Table 3. Tensile data at room temperature of a nickel-based superalloy [33]

	As built		Heat treated	
	Mean	Std Deviation	Mean	Std Deviation
Ultimate tensile strength – horizontal direction	980 MPa	5 MPa	1000 MPa	10 MPa
Ultimate tensile strength – vertical direction	870 MPa	10 MPa	890 MPa	10 MPa
Yield strength 0,2% – horizontal direction	720 MPa	5 MPa	680 MPa	5 MPa
Yield strength 0,2% – vertical direction	630 MPa	5 MPa	640 MPa	5 MPa
Elongation – horizontal direction	33 %	2 %	34 %	2 %

Elongation – vertical direction	48 %	2 %	49 %	2 %

Since the weldability characteristics of both nickel alloy and blade base material are known to be good, no issues are expected. Still, the full repair validation would require some extra work to check this aspect too. From a dimensional accuracy perspective, DMLM does not represent a high technical risk; it is by far the most precise and accurate process considered in this application, and also the resulting surface roughness would allow eliminating some of the necessary post-processing phases. An important part in the qualification of this technology for repair purposes would be a good understanding of the level of equipment modification that would be required, as well as the tooling characteristics that would be needed (e.g. tolerances, stiffness, etc.) and how to tune them with respect of the DMLM equipment.

Experience and available data suggest that all the technologies can process nickel-based super alloys and guarantee sufficient material properties for the application.

3.2 Process considerations

In this paragraph we are going through a technical analysis of the three technologies considered for the repair use to identify the main characteristics of their processes.

Laser cladding is a proven technology since it has been developed some decades ago. In this technology, metal deposition process is quite regular and even controllable with feed-back strategies; this allows to get a quite good accuracy and repeatability in terms of dimensional and geometrical performance. Common finishing processes are required only to remove a little overstock material produced by the process itself.

In addition, the deposited metal typically adheres well on the base material, resulting in a very good joint quality.

One of the most important drawbacks of this technology is represented by the machine itself: typically these systems are not cheap and, moreover, they are quite complex. System complexity can be correlated with issues from the equipment maintainability standpoint.

With equipment maintainability the focus is put mainly on two aspects:

- Time required to solve a machine breakdown;
- Personnel involved in machine breakdown solving.

Both laser cladding and DMLM, due to their complex hardware, typically requires equipment manufacturer personnel exclusively for both ordinary and extra-ordinary maintenance intervention. In addition, especially for DMLM, the process mean time between failure is quite short, especially if compared with the same parameter retrieved by the analysis of more classic technology.

For what concern the laser cladding, on the other hand, typically hardware is less complex and sometimes also facility personnel are authorized by equipment manufacturer to carry out the most common and simple maintenance interventions.

DMLM technology, with respect to repair applications, offers a great accuracy in the material deposition, with very a little overstock material required to get fully repaired parts. The drawbacks of this technology, however, are not a few:

- -material deposition rate is low (it is not crucial in repair application given the small amount of metal to be printed, but is still considerably slower than the other options);

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- it is required a tooling to clamp items to be repaired on the building platform (which is expensive both from the economic perspective and from the time required for the machine operability standpoint),
- -the quality of the connection is not ensured and, even in this case, maintainability is a very critical aspect.

Finally, CMT, even though presents a very low dimensional accuracy in the material deposition (which potentially implies more expensive finishing operation with respect to the other technologies), offers great performances in terms of deposition rate, process repeatability, flexibility (it can be used both in manual operations and in almost fully automated cells) and, unlike the other technologies taken into account in this work, equipment maintainability is very good (since the simplicity of the basic technological process used).

Table 4 collects and highlights the technical advantages and disadvantages of the presented technologies. Despite clear differences between the presented technologies, all of them are suitable candidates in terms of technical characteristics.

Table 4. Technical advantages and disadvantages for the presented technologies

Technology	Technical advantages	Technical disadvantages
Laser cladding	Proven technology Good accuracy and repeatability Good joint quality with base material	Equipment maintainability
CMT	Excellent deposition rate Equipment maintainability Good repeatability Good production flexibility	Low dimensional accuracy
DMLM	Excellent accuracy and repeatability	Low deposition rate Equipment maintainability Tooling required Uncertainty about joint quality

3.3 Business case and financial considerations

The original scope of the OEM is to scout new possible ways to perform tip blade repair, guaranteeing same quality at a lower cost of ownership. A cost analysis is hereby performed, considering all the relevant cost drivers of each repair technology. No indication on total repair costs will be given throughout this analysis. In fact, the costs hereby expressed are relative only to Step 5 presented in Figure 2, which is the actual scope of this article, together with the other steps that are directly influenced by modifications occurred in Step 5. In order not to get confused by the use of a specific currency and its value during this dissertation, these partial costs are measured as multiples of a dummy unit of measure, namely Unit of Cost (UoC). Since also production timeframes are directly linked to the activities' costs, timeframes are expressed by means of a dummy unit as well, i.e. are measured in Unit of Time (UoT). Some of the costs are only assumed, either from internal considerations or comparing existing work from similar case studies. Further refinement of the business case is an action that may be postponed later, once the choice

has been made and the technology has already been selected. There are many activities in the full blades repair process (e.g. inspections, heat treatments, coatings, external labor from suppliers, etc.) that constitute a great part of the total restoration cost.

As explained before, most of the repair process steps (from the activity nature standpoint) are the same despite the specific technology considered for the blade restoration.

This does not mean that, at the single step level, the activities are exactly the same; the steps of the repair workflow are the same, the activities carried out within the single step can be different (e.g. finishing step can require different assets depending on the repair technology used in Step 5). Basing on this, and considering that the steps that are actually indirectly affected by the specific repair technology are the 4 and 7 (Set-up and Finishing), in the presented assessment will be covered only data and costs coming from the technology adopted (e.g. stripping does not depend on the repair technique; it is a standalone intervention).

Once done that, the relative difference between each cost is evaluated, thus the cost saving imputable to a specific technology selection.

First, repair volumes are needed to perform the analysis. A reference yearly volume of 100 sets of blades per year is assumed. The average number of blades in each set spans from a minimum of 70 to a maximum of 120, depending on the selected technology, and so are blades dimensions; for the sake of this analysis, an average number of 95 blades is considered together with a reference blade type. Other useful data and assumptions that are needed to perform the analysis are enlisted below.

- Machine operators' annual cost is around 7960UoC/y. Given an average operator workload, and given the selected unit of measure for both costs and time, the cost rate of an operator becomes 14UoC/UoT;
- Timeframe considered for the machine hourly rate definition is the same for the three technologies considered in this work and is one year. However, the timeframe choice does not affect the final consideration, thanks to the fact that it modifies just the deposition costs (with a coefficient that is the same for the three technologies, i.e. a certain percentage of the system purchase cost) and the maximum number of repairable kit per year.
- CMT and laser cladding equipment need to be operated with continuous supervision, while DMLM equipment needs supervision only for the start-up, shut down, loading and unloading phases. Start-up and shut down requires 0.47UoT combined, while loading and unloading are estimated to require around 0.15UoT in total. All combined, the sum of these activities totals 0.62UoT for each production table;
- The depreciation rate of the equipment is linear, and is calculated in a timeframe of 8 years. This is the standard depreciation time that is applied to company equipment, although for DMLM equipment such number might need to be lowered. However, this difference is not included in the present article.
- All the necessary post-processing is already available by the shop (e.g. CNC milling)
- Internal calculations set an hourly rate for CNC at 8UoC/UoT.
- The company does not use a classic ABC method for the repair cost definition. In this paper will be considered both the classic method (that is the ABC) and the one

adopted by the company, which is based on the use of the OPCH index (detailed explained in the following).

- DMLM requires more time for initial preparation of a batch, but as the process starts the batch is completed with no more human intervention. Considering that there are many differences in terms of blade size (due to differences in the product family), 8 blades per job has been chosen as a reference for the next calculations. Basing on this assumption, 12 tables are required on average to perform the full repair of an entire blade kit. Figure 9 shows the blades disposition within a production table; it is important to note that the number of blades per job has been defined considering both the whole blade body (not only the section to be re-built) and the clamping system envelopes. Therefore, no more than 8 parts per job can be considered (for this family of blades).

- CMT and laser cladding require both roughing and finishing activities; DMLM needs only the latter.

- Specific heat treatments are needed after deposition, no matter the technology – they will have different characteristics depending on the deposition technology used, but not much in terms of costs

- Deposited material weight cost varies depending whether wire material or powder material is deposited. In the first case the cost of the deposited material is 0.8UoC per blade, in the latter case 1.6UoC per blade. This is due to the process nature itself, where DMLM produces more material scrap, such as powder lost during the building and condensate produced. These contributions, in DMLM technology, typically are negligible, but considering the repair intended use, in which only a small amount of powder is melted, their impact shall be considered.

- No cost of quality is considered in this analysis.

- No maintenance costs of the equipment are available. Therefore, for the sake of this work, they are considered equal, and negligible compared to the annual cost of the equipment. This choice is supported by the fact that, in a real application, maintenance costs depend on many factors (such as technical issues, commercial agreements, manufacturers, etc.) that they are not reliably foreseeable.

- Consumables costs are also neglected in this preliminary analysis. For CMT, metal plates are the consumables needed to support weld material deposition on rail tips.

- For DMLM, the tooling needed for repair is important in terms of costs and life duration. Given the current level of uncertainty on this, these costs are neglected for the moment.

- Electricity costs are non-negligible [34, 35]. Yet, they are already included in the facility overhead, and their allocation does not distinguish between specific production activities.

- In case of non-complete repair asset saturation, the machine hourly rate does not change (which is in line with traditional economic practice).

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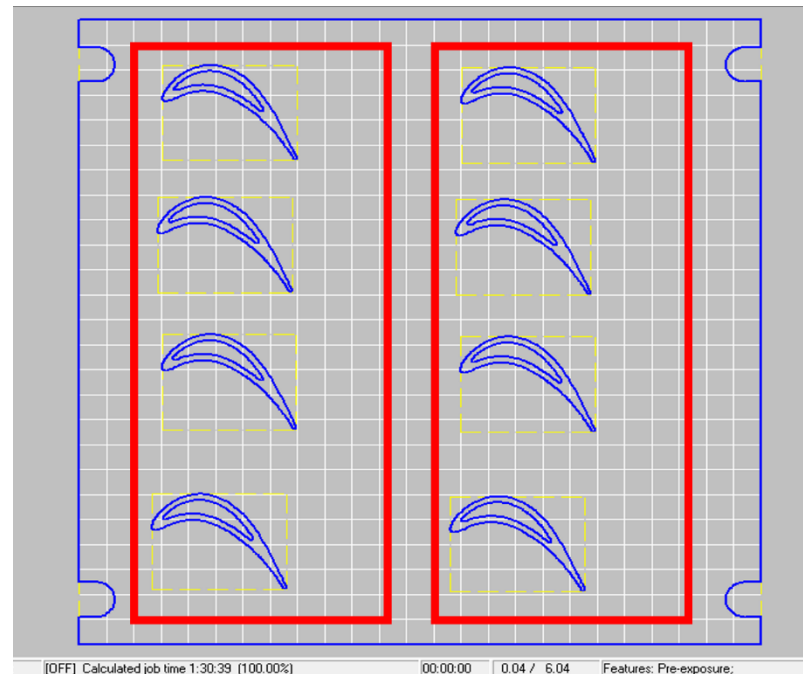
Figure 9. Visual simulation of blades' disposition on the platform inside the DMLM chamber; in red are represented the clamping system envelopes. Image copyright (2017) General Electric Company or its affiliates. Used by permission.

Table 5 sums up the numerical data that is needed to proceed with the business case.

Table 5. Numerical data deriving from the assumption

Assumption	Numerical data
Average number of blades per set	95 blades
Operator cost rate	14 UoC/UoT
Idle time for each DMLM table	0.62UoT
Time of equipment amortization	8 years
Machining cost rate	8 UoC/UoT
Number of DMLM tables (per kit)	12
Consumables, quality, maintenance, tooling and electricity costs	Neglected

With this assumptions and data, it is possible to better elaborate the potential of each technology in terms of cost saving. Table 6 enlists the data that are needed to reach meaningful indicators which are directly related to the cost drivers of the considered technologies. The equations used for calculation are enlisted below.

Total active time for repair = (Tip weld repair) x *(Number of blades)*   (4.1)
Total idle time = (Loading + unloading time) x *(Number of blades)*   (4.2a)
Total idle time (DMLM)= (Loading + unloading time) x *(Number of tables)*   (4.2b)
Total time for repair = (Total active time for repair) + (Total idle time)   (4.3)
Annual machine operating UoT = (Total time for repair) x *(Average volume per year)*   (4.4)

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Machine purchase cost per year = (Machine purchase cost) / (Time of equipment amortization) (4.5)

Machine cost rate = (Machine purchase cost per year) / (Annual machine operating UoT) (4.6)

Total machining time = (Post processing per blade) x *(Number of blades)* (4.7)

Table 6. Total UoT of activity, equipment cost rates and postprocessing effort needed for each technology on the presented application

	Laser cladding	CMT	DMLM
Tip weld repair (per blade) [UoT]	0.05	0.02	0.06
Loading + unloading time (per blade) [UoT]	0.03	0.03	-
Total active time for repair (UoT, per set)	**5.04**	**2.02**	**5.55**
Total idle time (UoT, per set)	**2.52**	**2.52**	**7.4**
Total time for repair (UoT, per set)	**7.56**	**4.54**	**12.95**
Machine purchase cost [UoC]	95000	40000	80000
Machine purchase cost per year[UoC]	11875	5000	10000
Machine cost rate [UoC/UoT]	**4.26**	**1.79**	**3.58**
Direct cost of build material (per blade) [UoC]	1.6	0.8	1.6
Post processing (pre and post machining) [UoT]	0.26	0.26	0.21
Total machining time (per set) [UoT]	**24.52**	**24.52**	**20.06**

For laser cladding, the manufacturing passages are already mapped in the shop manufacturing routings. Given the CMT process deposition rates, the cycle time is considerably lower than the other technologies. This data, moreover, was confirmed by preliminary test campaigns performed by the OEM. For DMLM, the manufacturing cycle time is estimated with the equipment manufacturer simulation software. Loading and unloading times do not vary significantly between laser cladding and CMT, while are remarkably different for DMLM. DMLM total time is much higher as a result of two factors: some idle time of the equipment, due to the start-up and shut down phase (during which the machine chamber has to be heated up and then cooled down) and some more time before that (estimated around 0.08UoT per table) where the operator sets the DMLM system process chamber to be operative. The same activities must be performed backwards, once the manufacturing cycle is completed and the machine is cooled down.

The sum of active and idle times for all the set of blades to be repaired within a year gives the total amount of hours the repair equipment is occupied. Adding up the cost of the equipment, and known the assumed depreciation, it is possible to derive a cost rate for each technology equipment. It is important to note that, for the sake of this analysis, it is imagined that the necessary equipment is purchased for the sole purpose of blade repairing. This assumption is hardly reasonable in practice. Despite this consideration and basing on the purpose of this work, that is to drive a potential user of blade repair through the choice of the more efficient technology, this assumption well fits the paper aims.

From internal calculations, the CNC machine hourly rate is around 8UoC/UoT.

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As later explained, the company does not use this accounting system for production; however, this rate is useful in a preliminary phase, since it allows to allocate costs in a way that reflects the actual costs of the technologies, given the level of utilization of both manpower and equipment. In fact, in the present analysis costs are allocated through an Activity-Based Costing (ABC) approach, considering both machines UoT and operators UoT as factors at first. The deriving results are presented in Table 7. Total costs are calculated as:

$$Total\ costs = (Deposition + labor\ costs) + (Builds) + (Post\ processing\ costs) \qquad (4.8)$$
$$Deposition\ costs = (Total\ time\ for\ repair) \times (Machine\ cost\ rate) \qquad (4.9)$$
$$Labor\ costs = (Total\ time\ for\ repair) \times (Operator\ cost\ rate) \qquad (4.10a)$$
$$Labor\ costs\ (DMLM\ only) = (Total\ idle\ time) \times (Operator\ cost\ rate) \qquad (4.10b)$$
$$Build\ material\ costs = (Direct\ cost\ of\ build\ material) \times (Number\ of\ blades) \qquad (4.11)$$
$$Post\ processing\ costs = (Machining\ cost\ rate) \times (Total\ machining\ time) \qquad (4.12)$$

Table 7. Total costs of the selected repair activities, using ABC technique, considering both operators and machines UoT as factors

	Laser cladding	CMT	DMLM
Deposition costs (per set) [UoC]	102	25	150
Labor costs (per set) [UoC]	105	63	106
Deposition + labor costs (per set) [UoC]	207	88	256
Build material costs (per set) [UoC]	151	76	151
Post processing costs (machining) (per set) [UoC]	196	196	168
Total cost (per set) [UoC]	**554**	**360**	**575**

However, as previously anticipated, the OEM uses an index, called OCPH (Operating Cost per Hour), to allocate the manufacturing costs within the shop. This index solely considers the allocated manhours on the specific manufacturing activity. The OCPH is calculated as the ratio between the total costs the shop floor incurs in and the total number of manhours throughout the year. It is an index that is updated periodically. For the specified technologies, due to the structure of the shop floor, no significant change in the OCPH is forecasted by the introduction of any of these technologies, thus it is possible to use the current value of the OEM, which totals 30UoC/UoT (expressed in terms of dummy unit of measures). That means that the impact of the installed equipment on the total expenditures is negligible. Even though this is not entirely true, yet it is good for assessing the calculations on a preliminary basis. The resulting numbers with this different allocation technique are presented in Table 8. In this case, total costs are calculated as:

$$Total\ costs = (Repair\ production\ costs\ w/\ OCPH) + (Post\ processing\ costs\ w/\ OCPH) + (Build\ material\ costs) \qquad (4.13)$$
$$Repair\ accountable\ time = Total\ time\ for\ repair \qquad (4.14)$$
$$Repair\ accountable\ time\ (DMLM\ only) = Total\ idle\ time \qquad (4.15)$$

Repair production costs (w/ OCPH) = (Repair accountable time) x *OCPH*   (4.16)

Post processing accountable time = Total machining time   (4.17)

Post processing costs (w/ OCPH) = (Post processing accountable time) x *OCPH*   (4.18)

Table 8. Total costs of the selected repair activities, using OCPH index as the only factor to allocate manufacturing costs within the shop floor activities.

	Laser cladding	CMT	DMLM
Repair accountable time [UoT]	7.56	4.54	7.64
Repair production costs per set (w/ OCPH) [UoC]	253.4	152	256.1
Post processing accountable time [UoT]	24.52	24.52	20.06
Post processing costs (w/ OCPH) [UoC]	821.5	821.5	842.8
Build material costs per set [UoC]	151.3	75.6	151.3
Total cost (per set) [UoC]	**1226.2**	**1049.2**	**1250.2**

These two different allocation techniques allow to highlight two important things. First and foremost, the value of the total cost highly increases when calculating the costs using the OCPH index. Specifically, the value of the post processing is significantly higher. This phenomenon suggests that the average equipment installed in the shop floor is highly valuable and that is rather automated. This comes by the definition of the OCPH itself, which is the ratio between total costs of the shop floor and operators' working time. Secondly, the OCPH allocation highlights how the DMLM accountable time is lower than its total time of repair, given the fact that it is the only technology among the three that can go unmanned. However, the low cycle time of each batch does not make this advantage too evident.

CMT looks like the technology that can bring the most benefits in terms of cost. However, a few more factors need to be considered to better elaborate the possible final decision. In fact, CMT is the equipment among the three technologies that costs less and needs less maintenance.

The lower machine cost is driven by the general machine simplicity.

The reduced maintenance costs are mainly due to the heat source nature; in fact, CMT uses a simple electric arc to generate heat, while all the other technologies are based on more sophisticated sources, which are more expensive and more critical from the maintenance stand point.

Even though this aspect has not been accounted because of the lack of data, a further business case refinement shall consider this, and make CMT even more attractive from a cost perspective. Secondly, it was assumed that tooling for DMLM equipment would be negligible in terms of costs, and also last for the entire lifecycle of the DMLM equipment itself. Although the last assumption might also be true, initial evaluations on tooling costs ranged around 10% the cost of the DMLM equipment, making this investment non-negligible. Also in this case, given the lack of data, this aspect has not been taken into consideration for now, but it is important to remind that a business case refinement would surely have a negative impact on DMLM technology attractiveness. Finally, consumables

have been neglected. Considering that consumable material is needed for each blade – when needed – a misevaluation of the costs of consumables has a high impact on the final business case. For the considered technologies, only CMT needs support plates for weld deposition on rail tips; even though their costs should be small, it is important to assess them correctly in a successive business case refinement, since it might lower CMT economic attractiveness.

As a final consideration, it is important to remember that, regardless of the technology chosen, a full qualification by the OEM is required. The costs related to the qualification vary a lot depending on the qualification scope. Thus, it is of paramount importance to assess the scope and inherent activities properly, which in turn depend on the level of technical and commercial risk the OEM is willing to accept. However, these draft financials clearly show how, despite all the assumptions, an investment on CMT would be highly advantageous for the OEM, while Laser Cladding and DMLM appear as very similar from the economic perspective.

In Table 9 are listed the maximum amount of blade sets repairable within a year (basing on the assumed yearly timeframe) and the set repair cost (for both the accounting strategies considered in this work). It is evident how the CMT technology offers the best benefits both in terms of single set repair cost and maximum number of set repairable within a year.

Table 9. Total costs of the selected repair activities, using OCPH index as the only factor to allocate manufacturing costs within the shop floor activities.

	Max. Productivity	Cost /Kit (ABC)	Cost /Kit (OCPH)
Laser Cladding	369	554	1226
CMT	615	360	1049
DMLM	215	575	1250

On the other hand, DMLM suffers a low productivity, with a quite high cost per single set repair. Costs related to the laser cladding are similar to the DMLM, but laser cladding offers slightly higher productivity. Nevertheless, considering all the assumptions made to get these evaluations, repair cost using DMLM and laser cladding technology are comparable.

Conclusions gathered are valid both considering values retrieved by the ABC approach and considering the OCPH index cost allocation approach.

Technologies performances can be assessed even from a different perspective, which is the cost to repair a certain amount of blade sets within a year.

Several set numbers have been taken into account; results are collected in Figure 10 and Figure 11.

From these plots, it is possible to see how each technology, with all its parameters (production time, post-process cost, equipment cost, etc.) can deal with different annual repair requests. In fact, on the horizontal axis is reported the number of sets to be repaired in the year, while on the vertical axis the total cost to repair the requested amount of blade sets.

Analyzing both the plots, it is clear how the CMT technology offers the greatest advantages both from the productivity and the economic standpoints. This consideration is valid considering both the accounting approaches.

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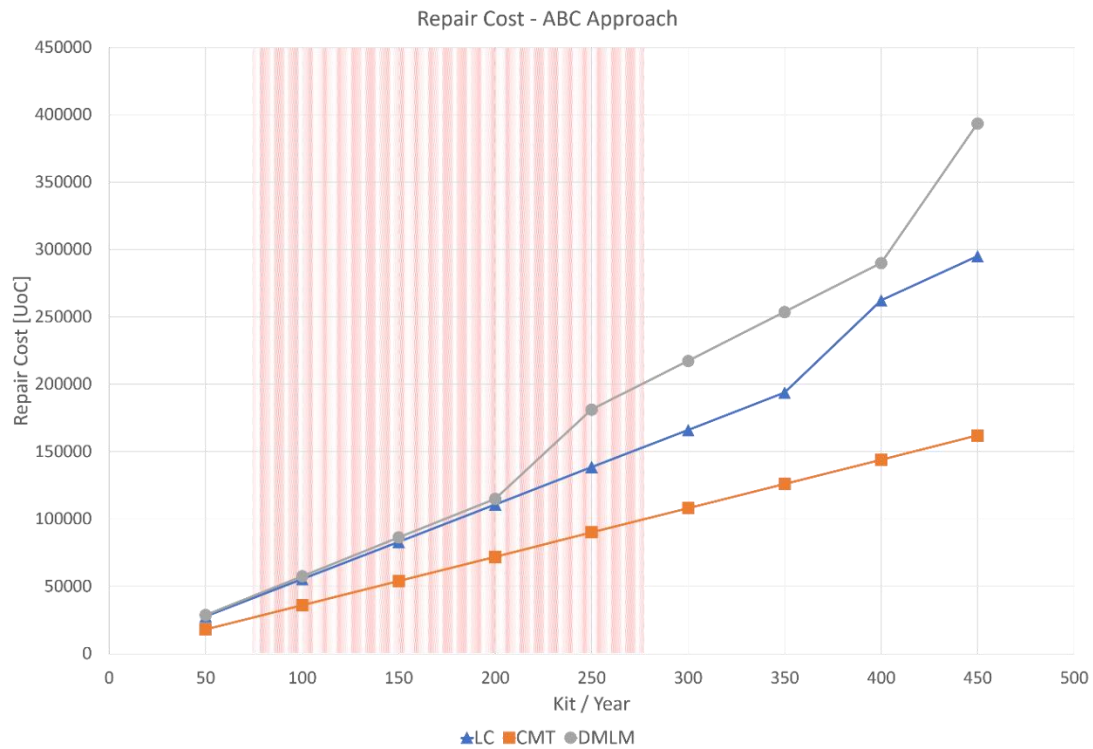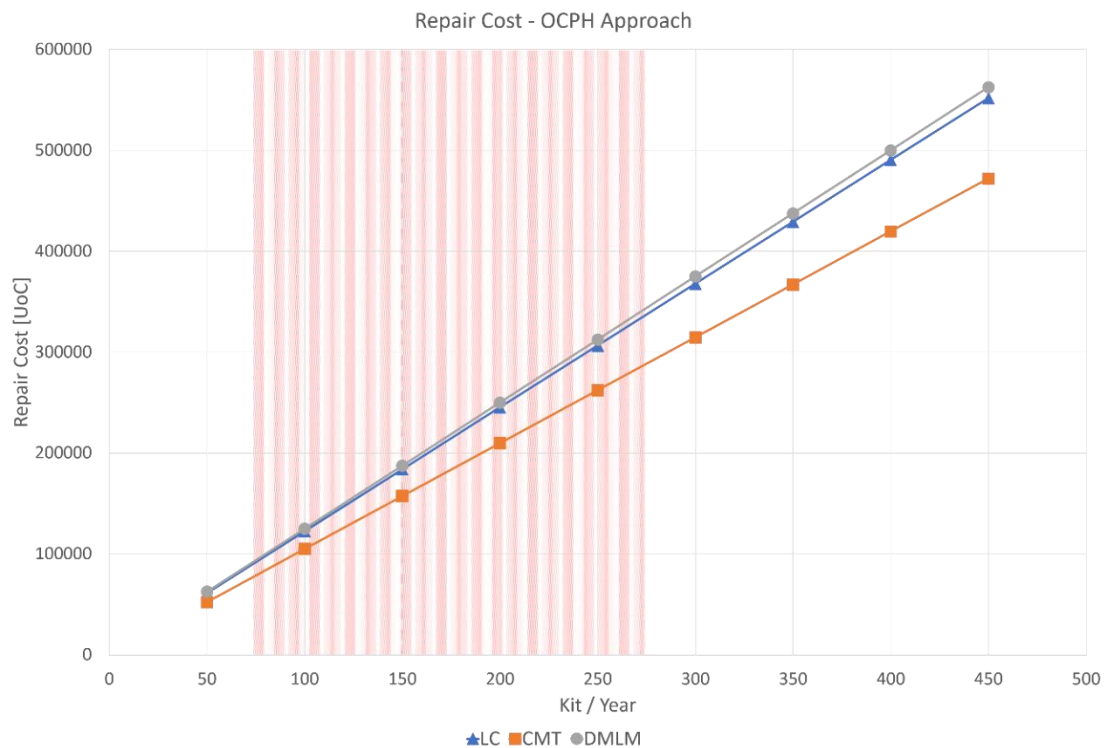
Figure 10. Total repair cost for different blade set per year computed with an ABC accounting approach (highlighted portion represents a reasonable working area)

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Figure 11. Total repair cost for different blade set per year computed with an OPCH index-based accounting approach (highlighted portion represents a reasonable working area)

For what concern laser cladding and DMLM, ABC and OCPH index cost allocation approaches give different results. This discrepancy is easily explainable considering the accounting method itself: one directly considers all the cost item for the repair cost assessment (ABC approach) while the other is based only on the man-hours" for the specific manufacturing activity. As said above, OCPH index is the ratio between the total costs the shop floor and the total number of man-hours throughout the year. Hence, it is not sensitive to the possible doubling of the repair equipment.

This scenario is faced when the repair demand exceeds 200 kits per year. In this case, DMLM does not have enough productivity to meet the demand. In this scenario, the author's assumption is to have two DMLM systems working in parallel. For this reason the deposition cost will increase (because of the use of two systems to repair a precise amount of blades processable by a single system that uses a different technology).

The deposition cost increase is represented by the line bending points in Figure 10. From the analysis of these pictures (especially putting the focus on a reasonable working area, that is from 75 to 250 blade set per year) it is well highlighted the advantages coming from. the adoption of CMT technology; it is shown how the DMLM technology suffers a low productivity, having a saturation point around 200 sets per year (this value will change according to the modification of the yearly timeframe).

This information is derived by many assumptions, but they are robust and conservative (as explained above).

To conclude, for the blade tip restoration application, CMT seems to be the best choice in terms of productivity and cost per repair. DMLM and laser cladding are equivalent from an economic standpoint, while the first has lower performance in terms of productivity.

Laser cladding, on the other hand, has the bigger purchase costs, which anyway is an information to be taken into account.

4. Conclusions and future developments

This paper deals with some of the possible repair technologies to be applied for blade tip repair. Among those, laser cladding, CMT and DMLM are considered and compared.

First, the advantages and disadvantages of the technologies are compared from a technical standpoint. A preliminary test campaign performed by the OEM has already highlighted how each of these technologies is potentially viable to guarantee the desired mechanical properties of the material and has already mitigated some of the technical risks. In particular, what has become evident is that all three technologies are able to deposit material that fulfills the mechanical characteristics required. Also, the processes are highly repeatable, especially compared to manual procedures. For now, some doubts remain regarding the metallurgical bond of base and deposited material using DMLM, while for both laser cladding and CMT its consistency has already been proven. The three technologies provide very different results in terms of geometrical accuracy of the deposited material and work through different equipment with different needs in terms of maintainability.

Afterwards, the economic viability of each solution is assessed. With the given assumptions, CMT technology seems to be the most viable technology to guarantee

automated operations, reliable and repeatable results while ensuring lower costs. DMLM still suffers of low productivity, which makes it economically unattractive and, even if not considered in the analysis, it would require additional tooling of the machine to perform the intended activity. Further benefits would arise considering the repair of smaller blades since it would allow for a higher number of blades printed in a single batch. Also, further developments in this specific technology are expected soon, as well as a lower cost of initial hardware, allowing for a cost trend inversion in the future years.

Future developments include an additional productivity boost of CMT through coupling with an adaptive scanning equipment. The industrialization of the process would be further boosted, allowing to load all the blades to be repaired in a single mask, which the robot would detect, scan and start depositing material blade by blade autonomously, with no load/unload phase in between. Also, more technologies could be included in the assessment. However, extending the analysis to additional technologies the OEM has never experienced would require extended validation efforts, both in terms of time and costs. In this framework, could be as an attractive alternative to investigate on.

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