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WIRE ARC ADDITIVE MANUFACTURING COMPARED TO CONVENTIONAL SUBTRACTIVE MANUFACTURING

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Abstract: *Wire arc additive manufacturing (WAAM) is an emerging technology that offers several benefits over conventional subtractive manufacturing methods, such as CNC milling. In this paper, we investigate the implications of WAAM for the production of large gauge thin-walled parts, which are typically difficult and costly to manufacture using milling technologies. This research proposes a design of a WAAM cell architecture and compare its performance with a conventional CNC machining centre in terms of equipment costs, manufacturing time, material loss and tool wear. A case study of a part that is manufactured by both methods which analyses the results is presented. During this research it was found that WAAM can reduce the manufacturing time by about 15%, the material loss by 97%, and eliminate the tool wear. This led to the conclusion that WAAM is a promising technology which can increase the efficiency and flexibility of manufacturing processes, especially for expensive materials that are more challenging to process using conventional methods. The limitations and future directions of WAAM are also discussed within this research.*

Key words: *WAAM, Subtractive manufacturing, Manufacturing Simulation, WAAM cell architecture, Cost-benefit analysis*

1. INTRODUCTION

Wire Arc Additive Manufacturing (WAAM) was first patented in 1920 and is probably the oldest, outwardly simplest, but least talked about of the range of additive manufacturing (AM) processes (commonly known as 3D printing). WAAM is a promising additive manufacturing process where an electric arc in combination with a wire as deposition material is utilized for manufacturing. This process is part of the direct energy deposition (DED) manufacturing, which includes, for example, laser cladding [1]. Over the past years, the demand for WAAM has potentially increased, and it has become a promising alternative to subtractive manufacturing. Research reported that the wire arc additively manufactured (WAAMed) material's mechanical properties are comparable to wrought or cast material. In comparison with other fusion sources, WAAM offers a significant cost saving and a higher deposition rate [2]. The welding processes used in WAAM are gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and plasma arc welding (PAW). The selection of the welding process for WAAM depends on the type of material and applications [2]. In most cases a robotic arm is used for motion control. This technique offers a high deposition rate (up to 10 kg/h) and can be used to fabricate metal parts with complex geometries. A post-deposition rolling process can be applied to the weld beads to enhance the mechanical properties of the deposited material and achieve similar performance as rolled parts.

Additive manufacturing technologies that use metal deposition by GMAW/GTAW welding offer a promising alternative for industrial parts production, as they can produce large parts with low cost and time compared to conventional methods [3]. This paper examines the feasibility and benefits of these technologies, focusing on Wire Arc Additive Manufacturing (WAAM), the mechanical properties of WAAM parts, and the process description for a specific case study. WAAM parts have comparable mechanical strength and toughness to cast parts [4], and the process can be automated using industrial robots for material deposition, handling robots for transportation, and machining centres with automated feeding and positioning for surface finishing [5].

Despite its potential for prototyping and structural integrity, WAAM has not advanced as much as other additive manufacturing technologies due to several drawbacks:

- The high heat input during the welding process, which causes residual stresses in the material.
- The poor precision and surface quality of critical surfaces, which require further machining for most applications.
- The lack of optimized "CAD to CAM" systems to include variable process parameters for generating and programming 3D material deposition paths.
- The absence of real-time monitoring and control systems for material deposition parameters.

1.1.Motivation

The research topic and the specific case study were chosen to illustrate the advantages that can be achieved by using additive manufacturing technologies, especially WAAM.

Therefore, the first aspect of interest is the economic factor, which shows the possible cost reduction by using the WAAM manufacturing technology mainly because conventional machining of large parts with thin walls removes up to 90% of the base material, compared to the material removal in the case of WAAM, which is minimal. The only material removal is done during the surface finishing operation.

A second factor to be considered is the manufacturing time. Since the material deposition rate of the WAAM technology is high, significant differences in processing time and therefore delivery time of the parts are observed. Nowadays, when most companies work according to a "Just in Time" model, this argument becomes important for them to remain competitive in the market. [6]

A final argument could be the production flexibility achieved given by the automation of the process. Thus, using a robotic cell specialized for additive manufacturing processes, a much higher parts nomenclature can be obtained compared to the classical processes. This can be achieved by using the robot both for material deposition and for the subsequent finishing operations, which create a manufacturing cell suitable for “lot size one” production.

2. METHODS

A functional part representing the nose cone of an aircraft fuselage (fig. 1) was selected as a case study to compare the performance of WAAM and conventional subtractive technologies. The dimensions of the workpiece to be made, i.e. a cone with a base of 503 mm and a height of 443 mm and a wall thickness of 7,5 mm and the mass of the finished part of 15,943 kg.

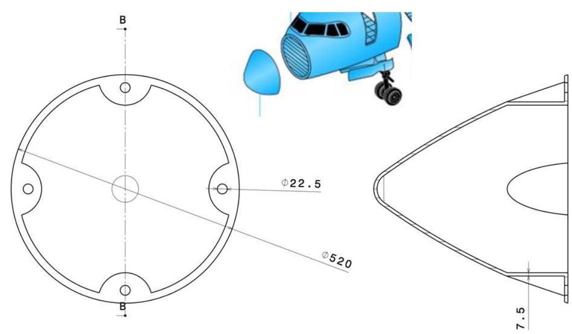


Fig. 1. “Fuselage cone” case study part

This part poses geometrical challenges and demands high mechanical and quality properties.

The part was made of Ti6Al4V, a titanium-aluminium alloy commonly used in the aerospace industry [7]. This alloy exhibits low machinability, but high weldability, which makes it favourable for WAAM.

To simulate the manufacturing process using WAAM, a manufacturing cell capable of a GMAW welding was designed. As depicted in figure 2, the following components are required for this purpose:

- 6-axis robotic arm (1)
- positioner for fixing workpiece (2)
- auxiliary controller for the robotic arm (3)
- welding source capable of GMAW (4)
- automatic GMAW gun (5)

• a safety system, including protection fences, optical barriers, gas exhaust system, etc. (6)

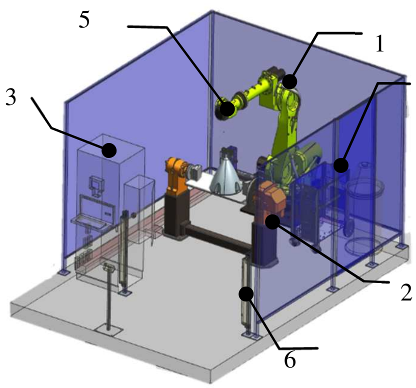


Fig. 2. WAAM cell

2.1. WAAM cell architecture

A Gantry-type robot, which has linear movements on the three working axes, can perform this process, but it has drawbacks in terms of the range and complexity of the parts that can be produced. Therefore, this study is focused on utilizing the capabilities of industrial robots. The theoretical model proposed, combines a welding source with a six-axis articulated robotic arm, which offers much more flexibility and versatility in manufacturing.

The articulated robotic arm is the key element of the additive manufacturing cell. The chosen articulated robotic (position 1 from figure 2) arm has a positioning accuracy and repeatability of ±0.03 mm, which meets the requirements for applying welding ropes and achieving the expected dimensional accuracy, with tolerances up to ±0.2 mm. To ensure accessibility, the orientation table of the fixtures was designed to have dimensions of 1000x500mm, which can accommodate larger fixtures if needed. Consequently, the robotic arm was chosen to have a working radius of 2032 mm (with axis 5 at 90º, in working position) and a minimum radius of 500mm, resulting in an effective working space of 1500 mm in radius. The WAAM speed considerations are also satisfied, the maximum speeds required for the AM process do not exceed 8.3mm/s, while the robotic arm can reach the maximum speed on a 500mm/s free path. Also, the axis positioning control is done with an absolute encoder instead of an incremental one. Thus, in the event of a power failure or accidental shut down/interruption (e.g. the safety optical barriers sensor is activated), the coordinates on each axis will be retained and work can be resumed from where it was left off.

The designed additive manufacturing cell also has a single-axis servo positioner with a 300 kg load capacity to enable more flexibility (figure 3). This is necessary for producing parts with higher geometrical complexity that require the part to be adjusted for optimal alignment of the welding gun. Additionally, the servo positioner can tilt the part orientation and clamping device that supports the material deposition. It can ensure accuracy and consistency of the parts produced and it can return to its working position in case of process interruption. The positioner consists of only the flange driven by a servomotor gear, while the auxiliary flange and its frame must be fabricated by the manufacturing cell integrators. The maximum distance between flanges is 1100 mm, and the performance of the actuator is determined by the maximum angular speed at the specified load of 160º/sec, and the maximum stroke of 740º.

The criterion from which the design of the manufacturing cell starts is the workspace required by the robot. Relative to this, the positioner with the clamping device and the workpiece will be positioned, at a distance recommended by the accessibility principles (approximately half of the maximum working radius) at a distance of 1100 mm measured from the centre of robot's rotational axis and that of the positioner.

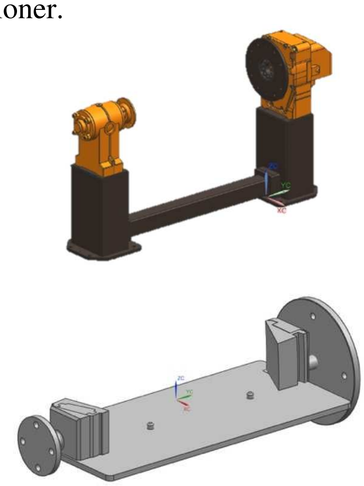


Fig. 3. Servo positioner with the designed frame and the auxiliary flange

Also, within the cell, the command-and-control centre will be placed, which will contain the electrical cabinet necessary for integrating all the elements of the cell together with the controller of the robotic arm. The chosen controller can control the following parameters: Continuous deposition of material without interruptions of the welding arc; Correlating material deposition synergistically with robot movements; Adjusting speed and implicitly welding parameters in relation to heating of workpiece, to obtain uniform beads.

Although WAAM can be done in several ways, the GMAW process, was chosen for theoretical representation. This welding process involves the use of the filler material (the welding wire) as an electrode and was chosen because of the high productivity resulting from a relatively large deposition rate of the material. As disadvantages over other processes, it remains an inferior surface quality.

The welding gun used for this process must be chosen based on two qualities: to be suitable for the GMAW process and to be integrable into a robotic manufacturing cell. Thus, the chosen welding gun is air-cooled, with a neck geometry inclined at 45^o, with a wire diameter capable between Ø 0.8-1.4 mm. An adjustable assembly system had to be designed so that it can be adjusted in its inclination to the 6th-axis of the robot, making it flexible in process changes. This clamping system uses elastic bushes, which precisely orientates the welding gun. Thus, the transition between the mounting point of the welding gun and TCP (tool control point), the programmed point of the tool, can be easily made.

An important element of the WAAM cell is the creation of a safe working environment for people working with industrial robots.

For consultation of safety rules when working with industrial robots or robot cells, the ISO 10218-2011 [8] standard has been considered. To achieve a safe working environment, 4 elements have been added to the system: a mechanical protection fence, shielding for protection against UV radiation, optical barriers, and an exhaustion station, as can be seen in the figure 2. The safety fence has 800 mm clearance from any moving element inside it, as the standard specifies. Ergonomics are also considered, leaving enough space for optimal operation inside the machine for the necessary programming, maintenance, and subsequent repairs.

Another aspect is protecting the welding robot, as it will be working in a high temperature and dusty environment. Therefore, it will be covered with a refractory foil with ceramic inclusions, for reduced maintenance of the equipment and prolonging its life by protecting the joints from metal splashes, dust and thermal radiation resulting from the GMAW welding process.

From the concepts listed above, the manufacturing cell components are selected as follows:

- Fanuc ArcMate 100i/8L robot
- A positioner for orienting and clamping the parts
- An auxiliary controller Fanuc R-30iB-Plus
- GMAW Miller Continuum™ 350 capable welding source
- Automatic GMAW gun - Binzel Abicor ABIROB® A500
- Protective fence with included shielding
- Optical barriers IFM OY047S with G1501S safety relay
- Exhaust gas station

2.2. Case study

The case study developed to support this paper's topic is based on a comprehensive comparison between classical manufacturing processes and the WAAM additive manufacturing process. Thus, a theoretical study was carried out with the help of accessible software packages, and representative values in terms of time units, cost and mechanical characteristics of the results were assessed after their use.

To analyse the manufacturing time, the real values of the two processes were simulated. The process starting data is defined by the material of the part, a Ti-Al alloy, specifically Ti6Al4V, and the mass of the finished part 15,943 kg. For this study only the active manufacturing time has been observed, without analysing the auxiliary times.

First, the conventional subtractive manufacturing process was simulated using the CATIA software package, specifically the Prismatic Machining module. The process was divided into 3 operations, 2 rough milling operations and one drilling operation. The tool and the milling parameters were chosen for Ti6Al4V using the CoroPlus ToolGuide application provided by the Sandvik [9]. In both cases carbide tools were used, specifically a CoroMill 300 ∅ 46 end mill and a 22.5x320 TiN coated drill.

The process parameters used for rough milling are: Depth of cut a_p=5 m; Cutting speed v_c=54.2m/min; Feed/revolution f_f=0.15mm/rev; Feed/tooth f_z=0.487mm;

To produce the part by the conventional milling it was necessary to divide the process into 2 operations, the first operation contains a roughing with a finishing pass for the outer surface of the cone, followed by drilling, then in the second operation the roughing processing of the inner surface of the cone, as can be seen in figure 4. The manufacturing time was determined by the machining simulation as the sum of the cycle time for each operation as follows:

Total CNC time = $T_{roughing1} + T_{drilling} + T_{roughing2}$ = 41h

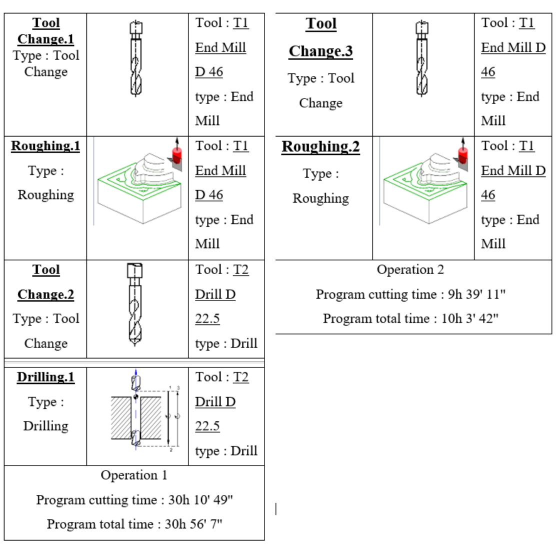


Fig. 4. Conventional subtractive manufacturing process

After this simulation it has been observed that the finished part has a volume of 3574.6 cm^3 and the rough stock has a volume of 121680 cm^3. These values give a percentage of material used of 2.93%, which means that the material loss through chipping is 97% for this part.

For the second case, the WAAM process consists of developing deposition trajectories. This is done by dividing the part into segments of uniform cross-section that mimic the cross-section of the weld beads to be deposited (slicing) taking into account the deposition direction, the positioning of the workpiece, the estimated cross-section of the weld bead and the welding and kinematic parameters required to achieve it. The material properties and thermodynamic behaviour also need to be considered.

For technological reasons it was chosen to deposit the walls of the "fuselage cone" part on a previously laser-cut flange, so that it was no longer necessary to separate the part from a pre-existing blank, thus adding auxiliary milling operations to the process.

After the WAAM process, the external profile of the part will be finished by a finishing turning operation, with an estimated depth of cut of max. 3±1.5mm.

A review of the literature in this field revealed that the most influential factor on the wall thickness of the deposited layers is the current. The higher the current, the more material is required to keep the arc gap constant. The energy level also affects the wall thickness, which increases as the energy level rises and decreases as the travel speed and the component size increase [10].

The parameters used for this process were chosen as presented below:

- Wire deposition speed = 6700mm/min
- Wire diameter = 1,2mm
- Welding current = 310 A
- Welding voltage - 27V
- Shielding gas flow Ar 99% - 15l/min

To this is added the finishing turning time of 0.38h and the waterjet cut [11] of the support flange which is 0.15h

Total TWAAM = 31,67h + 0,53h = 32,2h

2.3. WAAM Simulation

In the context of conventional manufacturing processes, computer-aided manufacturing (CAM) simulation is a well-established and validated technique. However, for WAAM processes, additional steps are required to accurately simulate the process. These additional steps are necessary to be taken into account for the unique characteristics and complexities of WAAM processes.

After analysing the material and welding process, the next step involved defining the layout of the manufacturing cell and programming the necessary trajectories for material deposition. This was accomplished using the Manufacturing module of the Siemens NX 12 software package, which facilitated the simulation. The programming of the robot's trajectory was divided into phases, including rapid movement to the working position, material deposition, and return to the starting position. These operations were defined as a result of programming the robot trajectories.

In order to realize the integrated additive manufacturing cell, it was necessary to define the required tooling, specifically the automatic GMAW gun. As this tool was not available in the software package library, it was imported as a 3D model and its characteristics (such as wire diameter) were defined. The coordinate system for positioning the tool holder on the sixth axis flange of the robot and defining the coordinate system of the TCP were also established (figure 5).

Fig. 5. Defining GMAW gun coordinate systems

After defining the tool characteristics, the kinematic model of the Fanuc ArcMate 100iB/8L robot was imported from the software package library. Its positioning was done by superimposing the coordinate system of its base over the coordinate system imported model. This served as the reference point for the positioning of the other components, which were defined relative to it. The tool was attached to the robot arm by aligning the coordinate system of the middle end of the robot's 6^{th} axis flange with the coordinate system of the welding gun's seating point at the end of its support. The servo positioner is placed relative to the robot position, then the support flange's mounting point is then oriented by the bolts and the servo positioner's support plate.

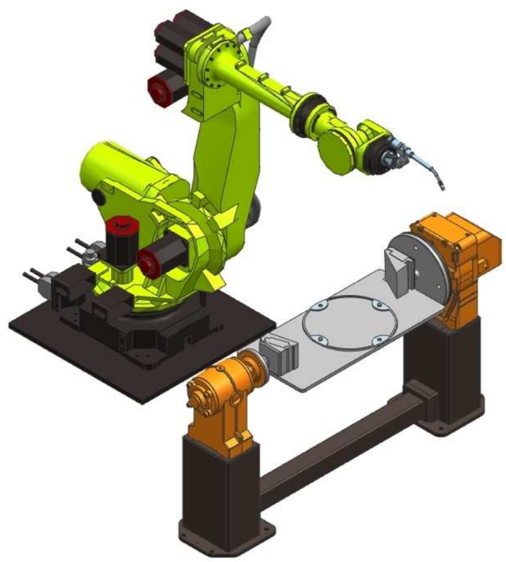
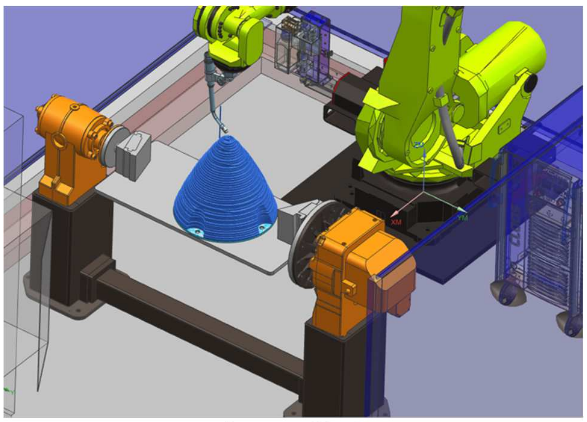


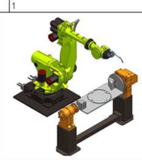
Fig. 6. Relative positioning of technological process elements

With the relative positioning of all elements of the technological process established, the trajectories were programmed. The first step involved rapidly positioning the robot in the working position, moving from the homing position to the support flange used for material deposition. The material deposition phase was defined using the Additive Manufacturing option in the Manufacturing module from the Siemens NX 12 software. This software module enables the user to select the active components of the technological process, divide the finished part into the material deposition support and the part fabricated by additive manufacturing and to define the divisions of the part as "slices" for automatic trajectory calculation. The material was divided into deposition slices by specifying the dimensions of the theoretical weld bead, their permitted radial overlap distances, and the axial pitch required for spiral overlap of weld beads to create the part.

Also, the programmed TCP inclination relative to the horizontal deposition plane needs to be specified. The welding gun needs to be perpendicular, so that the effect of the inert gas covering the weld pool is optimal. After this, the WAAM operation will be simulated, as depicted in figure 7.



Program Sheet

Part name:	Con_fuselaj_WAAM	Drawing name:	--
Unit:	1	Part number:	--
Pictures :		Description :	

Index	Operation Name	Type	Program	Machine Mode	Tool Name	Tool Path Time in Minutes	Path Image
1	RAPID_ADVANCE	Robot Linear	PROGRAM_1	AUTOMATIC	GMAW_TORCH	0.21	
2	PLANAR_ADDITIVE_SPIRAL	Planar Additive	PROGRAM_2	AUTOMATIC	GMAW_TORCH	1900.20	
3	HOMING	Robot Linear	PROGRAM_3	AUTOMATIC	GMAW_TORCH	0.15	

Author : a.trifu Checker : a.trifu Date : Sat Jun 5 00:23:19 2021

Fig. 7. The "fuselage cone" part at the end of the WAAM process

One of the main challenges in additive manufacturing is to ensure the quality and consistency of the deposited material. To address this issue, laser sensors to monitor and adjust the deposition process in real time can be used. The laser sensors measure the geometry and temperature of the molten pool and the bead profile, and provide feedback to the arc welding system [12]. This allows for an immediate correction of the arc position and power, as well as the path planning of the nozzle. By doing so, a better control of the bead shape, size, and orientation can be achieved, further improving the mechanical properties and accuracy of the final product.

2.4. Finishing of the WAAM parts

After the Wire Arc Additive Manufacturing (WAAM) operation, a subsequent turning operation will be performed to finish the outer profile of the part. A Coromant DSDNN 2525M 15 tool holder assembly with an SNMG 15 06 16-SMR 1115 rhombic plate will be used as the tool. With a speed of 483.33 mm/s and a feed rate of 0.7 mm/rev, the estimated time for the operation is 23 minutes, during which the insert will need to be changed twice. No internal turning is required, as only the outer surface of the "fuselage cone" part comes into direct contact with aerodynamic forces (figure 8). Additionally, the bolt recesses are expected to remain sufficiently deep even after material deposition by the WAAM process, so no further deepening of the bolt recesses is necessary.

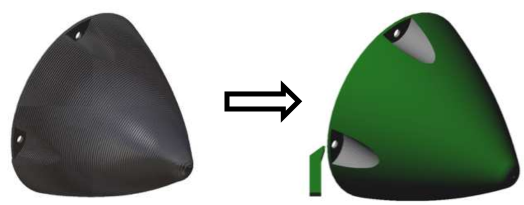


Fig. 8. Finishing turning operation after the WAAM process

3. RESULTS AND DISCUSSIONS

The cost comparison for the two manufacturing processes is based on the sum of all direct and auxiliary costs, which were added together to determine the total cost of carrying out these operations. The calculation assumes that all equipment will be used for a lot size one production, and excludes finishing costs, which were assumed to be similar for the semi-finished parts.

The costs associated with classical CNC manufacturing include the following:

- Machining centre (e.g. HAAS VF5): ~110,000 EUR
- CoroMill 300 R300-066C6-20H (1 piece): ~7,500 EUR

- Inserts R300-2060E-ML 2040 (28 sets of 5 pcs, or 140 pcs.): ~22,500 EUR
- Semi-finished cost (520x520x450, approx. 60 EUR/kg for 535 kg): ~32,000 EUR
- Manufacturing cost (30 EUR/hour for 50 hours): ~1500 EUR
- Programming cost (30 EUR/hour for 6 hours): ~180 EUR
- CAM software package cost: 10,000 EUR

The total CNC cost is therefore estimated to be ~183,680 EUR.

The estimated costs for producing the "fuselage cone" part using WAAM are presented below:

- FANUC ArcMate 100iD/8L robot: ~50,000 EUR
- Miller welding machine: ~25,000 EUR
- Cell integration cost: ~30,000 EUR
- Safety system cost: ~10,000 EUR
- Welding cost (80 kg - 4 packs): ~10,400 EUR
- Binzel Abicor ABIROB® A500 gun: ~6,000 EUR
- Programming costs (40 EUR/hour for 16 hours): ~640 EUR
- Software costs: ~25,000 EUR
- Consumable costs (gas lens, protective gas, electric current at 12 EUR/hour): ~384 EUR

The total estimated WAAM cost is therefore ~157,424 EUR.

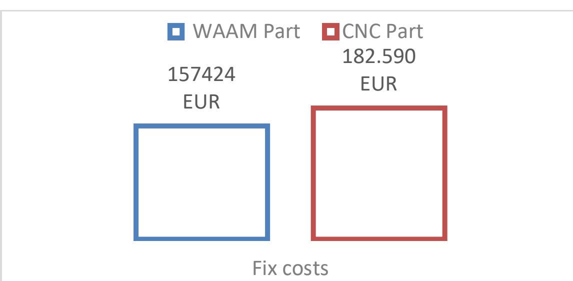


Fig. 9. Fixed cost chart comparing WAAM with milling processes for Ti6Al4V parts

As shown in figure 9, the fixed costs required to equip a WAAM cell are relatively lower compared to those required for a conventional subtractive manufacturing process.

For the analysis of the manufacturing time, it was assumed that the real values of the two processes were simulated for the same part with the same material, which is a Ti-Al alloy, specifically Ti6Al4V. However, as detailed in figure 10, a big gain conferred by using WAAM process is the shortening of the manufacturing time compared to conventional machining, by about 15%.

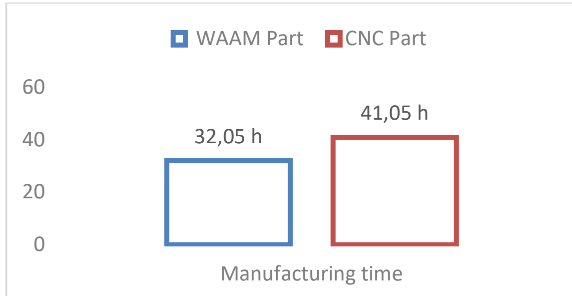


Fig. 10. Manufacturing time chart comparing WAAM with milling processes for Ti6Al4V parts

The undisputed advantage of WAAM is that it limits material loss and tool wear, with material loss for the same type of workpiece in this case being a 97% reduction as shown in figure 11.

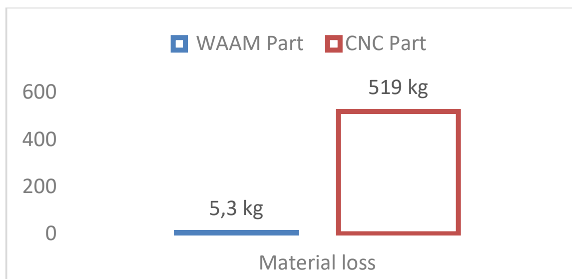


Fig. 11. Material loss chart comparing WAAM with milling processes for Ti6Al4V parts

4. CONCLUSIONS

The WAAM additive manufacturing process is a promising technology that can reduce part preparation time and part manufacturing costs, as well as it can increase the flexibility of manufacturing cells, especially for expensive materials that are more challenging to process using conventional chipping methods.

The WAAM process is particularly suitable for large gauge thin-walled parts, which would otherwise waste a lot of material through milling by conventional methods.

Different materials have different forming characteristics and product quality in additive manufacturing. The microstructure and mechanical performance of additive manufactured parts made of different metals vary significantly. Thus, it is important to conduct precise research on each metal material and create a comprehensive database of the additive parts with a specific metal material, including morphology characteristics, microstructure and mechanical properties, temperature evolution, thermal stress, and defects. A corresponding database should be established for each kind of metal material to facilitate the optimization of the additive manufacturing process and the quality control of the additive manufactured parts [10].

This paper has presented a theoretical concept of a manufacturing cell that uses the WAAM process and compared it to conventional subtractive manufacturing demonstrating the feasibility and benefits of using WAAM as an alternative to conventional subtractive manufacturing for producing complex metal parts. WAAM offers significant advantages in terms of material efficiency, manufacturing time, and cost reduction, while maintaining high quality and accuracy of the final product.

The results have shown that WAAM can reduce part preparation time and part manufacturing costs, as well as increase the flexibility of manufacturing cells, especially for expensive materials that are more challenging to process using conventional milling methods. However, there are still some limitations and challenges that need to be addressed in order to fully exploit the potential of WAAM. Some of the future work directions are:

- Experimental validation of the WAAM cell architecture and the simulation results using a real WAAM system and measuring the quality and accuracy of the produced parts.
- Optimization of the WAAM process parameters and the deposition strategy to improve the surface finish, the mechanical properties, and the geometrical accuracy of the parts.
- Development of a closed-loop control system that can monitor and adjust the WAAM process in real time based on feedback from sensors and cameras.
- Investigation of the environmental impact and the energy consumption of the WAAM process compared to conventional subtractive manufacturing.
- Extension of the WAAM process to other materials and applications, such as multi-material parts, complex geometries, and functional gradients.
- Implementation of laser sensors that will give feedback to the deposition structure of the beads, giving an instant control of the arc stabilization, and the necessary path adjustments.

The WAAM process parameters are the factors that affect the quality and performance of the wire arc additive manufacturing (WAAM) process. These parameters include the arc current, arc voltage, wire feed rate, travel speed, interlayer temperature, and shielding gas flow rate. Optimising these parameters can improve the mechanical properties, dimensional accuracy, surface finish, and deposition efficiency of the WAAM products.

To optimise the WAAM process parameters, various methods can be used, such as experimental design, numerical simulation, artificial neural network, genetic algorithm, and response surface methodology. These methods can help to establish the mathematical models that relate the process parameters to the desired responses, such as tensile strength, hardness, porosity, and deposition rate. By using these models, the optimal values of the process parameters can be determined that maximise or minimise the responses according to the design objectives.

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FABRICAȚIA ADITIVĂ CU ARC ELECTRIC ÎN COMPARAȚIE CU PROCESELE DE FABRICAȚIE CONVENȚIONAL PRIN AȘCHIERE

Rezumat: Fabricația aditivă cu arc electric (WAAM) este o tehnologie emergentă care oferă mai multe avantaje față de metodele convenționale de fabricație substractivă, cum ar fi frezarea CNC. În această lucrare, investigăm implicațiile WAAM pentru producția pieselor de gabarit mare cu pereți subțiri, care sunt, de obicei, dificil și costisitor de fabricat cu ajutorul proceselor de așchiere convenționale. Propunem o arhitectură a unei celule WAAM și comparăm performanțele acesteia cu cele ale unui centru de prelucrare CNC convențional în ceea ce privește costurile echipamentelor, timpul de fabricație, pierderea de material și uzura sculelor. Prezentăm un studiu de caz al unei piese pentru care este simulat procesul de fabricație prin ambele metode și analizăm rezultatele. Am constatat că WAAM poate reduce timpul de fabricație cu aproximativ 15%, pierderea de material cu 97% și poate elimina uzura sculei. Concluzionăm că WAAM este o tehnologie promițătoare care poate crește eficiența și flexibilitatea proceselor de fabricație, în special pentru materialele scumpe, care sunt mai dificil de prelucrat cu ajutorul metodelor convenționale. De asemenea, discutăm despre limitările și direcțiile viitoare ale cercetării in domeniul WAAM.

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