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Ph.D. Thesis

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Development of a repair of the selected gas turbine component by the use of robotic multi-layer wire arc cladding process

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To my grandfather Jan

Mojemu dziadkowi Janowi

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Abstract

Additive manufacturing (AM) is a set of methods for precise and repeatable production of various elements through additive techniques consisting in multiple overlapping layers in order to achieve the assumed shape and dimensions. The first, modern methods of 3D printing began to be used in the eighties of the last century and are now subject to they have been extremely intensively developed. These methods made possible to significantly shorten the process development and implementation of a model, prototype, and the final product.

The additive methods that are based on arc welding such as MIG/MAG (Metal Inert Gas/Metal Active Gas) have been known for years. They have been using for cladding. A process of adding or depositing materials to a workpiece. The electrode is being deposited and added to the exterior of the part or component. These methods are proved to be low cost, high deposit and easy to automate/robotized. Despite the number of advantages of wire arc additive methods and larger availability of more and more perfect devices. There are only few publications that describe how to use thus method to creating a 3D part. Some of them refers to Wire Arc Additive Manufacturing and there mostly aimed at prototyping various 3D models made of steel, aluminum for industrial purpose. Using wire arc additive methods for services such as repairs/ modification and retrofits is very limited. However, this method being used on robot can be successfully implemented to repair gas turbine hardware.

Based on the above the robotic repairs using additive techniques (arc surfacing, CMT) are the right direction of research. There is a lack of research work that would focus on this type of activity in relation to turbine components (turbine wheels, fuel injectors, diaphragms, turbine blades, etc.)

Regeneration / repair of parts of gas turbines (as well as steam) with the use of robotic multilayer arc cladding is therefore a prospective area for introducing innovations related to the broadly understood Wire Arc Additive Repairs using a robot, welding source and peripheral devices, being at the same time a competitive solution to the currently used additive manufacturing methods /repairs such as SLS, SLM, DMLS.

In the present thesis work, an innovative wire-arc additive repair process is used to repair the selected gas turbine component in a way that it more robust and have longer life cycle. This new repair process possesses significant time and cost saving in comparison to traditional printing methods.

Key words: WAAM, Diaphragm, Gas Turbines, CMT, Robotic additive repair, Arc welding, Ni-Resist.

Abstrait

La fabrication additive (Additive Manufacturing) est un ensemble de méthodes destinées à une production précise et répétable d'éléments variés par le biais de techniques additives, consistant en une multitude de couches superposées pour atteindre la forme et les dimensions prédéfinies. Les premières méthodes modernes d'impression 3D ont commencé à être utilisées dès les années 1980, et sont maintenant le sujet d'un développement très intensif. Ces méthodes ont contribué à réduire de manière significative le procédé de développement et d'implémentation de modèle, de prototype et du produit final.

Les méthodes de fabrication additive basées sur la soudure à l'arc comme les soudures MIG/MAG sont connues depuis de nombreuses années. Elles ont été utilisées pour le « cladding ». Un procédé d'ajout ou de dépose de matière sur une pièce de travail. L'électrode est déposée et ajoutée sur l'extérieur de la pièce ou du composant. Ces méthodes sont prouvées pour être bas coût, permettent d'obtenir un dépôt de matière important et sont facilement automatisables ou robotisable. Malgré les nombreux avantages des méthodes de soudure à l'arc et la large disponibilité d'appareils de plus en plus efficaces, il n'y a que peu de publications décrivant comment utiliser ces méthodes pour la fabrication de pièce 3D. Quelques-unes d'entre-elles font référence à la fabrication additive arc-fil (« Wire Arc Additive Manufacturing ») et sont principalement destinées au prototypage de divers modèles 3D fait d'acier ou d'aluminium, à des fins industrielles. L'utilisation de la fabrication additive arc-fil pour des services comme la réparation, la modification ou la modernisation de pièce est très limitée. Néanmoins, cette méthode utilisée par le biais de robot peut être implémentée avec succès pour la réparation de composants de turbines à gaz.

Se basant sur ce qui est indiqué ci-dessus, les procédés de réparation robotisés utilisant les techniques additives (« arc surfacing », CMT) nous donnent la bonne direction de recherche. Qui plus est, les travaux de recherche portés sur ce type d'activité en relation avec les composants de turbines à gaz (roues de turbine, injecteurs de carburant, diaphragmes, lame de turbine, …) font défaut.

La régénération ou réparation de pièces de turbines à gas (ou turbines à vapeur) utilisant le « cladding » multicouche à l'arc robotisé est alors une voie prospective pour l'introduction d'innovations liées au procédé largement répandu de fabrication ou réparation additive à l'arc-fil utilisant robot, source et appareils périphériques de soudure ; tout en étant dans un même temps une solution compétitive comparée aux méthodes de fabrication additive actuelles comme le SLS, SLM, DMLS.

Cette thèse présente un procédé innovant de réparation additive à l'arc-fil utilisé sur les composants de turbine à gaz sélectionnés, de façon à les rendre plus robustes et à allonger leur cycle de vie. Ce nouveau procédé de réparation permet des gains de temps et de coûts significatifs en comparaison avec les méthodes d'impression traditionnelles.

Mots clés : WAAM, Diaphragme, Turbines à gas, CMT, Réparation additive robotisée, Soudure à l'arc, Nickel résistant.

Abstract (概要）

アディティブ・マニュファクチャリング（AM）は、材料を積層し立体を、所望の形状や寸法を造形する、精密で反復可能な生産の方法の一連です。最初の現代的な 3D プリントの方法は、前世紀の 80 年代に使用され始め、現在、非常に強力に開発されています。これらの方法により、モデル、プロトタイプ、および最終製品の開発と実装のプロセスを大幅に短縮することが可能になりました。

MIG/MAG などのアーク溶接に基づく積層方法は長年にわたって知られており、クラッディングに使用されています。材料をワークピースに追加または堆積するプロセスです。電極を溶かし、部品または部品の外側に堆積されます。これらの方法は、低コストで、高い堆積量があり、自動化/ロボット化が容易であることが証明されています。ワイヤーアーク積層方法の利点が数多くあるにもかかわらず、より完璧な設備が簡単に入手する可能になっているにもかかわらず、この方法を使用して 3D 部品を作成する方法について説明した出版物はほとんどありません。そのうちのいくつかはワイヤーアーク積層製造を参照し、主に鋼鉄やアルミニウムの産業用の様々な 3D モデルのプロトタイピングを目的としています。修理/改造などのサービス分野にワイヤーアーク積層方法を使用することは非常に限られています。だが、ワイヤーアークはロボットを理由して、ガスタービン部品を修理することができます。

記の内容に基づいて、アークサーフェス加工、CMT などの積層技術を利用したロボットによる修理技術は、研究の正しい方向であると考えられます。ただし、タスタービン部品（タービンホイール、燃料ノズル、ダイアフラム、動翼など）に関連した研究がが不足しています。

ワイヤアーク積層技術が使用するロボット、溶接機、および周辺機器を用いた革新技術である積層アーククラッディングは、ガスタービン部品（及び蒸気タービン）の再生/修理に対して、SLS、SLM、DMLS など現在使用されている製造/修理方法と比べ、競争力のある解決策と見られます。

本論文では、革新的なワイヤアーク積層修理プロセスで、選択されたガスタービン部品を、より頑丈でより寿命が長くなるように修理することができました。この新しい修理プロセスは、従来のプリント方法と比較し、著しい時間とコストの節約を実現しました。

キーワード: WAAM、ダイアフラム、ガスタービン、CMT、ロボットによる積層修理、アーク溶接、Ni-Resist。

Streszczenie

Wytwarzanie addytywne (AM) to zestaw metod precyzyjnego i powtarzalnego wytwarzania różnych elementów technikami przyrostowymi polegającymi na nakładaniu wielu warstw materiału w celu uzyskania założonego kształtu i wymiarów. Pierwsze, nowoczesne metody druku 3D zaczęto stosować w latach osiemdziesiątych ubiegłego wieku i obecnie podlegają one niezwykle intensywnemu rozwojowi. Metody te pozwoliły na znaczne skrócenie procesu rozwoju i wdrożenie modelu, prototypu oraz końcowego produktu.

Metody addytywne bazujące na spawaniu łukowym takie jak MIG/MAG (Metal Inert Gas/Metal Active Gas) znane są od dziesięcioleci. Stosowane są one między innymi w procesie napawania. Proces ten polega na nakładaniu materiału na powierzchnie części. Stopiwo uzyskane z elektrody topliwej i wymieszane z nadtopioną warstwą wierzchnią materiału bazowego nakładane jest na część lub komponent. Udowodniono, że metody te są konkurencyjne cenowo, zapewniają wysoki depozyt materiału oraz są łatwe do zautomatyzowania/robotyzacji. Pomimo wielu zalet metod addytywnych oraz coraz większej dostępności doskonalszych urządzeń. Niewiele jest publikacji opisujących sposób wykorzystania tej metody do tworzenia części 3D. Część z nich odnosi się do Wire Arc Additive Manufacturing i ma na celu prototypowanie różnych modeli 3D wykonanych ze stali, aluminium do celów przemysłowych. Stosowanie metod addytywnych z wykorzystaniem łuku spawalniczego w obszarze napraw/modyfikacji i modernizacji jest bardzo ograniczona. Jednak ta metoda w wersji zrobotyzowanej może być z powodzeniem zaimplementowana do naprawy części turbin gazowych.

Z powyższego wynika, że właściwym kierunkiem badań są zrobotyzowane naprawy z wykorzystaniem technik addytywnych (napawanie łukowe, CMT). Brakuje prac badawczych skupiających się na tego typu działaniach w odniesieniu do elementów turbin (dyski turbin, wtryskiwacze paliwa, membrany, łopatki turbiny itp.)

Regeneracja/naprawa części turbin gazowych (a także parowych) z wykorzystaniem zrobotyzowanego wielowarstwowego napawania łukowego jest zatem perspektywicznym obszarem wprowadzania innowacji związanych z szeroko rozumianymi naprawami addytywnymi z wykorzystaniem robota, źródła spawalniczego oraz urządzeń peryferyjnych. Jest to jednocześnie konkurencyjne rozwiązanie do stosowanych obecnie metod wytwarzania przyrostowego/napraw takich jak SLS, SLM, DMLS.

W niniejszej pracy zastosowano innowacyjny proces naprawy addytywnej wybranego elementu turbiny gazowej w taki sposób, aby był bardziej niezawodny i posiadał dłuższą żywotność. Zaproponowany proces naprawy zapewnia znaczną oszczędność czasu i kosztów w porównaniu do tradycyjnych metod druku.

Słowa kluczowe: WAAM, Diaphragma (membrana uszczelniająca), Turbiny gazowe, CMT, Zrobotyzowane naprawy przyrostowe, Spawanie łukowe, Ni-Resist.

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List of abbreviations

ASME	- **A**merican **S**ociety of **M**echanical **E**ngineers
CMT	- **C**old **M**etal **T**ransfer
CTQ	**-C**ritical **T**o **Q**uality
FPI	- **F**luorescent **P**enetrant **I**nspection
GD&T	- **G**eometric **D**imensioning **and T**olerancing
GMAW	- **G**as **M**etal **A**rc **W**elding
GTAW	- **G**as **T**ungsten **A**rc **W**elding
ISO	- **I**nternational **O**rganization for **S**tandardization
MAG	- **M**etal **A**ctive **G**as
MIG	- **M**etal **I**nert **G**as
NDT	- **N**on-**D**estructive **T**esting
RDI	- **R**ed **D**ye **I**nspection
VTI	- **V**isual **T**esting **I**nspection
WAAM	- **W**ire **A**rc **A**dditive **M**anufacturing
WAAR	- **W**ire **A**rc **A**dditive **R**epair

1. Introduction

1.1. Gas Turbine overview

A turbine is any type of rotating device that uses the action of a fluid to produce work. Windmills and hydroelectric dams have used turbines for decades to generate electricity using an electric generator [3]. However, in the history of energy conversion, the gas turbine is a relatively invention. The first practical gas turbine used to generate electricity has been launched in Switzerland in 1939 [47]. The first gas turbine to power an airplane was also developed in 1939 [47]. The name "gas turbine" can be misleading, because for many it means an engine that uses gas as fuel. In fact, a gas turbine has a compressor to compress the gas (usually air), a combustion chamber and a turbine to generate power from the hot air flow. A gas turbine is a unit that uses a continuous combustion process. Unlike diesel engines, where intermittent combustion occurs. Gas turbine technology has been constantly evolving since its inception and continues to evolve [36]. Both smaller gas turbines and large industrial gas turbines for power generation are produced. Their development is aided by computer design and the development of advanced materials: base materials with higher heat resistance (e.g., single crystals) or ceramic coatings that protect the part material from increasingly higher temperatures. The efficiency of the simple cycles of early gas turbines was practically doubled using internal cooling, regeneration (or recuperation). The efficiency of gas turbines in the simple cycle is about 40 percent, in the combined cycle it reaches 60 percent. On the emission side, the challenge is to achieve lower NOx emissions [2].

1.2. Gas Turbine – construction overview.

A modern gas turbine consists of three key elements: a compressor, a combustion chamber, and a turbine (Fig.1.1). The air is sucked into the compressor and compressed, then fed into the combustion chamber, where the continuously injected fuel, the resulting fuel-air mixture releases heat, which raises both the temperature and pressure of the mixture. This high-temperature gas stream is then fed to a turbine to generate power. In a traditional gas unit, the turbine stages drive both the compressor and the generator [31].

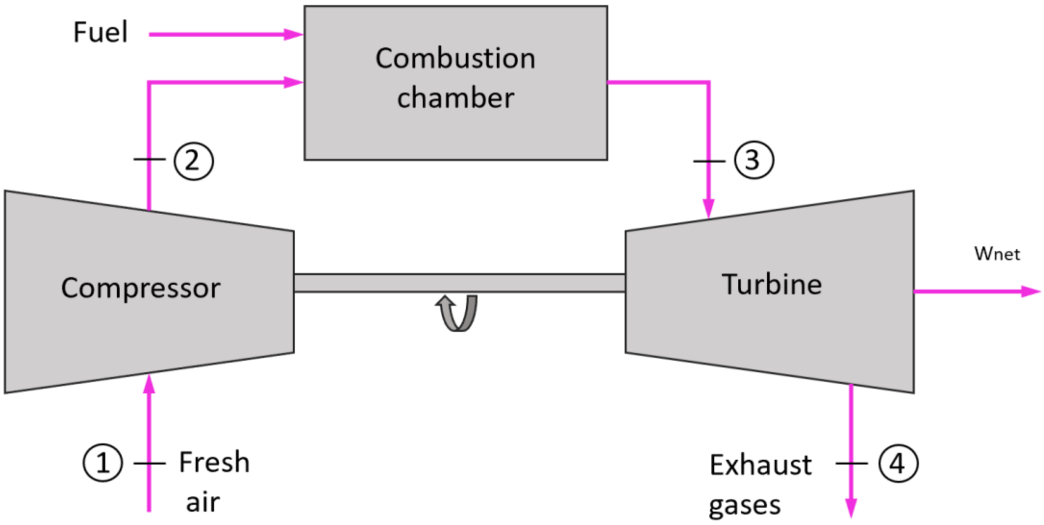

Fig. 1.1 Gas turbine principle

The turbine part of a gas turbine is a kind of heat engine whose energy conversion efficiency is determined by the efficiency of the Carnot cycle, which depends on the difference between the inlet and outlet temperatures. This means that inlet gas temperature is a key parameter in determining overall efficiency, and much of the development of modern gas turbines is focused on finding materials and techniques that enable higher turbine inlet temperatures to be achieved [31].

The actual cycle in which a gas turbine operates is called the Brayton cycle. Its distinctive feature is that heat is added to the working medium (liquid), air, at constant pressure. Originally, the Brayton engine was a type of reciprocating engine with one piston to compress air, which then passed into a mixing chamber where fuel was added. Upon entering the expansion chamber, this mixture was ignited, where it led another piston. The piston of the compression cylinder was driven by the piston of the mixing chamber. The gas turbine cycle has similar sequences of compression, combustion, and expansion, although they operate completely differently [5, 73].

1.3. Combustion system

In modern gas turbines, the turbine inlet temperature is continuously increased to improve the efficiency of the gas turbines. As a result, new materials, ceramic coatings (TBC) and advanced cooling methods for turbine components are being developed to improve the reliability and durability of turbine components [43]. The high flame temperature in traditional gas turbine combustion chambers results in relatively high levels of NOx emissions. In advanced combustion systems to reduce NOx, the maximum possible amount of air is pre-mixed with the fuel so that the flame temperature and NOx emissions of the pre-mixed mixture become lower than in convective combustion [50]. Many combustion chambers of modern gas turbines do not use a cooling film to directly lower the flame temperature. The combustion liner is protected from the hot gas stream by forced convection cooling, such as air cooling and the use of fins for more efficient heat transfer [45].

Diffusion flame and pre-mix flame are the two main types of combustion that are used in gas turbines. In addition to the type of flame, there are two types of construction of the combustion chamber: annular and tubular [59]. The ring type is used in aircraft drives, where small cross-section and low weight are key parameters (Fig.1.2). Silos or tubular combustors are less expensive and are used in industrial turbines. While there are different types of combustors, all combustors have the following components: diffuser, housing, combustion jacket, fuel injectors, and cooling system [31].

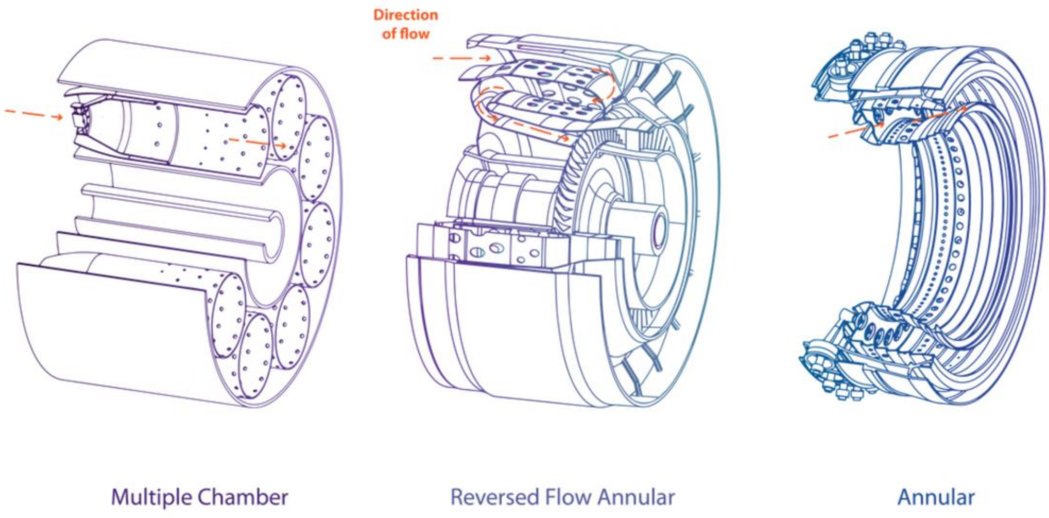

Fig. 1.2 Typical *Combustion system arrangements* [72]

- Materials used in gas turbine combustion systems

Combustion system components for aerospace and industrial gas turbine applications are designed to address the increased gas stream temperatures prior to entering the turbine and the need for improved emission control [47]. Considerable efforts have therefore been made to develop these components using advanced materials and manufacturing processes. The primary material criterion is to improve creep strength at high temperatures without decreasing oxidation/corrosion resistance. Traditionally, combustion chamber components are manufactured from nickel-based superalloys. An example of such an alloy is Hastelloy X, a material with higher creep strength that was introduced in the second half of the 20th century. Then, Nimonic 263 was introduced. It has even higher creep strength. With the increase in combustion temperature, newer versions of gas turbines began to use cobalt-based superalloys such as HS-188. Nickel-based superalloys 617 and 230 are now widely used in the manufacture of gas turbine gas chambers [15].

In addition to designing parts of the combustion chambers using modern materials, the combustion liner, transition pieces and components operating at higher combustion temperatures receive special ceramic coatings (TBC). These coatings serve to provide an insulating layer and reduce the temperature of the base material [37].

1.4. Turbine

Axial flow turbines are the most commonly used compressible fluid turbines. These turbines power most gas turbine units except for smaller units and are more efficient than centrifugal (radial) turbines over wider operating ranges. Axial turbines are also used in steam turbines, however, there are some significant differences between the design of an axial flow gas turbine and an axial steam turbine. In recent years, the development of modern gas turbines has required innovative cooling systems. Axial flow turbines are designed for a high work regime (work per turbine's stage squared of blade rotational speed of turbine blades) for lower fuel consumption and lower turbine noise [44, 48].

The axial flow turbine, like its counterpart i.e., the axial flow compressor, has a flow that enters and exits in the axial direction. There are two types of axial turbines: action turbine and reaction turbine [5]. In an action turbine, all of the enthalpy drop occurs in the turbine stator. Therefore, the gas stream has a very high velocity entering the turbine rotor (Fig.1.3). The reaction turbine splits the enthalpy drop between the turbine stator and the turbine wheel. Most axial flow turbines consist of more than one stage, with the first stages typically being action (0% reaction) and the subsequent stages having approximately 50% reaction. Action steps produce about twice as much energy as a comparable reaction step, while the efficiency of an action step is less than that of a reaction step [5,48].

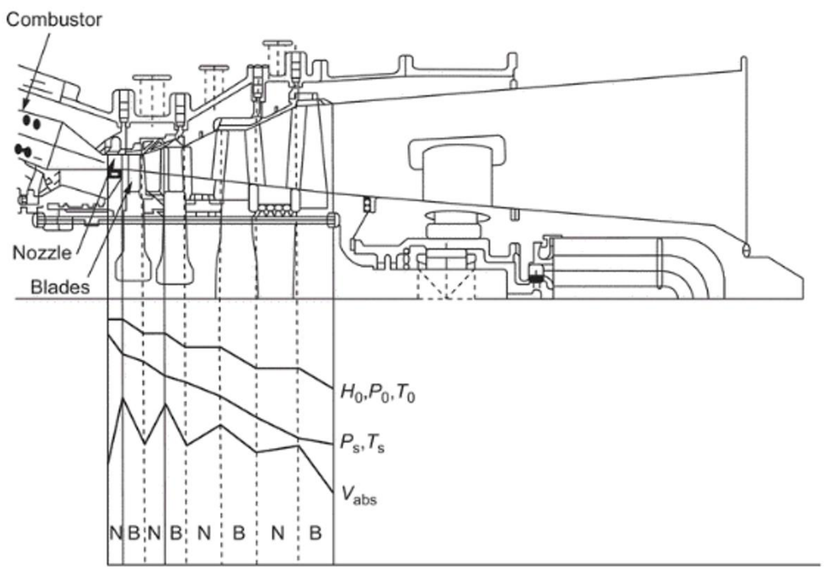

Fig. 1.3 Scheme of an axial turbine flow characteristic [44]

Due to the development of metallurgy, turbine parts can work at higher and higher temperatures. The development of directionally casted rotor blades and the introduction of monocrystalline turbine blades together with new types of coatings and advanced cooling systems lead to an increase in the temperature of the gas stream in front of the turbine. The air taken from the interstage compressor ducts, used to cool the first stage of the turbine, has a high temperature. Thus, current cooling systems using air from compressor interstages are also ceramic coated to prevent corrosion of the cooling channels [49].

The second stage blades in modern gas turbines also have air cooling and ceramic coatings (Fig.1.4). The temperature in the second stage of the turbine is much lower than the gas stream in front of the first stage stator. Despite this, it is high enough that cooling of the blades and power nozzles is required. Second stage power nozzles temperatures vary between four-stage and three-stage turbines. The third and fourth stages are usually uncooled [5]. The blades of the last stages are long; therefore, they have a seal to ensure adequate clearance between the turbine casing and the tip of the rotor blade.

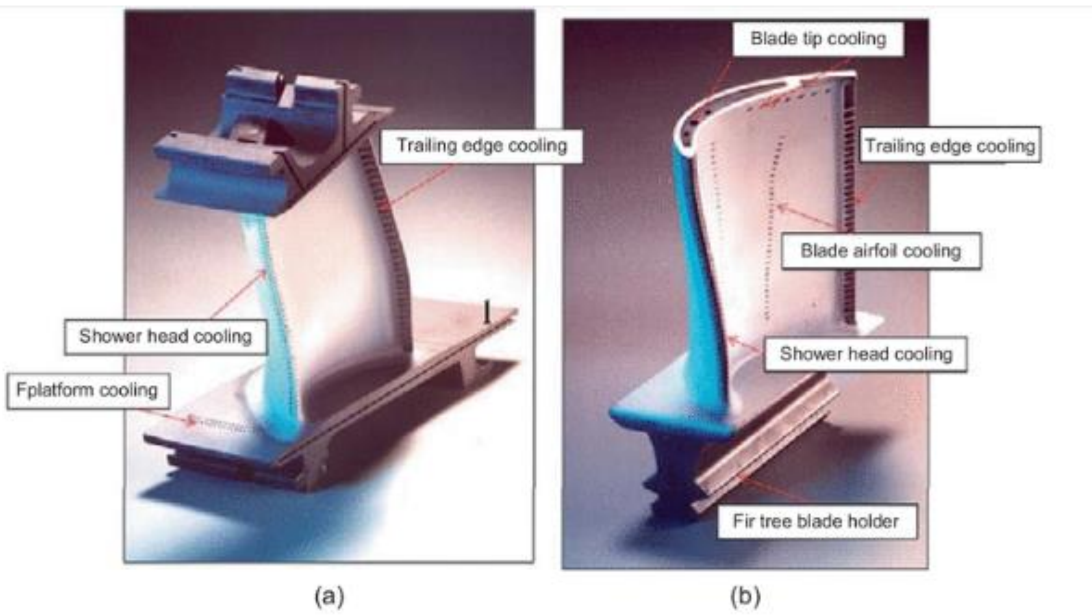

Fig. 1.4 Power nozzle (a) and rotating blade (b) of the second stage [44]

- Materials used in turbines

As described above, in recent years there has been great progress in the cooling of power nozzles and rotating blades, from air and steam cooling to the development of new designs of turbine blades. The production of blades operating at very high temperatures is aimed at eliminating both transverse and linear grain boundaries, resulting in parts with a single crystal structure. Most power nozzles and blades are cast by the equiaxed casting process. In this process, molten metal is poured into a ceramic mold under vacuum to prevent the highly reactive elements in superalloys from interacting with oxygen and nitrogen. By properly controlling the thermal conditions of the metal and the mold, the molten metal crystallizes from the surface to the center of the mold to form an equiaxed structure [15].

The directional solidification (DS) process is also used for the production of power nozzles and turbine blades. The process has been first used in aircraft engines more than 30 years ago and was adopted for the production of aircraft blade profiles in the early 1990s. The result of the process is a blade with an oriented grain structure that runs parallel to the main axis of the part and does not contain any lateral grain boundaries (Fig.1.5). The elimination of transverse grain boundaries provides additional creep strength, and the orientation of the grain structure provides a favorable modulus of elasticity in the longitudinal direction for increased fatigue life. The impact strength of DS blades is also better than that of equiaxed blades by about 1/3 [37].

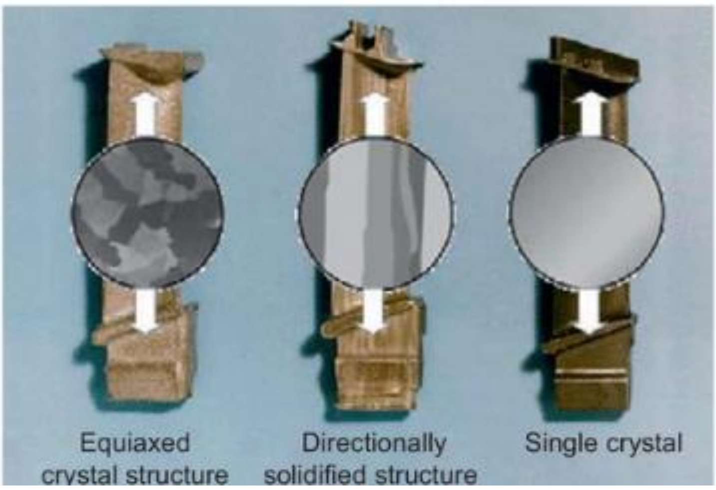

Fig. 1.5 Three basic types of castings used in the manufacturing process of rotating blades. [44]

Monocrystalline components have been used in gas turbines since the late 1990s. These blades offer greater creep and fatigue strength by further eliminating grain boundaries. In a single crystal, all grain boundaries are eliminated. By eliminating grain boundaries and at the same time phases that strengthen this boundary, an adequate increase in strength at high temperature is ensured. Lateral creep and fatigue strength are increased compared to equiaxed and directionally cast (DS) materials. addition of rare earth elements, such as e.g., rhenium, improve creep strength and fatigue strength. They also slow the diffusion of these alloys at high operating temperatures [15,37].

Summarize the topic of the development of turbine parts, it is worth mentioning that intensive research and development work is underway on advanced materials for gas turbine applications. Significant advances in technology have also been noted in the application and chemical composition of ceramic coatings. Current coatings can perform their function 10-20 times longer than coatings used in the early 1990s. As much as 100% improvement has been noted in the length of "life" of rotor blades [4, 15]. This is due to the use of modern ceramic coatings.

1.5. Additive Manufacturing

Additive manufacturing (AM), or layer-by-layer technologies, are one of the most dynamically developing areas of digital production. They can significantly speed up the solution of preproduction phase, and in some cases, they are already actively used for the production of finished products and are breakthrough technologies of this century [6]. Most of the currently existing additive technologies for the manufacture of metal products are based on the use of powder systems as a base material for the formation of final products. At the same time, the range of structural materials increase as the additive technology develops [12].

Depending on the final result, there are several areas of application of additive technologies [10,12]:

- Parts manufacturing (Rapid Patterns) used as templates for the final product. Often used in precise industry.
- Direct digital manufacturing (Direct Digital Manufacturing, DDM) is the production of the final product by additive methods.
- Molds prototyping (Rapid Tooling) using additive methods. Then they can be used for molding and casting products.

The terms additive manufacturing and 3D printing are often used interchangeably. The term "3D printing" has been around for a long time and is more commonly used when referring to low-cost home printers. For industrial production scale, a of term additive technologies has been using. According to the ISO/ASTM 52900 standard, it is the production of objects by applying material with a printhead, nozzle, or other printing technology.

The main technologies used in the creation of products on additive installations[18, 19]:

- CJP (Color Jet Printing) is a full-color 3D printing technology by gluing a special gypsum-based powder,
- DLP (Digital Light Processing) is a stereolithographic 3D printing method using digital LED projectors,
- FDM (Fused Deposition Modeling) - a method of layer-by-layer deposition using a plastic filament or granules,
- SLS (Selective Laser Sintering) - selective laser sintering under laser beams of particles of powdered material until a physical object is formed based on the given CAD model;
- SLA (Laser Stereolithography) - laser stereolithography, based on the layer-by-layer hardening of a liquid material under the action of a laser,
- LCD (Liquid Crystal Display) - another type of photopolymer printing, when the photopolymer resin is illuminated by an LED UV matrix through an LCD screen mask;
- Binder Jetting - layer-by-layer bonding of a composite powder (polymer, metal etc.) with a binder,
- MJP (MultiJet Printing) - multi-jet modeling using photopolymer or wax.

Additive manufacturing has a big impact on the production of many products. Enterprises successfully apply this technology to the production of finished products. According to experts, direct manufacturing will become the largest application area for additive technologies. This technology can affect production and services more than other traditional methods [19].

The industry continues to evolve with new methods, technologies, materials, applications, and business models emerging. The geography and scope of industrial application of AM is expanding. Additive technologies have already had a huge impact on the development of design and manufacturing; in the future, their role will increase more and more [17].

1.6. Wire arc additive manufacturing (WAAM)

WAAM is a printing with a metal wire, which uses the arc welding method (Fig.1.6). Practically from any metal or alloy, simple and complex objects with different technical characteristics are created. As a result, production time is reduced and materials for the preparation and disposal of metal chips are saved [23].

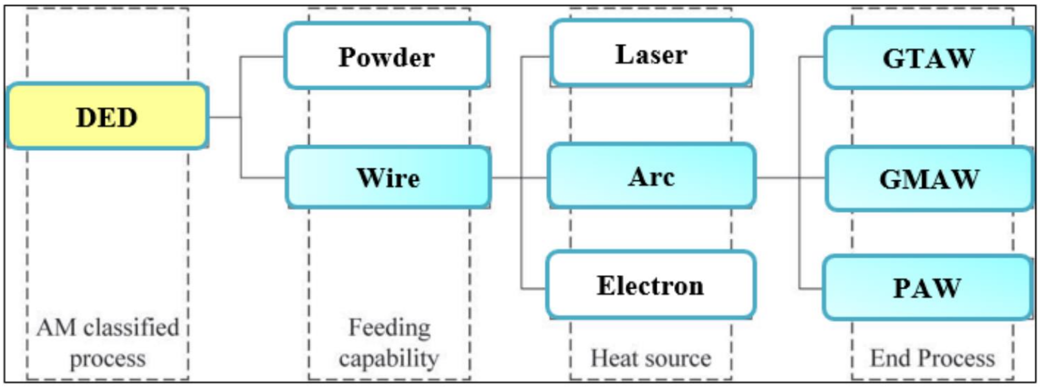

Fig. 1.6 Typical classification of WAAM [13]

The formation of metal products using the melting of wire material is a key vector in the development of additive technologies. This solution makes it possible to get rid of the problems associated with the low productivity of existing methods, the high cost of the equipment used, and the limited types of materials used, due to the traditional use of powder systems melted by a powerful heat source as the base material for the additive formation of products [10]. The potential for the development of technology for forming parts with melted wire is very high and is currently not fully disclosed in the world.

There are examples of installations in which the manufacture of a part occurs in a vacuum using an electron beam, which turns out to be a very productive solution for a number of high potential materials, in particular, titanium and other reactive metals and their alloys [13]. However, electron beam installations have a number of disadvantages, which include, first of all, the need to use high-voltage voltage sources for the operation of an electron beam gun, stepped pumping systems to achieve deep vacuum, in some cases with electron beam processes require special protection of operating personnel from radiation that occurs when the electron beam interacts with the material being processed, which greatly complicates the operation of the installations [23, 24]. On the contrary wire feed into the impact zone makes it difficult to form parts of complex shape additively. In addition, the disadvantages can also include the high cost of both the installation itself and its operation. In many cases, it is a challenge to create simpler and practically accessible for all industries, and most importantly, cheaper and more versatile installations for the additive formation of products in a vacuum, which make it possible to make the most of the available elements of equipment and technology. One of the most common sources of heat in welding and surfacing is the electric arc. Today, there is a wide variety of welding methods used in Wire Arc Additive Manufacturing (WAAM). The use of arc and welding sources for melting wire material in the implementation of layer-by-layer technologies has been actively developing in the world in recent years [14]. It is worth noting the WAAM is used also to develop large-sized products using arc wire technologies or consumable electrode surfacing treatment technology with pulsed wire feed with cold metal transfer (Cold Metal Transfer - CMT).

1.6.1. Cold metal transfer characteristic

The CMT process is a GMAW process that has a completely new type of droplet separation. This allows the CMT process to be used where GMAW welding technologies were either not used before or were extremely difficult to use.

CMT stands for Cold Metal Transfer. From the name the process allows for the "cold" transfer of metal during welding or soldering. Compared to the conventional GMAW process, there is significantly less heat input [46].

The process is based on short circuit welding. During such a process, the formation of a short circuit is accompanied by a significant increase in current (a sharp decrease in voltage and an increase in resistance), which certainly leads to an increase in heat input into the base metal. With a CMT arc, the situation is different, at the first detection of a short circuit, the current decreases to the minimum allowable value, at the same time, the droplet breaks off due to the reverse movement of the welding wire (Figure 1.7) That is why the metal transfer is carried out at a current value almost equal to zero and therefore the contribution of heat is very small (that is why it is called CMT - cold metal transfer) [41].

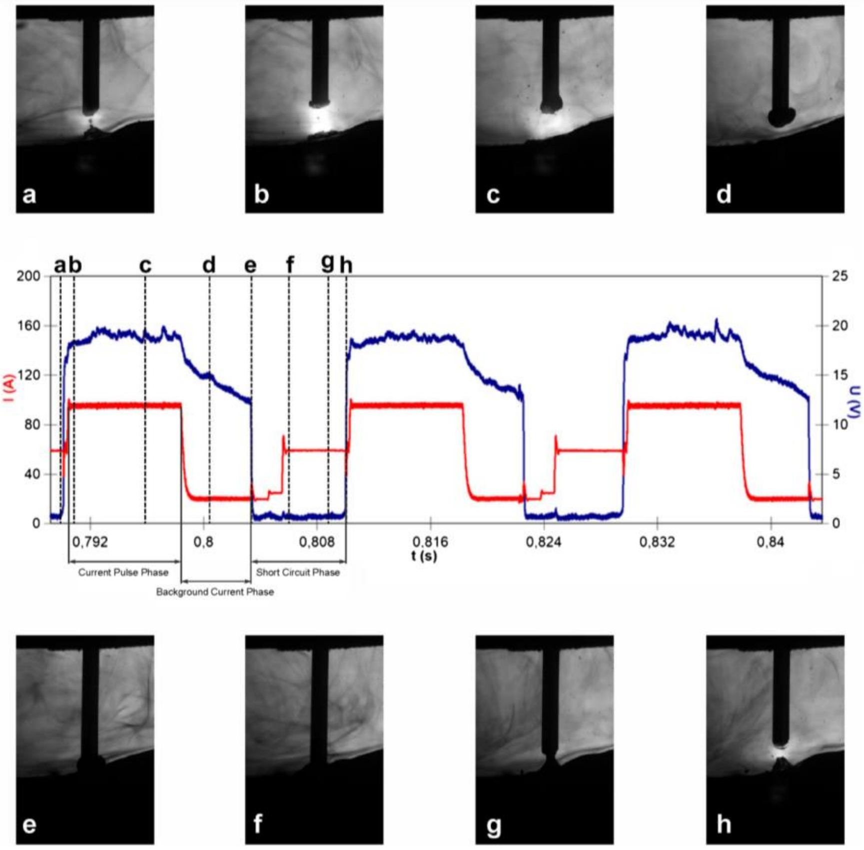

Fig. 1.7 Typical CMT ocillogram with current and voltage signals and correspondent metal transfer behaviour [53]

The whole sequence is as follows [7, 46]:

- While the arc is burning, the welding wire is brought to the pool.
- At the moment the welding wire enters the weld pool, the arc is extinguished, the current is reduced to prevent the created bridge from breaking.
- At the moment of a short circuit, the current is reduced to a minimum, the welding wire is pulled back to facilitate the separation of the drop.
- The wire is fed back into the weld pool, the arc is ignited, and a new welding cycle begins.

Depending on which characteristic has been selected, this reciprocating motion can be repeated (frequency) up to 70 times per second.

The CMT technology has the following advantages over conventional MIG/MAG welding processes [16]:

- Due to the low heat input, light and ultra-light sheets of metal (thickness less than 0.3 mm) can be joined with the best result (in the case of mechanized and automated welding). This is exactly the area for which the CMT process was developed.
- More stable welding process due to mechanical arc tracking.
- Welding in a combined mode with a pulse, influences the penetration and geometry of the weld bead.
- The arc length is measured and adjusted "mechanically" rather than "electrically" by means of voltage measurements, as is the case in conventional GMAW (MIG/MAG) processes. This makes the CMT process insensitive to the surface of the parts, to changes in the welding speed, which change the amount of stress and, consequently, the length of the arc. The result is a very stable arc. Even during robotic/automated welding, the arc will not be interrupted.
- Absence of spatter during welding and soldering.
- The CMT process also provides faster welding and higher deposition rates than conventional processes.
- Possibility of welding over a large gap, lower tooling requirements.
- High welding speed in manual mode

1.6.2. CMT application

The CMT process is excellent for joining light and ultra-light sheets. The advantages are also obvious when joining aluminum materials up to 3 mm thick, CrNi materials (such as stainless steels, heat resistant nickel alloys, etc.) and steels up to 2 mm thick [26]. When surfacing on galvanized sheets (plating), the main advantage is the almost complete absence of spatter. All the above applications have the common advantage that welding, and surfacing are carried out at speeds higher than those typical for conventional welding and surfacing processes (depending on the geometry, the desired penetration value, and the size of the “a” dimension).

The CMT process is an easy-to-use method for joining different materials together such as steel to aluminum [46]. In addition, CMT has more than satisfactory mechanical and technological qualities. It is not only steel-aluminum joining that attracts attention, but also a whole range of promising applications. This includes spatter-free soldering of coated sheets, as well as welding of thin-walled aluminum sheets or welding of magnesium [53]. Numerous tests are being carried out that will determine what further application possibilities will be developed for the CMT process.

Based on the above the CMT method can be used wherever excellent quality and appearance of the joint (no spattering), elimination of additional post-welding treatment, high speed and efficiency of the welding process are required. Therefore, CMT was immediately used in the automotive industry and aviation industries - due to previously unattainable welding effects and process properties [46].

1.6.3. Gas metal arc welding (GMAW)

Gas metal arc welding is the well-known method of arc welding, widely and actively used in Industry all over the world. GMAW is represented by the traditional welding processes carried out both in an inert gas (Metal Inert Gas - MIG), and in active gas atmosphere (Metal Active Gas-MAG). Although this welding method can be manual, semi- or automatic. This method is much simpler to use and cheaper than other welding methods of surfacing and cladding. Cladding itself is a process of weld overlay covering an entirely new surface that can be used with a large variety of overlay materials in different forms such as wire, powder, or cored wire. Metallurgical bonding of the weld overlay with the parent material ensures high utility values of the cladded layer [39]. Cladding can be used to repair parts, complex geometry, and cylindrical shaped surfaces.

Wide application of GMAW methods has been mainly recognized by availability of welding equipment and filler variety (including solid and cored wires), high efficiency of the cladding process, low cost. As mentioned above the process efficiency and performance can be highly increased by automation and robotization.

Multi-layer arc surfacing for services purposes is similar to incremental 3D printing. Such application of GMAW can be determined by the following properties [40]:

- Current and wire feed speed are independent of each other and can be controlled separately (arc without wire feed),
- Higher arc energy density,
- Better layer fusion,
- Multi-wire feed possible, therefore higher deposition rates, that can be transfered into short time of creating 3D models,
- Very good weld penetration,
- Easy to robotize and automatio,
- High avaiabilty of welding machines along with consumeables,
- Easier to reconfigure the system when using a different wire diameter,

- Not prone to undulation of the bead profile.

On the contrary there are numerous concerns and constrains of this method:

- low accuracy and irregular printing surface,
- welding deformation and humping,
- large heat input, increasing as the process proceeds,
- Unfavorable material structure and mechanical properties (repeating long-term thermal cycle).

Despite numerous limitations, there is significant engineering and science activity in creating

Parts and objects relaying on 3D GMAW additive deposition. This technology is designed to form complex and large volume of structures along with low surface parts requirements [60]. Simultaneously the additive process through the electrode current density and plasma temperature is significantly higher. Thus, welding wire melts faster and cladding efficiency is high. However, welding rapid prototyping is not perfect and accuracy control is demanding. To overcome the above challenges GMAW is often used with a welding robot to allow rapid prototyping based on path programming (Figure 1.8). This is justified by the high precision of welding robots motion mechanism and motion repeatability [39].

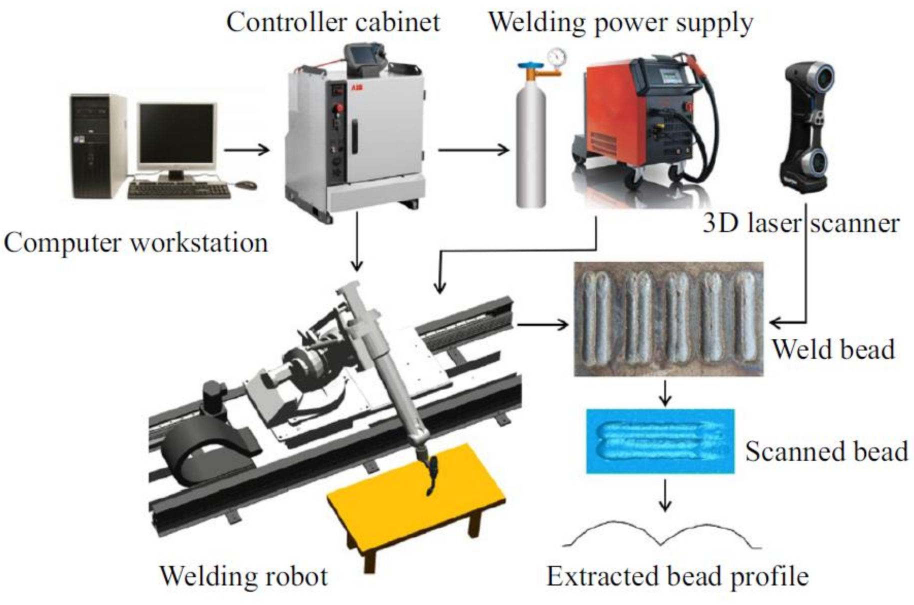

Fig. 1.8 GMAW based 3D printing system [22]

1.6.4. Plasma arc welding (PAW)

Plasma arc welding is a process in which an arc is created between a non-consumable tungsten electrode (cathode) and a copper anode in the torch. Inert gas (usually argon) is passed through a nozzle, which, moreover, focuses the electric arc. It leads to a higher energy density and the formation of a more stable arc that can be transferred in better penetration and reduction of the cross- section area and width of the weld beads [40].

In PAW the arc is first induced between the copper nozzle and the electrode by means of pilot arc through high frequency discharges. This type of arc is a non-transferred arc with low current. It allows the ionization of the plasma gas and allows the start of the transferred plasma arc in a way that it creates a designated path for conductance between the part and the electrode. Because of that an expansion in volume due to the high temperatures is noticed and is forced through the constrictive nozzle, reaching high velocities. Although, the plasma gas flow is inadequate and by that a secondary shielding gas is required to provide adequate shielding effect [1].

In the non-transferred mode, the current is moving from the electrode to the restrictive nozzle and to the power supply. In transferred arc mode, the current is being transferred between the electrode and the part and back to the power supply.

The welding voltage primarily affects the width of the weld beads (an increase of voltage increases the weld width) and the welding current mostly influences the penetration depth (higher penetration with higher current). The appropriate current depends on the exact conditions of welding such as the consumables used, the thickness of the substrate, travel speed and torch angle.

Plasma arc have an extremely wide range of operation. The non-transferred arc is used in special welding applications where it is not desirable to make the work piece part of the electric circuit. It is also used for fusing nonmetallic materials, such as ceramics and certain types of glass. Plasma rapid prototyping (Fig.1.9) can be divided into the following technologies: pulse plasma welding rapid prototyping, micro beam AM and plasma arc powder deposition rapid prototyping [57].

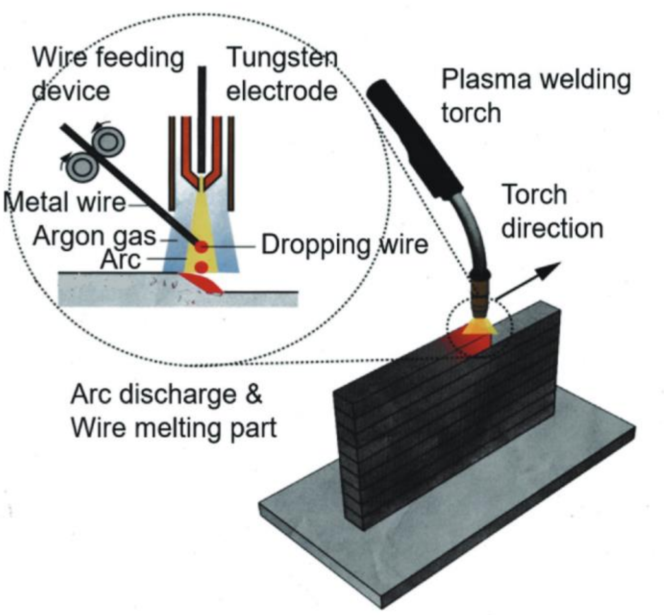

Fig. 1.9 WAAM equipment synchronized with plasma arc welding. [57]

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Advantages of Plasma Arc Welding [40]:

- Limited spattering and no fumes during the printing process,
- Low chance of tungsten inclusions due to mounting electrode inside constricted nozzle,
- Low residual stress and distortion due to low heat input,
- The plasma is directional, and the torch can be positioned in different directions,
- High mechanical properties of weld joint/overlay.

Challenges of Plasma Arc Welding:

- Complex adjustment of the welding parameters due to high installation requirements,
- Welding process is very sensitive to the physical properties of the fillers and to the chosen welding parameters,
- Equipment is more complex and costly than other arc processes, such as GTAW,
- Deposition rate is relatively small comparing to GTAW process.

1.6.5. Gas tungsten arc welding (GTAW)

Gas metal arc welding (GMAW) is also well known as tungsten inert gas (TIG) welding method. This is an arc welding process using a non-consumable tungsten electrode to generate arc welding process. The electric arc is to transfer the heat to the welding pool and if needed melts the consumable wire in the welding pool. Filler wire can be fed manually or automatically while the welding arc exists between the non-consumable electrode and the parent material [40].

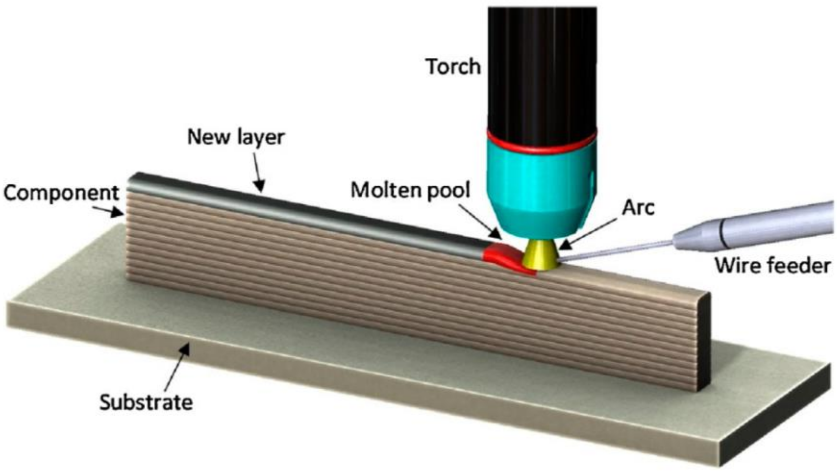


Fig. 1.10 WAAM equipment synchronized with GTAW [23]

During the welding process the welding arc and pool are stable, the torch is moved along the joint to melt and make the weld bead. In recent years, GTAW process has been evolving and it is already applied to wire arc additive processes (Fig.1.10). This is enhanced by the integrated control of GTAW [23]. There are three main areas of focus [25, 40]:

- Welding parameters control

  GTAW method is a process that combines the voltage welding current, travel speed, and shielding gas flow rate. In additive applications also preheating and interpass temperature control are the key factors. Control of these parameters ensures an appropriate thermal cycle range during incremental additive process.

- Since welding current mainly influences the penetration depth compared to its impact on width of the weld. The appropriate welding amperage should reflect to the specific welding conditions (parent material thickness, type of material, joint preparation, and travel speed) and create the applicable amount of energy into the weld pool.

- Supplementary with current, a higher voltage during the welding is used, the increased width of weld is made. Welding voltage is affected by arc length between non consumable electrode and the part. Larger arc length generates larger width of the weld and decreases the arc penetration. Control of the correct arc length is important for GTAW process. When it is too long. The arc would induce welding imperfections such as porosity and oxidation. On the contrary, when the arc is too short it may cause short circuit, non-consumable electrode damage or tungsten inclusions.

- Travel speed should be designed to reflect the welding material and the applicable welding position. To avoid distortion the welding speed should not be too slow. This is crucial for high thermal conductivity materials such as aluminum alloys. If the travel speed is to fast it may affect shielding gas protection and lead to cracks, oxidation, and incomplete melting of the consumable wire.

- The shielding gas flowing rate is critical to quality. Using the applicable flowing rate of the inert gas, the laminar flow is ensured and antioxidation protection is achieved. If the flowing rate is inadequate. This would cause inappropriate shielding and induce weld porosity.

- Welding pool control

Molten drop transfer and bridging without interrupting transfer mode is generally used in GTAW process. Globular transfer mode along with the diameter of molten droplet is greater than the diameter of welding wire. Molten droplets are dropped away from filler wire by gravity force once the size of the droplet is large enough. The weld bead shape and the weld penetration are comparatively uniform and finger-like shaped penetration is avoided [36] using this transfer mode. Nonetheless, this transfer mode will affect the welding arc stability and led to nonacceptable geometry of the weld shape. Thus, this transfer mode is rarely applied unless for low weldable materials. On the contrary, in bridging without interrupting transfer mode, the filler weld will first contact molten pool and immediately blast away by the overheating and then directly transfers into the molten pool. Bridging without interrupting of transfer mode can be used to accurate control of the weld shape. Thus, it can be assumed as the most appropriate transfer mode for GTAW wire feed WAAM process.

- Filler material control

There are two main and broad categories of nickel alloy: solid-solution-strengthened alloys and precipitation-hardened alloys. GTAW welding is generally preferred for precipitation-hardened alloys where possible. To achieve the best results, the shielding gas used is generally argon or helium, or a mixture of both for welding nickel alloys. As for the filler materials. They usually match the parent metal being welded. These filler wires usually contain small amounts of other elements to reduce the probability of cracking. Commonly, these elements include aluminum, titanium, or niobium, either individually or as a mix. GTAW can be integrated with both conventional cold wire and hot-wire feeding system. Wire feed control is one of the methods to eliminate the welding imperfections in WAAM shaping process of the weld beads. If wire feed system is wrongly set up the deposition process may become unstable and result in non-acceptable surface appearance.

1.7. Wire arc additive manufacturing (WAAM) – current state of art

Wire Arc Additive Manufacturing (WAAM) is a key technology to manufacture metal parts from welding wires using a standard welding robot. It can be easily used to produce single parts, small series, or prototypes, with complex (internal) geometry or products composed of several materials [28].

The technology has many advantages; a standard welding robot with welding wire can be used. In principle, WAAM technology can therefore be used by any company with an industrial welding robot. This opens many possibilities for companies that already use this welding technology. All materials that can be welded with GMAW/GTAW can be also used to manufacture a full-size parts using a wire arc incremental printing method. This technology is also an attractive alternative to any conventional/non-conventional manufacturing processes such as CNC milling, casting or EDM machining (Fig.1.10). Where conventional milling techniques have their limitations. WAAM 3D metal printing offers nearly limitless design possibilities [27, 54].

The metal deposited by the WAAM process can be of very high quality – as good as that of wrought and often better as of castings. It has been observed that WAAM has significantly lower porosity than castings. WAAM is also recognized as a moderate material-consuming process. It is proofed that the reduction percentage can vary from one application to another, but can reach up to 70% in certain applications, compared to traditional manufacturing processes [10, 55].

Year	Specific area	Material	Heat source	Improvement features	Author
2012	Positional welding-inclined fabrication	Mild steel and aluminium	CMT	– Limited accessibility and no manipulation needed – Produces walls from different angles – Closed shapes can be printed	Kazanas et al. [26]
2013	Profiled roller and slotted roller	Mild steel	CMT	– Minimizes the distortion phenomena – Decreases surface roughness	Colegroves et al. [27]
2014	Design of tool-path generation strategy	Mild steel	MIG	– Shortens the starting-stopping point rate – Increases surface accuracy	Ding et al. [32]
2016	Double wire feedstock	Iron and aluminium wire rods	TIG	– Fabricates components with two materials at the same time – Reduces the deposition rate	Shen et al. [44]
2016	Optimization of T-shaped structure	Carbon steel	MIG	– Optimizes deposition strategy – Reduces residual stress and strain – Increases height accuracy	Venturiri et al. [34]
2016	Hybrid manufacturing	Mild steel (ER70S-6)	TIG	– Refines dimensional accuracy – Fabricates cylindrical geometries	Kapil et al. [35]
2016	Adaptive path planning	Copper steel	MIG	– Enhances geometrical accuracy – Prevents void form during deposition	Ding et al. [33]
2016	Rolling deformation	Ti–6Al–4V	TIG	– Enhances β grain – Reduces strain level	Donoghue et al. [28]
2017	Combination of TIG and MIG	Aluminium ER4043	TIG-CMT	– Improves contact angle and weld bead dilution	Liang et al. [36]
2017	Bulk deformation method	Not stated	Not stated	– Improves grain structure – Lessens residual stress and distortion	Colegroves et al. [29]
2017	Double wire deposition	Copper (ER 70S-6 and ER110S-G)	MIG	– Optimizes mechanical properties, especially hardness of structure	Somashekara and Suryakumar [41]
2017	Slicer and process improvement-MOSTMetalCura	Mild steel (ER70S6)	MIG	– Eliminates overlap movement – Infill deposition starts instantly – Complex geometries can be fabricated	Nilsiam et al. [45]
2017	Single electrode (MIG) and double electrode (MIG-TIG)	Steel (H08Mn2Si)	MIG and TIG	– Decreases molten pool volume 30% – Decreases heat accumulation	Yang et al. [43]
2017	Flat and inclined position deposition	Steel (H08Mn2Si)	MIG	– Contact inclined-angle can be set greater than 45°	Xiong et al. [16]
2018	Thermal stress relief and rolling	Ti-6Al-4V	PAW	– Removes crystallographic texture – Decreases hydrostatic tensile stresses	Honnige et al. [30]
2018	Doubled wire system	Al-Co (ER2319) and Al-Mg (ER5087)	TIG	– Refines mechanical properties – Optionally uses two different materials simultaneously during deposition	Qi et al. [42]
2018	Combination of AM and SM	Mild steel (ER70S-6)	MIG and CMT	– Allows advanced geometric shapes to be fabricated – Decreases heat accumulation – Includes surface finishing process	Prado-Cerqueira et al. [37]
2018	Inert gas trailing shield	Ti-6Al-4V	TIG	– Prevents atmosphere oxidation – Enhances inert gas shielding	Bermingham et al. [46]
2018	Double wire feeding	Stainless steel	PAW	– Increases process efficiency – Raises deposition rate higher than that with single wire feeding process	Feng et al. [38]
2018	Low cost application	Mild steel (ER70S-6)	MIG	– Lowers cost of application – Advances material properties – Is sustainable	Nilsiam et al. [47]
2018	Enlargement of roller size	Ti-6Al-4V	PAW and TIG	– Increases recrystallised extent area – Allows roller load to be increased – Further refines grain	McAndrew et al. [31]

Fig. 1.10 Designs and modifications of the WAAM [13]

As with any of the 3D printing methods, most applications require a specific scope of post-processing processes to achieve the desired mechanical properties [58]. In some cases, WAAM may require the use of the same post-processing steps that are used for any casted or fabricated component such as post weld heat treatment, machining, assembly etc. However, there may be no need to apply hot isostatic pressing (HIP) due to high density of the printed workpieces [10,24].

1.7.1. Advantages and disadvantages of the WAAM process

Among other additive manufacturing processes, WAAM continues to evolve strongly. In particular, several process variants have been developed recently in order to optimize the microstructure and the mechanical properties of the parts. The certification and validation of WAAM parts is a key point that will have to be resolved [24]. Simultaneously there is a need to develop in situ control methods to allow to apprehend the appearance of imperfections and to be able to perform repair action in real time .

Following are the advantages and limitations of the Wire Arc Additive Manufacturing Technology [13, 24]:

- WAAM advantages

Broad and diverse family of wire arc methods offers many advantages. First of all, the deposition rate is high, which significantly reduces production times. Then, the WAAM offers the possibility of prototyping large parts. Machine costs and production costs are also lower than those realized with powder bed fusion (SLM/LBF) machines. Finally, there is a wide variety of welding filler materials for different applications.

- WAAM limitations

The WAAM process attracts number of manufactures both technically and economically. However, some shortcomings can hinder its implementation. It is necessary to minimize the appearance of the imperfections or/and to control their appearance in order to benefit from all the advantages of this technique. The major defects reported are porosities, heat affected zones (HAZ), residual stresses, anisotropy of properties and finally cracking and distortion. Numerous causes come from the appearance of these imperfections, such as for instance an unstable weld pool, inappropriate deposition energy, a high thermal gradient etc. The influence of the manufacturing environment such as contamination by surrounding productions processes or wrong set up of the process parameters may cause a quality gap such as cracking, deformation or oxidation of the of manufactured elements.

To summarize the WAAM manufacturing technologies are experiencing rapid development in the industry. They offer more freedom in the conception and design of parts and compared to manufacturing technologies by material removal (subtractive manufacturing) and depending on the case can be less energy consuming and in general generate less waste [10, 33].

WAAM technology has several advantages compared to metal additive manufacturing processes using a powder bed: rapid production of raw materials, better control of the supply chain and reduced production costs driven by lower investment rate.

WAAM also meets hybrid needs by combining it with 5-axis machining or a robotic. Thus, it opens promising prospects on the repair market or for the manufacturing of large parts, particularly in the aerospace, energy, and automotive sectors [24].

Nowadays WAAM technology is aimed at developing and qualifying each customer's individual application to support successful implementation of the WAAM process in its production.

2. Thesis and objectives

2.1. Motivation and general objectives

Wire Arc Additive Manufacturing is a technology that decreases part cost by reducing material wastage and time to market. It gives a flexibility in designs phase and enables prototyping of complex and demanding components. It is also the low-cost printing technology comparing to a numerous additive technologies and easy to robotize. Therefore, in the energy industry there is a gap to substitute the development of repair process with current state of the art wire arc additive methods that primarily have been using for manufacturing large structures and complex components.

Despite a number of advantages of 3D incremental printing and the availability of more and more perfect devices, there a small number of publications and tests concerning for the additive repairs. Reviewing technical journals and scientific publications a reader can find detailed description of manufacturing of full-size objects. However, there are just few publications and patents on wire arc additive repairs of the rotating machines such as gas turbines.

The conclusions from the above review show that robotic repairs using additive techniques (wire arc cladding, CMT) are the right direction of research. There are a lack of research works that would focus on this type of activity in relation to turbine components (turbine vanes, fuel injectors, diaphragms, turbine blades, etc.). In turn, the patent/innovation review in the field of Cold Metal Transfer (CMT) technology focuses on the "automotive" area and the creation of new additive materials. There are no works on the application of CMT in the power industry.

Modifications/repairs of parts of gas (and steam) turbines using robotic multi-layer arc cladding is therefore a promising area for introducing innovations related to the broadly understood Wire Arc Additive Repairs using a robot, welding source and peripheral devices, while being a competitive solution to the currently used additive manufacturing methods /repair such as SLS, SLM, DMLS.

The following are the aspects where research oversee a big field for extensive tests and experiments:

- Parts deformation and delamination
- Low accuracy of the additive prototyped objects
- Need to perform additional processes such as pre/post wed heat treatment
- Complex tooling and fixturing supporting additive processes.

- Necessity to use additional sensor to control material temperature and part location
- Destructive and Non-Destructive methods to validate the prototyped elements

2.2. Thesis

The innovativeness of the work is to focus on the unexplored areas of the wire arc additive repair of as turbine hardware. Thesis is aimed at the use of a robotic GMAW process, which would allow restoring the efficiency of the repaired part, its modification (dimensional, metallurgical, etc.) without the need to replace it with a new part. The previous practice of repairing gas turbine components with welding methods, mainly by arc surfacing, allowed them to be restored to their nominal shapes and dimensions. It is mainly used for resurfacing/modifying surfaces and rebuilding small parts. Extensively developing methods of incremental 3D printing allow for the production of a new part, but also for the repair of large volumes of machines and parts. Modern printing methods such as SLM (Selective Laser Melting) or SLS (Selective Laser Sintering) require special, advanced manufacturing methods, driving high investment. On the other hand, the lack of an appropriate repair process for more and more advanced turbine components makes it necessary to replace parts with new ones after defined operating periods, which generates high costs for the customer. Multilayer arc cladding for repair purposes shows some similarity to incremental 3D printing, hence the concept of using robotic GMAW wire arc cladding in the low-energy CMT (Cold Metal Transfer) variant for incremental repair of gas turbine components looks very promising.

There are presumptions (on the basis of performed tests) that it is possible to weld build up (cladding) the affected parts more effectively, faster, and easier. On the other hand, using the results of the static strength test, it is possible to perform finite element analysis more precisely when simulating this type of repair.

The proposed method of repair/modification can be included in the broader concept of incremental methods. Understanding the variables of the proposed incremental process, selection of optimal cladding parameters and stabilization of the process are necessary to carry out correct analyses.

Therefore, the turbine diaphragm is an excellent example of a part that is a candidate to repair by the wire arc additive process. There is high volume of this parts coming in for a repair that have been modified/repaired by the manual welding methods.

An important element of the considerations is the process of qualifying additive arc repairs. Currently, there is no uniform standard in the industry on how such samples should be made and tested. Taking into account that robotic additive welding arc repair is an advanced cladding process, there is a need to propose how such samples should be made and tested.

The main objectives of the present research subject are: to investigate the feasibility of applying the WAAM process to investigate the influence of different parameters on the mechanical properties of the prototyped wedling specimens and perform the feasibility studies on the repair of the gas turbine components. In the last experimental chapter the proposed robotic multi-layer cladding process will be verified and validated to perform a repair on the selected gas component.

Based on the above, the main goal of the research study is to identify the challenges involves in cladding and additive manufacturing of the gas turbine componets. In addition to identify the benefits and advantages over conventional process (GTAW, GMAW). The following assignmets are definied based on the research challenges:

- Make an investigation about additive manufacturing.
- Find a suitable additive manufacturing process that can be used to repair gas turbine componets.
- Perform a functional repair on the selected gas turbine hardware

In conclusion the aim of the thesis is to invstigate the feasibility of a **repair of the selected gas turbine component by the use of robotic multi-layer wire arc cladding process.**

3. Materials screening

Materials screening is a process of ensuring the satisfactory performance of a welded structure, the corresponding quality of the weld beads and it is determined by adequate testing procedures [32]. Therefore, the welds are verified under conditions that are the same or more severe than those encountered by the welded structures in the field.

Most of the welds, quality is tested based on the function for which it is intended. In this chapter the focus in on deposition on surface of multiple beads in each layer and multiple layers in each build-up. There are few ways to verify if a weld build up is correct:

- Distribution: Weld material is distributed equally onto a surface of the substrate. It will be verified through the visual testing and dimensional inspection.

- Imperfections: A weld defect is any flaw or imperfection that compromises the intended use of a weldment. These are classified according to ISO 6520. This also implies an imperfection. Weld can have a discontinuity and not be considered defective. These acceptable limits are specified in ISO 5817 and ISO 10042. The most common weld imperfections are Cracks, Inclusions, Lack of fusion, Porosity, Undercut, Poor penetration, Burn through, Under-fill, Excess reinforcement, Spatter, Over-roll/Overlap, Mechanical damage. Verification of the imperfection will be performed by destructive and non-descrutive tests (VT and PT).

- Spattering: The weld is free of imperfections materials such as slag or spattering. The slag and spattering after cooling should be cleaned out from the workpiece. It should be removed easily. Visual observation is enough to verify post weld condition.

- Porosity: The weld surface should not have any irregularities or any porous holes (called porosity). Holes contribute to weakness. Reported holes usually indicates that the parent metal was cleaned enough before cladding. Verification of the porosity will be performed by destructive and non-descrutive tests (VT and PT).

- Distortion: The Heat input is critical to control deformation. In general, high heat input indicate a potential quality issues. Dimensional inspection and blue light scanning will be applied to verify any distortion after additive cladding.

- Strength: Most welds need to demonstrate the required strength. One way to ensure proper strength is to start with a filler metal selection that is higher than given strength requirement. For the actual test the filler is the same one as the substrate. For the further research the company data on mechanical and oxidation properties will be used.

As already mentioned, a proper prediction of a part behavior is crucial to obtain assumed conditions and achieve desired performance. A first development has been run on welding coupons to select the proper parameters to define and describe all significant thermal behaviors and constraints.

3.1. Test objectives

The objectives is to apply CMT technology to at least one alloy in each Power material family (nickel and cobalt superalloys). The approved Fronius GMAW CMT welding process is aimed to perform welding trials for selection of the proper welding parameters and execute the proposed definition of the welding samples that can be used for wire additive arc repair technology validation and further Power component repair process [38]. The main focus of the tests is on surface deposition.

3.1.1. Technology CTQs

There are two areas of focus as for Critical to Quality. The first one weldability and the other one is Mechanical Properties. The weldability requirements mainly based on AWS D17.1 Class A specification [62]. The standard document provides the general welding requirements for welding aircraft and space hardware. It includes but is not limited to the fusion welding of different materials such as nickel-based, iron-based, cobalt-based, magnesium-based alloys using electric arc and high energy beam processes.

The weldability CTQs are as follows:

- Cracks: no allowed
- Incomplete fusion: no allowed

- Porosity (Surface):
    - Size: 0.25T or 0.03-in whichever is less
    - Spacing: 8 times the size of the larger adjacent imperfection
    - Accumulated length in any 3-in of Weld: 1T or 0.12-in, whichever is less

- Porosity (Sub-surface)
    - Size: 0.33T or 0.06-in whichever is less
    - Spacing: 4 times the size of the larger adjacent imperfection
    - Accumulated length in any 3-in of Weld: 1.33T or 0.24-in, whichever is less

The mechanical proprieties CTQ is:

- Cross-weld mechanical properties (All weld metal/ST tensile (along/normal to weld)
    - UTS > 50% of base metal
    - Yield > 50% of base metal
    - Elong. > 50% of base metal
    - OR
    - Interface Strain > 50% of base metal RT strain capacity

3.1.2. Materials and Welding wires

Selection of to the materials and welding fillers fully corresponds to the most common materials used in industrial gas turbines. Nickle and cobalt Super alloys exhibit excellent mechanical strength and creep resistance at high temperature, good surface stability, corrosion, and oxidation resistance. Thus, the representatives of those two super alloys have been selected for the further tests. All the materials used for materials screening have confirmation certificates.

Definition of the materials is as follows:

- Sheets of metal:
    - Hastelloy X W 300mm x H 300x T 6.25 mm
    - HS188 W 300mm x H 300x T 6.25 mm

- Bars of metal:
    - Hastelloy X dia. 40mm x L 300mm
    - HS188 dia. 40mm x L 300mm

- Welding wires:
    - Hastelloy-X AMS 5798 dia. 0.8 mm / 0.031 in
    - HS188 AMS 5801 dia. 0.8 mm / 0.031 in

3.2. Definition of the welding samples

Both for bars and sheet metal a total number of 6 coupons have been prepared for each of the supper alloy. The samples have been made according to the proposed definition (Fig 3.1). 3 coupons (sample type 100% overlay) have been welded on Hastelloy-X (AMS 5536) base material and respectively 3 coupons on HS188 (AMS 5608) substrate.

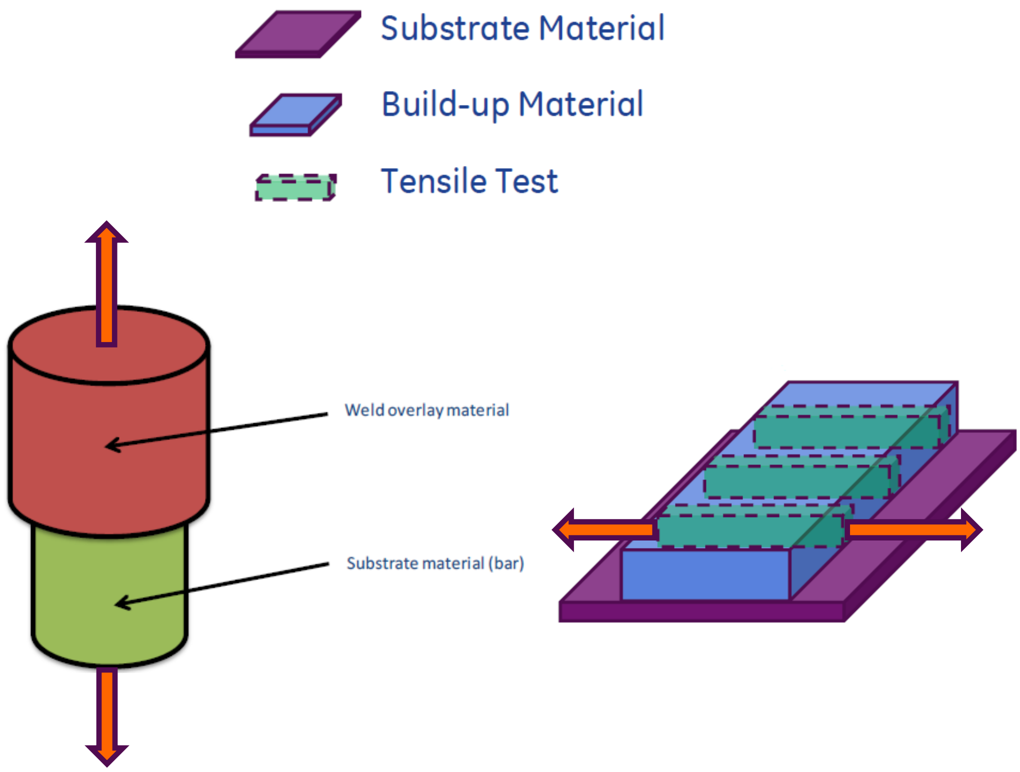


Fig. 3.1 Definition of the welding samples.

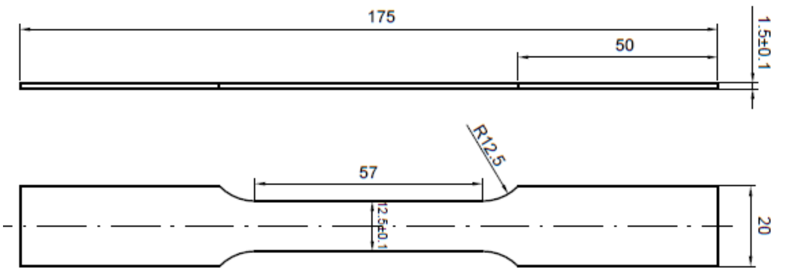
All of the samples have met the following requirements:

- The samples shall be welded by using the CMT synergic lines
- Only robotic welding is allowed to obtain repeatability

- Samples shall pass the VT and PT tests (acceptance levels taken from AWS D17.1 Fusion Welding for Aerospace Applications) [62]
- Samples must pass the X-Ray test (Standard's ASTM E 1742/E1742M-12, ASTM E747, AWS D17.1) or pass the destructive material evaluation [66, 67]
- Samples prior tensile test shall be stress relieved

When the samples (100% overlay) are prepared. The next phase is to cut out of them the tensile test samples according to ASTM E8/E 8M standard [68]. Those samples (Fig 3.2) are used for mechanical tests to verify the mechanical properties against defined CTQs. Since the coupons are made out of bars and sheet metal. Both flat and rounded test samples have been milled out.

Flat Tension Test Sample ASTM E8/E 8M



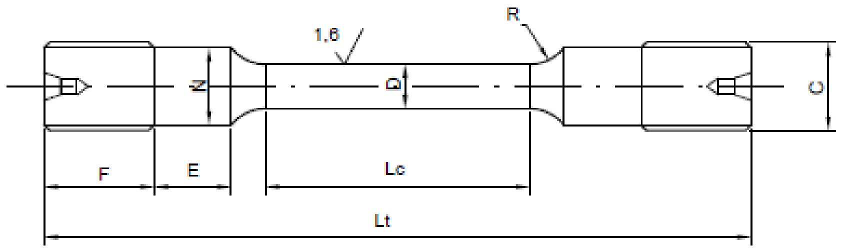
Hastelloy-X Qt-y 3

HS188 Qt-y 3

Dimensions in mm.

D	6,0±0.10
Lt	75±0.10
Lc	32
C	M10x1
E	7
F	12
R	5.5
N	9

Rounded Tension Test Sample ASTM E8/E 8M type Type III



Hastelloy-X Qt-y 3

HS188 Qt-y 3

Fig. 3.2 Definition of the tensile samples. [68]

As it was mentioned. All of the welded samples need to be heat treated in vacuum furnace to perform stress relieve. The proposed cycle is as follows:

Heat Treatment Program (Fig 3.3):

- Minimum Vacuum = 1micron [1x10-3 Torr]
- Heat Rate = 25 °F (14°C) per minute
- Soak Temp = 2150°F
- Soak Time = 50 - 55 minutes
- Cooling Rate = 50 °F - 150 °F (28 °C - 83 °C) per minute to 1000 °F (538 °C)
- Remove the parts from the furnace when the temperature is below 175 °F (80 °C).

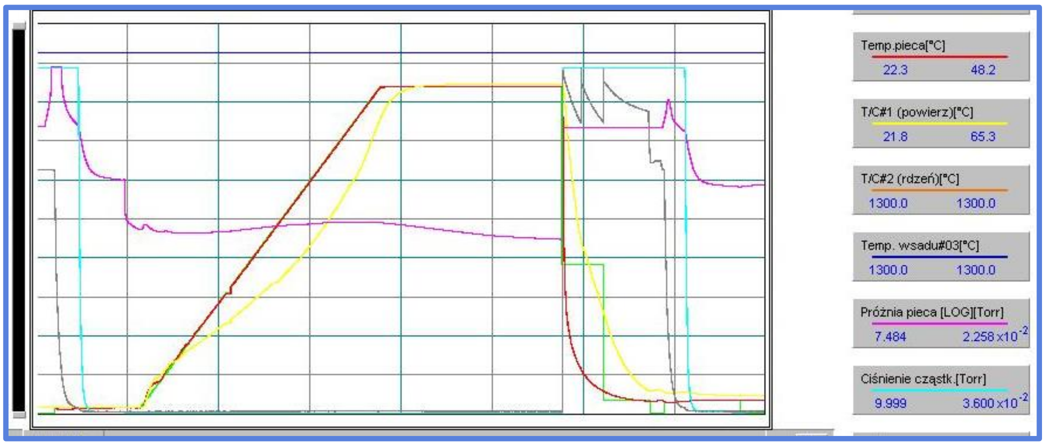


Fig. 3.3 Stress relief program & chart Heat Treatment for Hastelloy-X and HS188.

3.2.1. Welding trials

Welding trials have been performed for selection of the proper welding parameters. They have been done on a mild steel substrate (S255) to minimize the cost of tests [32]. The trials are aimed to select the optimum synergic line and the select the welding parameters such as voltage, amperage, torch travel speed, torch amplitude and many more. The undergone tests with the corresponding parameters are in Table 3.1.

Table 3.1. Welding trials for selection the proper welding parameters (S255 mild steel substrate)

No. Bead	Syner Line	Ampers [A]	Voltage [V]	GAS
1	NiBAS625	103	18.1	Argon
2	NiBAS625	103	18.1	Argon
3	NiBAS625	103	18.1	Argon
4	NiBAS625	140	18.1	Argon
5	NiBAS625	140	18.1	Argon
6	NiBAS625	160	17.6	Argon
7	NiBAS625	160	17.6	Argon
8	NiBAS625	160	17.6	Argon
9	NiBAS625	130	16.3	Argon
10	19/9 0777	130	18.6	Argon+CO2
11	19/9 0777	130	18.6	Argon+CO2
12	19/9 0777	140	18	Argon+CO2
13	19/9 0777	120	15.3	Argon+CO2
14	19/9 0777	140	18	Argon+CO2
15	19/9 0777	125	18	Argon+He+CO2
16	19/9 0777	140	18.1	Argon+He+CO2
17	19/9 0777	140	18.1	Argon+He+CO2
18	19/9 0777	140	18.1	Argon+He+CO2
19	19/9 0777	140	18.1	Argon+He+CO2
20	19/9 0777	140	18.1	Argon+He+CO2

Synergic lines provides unit current pulses to detach identical molten droplets of predetermined volume from the electrode wire, combined with the other parametric relationships necessary for stable wire burn out. Unit pulses are very unique to a given material, to a chosen wire diameter and their details are programmed into a synergic welding set.

Based on a number of welding trials. Synergic line 19/09/0777 with the corresponding parameter (row 20 in Table 3.1) has been selected to weld the welding samples (Figure 3.4).

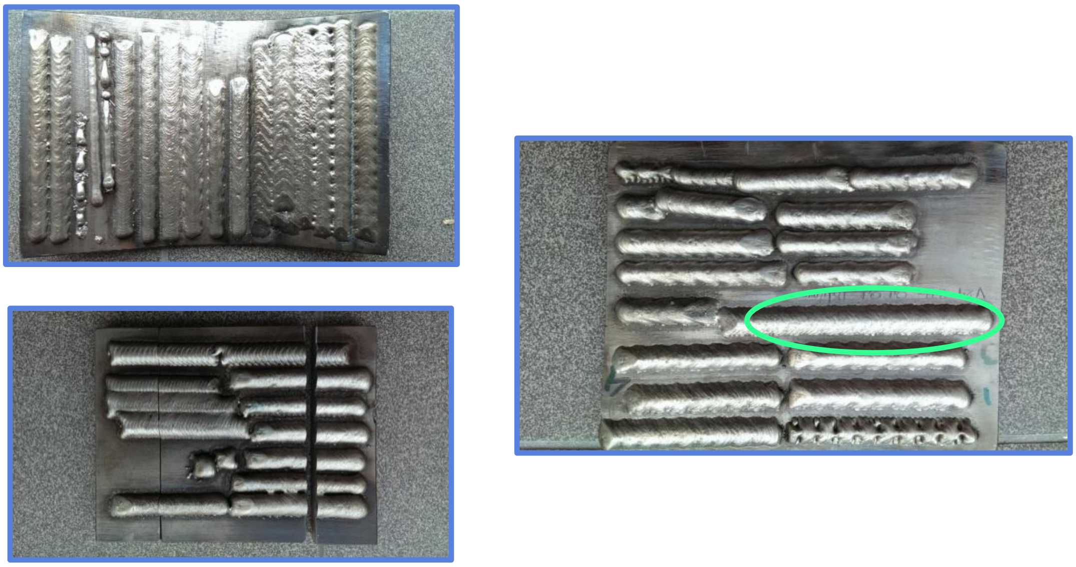


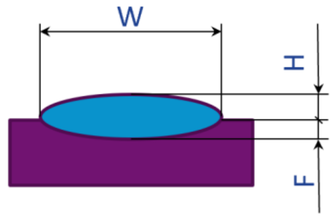
Fig. 3.4 Initial welding trials.

3.2.2. Deposition ratio and the influence of welding parameters

The deposition of weld bead is composed of a substrate (base metal) and an filler wire metal. Its composition ratio depends highly on the welding process conditions. During cladding process, the welding pool consists of the droplet metal of filler wire and the melted parent metal. The weld is formed during the continuous formation and solidification of the welding pool. The proportion of the locally melted substrate in the weld metal is determined by the "penetration ratio". It is related to the local penetration of the parent metal and the melting of the filler wire, as well as the welding position, welding parameters, joint geometry and shape, number of weld passes and the metal properties of the weld bead. Figure 3.5 is an output of the welding trials. It shows the correlation between welding parameters and weld bead shape, geometry, and penetration.

Factor	More/Less	W-Width	H-Height	Fusion
V-speed	↑	↓	↑	↓
V-speed	↓	↑	↓	↑
A-Amplitude	↑	↑	↓	-
A-Amplitude	↓	↓	↑	-
L-R Dwell	↑	-	↓	↑
L-R Dwell	↓	-	↑	↓
Current	↑	↑	↓	↑
Current	↓	↓	↑	↓
Torch Angle	↓	↑	↓	↑
Torch Angle	↑	↓	↑	↓
Oscillation	↑	-	↑	↑
Oscillation	↓	-	↓	↓

↑ Parameter increases ↓ Parameter decreases



Deposition ratio
Hast-X
W 14 mm
H 2.8 mm
F 0.7 mm

HS188
W 12.8 mm
H 3.5 mm
F 0.7 mm

Fig. 3.5 Deposition ratio and the influence of welding parameters.

3.2.3. Sample preparation for cladding

Before cladding, whole area of the substrate has been grinded out and degreased to ensure the surface is clean. Moreover, both bars and sheet of metal have been tack welded to the positioner plate to avoid movement. Starts and stops have been determined and cut off after cladding process. This is to ensure that the tensile samples are cut out of the area free of welding imperfections (Fig 3.6).

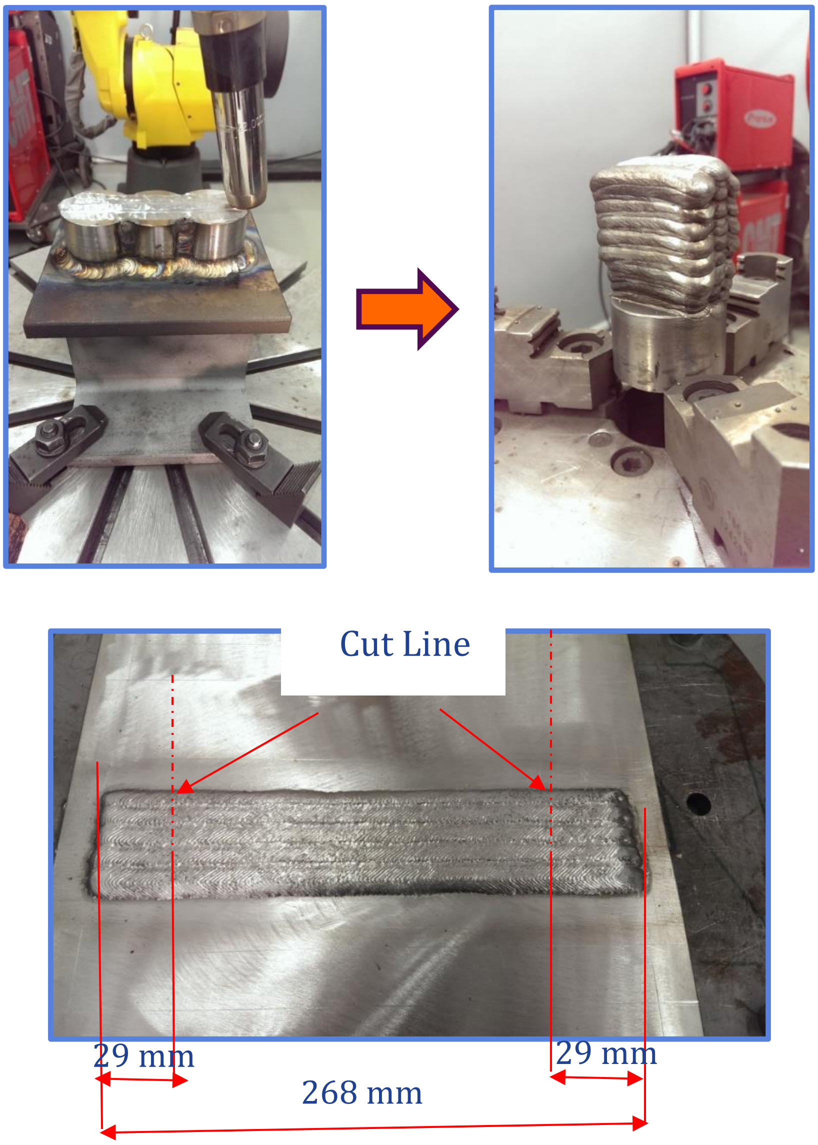
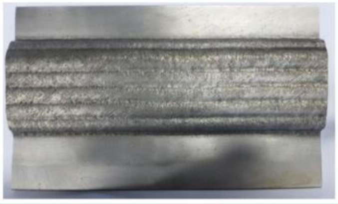


Fig. 3.6 Sample preparation for cladding.

3.3. Results

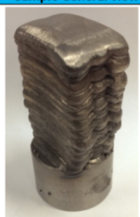
3.3.1. Weld test record – HastX

In total 6 welding 100 % weld overlay samples have been cladded. 3 out of them on Hastelloy-X (AMS 5536) sheet samples and 3 on Hastelloy-X (AMS 5536) bar samples. Hastelloy-X (AMS 5536) is a representant of nickel base super alloys. The final welding and robotics parameters are in Fig 3.7 and Fig 3.8.

		Sample General view
Supporting Document:	Material Screnning	
Component Welded:	-	
Welding power supply:	Fronius TPS 5000-CMT	
Remote control:	RCU 5000i	
Synergic line:	C960	
Database used:	DB 03-0366	
Torch:	Robacta Drive CMT 350	
Cooling Type:	Water	
UST Firmware:	-	
RCU Firmware:	1.15.103	
Wire Feeder Firmware:	-	

Settings					
Welding Process:	GMAW	**Filler Material:**	AMS 5798	**Base Material:**	Sheet Hastelloy-X AMS 5536
Current/Polarity:	DCEP	**Diameter:**	0.031 in	**Thickness:**	0.250 in
Transfer Mode: CMT	CMT	**Electrodes:**	1	**Base Material:**	-
Type:	Automatic	**Tip to Work Distance**	10 mm	**Thickness:**	-
Details:	Robotic	**Joint:**	Cladding	**Backing:**	-
Torch Angle:	75°	**Groove:**	N/A	**Preheat:**	Ambient
Work Angle:	Push	**Position:**	1-G Flat	**Gas:**	78%Ar+20%He+2%CO2

Fig. 3.7 Weld Test Record Hastelloy-X sheet samples

		Sample General view
Supporting Document:	Material Screnning	
Component Welded:	-	
Welding power supply:	Fronius TPS 5000-CMT	
Remote control:	RCU 5000i	
Synergic line:	C960	
Database used:	DB 03-0366	
Torch:	Robacta Drive CMT 350	
Cooling Type:	Water	
UST Firmware:	-	
RCU Firmware:	1.15.103	
Wire Feeder Firmware:	-	

Settings					
Welding Process:	GMAW	**Filler Material:**	AMS 5798	**Base Material:**	Sheet Hastelloy-X AMS 5536
Current/Polarity:	DCEP	**Diameter:**	0.031 in	**Thickness:**	0.250 in
Transfer Mode: CMT	CMT	**Electrodes:**	1	**Base Material:**	-
Type:	Automatic	**Tip to Work Distance**	10 mm	**Thickness:**	-
Details:	Robotic	**Joint:**	Cladding	**Backing:**	-
Torch Angle:	75°	**Groove:**	N/A	**Preheat:**	Ambient
Work Angle:	Push	**Position:**	1-G Flat	**Gas:**	50%Ar+50%He

Fig. 3.8 Weld Test Record Hastelloy-X bar samples

3.3.2. Weld test record – HS 188

In total 6 welding 100 % weld overlay samples have been cladded. 3 out of them on HS188 (AMS 5801) sheet samples and 3 on HS188 (AMS 5801) bar samples. HS188 (AMS 5801) is a representant of cobalt base super alloys. The final welding and robotics parameters are in Fig 3.9 and Fig 3.10.

Supporting Document:	Material Scrennig	**Sample General view**			
Component Welded:	-				
Welding power supply:	Fronius TPS 5000-CMT				
Remote control:	RCU 5000i				
Synergic line:	C960				
Database used:	DB 03-0366				
Torch:	Robacta Drive CMT 350				
Cooling Type:	Water				
UST Firmware:	-				
RCU Firmware:	1.15.103				
Wire Feeder Firmware:	-				
Settings					
Welding Process:	GMAW	**Filler Material:**	AMS 5801	**Base Material:**	Sheet HS188 AMS 5608
Current/Polarity:	DCEP	**Diameter:**	0.031 in	**Thickness:**	0.250 in
Transfer Mode: CMT	CMT	**Electrodes:**	1	**Base Material:**	-
Type:	Automatic	**Tip to Work Distance**	10 mm	**Thickness:**	-
Details:	Robotic	**Joint:**	Cladding	**Backing:**	-
Torch Angle:	75°	**Groove:**	N/A	**Preheat:**	130°C
Work Angle:	Push	**Position:**	1-G Flat	**Gas:**	50%Ar+50%He

Fig. 3.9 Weld Test Record HS188 sheet samples

Supporting Document:	Material Scrennig	**Sample General view**			
Component Welded:	-				
Welding power supply:	Fronius TPS 5000-CMT				
Remote control:	RCU 5000i				
Synergic line:	C960				
Database used:	DB 03-0366				
Torch:	Robacta Drive CMT 350				
Cooling Type:	Water				
UST Firmware:	-				
RCU Firmware:	1.15.103				
Wire Feeder Firmware:	-				
Settings					
Welding Process:	GMAW	**Filler Material:**	AMS 5608	**Base Material:**	Sheet HS188 , AMS5801
Current/Polarity:	DCEP	**Diameter:**	0.031 in	**Thickness:**	0.250 in
Transfer Mode: CMT	CMT	**Electrodes:**	1	**Base Material:**	-
Type:	Automatic	**Tip to Work Distance**	10 mm	**Thickness:**	-
Details:	Robotic	**Joint:**	Cladding	**Backing:**	-
Torch Angle:	75°	**Groove:**	N/A	**Preheat:**	Ambient
Work Angle:	Push	**Position:**	1-G Flat	**Gas:**	50%Ar+50%He

Fig. 3.10 Weld Test Record HS188 bar samples

3.3.3. NDT results

All of the welded coupons have been NTD tested (Fig 3.11 and Fig 3.12). In addition to that metallographic evaluation has been performed (Fig 3.13).

The NDT criteria are as follows:

- Cracks: no allowed
- Incomplete fusion: no allowed
- Porosity (Surface):
  - Size: 0.25T or 0.03-in whichever is less
  - Spacing: 8 times the size of the larger adjacent imperfection
  - Accumulated length in any 3-in of Weld: 1T or 0.12-in, whichever is less
- Porosity (Sub-surface)
  - Size: 0.33T or 0.06-in whichever is less
  - Spacing: 4 times the size of the larger adjacent imperfection
  - Accumulated length in any 3-in of Weld: 1.33T or 0.24-in, whichever is less

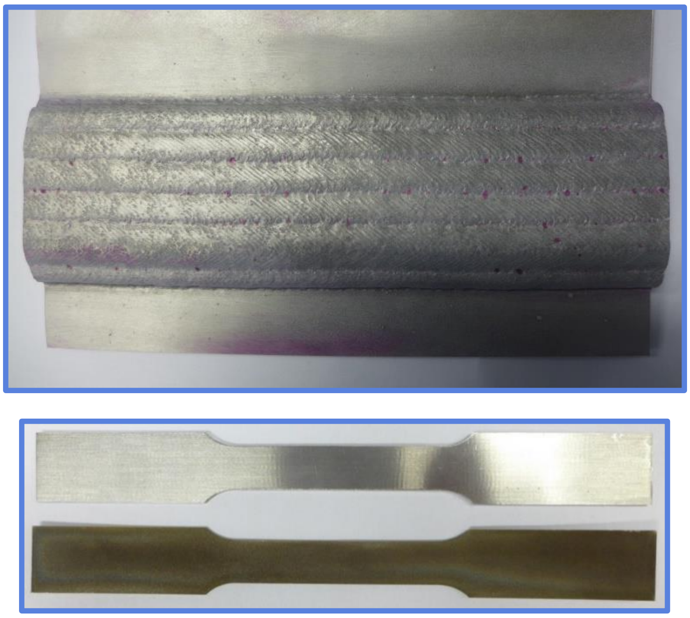


Fig. 3.11 PT inspection of P1 sample and flat specimen after WEDM machining.

Fig. 3.11 PT inspection of B1 sample and rounded specimen after WEDM machining.

Penetrant and Visual testing show that all of the samples meet a given acceptance criteria of AWS D17.1 standard (Table 3.2). During the surface examination some of the porosity has been reported. However, everything was withinn the acceptable limits. The X- ray inspection (not included into report) results are more questionable. Only 3 samples meet the limit. It should be noted that x-ray requirements come from Aviation specification, and they are very conservative. The further examination on cut-ups proofs that the quality of the samples has been acceptable.

Table 3.2. Summary of VT and PT examination

Material	Sample Type	Marking	NDT VT	NDT PT
Hastelloy-X	Sheet	P1	Passed	Passed
Hastelloy-X	Sheet	P2	Passed	Passed
HS188	Sheet	P1	Passed	Passed
HS188	Sheet	P2	Passed	Passed
HS188	Sheet	P3	Passed	Passed
Hastelloy-X	Rounded	B2	Passed	Passed
Hastelloy-X	Bar	B3	Passed	Passed
Hastelloy-X	Bar	B4	Passed	Passed
HS188	Bar	B2	Passed	Passed
HS188	Bar	B3	Passed	Passed
HS188	Bar	B4	Passed	Passed

3.3.4. Tensile Test results for the flat and rounded specimens

Tensile tests have been performed at the certified mechanical laboratory. The machine details and test conditions is as follows:

- Test machine: Servo hydraulic, MTS 810 model 318, 10 load frame, S/N 102264131B, 100 kN
- Extensometer: MTS 632.53F
- Temperature conditions during test" Room temperature 22-27℃
- Initial speed: 0.1 mm/min
- Secondary speed: 1.5 mm/min
- Removal point: 1.5 %

The mechanical proprieties requirements is:

- Cross-weld mechanical properties (All weld metal/ST tensile (along/normal to weld)
    - UTS > 50% of base metal
    - Yield > 50% of base metal
    - Elong. > 50% of base metal
    - OR

- Interface Strain > 50% of base metal RT strain capacity

Tensile test results (Table 3.3 -3.5) shows all of the critical parameters and the their difference comparing to the new make material. Ultimate average tensile drop off is in the range of -10.7% to -20.9 % and average tensile stress at offset yield (0.2%) varies from -6.2% to 17.9%. This data is very promising and give some space to go beyond the repair of stationary gas turbine hardware.

Since cladding can be also considered as "casting" process. The elongation values are much less than the parent forged substrate. Decrease of elongation of – 64.7 % is the maximum offset reported on flat specimens. It is worth noticing that the definition of flat and rounded specimens is quite different (milled out of overlay material and milled out of parent plus overlay material) and give different perspective on feasibility studies of additive repairs. For rounded coupons the reported average drop off is max 7.4%.

Table 3.3. Tensile Test results for the flat specimens- Hastelloy-X (AMS 5536)

Method	Data from vendor	Ultimate tensile strength (MPa)	Tensile drop from Base metal %	Stress At Offset Yield (0.2%)	Stress At Offset Yield (0.2%) drop	Elongation A4 %	Elongation A4 % drop	Reduction of area %
Base Metal	Haynes	755	-	315	-	49	-	-
SB-435/N06002	ASME IX	655	-13.2%	-	-	-	-	-
CMT	P1-3 Hast-X	610.71	-19.1%	323.93	2.8%	19.03	-61.2%	43.4
CMT	P1-4 Hast-X	607.1	-19.6%	333.7	5.9%	17.54	-64.2%	32.95
CMT	P2-1 Hast-X	714.5	-5.4%	415.2	31.8%	30.98	-36.8%	28.86
CMT	Average	**644.1**	**-14.7%**	**357.61**	**13.5%**	**22.52**	**-54.0%**	**35.07**
	StdDev	**61.0**	**8.1%**	**50.1**	**15.9%**	**7.4**	**15.0%**	**7.5**

Table 3.4. Tensile Test results for the flat specimens- HS 188 (AMS 5608)

Method	Data from vendor	Ultimate tensile strength (MPa)	Tensile drop from Base metal %	Stress At Offset Yield (0.2%)	Stress At Offset Yield (0.2%) drop	Elongation A4 %	Elongation A4 % drop	Reduction of area %
Base Metal	Haynes	945	-	465	-	53	-	-
-	ASME IX	-	-	-	-	-	-	-
CMT	P2-1 HS 188	676.7	-28.4%	522.4	12.3%	14.94	-71.8%	37.29
CMT	P2-2HS 188	795.8	-15.8%	570.8	22.8%	19.28	-63.6%	32.57
CMT	P2-3HS 188	768.6	-18.7%	550.9	18.5%	21.97	-58.5%	56.27
CMT	Average	**747**	**-20.9%**	**548.0**	**17.9%**	**18.73**	**-64.7%**	**42.0**
	StdDev	**62.4**	**6.6%**	**24.3**	**5.3%**	**3.5**	**6.7%**	**12.5**

Table 3.5. Tensile Test results for the rounded specimens- Hastelloy-X (AMS 5536)

Method	Data from vendor	Ultimate tensile strength (MPa)	Tensile drop from Base metal %	Stress At Offset Yield (0.2%)	Stress At Offset Yield (0.2%) drop	Elongation A4 %	Elongation A4 % drop	Reduction of area %
Base Metal	Haynes	755	-	315	-	49	-	-
SB-435/N06002	ASME IX	655	-13.2%	-	-	-	-	-
CMT	B1 Hast-X	672.7	-10.9%	296.6	-5.8%	47.46	-3.1%	61.95
CMT	B2 Hast-X	673.8	-10.8%	293.6	-6.8%	42.25	-13.8%	43.51
CMT	B3 Hast-X	675.9	-10.5%	291.4	-7.5%	44.7	-8.8%	51.36
CMT	B4 Hast-X	675	-10.6%	300.2	-4.7%	48.15	-1.7%	54.79
CMT	Average	**674.4**	**-10.7%**	**295.45**	**-6.2%**	**45.64**	**-6.9%**	**52.9**
	StdDev	**1.4**	**0.2%**	**3.8**	**1.2%**	**2.7**	**5.6%**	**7.7**

Table 3.6. Tensile Test results for the rounded specimens- HS 188 (AMS 5608)

Method	Data from vendor	Ultimate tensile strength (MPa)	Tensile drop from Base metal %	Stress At Offset Yield (0.2%)	Stress At Offset Yield (0.2%) drop	Elongation A4 %	Elongation A4 % drop	Reduction of area %
Base Metal	Haynes	945	-	465	-	53	-	-
-	ASME IX	-	-	-	-	-	-	-
CMT	HS 188-B2	799.4	-15.4%	385.6	-17.1%	49.25	-7.1%	65.47
CMT	HS 188-B3	800.8	-15.3%	384.5	-17.3%	45.89	-13.4%	48.27
CMT	HS 188-B4	800.6	-15.3%	388.5	-16.5%	52.02	-1.8%	67.53
CMT	Average	**800.3**	**-15.3%**	**386.2**	**-16.9%**	**49.05**	**-7.4%**	**60.42**
	StdDev	**0.8**	**0.1%**	**2.1**	**0.4%**	**3.1**	**5.8%**	**10.6**

3.4. Discussion

Summary of the welding tests and their impact on wetting profiles and bead contour:

- Both of alloys have poor wetting profile (lack of fluidity) which affects the shape of the bead contour, so it is difficult to fuse these profiles into subsequent beads,
- Limited welding amperage on the 19/9 synergic line (max 140A for dia. 0.8 mmm
- Thick positioner mounting plate is working as a heat sink which takes away heat from the sample during welding,
- Increasing the wire stick-out length which gives higher deposition ratio and smother transition zone between the bead and substrate is not possible in CMT mode.
- Special synergic line may be required for nickel or cobalt base alloy for cladding process.

An important element of the considerations is the process of qualifying wire additive arc repairs. Currently, there is no uniform standard in the industry on how such samples should be made and tested. In accordance with the applicable standards in welding - according to PN-EN ISO 15614-1: 2017, the following stages of welding technology qualification can be distinguished:

- Detailed analysis of welding production (determination of basic welding variables: welding process, grade of basic material, dimensions of elements, type of joints - thickness, diameter, welding positions),
- Selection of a test joint,
- Development of a preliminary welding procedure manual - pWPS,
- Execution of a test joint,
- Non-destructive and destructive testing of welding technologies,
- Issuing the WPQR welding technology qualification protocol by a notified body,
- Development of the welding process manual – WPS

The shapes of test joints and the scope of tests for individual joints are described in the above-mentioned standard. Taking into account that robotic additive welding arc repairs are an advanced surfacing process, there is a need to propose how such samples should be made and tested. As part of the experimental and implementation work, cylindrical and flat specimens according to ASTM E8/E 8M have been made. The proposed definition of the samples along with the acceptance tests and criteria show a potential to be implemented and further developed. Nowadays mainly the mechanical tests results are more favorable for some of the selected stationary turbine elements. Further development of the wire arc additive technology and synergic lines (CMT) can exceed the wire arc additive repairs to other turbine hardware.

4. Gas Turbine Diaphragm repair - development

Modern practice of reconstruction of post-service Gas Turbine hardware, using additive arc welding methods, is aimed at restoration of the nominal geometry and dimensions, as well as other part's features. Dynamic development of additive methods and techniques foster repair and modification of different hardware including Gas Turbine (GT) components. The main goal of this thesis is to prove viability of the repair concept of using robotized additive arc welding process to restore and modify Gas Turbine diaphragms using different filler wires from the substrate. The proposed hybrid repair is targeted on diaphragm, that is cast of nickel iron and the filler wire for welding the passes is an austenitic stainless steel. Gas turbines are constructed in such a way that hardware operating in the most demanding working conditions can be repaired or replaced at strictly defined outage intervals [74]. Repairs performed in hot module of gas turbines generally include the reconstruction of the surfaces and shapes of worn components, restoration of protective coatings and repair of cracks. One of the turbine's components that undergo such periodic repair is the diaphragm.

4.1. Workstation set up

The workstation used for initial trails and further repair process development is shown on Fig. 4.1. Station configuration is as follows:

- Industrial robot FANUC ArcMate 120iC with controllers R-30iB,
  - payload: 20 kg,
  - reach: 1811 mm,
  - repeatability: ±0,08 mm,
- Operator Control Panel,
- Two-axis FANUC positioner,
  - diameter shield: dia of 500 mm,
  - motion range J2: n*360, added function of continuous turn,
  - motion range J1: 270 deg,
  - max load capacity at wrist: 500 kg,
- CMT 5000 CMT/GMAW/PULSE welding source with wire feed system,
- Robot base,
- Welding fixture with 1 part,

- Torch Center Point (TCP),
- Equipment of the station related to safety in work (cover fence - system of protection panels with sheet metal, light barriers, manually slide curtain).

The RCU 5000i device has been used for remote control. All functions available on the welding power source can be retrieved using the RCU 5000i. In addition, additional functions are available such as optimization of welding characteristics. Connection to the welding power source is being realized via a LocalNet plug.

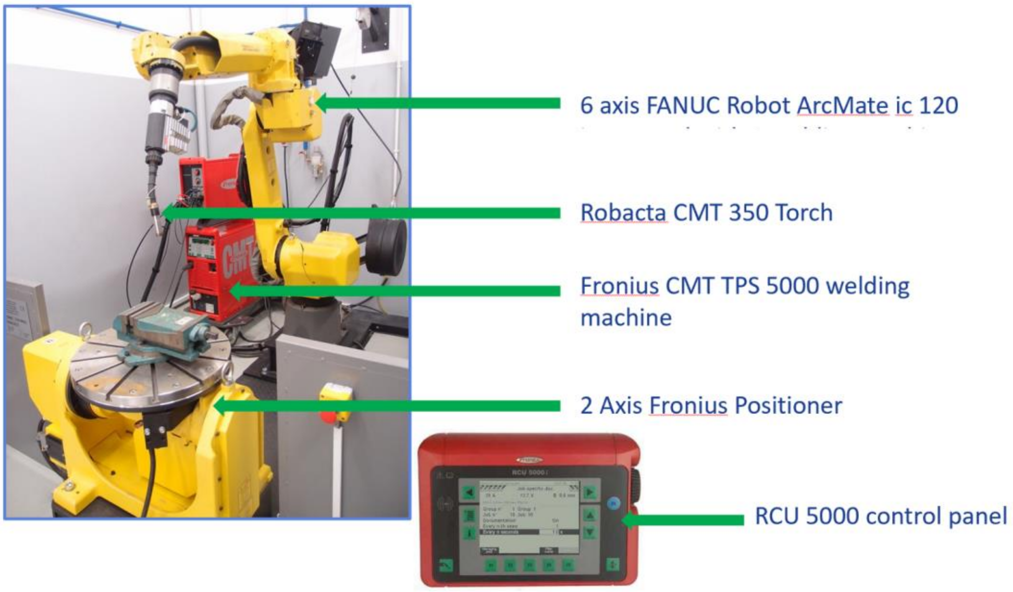
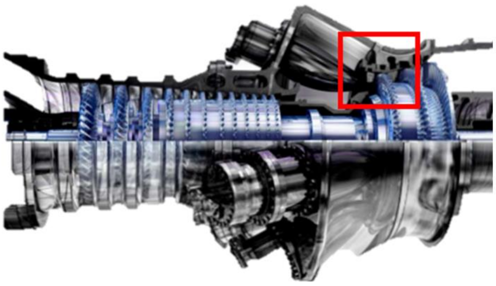


Fig. 4.1 Workstation with an Industrial robot FANUC ArcMate120iC, 2 axial positioner (Fanuc) and TPS 5000 CMT welding source (Fronius)

4.2. Diaphragm – hardware description

Diaphragms in the gas turbine are arranged in a form of a ring around the entire circumference between the power nozzles and the turbine rotor (Fig. 4.2). The main function of the diaphragm is to secure sealing between the lower base of the power nozzle and the turbine rotor. It is important due to loss of power and decreased efficiency of the turbine caused by leakage in a gap between the power nozzle and the rotor [5].



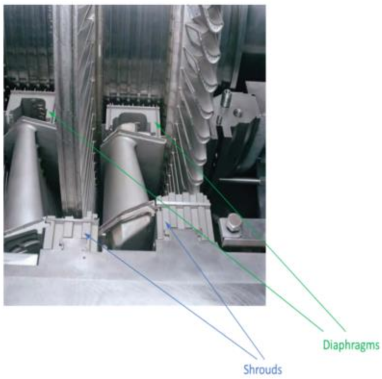


Fig. 4.2 Cross overview of the gas turbine and Power nozzle assembly with marked diaphragm

A Gas Turbine diaphragm consists of stages, where the number and size of the stages and segments depends on the power output of the turbine. The diaphragm creates ring, that apart from serving certain purposes, retains the stator vanes in its annular area. In each stage, a diaphragm contains upper and lower section. Those sections are assembled to the corresponding halves of the casing. This configuration makes the assembly/disassembly of the diaphragms viable. In addition, as there is a significant pressure drop across a turbine stage, the diaphragm also serves as a partition between the pressure stages [42]. By configuration of the gas turbine, the gas flows through the stationary vane causing a pressure drop across the stage.

A radial clearance is required between the diaphragms and the rotor to allow free rotation of the shaft. The gas that may leak across the tips of the diaphragm impose a decrease of performance known as tip-leakage loss. To reduce the bleeding loss, the diaphragm usually holds a labyrinth seal that match with a shaft sealing surface (Fig 4.3) [68, 70].

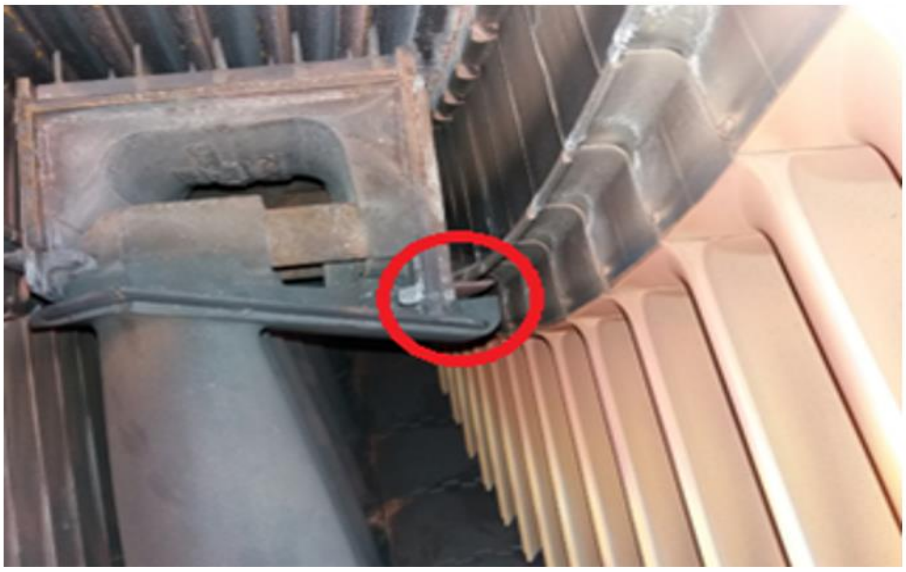


Fig. 4.3 Example of a diaphragm and its sealing function

During the turbine's operation, the diaphragms are likely to be exposed to several factors causing their oxidation. This gas turbine hardware operates in a high temperature environment that often exceeds base metal thermal properties. The diaphragm is mounted radially to the stationary vanes of the nozzle segment and forms an air seal all around the rotor. Thus, the diaphragm is not directly affected by the hot turbine gas. This hardware is typically fabricated from a material such as a cast nickel-iron (Ni-Resist.). It is a cast iron that is generally used for heat and corrosion resistant applications. The excessive temperature causes erosion and oxidation of the rail section in the area where the diaphragm is attached to the nozzle [21].

4.2.1. Materials used for diaphragms

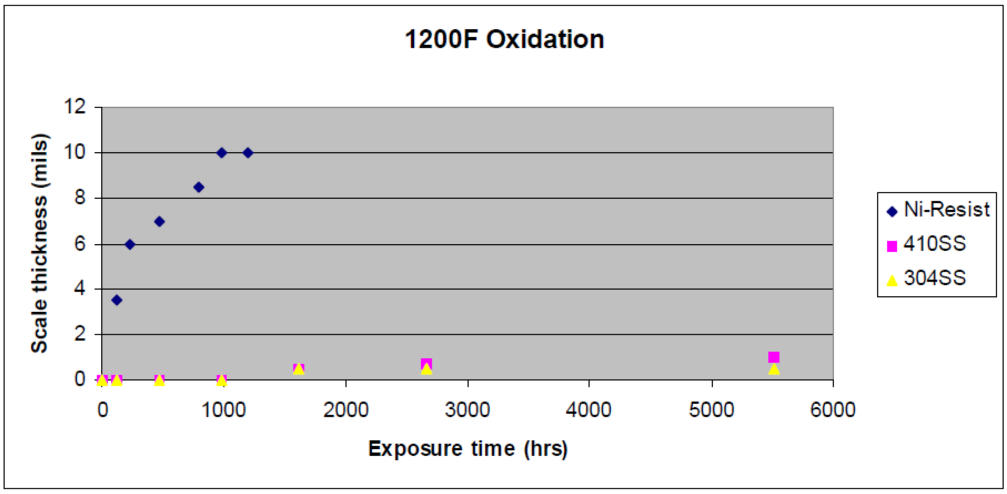
The turbine diaphragms are fabricated of creep and hot corrosion-resistant materials. The second stage of the diaphragm, that is the subject to go through the tests, is a component made of Ni-Resist. Its chemical composition given in Table 4.1. The primary application for Ni-Resist is Automotive Exhaust, Gas Turbines and Turbocharger Systems, where the temperature varies between 500 and 1050°C. Ni-Resist is a first choice in these applications because its hot strength, low coefficient of thermal expansion and ductility, provide sufficient resistance to such severe thermal shock [71]. From the services standpoint, Ni-Resist is a hard weldable material. The tested diaphragm is made of Ni-Resist D-2B that has higher chromium content which results in better corrosion-erosion and corrosion resistance than Ni-Resist D-2 [64].

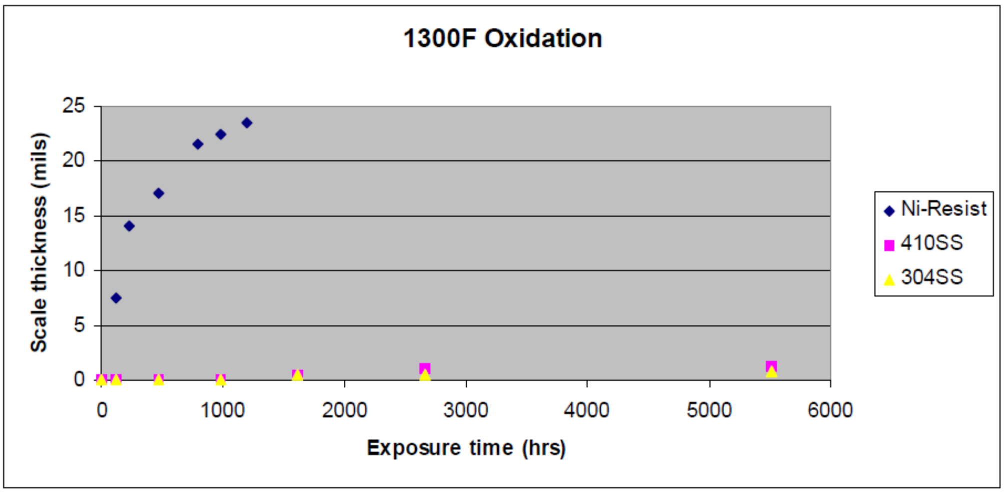
Table 4.1. Tensile Test results for the rounded specimens- HS 188 (AMS 5608) . Chemical composition of Ni -Resist alloys [%] [64]

[% weight.]	Ni	Cr	Si	Cu	Mn	C max	Other
NiResist D2	18.0-22.0	1.75-2.75	1.0-3.0	0,5 max	0.70-1.25	3.0	-
NiResist D-2W	18.0-22.0	1.50-2.20	1.5-2.2	0,5 max	0.5-1.5	3.0	.12-20Nb
NiResist D-2B	18.0-22.0	2.75-4.00	1.5-3.0	0,5 max	0.70-1.25	3.0	

4.2.2. Welding materials used for diaphragm repair.

The welding fillers used for repair of Ni-Resist diaphragms are generally Ni-rod 55 and Ni-rod 44 (AWS A5.15) [65]. These welding materials have low hot corrosion resistance (Fig.4.4). Using them in welding repair processes results in parts' degradation. Thus, parts need to be refurbished when the turbine interval is completed. Manual (without preheat) welding/cladding with those fillers induces cracks (material prone to hot cracking) in a fusion zone that come-out onto the surface.





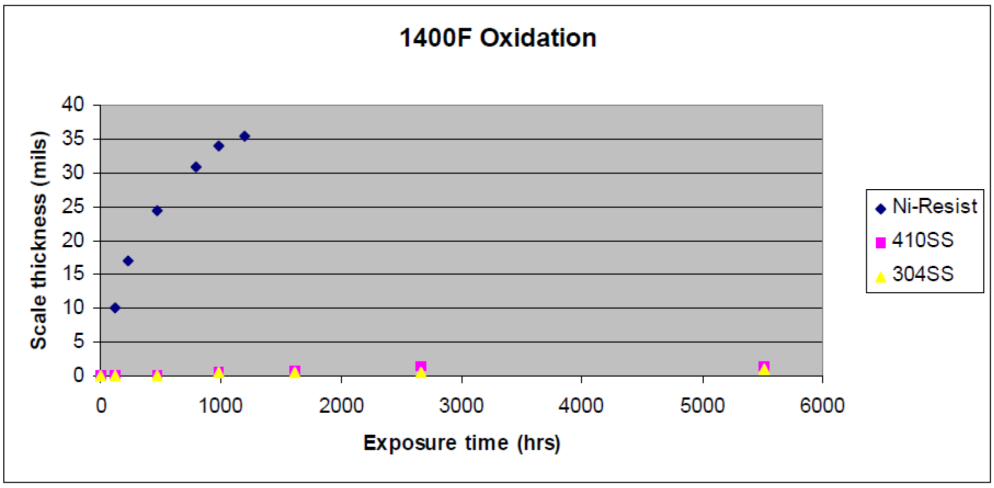


Fig. 4.4 Oxidation curves for 304SS, 410SS, Ni-Resist

The carried-out test proves that good results have been achieved when the diaphragm is cast of nickel iron and the welding filler for is an austenitic stainless steel (for instance 308 LSi) [30]. It is worth underlining that it is a challenge to find welding fillers with similar thermal coefficient to Ni-resist parent metal. During the cladding some cracks may be reported in the fusion zone. Nevertheless, they are inside the substrate and are acceptable from the serviceability standpoint. Chemical properties of the tested fillers are in Table 4.2.

Table 4.2. Chemical composition of Ni-rod 44, Ni-rod 55, 308 LSi welding fillers [AWS A5.15] [65]

[% weight.]	C	Mn	Si	Ni	Fe
Ni-rod 55	0.1	0,1	0,8	55,0	Balance

[% weight.]	C	Mn	Ni	Fe
Ni-rod 44	1,5	1,1	44,0	45,0

[% weight.]	C	Mn	Si	Cr	Ni	Mo
308 LSi	0,03 max	1,0-2,5	0,65-1	19,5-22,0	9-11	0,75 max

4.3. Robot programming development

During the development process the diaphragm has been mounted in the designated fixture on the robot's rotating table. This allowed welding at a different angle inclination of the workpiece. The intent was to make cladding in a flat position. All the sequences, locations and quantity of the welding beads have been determined through development.

A part prepared for additive repair, through milling operations, has straight angles, that are the reference points for the welding robot. These characteristic points A, B, C, D, are the so-called origin points (Figure 8c), on which the User Frames (UF) are built (for each point there is 1 UF working surface). They are the reference points for the offsets for the individual welding beads. The final program is written in the appropriate UFs where the values of the start and end of the weld are defined by register points (PR). The register points are offset (to + or -) according to the given values. In order to perform cladding in the right place, the robot shall have the following data [61]:

- the tilt angle of the part,
- reference point as the base for making a specific welding bead,
- offset in relation to the reference point (its X and Z direction and its value expressed in mm).

In addition, the initial program consisted of motion instructions, input / output instructions, register handling instructions and branching. Each instruction had a consecutive number. The program has been realized through sequential execution of instructions. In the initial phase, the program for the robot consisted of a number of single move instructions that determined the tool center point (TCP) of the robot from the current position to the desired position onto diaphragm at the specified speed and with a linear movement. The method steps for initial programming are shown in (Fig.4.5).

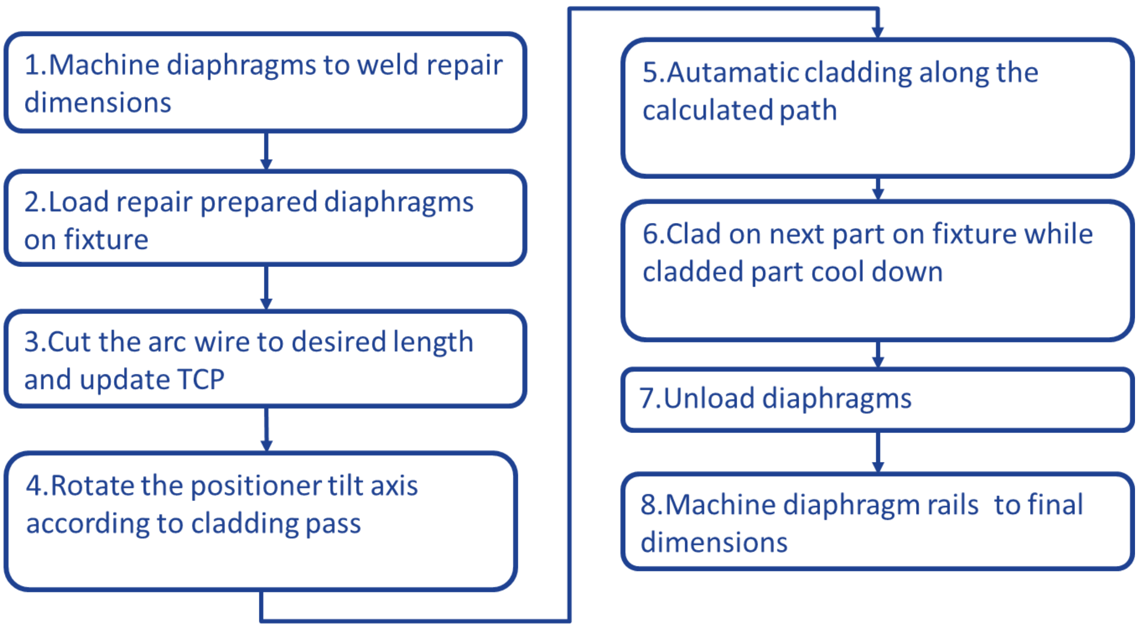


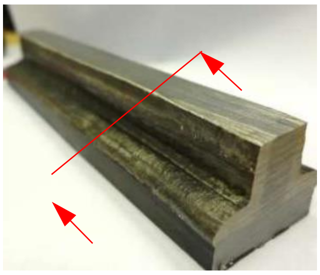
Fig. 4.5 Initial robot programming – method steps

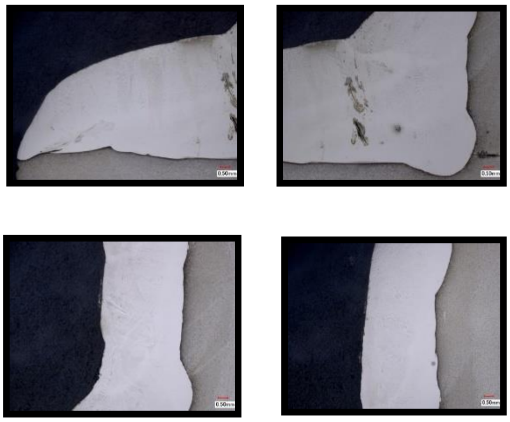
4.4. Synergic lines and welding parameters

The initial steps of development involved creating non-complex geometric forms (Fig.4.6) such as vertical walls in order to set the initial technological parameters and generic settings of the welding source and programmed robot [7, 9]. Initial trials showed that the CMT mode was not applicable (due to concave shape of the cladded beads) for further trials. Thus, MAG pulse mode has been selected (Fig.4.7). It was characterized by higher arc stability (no short circuit), low spattering and sufficient flow of the cladded beads [9]. In addition to that, it has become feasible to perform additive cladding with wide layers where the wall thickness went up to 10 mm. When cladding flat layers, every weld bead was overlayed on each other approx. 200 mm long by corrective lifting of the welding torch in the vertical direction. The whole cladding has been made in a flat position with vertical orientation of the torch. Additional fillet welds have been performed along the length of corners. In parallel, welding parameters have been refined such as starting current (more than 100%), end current (more than 40%) and slope function (flat weld beads less than 1s). During the tests on a real part, large shrinkage stress has been observed. Cladded layers bend inward an upward direction resulting in nonacceptable imperfections. This has been resolved by installation of run-in/run-out plates. It has been also reported that when cladding the first beads (part is “cold”) welding layers have been too wide. To diminish this and have equal size of the cladded layers, Right -Left and Left -Right welding movements have been successfully validated and applied.

(a) **(b)** **(c)**

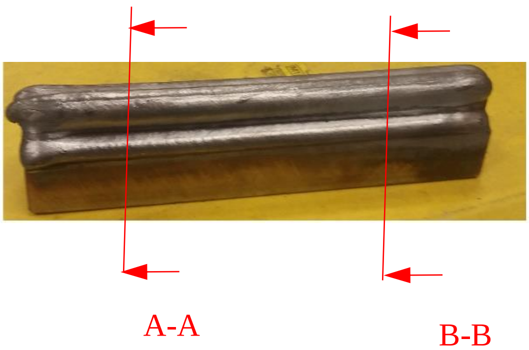
Material Mild Steel S235J
Material Thickness 10 mm
Weld wire dia less than 2 mm
UTP
Gas M12
Synergic Line 19/9 Std Mag Pls
Current 200A
Arc Length +10%
Travel Speed 40 cm/min





(d) **(e)** **(f)**

Material Ni-Resist Cast Iron
Material Thickness 8 mm
Weld wire dia less than 2 mm
308LSi
Gas M12
Synergic Line 19/9 C1700+P
Current 102A
Travel Speed 35cm/min



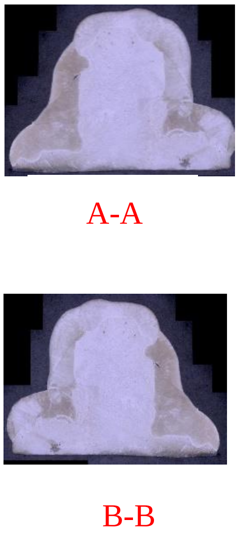


Fig. 4.6 Development of process parameters for diaphragm additive repair, welding parameters (sample 1) used in the development phase (a), additive mockup using (a) parameters (b), cut ups of (b) printout (c), welding parameters (sample 2) used in the development phase (d), additive mockup using (d) parameters (e), cut ups of (e) printout (f)

First welding trails have been conducted on mild steel phantoms and 9FA/7FA diaphragms cut up sections to verify the synergic lines, welding parameters, various fillers and travel speed. Evaluation of the samples are shown in (Fig.4.8).

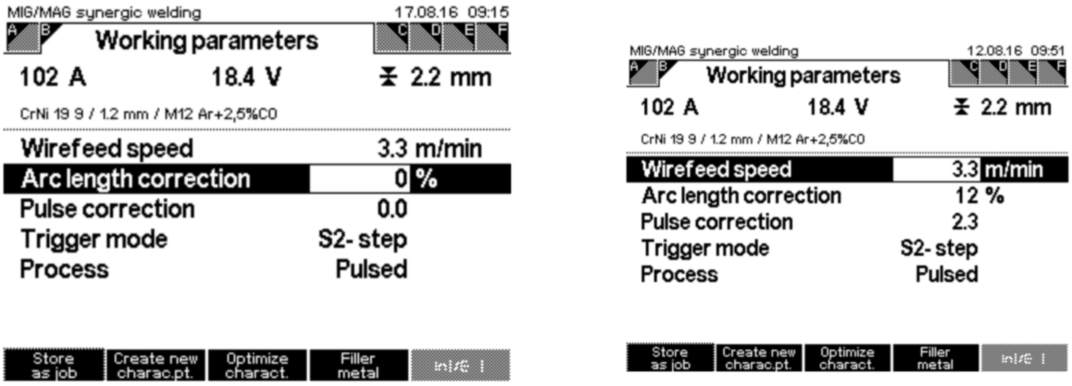


Fig. 4.7 Synergic lines ("jobs") for fillet (left) and flat (right) weld beads (reference)

In the development phase the following samples (Table 4.3) have been made and evaluated (destructive and non-destructive tests) for the UTP , Ni 44, Inconel 625 and 308 LSi weld filler:

Table 4.3. Tests samples performed at initial development phase

Sample No.	Material	Material thickness [mm]	Weld wire diameter [mm]	Synergic line	Current [A]
1	Mild Steel S235J	10	1.2 UTP	19/9 Std Mag	200
2	Ni-Resist Cast Iron	10	1.2 UTP	19/9 Std Mag	170
3	Ni-Resist cast iron	5	0.9 Ni 44	C1700+P	130
4	Ni-Resist Cast Iron	8	0.9 Ni 44	C1700+P	170
5	Ni-Resist cast iron	15+9	0.89 Ni 44	C1700+P	170
6	Ni-Resist cast iron	15+5	1.143 Inco 625	MAG-Pulse	135
7	Ni-Resist cast iron	20+10	1.2 308LSi	MAG-Pulse	102

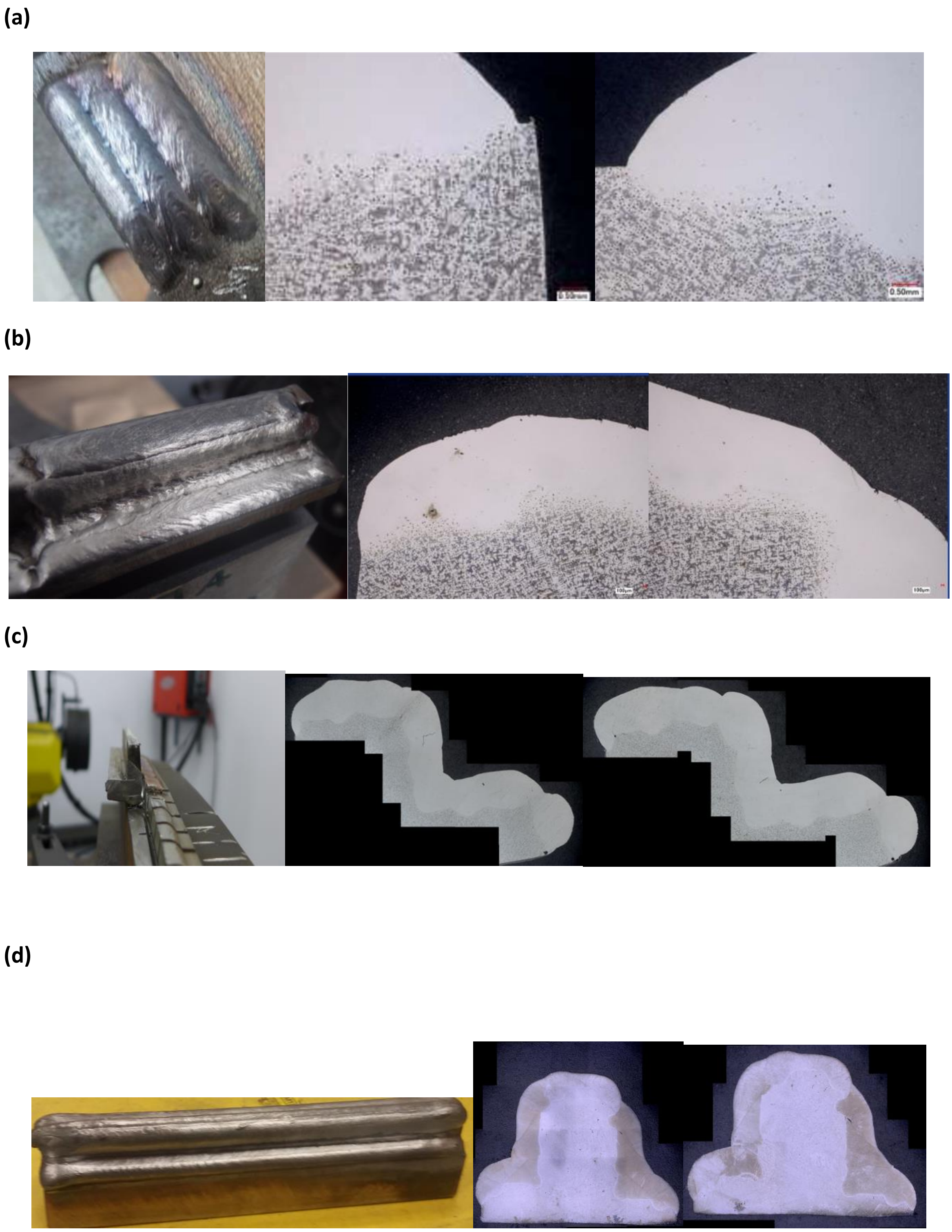


Fig. 4.8 Metallographic evaluation of selected specimens. sample 3 (a), sample 5 (b), sample 6 (c), sample 7 (d)

4.5. Results

The overall results of the welding trials, that is a combination of programming of a welding robot and welding source provides the results that further will be used for diaphragm repair. Welding tests showed that CMT mode is not the best choice due to low heat input and limited ductility of the cladded layers, that strongly affects the geometry of the welding beads (especially width). Thus, CMT mode has been replaced by MAG Pulse mode. As for the weld fillers used in a development phase. The most promising and acceptable results give 308 LSi welding material. It has the desired flowability and has better anti-oxidation properties than the substrate of the diaphragm. However, some of the imperfections can be induced in the material during the wire arc additive process but they are not come onto a surface. Usage of UTP and Ni 44 weld filler caused unacceptable imperfections especially once welding long passes. Inconel 625 was the most expensive alternate option (comparing to other tested fillers) [34]. It has good anti-oxidation properties and during the trials showed more imperfections than stainless steel weld filler.

As seen in (Fig.4.9) the deposition of a weld filler on a test sample is quite significant. Due to that and the properties of the weld filler and diaphragm substrate a special tool need to be introduced to allow the workpiece to cool down. To sustain the productivity the tool needs to accommodate more than one part.

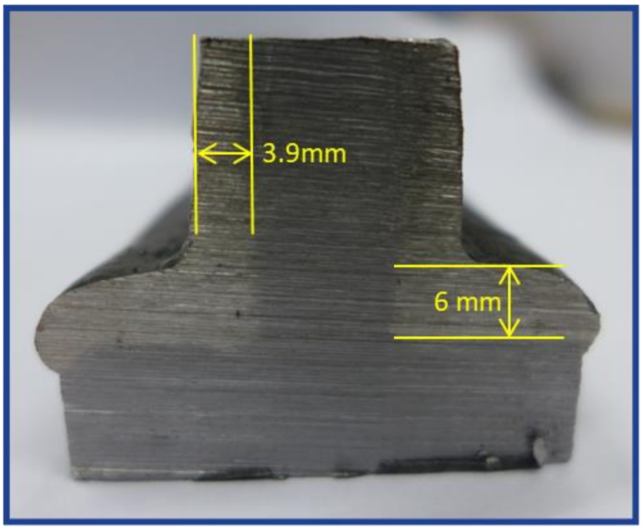


Fig. 4.9 Cladded mockup of diaphragm rail

4.6. Discussion

The design, function, post service condition and material composition of the 7F/9F gas turbine diaphragm makes it an ideal workpiece for wire arc additive repair. It is a stationary component that works in demanding working condition. Post service inspection reports of this part indicate what need to be repaired to allow the part for further turbine operation. In a past the diaphragms have been repaired by manual GMAW (MAG) welding followed by GTAW (TIG) touch up repairs. This was not productive and efficient and caused a lot of reworks. Proposed incremental additive repair is aimed to repair the part faster, with no reworks and increasing the durability of the part by using weld filler with higher anti oxidation properties.

5. Diaphragm repair and implementation

5.1. Scope of the repair

Hot combustion gases flow axially along hot gas path through power nozzles and impact and rotate blades. In addition, a cooling airflow is guided into a wheel space of turbine section. The cooling airflow from a compressor portion is directed through various components of turbine stages to improve wear, reduce localized hot spots, and increase an overall component life cycle. Each nozzle includes a corresponding diaphragm, one of which is shown in Fig 5.1 that provides a seal which prevents hot gases from passing from hot gas path into the rotor area. Loss of hot gases from hot gas path into the rotor space reduces efficiency of turbine module. Over time due to high temperature and working conditions portions of diaphragm may become worn and require localized repair. The excessive temperature causes oxidation and erosion of the rail section where the diaphragm is attached to the nozzle. This paragraph demonstrates a robotized method of repair of 9FA & 7FA diaphragms rails [35].

A method of refurbishing worn/oxidized diaphragm rails for gas turbines comprises machining of the worn/oxidized section of the diaphragm rails such that a clean and geometrically accurate machined surface is achieved. Additive cladding one or more layers on these machined surfaces create a cladding that overtops the nominal dimensions of new diaphragm. The method further encompasses machining the cladded layer such that it has the nominal dimensions of the new-make diaphragm [35].

The suggested robotic additive process (hybrid repair) is aimed to repair/modify 9F/7F diaphragms, that are made of cast of nickel iron and the filler material for cladding the passes is an austenitic stainless steel.

(a) **(b)**

Fig. 5.1 Gas turbine diaphragm (a), Diaphragm rail (b)

5.2. Wire arc additive repair – innovative approach

Repair of the diaphragm shows possibility of 3D additive wire arc welding using GMAW Pulse (MAG Pulse) cladding. Laser additive techniques usually offer accurate, high-quality printouts. Selective Laser Melting (SLM) method, where a laser beam traverses the surface of the powder layer along a predefined profile [29] is a low deposit process used often for blade tip restoration. However, it runs on very expensive equipment and consumables [55]. This is also associated by a long time to prototype the parts. On the contrary, for many years modifications/repairs of gas turbines components have been performed by using best cost competitive methods, including arc welding sources with a gas-shielded consumable electrode [20]. The additive weld build-up process by GMAW can be used to repair degraded and damaged areas on complex shaped surfaces and it is driven by availability of the welding machines, low cost, variety of consumables, high process efficiency and high deposit rate. Specified advantages can be extended by automation, including robotization [11].

The diaphragm repair described further shows possibility of 3D additive wire arc welding using GMAW (MAG) Pulse cladding. The following technological assumptions have been made [7, 9, 55]:

- single-pass cladding - a feature made of a single, multi-layer weld bead
- recurring stops of the process for cooling down of the hardware to control inter-pass temperature (pyrometric control). The part temperature during cladding shall not to go below a minimum temperature to avoid hot cracks in fusion. To prevent that . The applicable tooling that accommodates multiple diaphragms has been designed and implemented. During diaphragm repair the robot switches from part to part in order not to overheat the components.
- robotization of the process with manual trajectory programming,
- multi-pass overlay cladding - multiple application of layers of molten metal with a vertical and horizontal direction increment,
- movement of the welding robot or simultaneous movement of the robot and rotary positioner table (tilt with continuous rotation)
- cladding with the GMAW (MAG) Pulse method using CMT welding source,
- use of advanced control of the welding parameters (gradual rise or drop of the current at the beginning and the end of the weld bead),
- recurring stops of the process for cooling down of the hardware to control inter-pass temperature (pyrometric control). The part temperature during cladding shall not to go below a minimum temperature to avoid hot cracks in fusion. To prevent that . The applicable tooling that accommodates multiple diaphragms has been designed and implemented. During diaphragm repair the robot switches from part to part in order not to overheat the components.

5.3. Robot programming

Repaired components have dimensional and positional variation due to 3 main reasons:

- Post service distortion,
- Run-in/run-out plates preparation,
- Machining tolerances (part preparation)
- Tolerance of tooling

The mentioned variations result in irregular surface and low accuracy affecting weld quality in robotic cladding. Thus, to eliminate these variations and achieve high fusion with accurate positioning. Robotic welding system requires to adaptively set up specific cladding tool paths for each part. Multi-layer cladding generates heat that need to be controlled and decreased during the process. In order to control the heat input and refine process cycle time development the optimal solution is to load three components in the fixture so as a robot can weld the next part while previously cladded part cools down to the certain limits

Once the adaptive tool path generation and cycle time optimization goals are implemented. The robotic welding system comprises the following components

- 6 axis welding robot manipulator with the specified welding software and hardware options,
- 2 axis rotary positioner table,
- Welding fixture to accommodate multiple diaphragms,
- GMAW (MAG) Pulse welding source and wire feed system,
- Torch service station,
- Torch Center Point (TCP) update station with the corresponding camera,
- Robotic safety system

Wire arc additive repair process starts once an operator loading multiple diaphragms into the robotic booth and starting up the system. Robot in the first step cleans a welding torch, cuts weld wire to the desired length and update TCP using camera system. TCP and automated torch service update is crucial to get accurate positional data with the weld wire probing.

Robot initially touches both sides of the run-in/run-out plates to calculate rail length and start/end positions. Then the robot touches 5 edges of the prepared rail to get positional data of reference points A, B, C, D. This is shown as a "slice search" in Figure 5.2.

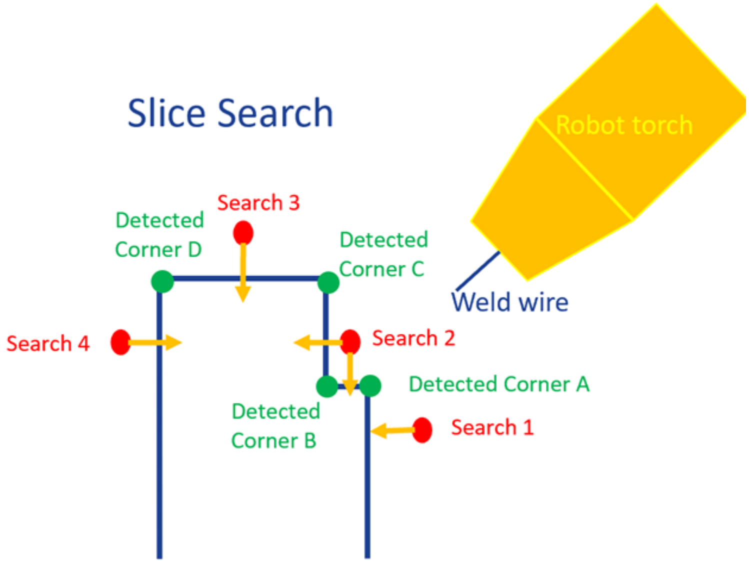


Fig. 5.2 Identification of positional data of reference points

Robot is repeating slice search five (5) times along the rail with a separation between each slice to create radial arc tool path along the rail (Fig. 5.3). The parts are probed, and data is stored for all parts before starting the cladding. Robot is probing all components in positioner at "0" tilt position. Each and every cladding pass has the specific tilt position and defined offsets from certain reference corner. Data for all passes are stored in a recipe program. For each cladding pass robot goes through recipe program and tilts positioner to defined angle. Weld positions and coordinate system updates automatically for each part and robot welds the specific pass with certain offsets from the specific reference point.

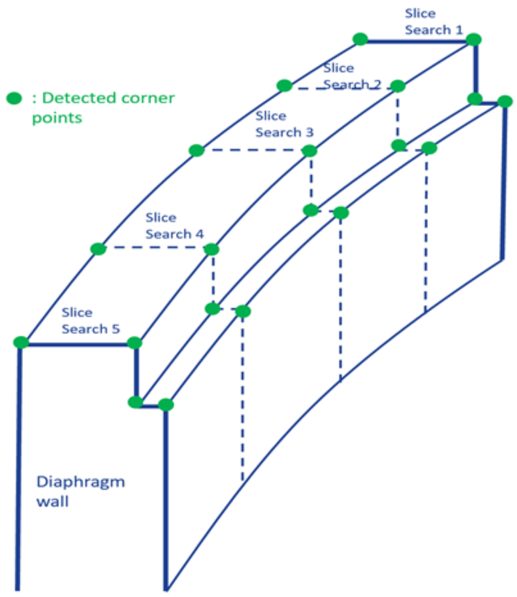


Fig. 5.3 Process of creating radial arc tool path along the diaphragm rail

5.4. Repair steps

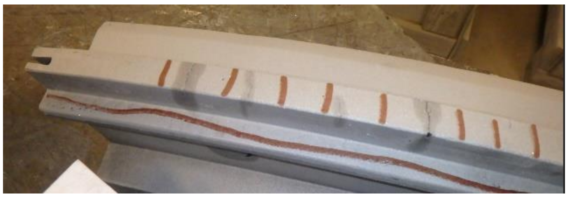
During the recurrent outage of the turbine all the affected diaphragms assemblies are inspected and disassembled if they do not meet serviceable criteria. As written before, typically, due to high operating temperature that causes erosion and oxidation. The affected components are sent out to designated repair Service Centers (SC) where they come in for repair. When parts have undergone incoming processes upon arrival at an SC (dimensional inspection, power nozzle disassembly, cleaning, side seal removal etc.). They are classified for light, medium, heavy, or super heavy repair. The described process is applicable for heavy repair of 7FA diaphragm. It is also applicable to 9FA components with some slight adjustments.

The first step of the repair is to mark up all the areas that need to be machined off during welding preparation. Components are machined by multi-axis CNC machine by using the applicable tooling where the diaphragms are mounted on and datums are constrained. The part’s definition before and after machining is shown in (Fig.5.4).

(a)

(b)

(c)



(d)

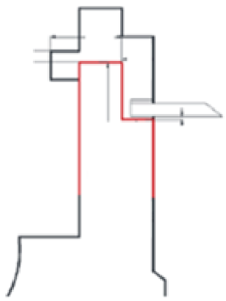
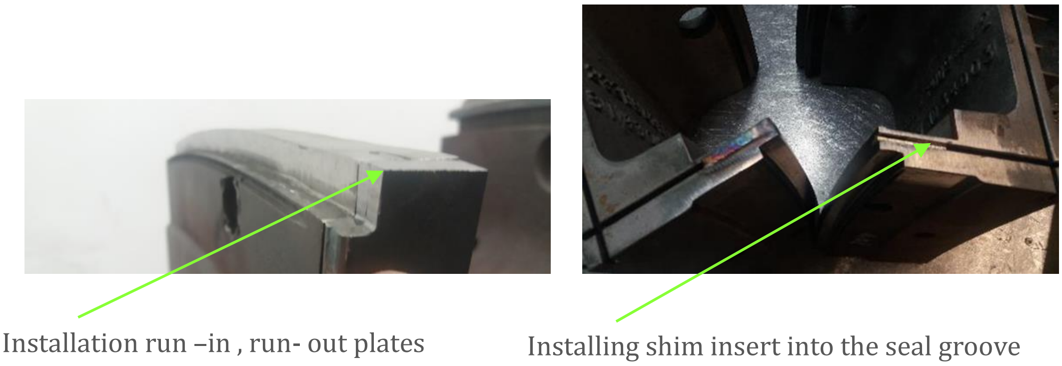


Fig. 5.4 Diaphragm assembly as received by Service Center (a), part after initial machining (b) marked up diaphragm rail (to be machined out) before initial machining (c), cross section of the diaphragm after initial machining – red contour (d)

The initial machining process is followed by NDE (ISO 3452-1) inspection to verify if the component is ready for wire arc additive repair [63]. Before mounting diaphragms on in the welding fixture, run-in and run-out plates are GTAW welded, shims are inserted into the seal groove (to avoid its closure during the welding), assembly welds are grinded out to diaphragm surface and previously developed welding parameters are called out (flat and fillet weld beads).

Once the additive process starts, three (3) diaphragms are measured by welding wire using touch sense mode. As it was written before there only two synergic lines (Fig. 5.5) and two welding positions to repair the parts. During the additive repair, the welding torch installed on the robot's arm changes the component after weld build-up of some of the layers to have the part cooled down (to avoid decrease/trespass the inter-pass temperature of the diaphragm). The rotating table synchronized with the robot changes its tilt and position to allow cladding in flat and fillet positions. This is to ensure that the welded layers have the right geometry and minimizes the welding imperfections. The process is finished when the hook is fully restored. For the developed process it takes more than 50 welding beads (Fig. 5.6) to restore the hook (heavy repair mode).

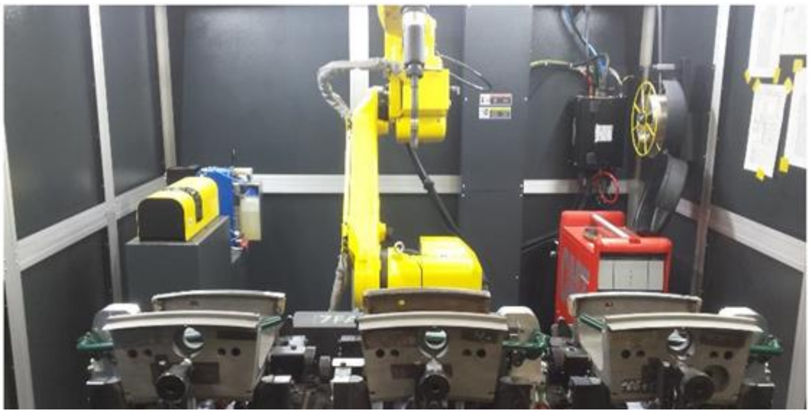
(a)



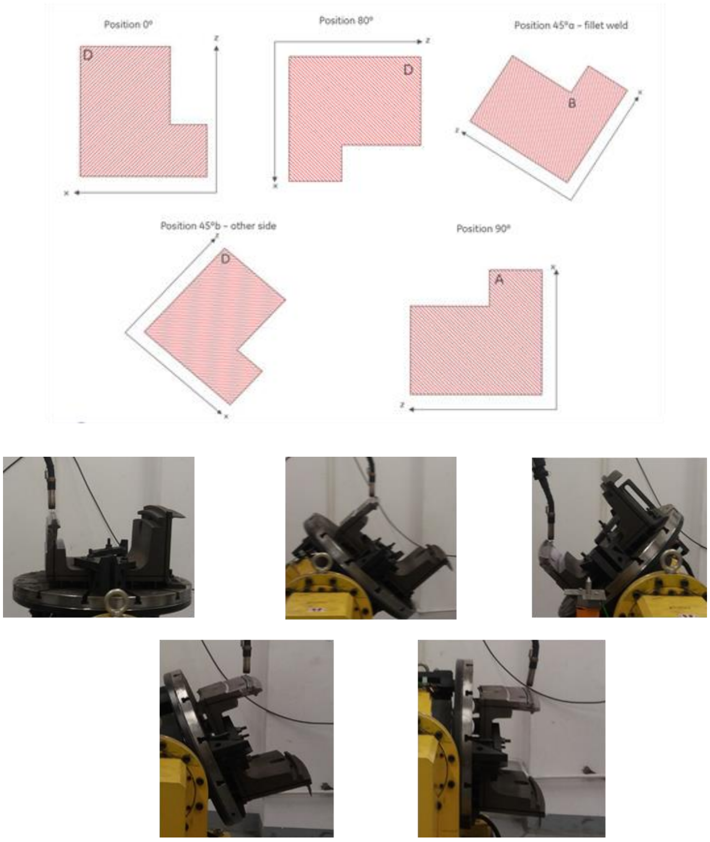
(b)

Fig. 5.5 Installation of shims into seal grove and run-in/run-out plates on a both sides of the diaphragm rail (a) , synergic lines ("jobs") for flat and fillet weld beads (reference) (b).

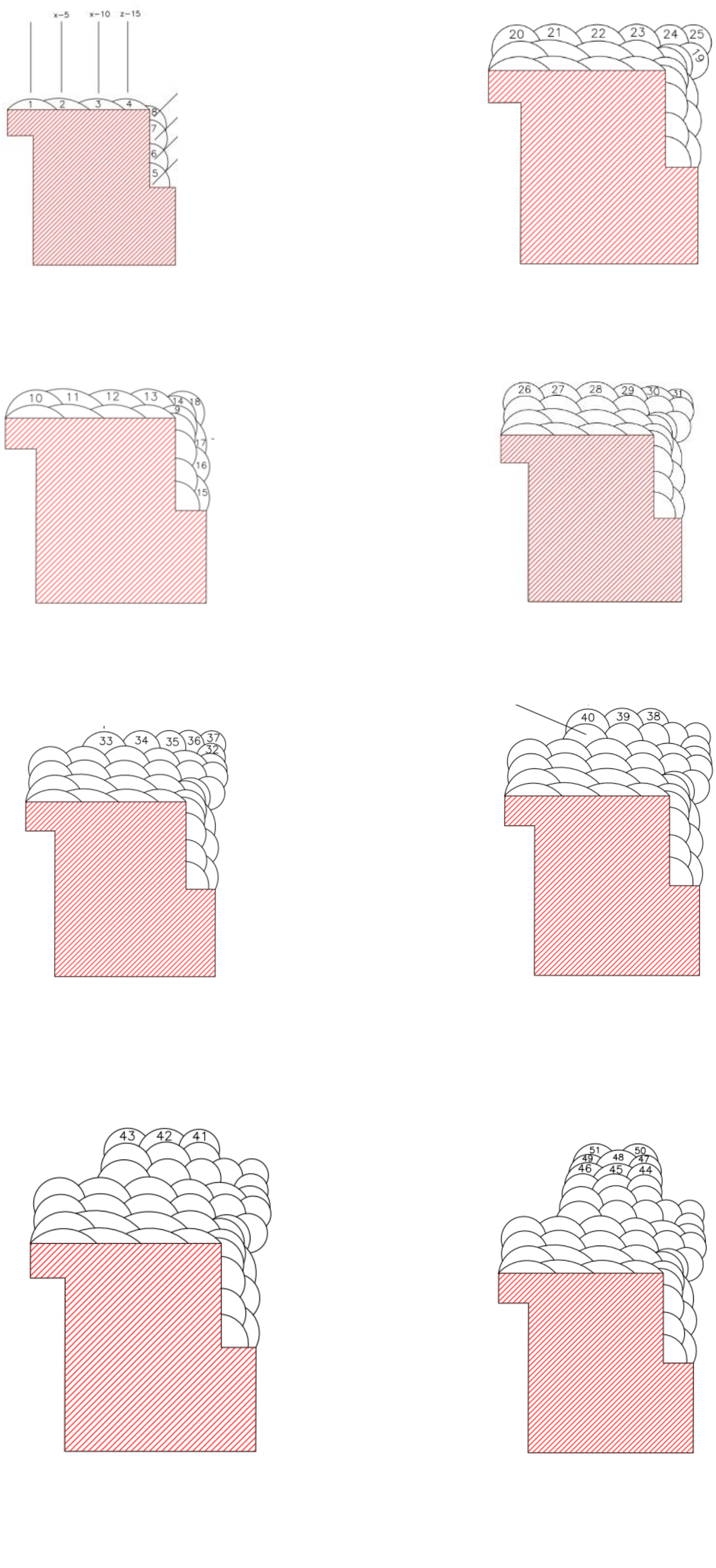
(a)



(b)


Position 0°
D
Position 80°
D
Position 45°a – fillet weld
B
Position 45°b – other side
D
Position 90°
A

(c)


x-5
x-10
z-15
1
2
3
4
5
6
7
8
20
21
22
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24
25
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11
12
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33
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45
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(d)

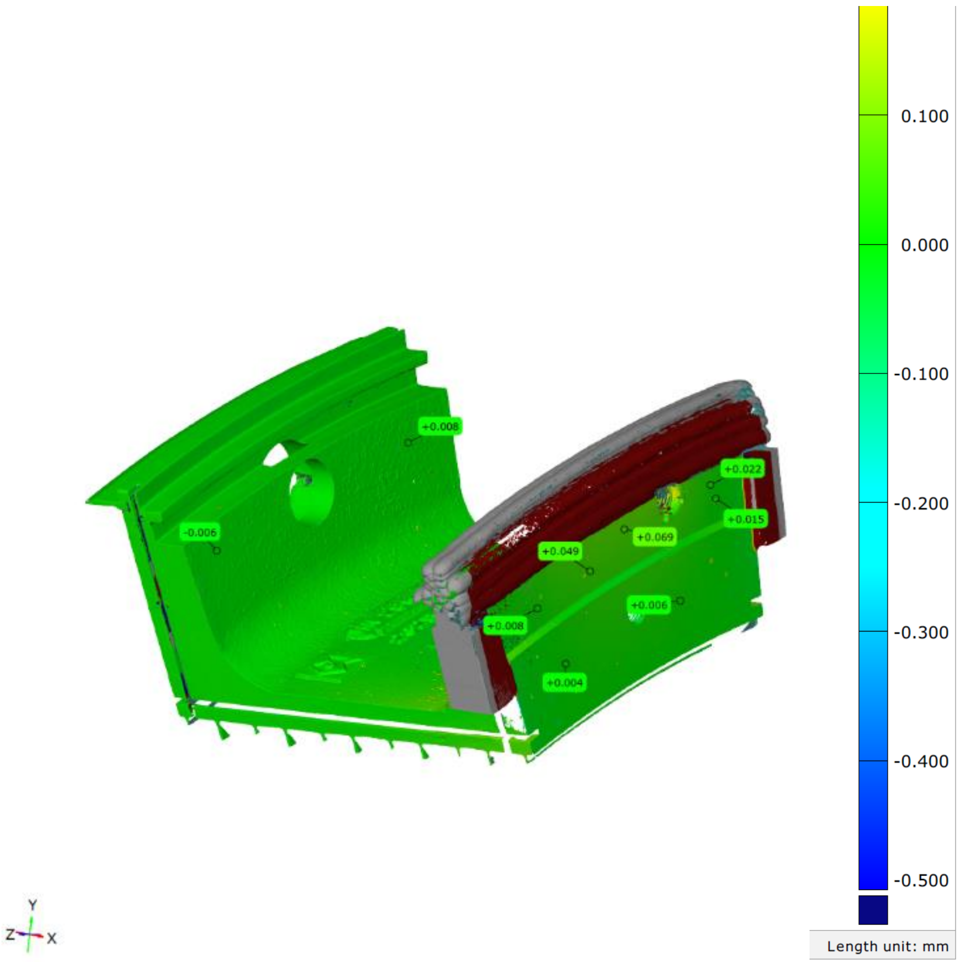


Fig. 5.6 Parts in the designated welding fixture (a), welding angles applied during the additive repair process (b), different stages of cladding a worn diaphragm rail (c), dimensional comparison (blue light scanning) of the part after the wire arc additive repair (super heavy scenario) – verification of part's distortion after cllading– difference from the nominal geometry is shown (d).

After welding, the hardware goes through a post machining process. The developed repair process considers an additional material allowance. Thus, portion of the material is machined off to bring the part to the nominal drawing limits. This step is followed by the Red Dye examination (Fig. 5.7) . If there are any nonconformities, they are being repaired by a manual GTAW welding touch up process.

(a)

(b)

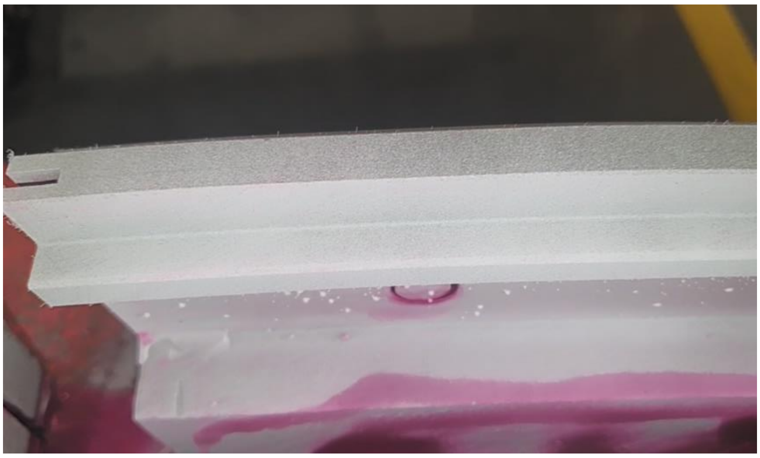
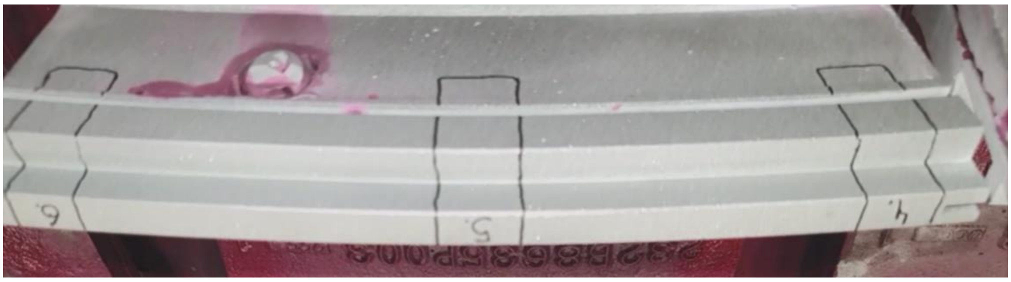


Fig. 5.7 Diaphragm rail after final machining process (a) followed by the Red Dye inspection (b)

During the development of the repair parameters, the first batch of parts have been evaluated by destructive tests. Cut ups have been performed in selected areas to evaluate the quality of the proposed additive process (Fig. 5.8).

(a)



(b)

(c)

(d)

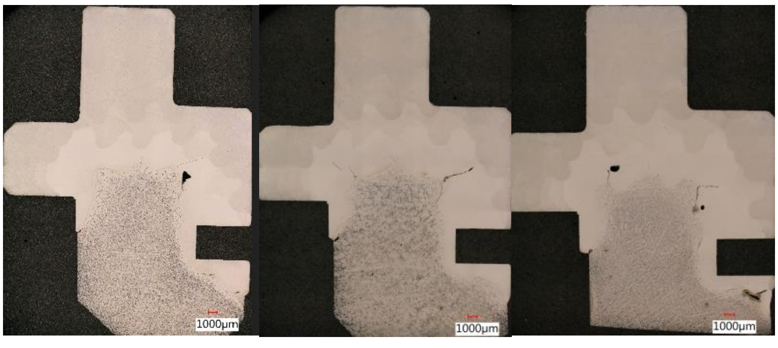


Fig. 5.8 Cut ups after final machining and Red Dye inspection (a) (b) (c) – Material evaluation results of the first batch of diaphragms -cut up no.4 shown (d).

5.5. Results

The proposed method has been successfully executed repairing diaphragm cast of a nickel and if the cladding consists of a weld filler from austenitic stainless steel, such as 308LSi stainless steel. The developed repair is flexible since only the worn parts of the diaphragm rail member are machined and cladded. Those parts of the rail that are not worn or eroded not need be cladded. This means that solely the worn parts of the diaphragm are repaired, reducing costs for machining, and cladding of the diaphragm. In case the distance between the machined surfaces and the nominal dimensions of the part are greater than the thickness of one layer of the cladding, several layers up to ten or even more layers can be cladded to the machined surface of the diaphragm. At the end of the welding additive process the surface of the cladding (layer) overtops the nominal dimensions of a new make diaphragm. Thus, the last step of the repair consists of machining the cladded overlay to the nominal dimensions of a new-make component according to the manufacturer's specification. Machining may be a milling process or any other suitable process.

The developed process may be further improved if the core welding parameters, such as voltage, current and other parameters are adapted accordingly. It is possible to adapt these parameters for each pass of a layer, each layer or only once for welding a complete cladding.

To avoid or at least mechanical stress due to the cladding process it is suggested that in case the machined surfaces have a symmetric cross-sectional area the passes are welded alternating on each side of the axis of symmetry.

5.6. Discussion

It has been proven advantageous if the cladding process is a GMAW process. Further, it has been proven advantageous if the cladding process is supported by an inert gas, wherein the inert gas preferably consists of more than 90% argon and the rest CO2. Combination of the GMAW process with a precisely programmed movement of the robot and positioner as well as the applicable cycle of the welding arc power supply shows that a wire arc additive repair process is feasible on gas turbine components. It has been demonstrated that the wire arc multi-layer additive repair reduces “repair time” of the diaphragm (more than 50%) and provides unique high-performance parameters of the modified parts. Comparing to other modern 3D methods it is considered as a best low cost and easily available process of repairing turbine components. The developed process is beyond laboratory and research scope, it has been already fully implemented in one of the General Electric Repair Service Centers and has a lot of potential to be leveraged to repair other components. Currently the described process is used for light, medium, heavy, and super heavy repairs. For each of these variants there is a different combination of welding parameters and robot/positioner movement. Moreover, introduction of different weld fillers in specific areas of the modified parts is aimed to optimize their durability through the whole life cycle. The selected matrix of the substrate and chosen filler have been analyzed, tested, and verified against anti-oxidation resistance and proved more robust condition of the diaphragm after a control interval. The process is feasible to scale and adjust to other stages and gas turbine frames.

6. Summary and Conclusion

The present research work has investigated the feasibility of using the robotic multi-layer cladding process to repair gas turbine diaphragm that was operating in the turbine for the whole interval. Also, the influences of the parameters during the WAAM process, especially the welding parameters, deposition, interpass temperature and travel speed of the torch on a robot arm have been investigated in details to aim at increasing the process repeatability and stability during repair. Subsequently, in order to obtain further condition of the repaired hardware, an in-depth study of the whole repaired parts and cut up samples have been performed. In addition, the material screening process mainly references to qualification of WAAR processes. Provides the direction on how the specimens for additive technology qualification can be fabricated and evaluated.

A general summary of the principal results obtained from the above work is presented as follows:

- By using the wire-arc additive repair (WAAR) process which incorporates a robot, it is feasible to repair the the gas turbine diaphragm.
- According to the obtained mechanical and oxidation company data the proposed repair can be a hybrid repair process that utilizes weld filler (308L series) different form the substrate (Ni-resist).
- The repaired hardware can be successfully assembled back to the turbine along with having enhanced life cycle.
- Geometry of the part, number of layers that is deposit, height, interlayer-temperature and heat input considerably affected the residual stresses in a WAAR part.
- CMT mode was not applicable (due to concave shape of the cladded beads) for the repair. MAG pulse mode has been used for the repair due to higher arc stability (no short circuit), low spattering and sufficient flow of the cladded beads.

6.1. Research contributions

This project contributes to a better understanding of Wire Arc Additive Repair process and its application in a technology qualification and gas turbine component repair. In the research study, the state-of-the-art of current CMT methods are screened. Further, the study specified the critical parameters related to a qualification of specimen technology, assessed the pros and cons of wire arc additive process, and investigated its use on real hardware.

Wire Arc Additive Repair inspection technologies are currently not fully developed or high cost. Progress in this field is a key challenge in going from the specimen level to the part level, and then full-scale production. In process monitoring for any cladding imperfection is critical to achieve the desired quality. Even small non-conformance in prototyped parts can have a large impact on performance and safety in turbine engines. The current inspection methods generally involve destructive testing to capture any imperfections such as cracks, porosity, and voids. These are generally time-consuming and expensive. However, the right approach to the WAAR qualification will contribute to sustain and even increase the component life. Even though there is still lack of a layer-by-layer inspection process that is efficient and accurate. Thus, a critical aspect of qualification requires a combination of destructive and non-destructive examination methods that account for process variabilities that need to be wisely included in the specification for qualification [51]. Nowadays sophisticated optical and thermal measurement systems are being developed for in process monitoring of WAAR prototyping and fabrication. However, the parameters (including resolution) of many of these methods and techniques are not developed to capture all of the imperfections while prototyping the component. It need to be emphasized that the final inspection of the part (as for diaphragm) is based on the part requirements and working condition, not necessarily on the smallest imperfection that can be detected. The ability to define the repair process boundaries as for material properties, serviceable limits, repair criteria etc. are critical and for the repair process itself and associated process control requirements [51]. It is also advisable to consider the repair history of a component that goes through WAAR repair. For instance, if six tensile test specimens are manufactured one-by-one sequentially, the material properties may be different when all six specimens are made simultaneously without any post-heat treatment. In the alternate scenario the component will be repaired quickly and will experience a higher mean temperature. Specimen variability has been seen in the performed mechanical tensile tests. Beside many of the challenges wire arc additive process offers many of feasible ways to prototype and implement the advanced repairs of gas turbine components at short development cycle times and best costs [51]. Even though, more can be done, and challenges still exist in controlling the arc additive process to further ensure the repair of repeatable and reliable components. Number of technical challenges have been discussed as being the key to accelerated qualification of WAAR components and faster adoption of the wire arc additive technology to gas turbine hardware. All of these need to be included as part of the qualification processes for wire arc additive processes.

On the component side it has been proofed that application of the wire arc multi-layer additive repair significantly reduces "repair time" of the diaphragm and contribute to higher performance parameters of the repaired part. The wire arc additive repair is characterized by high deposition rate, availability and low cost of welding sources and consumables, ease of robotization and easy to control the process like welding GMAW - inverter sources with synergic control [8, 39]. The industrialized robotic additive process (hybrid repair) demonstrates that very good results have been achieved if the diaphragm is cast of nickel iron and the filler material for welding the passes is an austenitic stainless steel (for instance 308 LSi). This is one of the novelties introduced to the described repair process that has granted the patent (ex US11148235B2).

6.2. Further research

Described and proposed research provides answer to challenges related to wire arc additive repairs and modifications of gas turbine diaphragm. However, their number of stationary components (in long term perspective also rotating parts) and WAAR areas that can still be investigated in the future:

- The diaphragm repair process is currently implemented in one of the General Electric Service Centers. The developed process is used to repair 7F/9F diaphragms. Currently, works are being carried out on the use of the current robotic station to repair/restore of the sealing slot (Fig. 6.1)

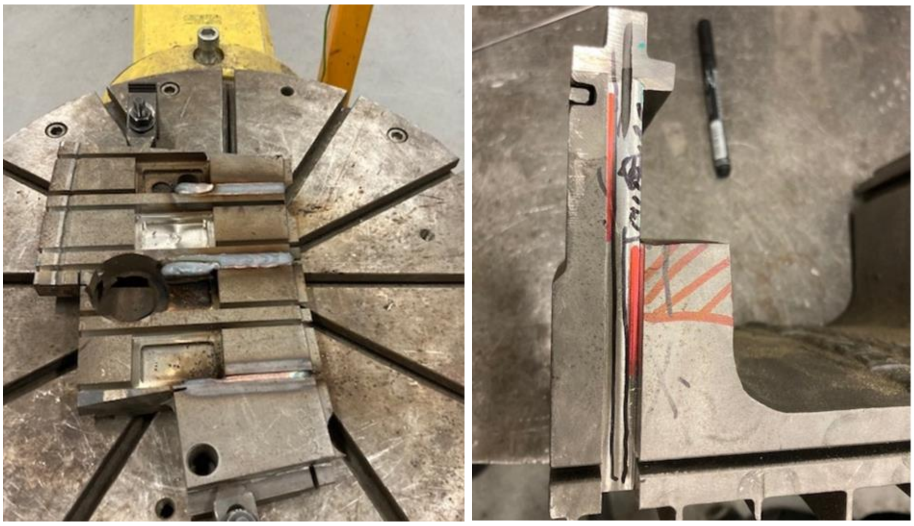


Fig. 6.1 Diaphragm seal slot repair by wire arc additive method.

- Robotic multi-layer wire arc cladding is being investigated to repair gas turbine fuel nozzles (FN). Fuel Nozzles tips work in the close area of the flame that results in oxidation. The proposed regeneration process is aimed to eliminate the disadvantages of the manual process and ensure high repeatability. It is possible to repair these parts both with the original parent material as well as with materials with better anti-oxidation properties (e.g., cobalt or nickel alloys). As part of the scientific activity, a repair simulation (robotized welding) of fuel nozzles has been performed. The purpose of the tests was to determine the boundary conditions (parameters, shrinkage, measurement inspection, machining) when repairing fuel nozzles tips. The modification is aimed to restore thickness of the FN surface according to the new-make drawing and to verify the use of a filler material other than the substrate (currently HastX nickel alloy). The performed trials and obtained results qualify the repair for use in the repair facilities (Figure 6.2).

a)

b)

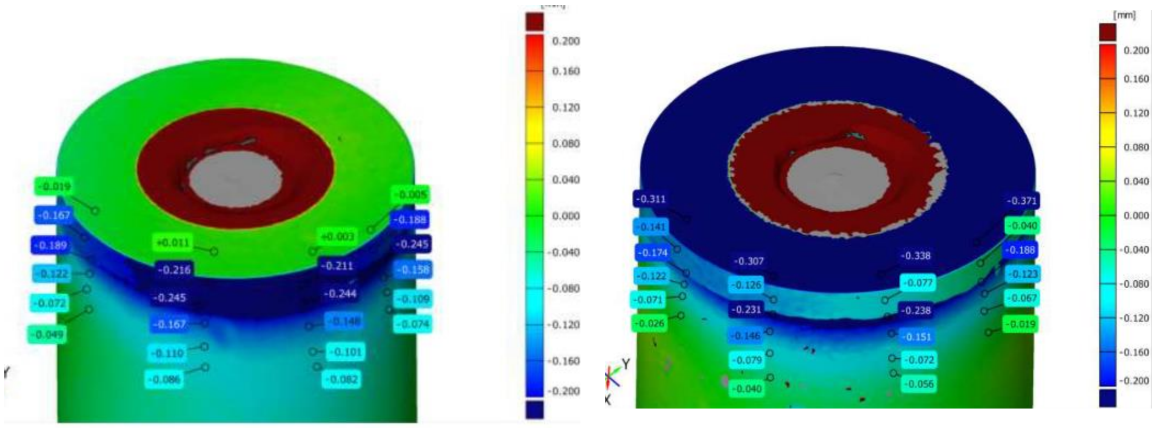
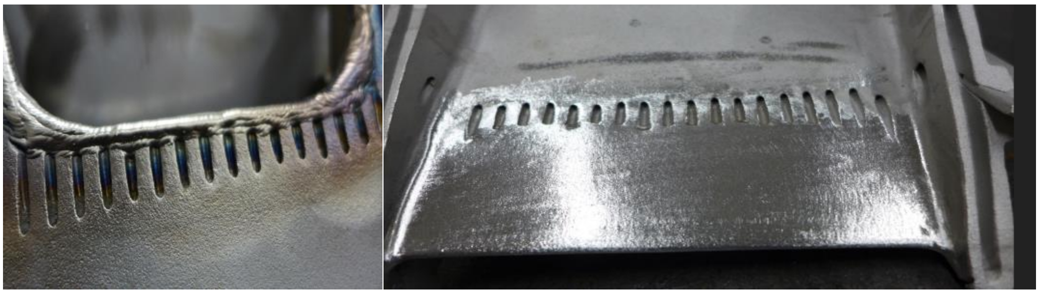


Fig. 6.2 Gas turbine Fuel Nozzle - the process of wire arc additive robotic repair (robot welding, post machining) (a), Dimensional inspection (shrinkage, strain) after additive robotic repair – difference from the nominal geometry is shown (b)

- A simulation of modification (manual GTAW welding) of the gas turbine first stage power nozzle (PN) has been performed (Fig. 6.3). The purpose of the test was to determine the boundary conditions (parameters, shrinkage, measurement inspection, heat treatment effect) when modifying the trailing edge of the PN's vane. The modification is aimed to restore the trailing edge of the vane according to the changed geometry and to enable the use of a material other than the base metal (currently FXS 414 cobalt alloy). The trials provides the substantiation to proceed with the wire arc robotic repair.

a)



b)

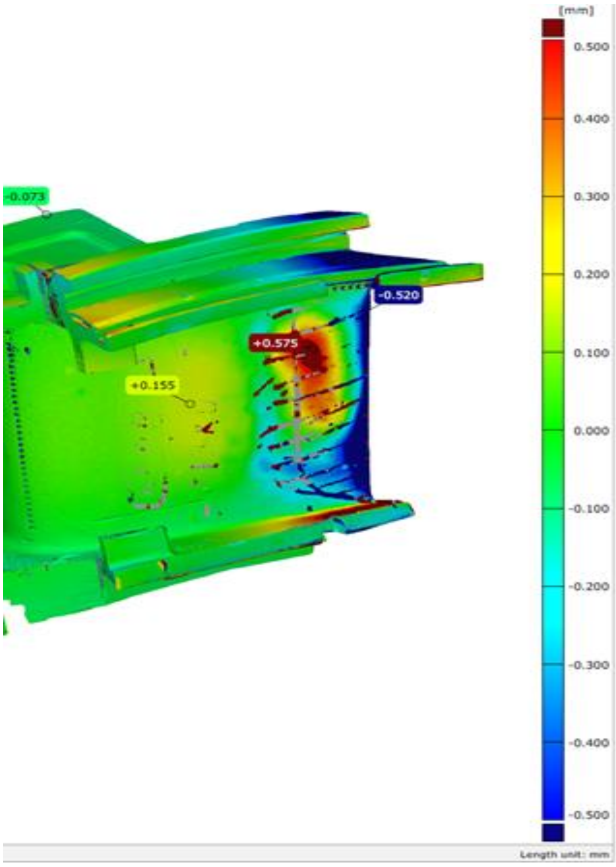


Fig. 6.2 Gas turbine power nozzle during and after manual GTAW repair of the trailing edge, (a), Dimensional inspection-blue light scanning (shrinkage, strain) after GTAW repair – difference from the nominal geometry is shown.

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(12) **United States Patent**
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(10) **Patent No.: US 11,148,235 B2**
(45) **Date of Patent: Oct. 19, 2021**

(54) **REPAIR OF GAS TURBINE DIAPHRAGM**

(71) Applicant: **General Electric Company,** Schenectady, NY (US)

(72) Inventors: **Andrzej Marcin Ostrowski**, Laskarzew (PL); **Krzysztof Dynak**, Warsaw (PL); **Michal Kowalczyk**, Baranow (PL); **Marek Miekus**, Warsaw (PL); **Piotr Jerzy Steckowicz**, Warsaw (PL); **Tomasz Michal Szewczyk**, Warsaw (PL)

(73) Assignee: **General Electric Company,** Schenectady, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 59 days.

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(58) **Field of Classification Search**
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See application file for complete search history.

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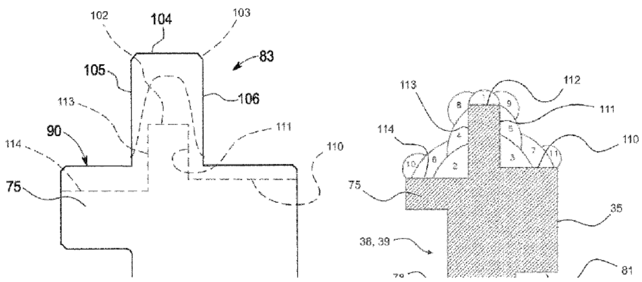
(57) **ABSTRACT**

A method of refurbishing worn diaphragm rails for turbo machines. This method comprises machining the worn part of the diaphragm rails such that a clean and geometrically exact machined surface is achieved. Welding one or more layers on these machined surfaces builds up a cladding that overtops the nominal dimensions of new diaphragm. The method further comprises machining the cladding such that it has the nominal dimensions of a new diaphragm.

14 Claims, 11 Drawing Sheets



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(54) **REPAIR OF GAS TURBINE DIAPHRAGM**

(71) Applicant: **General Electric Company**, Schenectady, NY (US)

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(73) Assignee: **General Electric Company**, Schenectady, NY (US)

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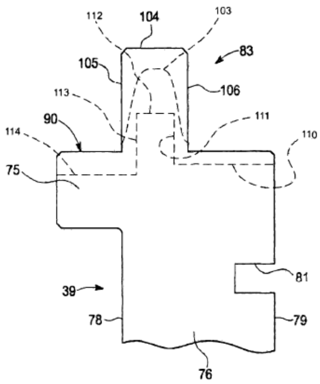
(57) **ABSTRACT**

A turbomachine diaphragm including a sealing section having a first end portion that extends to a second end portion through an intermediate portion; and at least one rail member including a first end section that extends from the first end portion of the sealing section to a second end section through an intermediate section having an inner surface section and an outer surface section, the second end section including multiple weld passes disposed on opposed sides of the second end section for mitigation of thermal tensions on the diaphragm, the multiple weld passes forming a cladding welded to the diaphragm, wherein the cladding includes a stainless austenitic steel.

6 Claims, 11 Drawing Sheets



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(54) **MULTIFRAME BLADE TIP WELDING FIXTURE**

MEHRFACHRAHMEN ZUR FIXIERUNG VON SCHAUFELSPITZEN BEIM SCHWEISSEN

MONTURE MULTI-CADRE POUR LE SOUDAGE D'EXTRÉMITÉS D'AUBES

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