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Design and Testing of a WAAM Retrofit Kit for Repairing Operations on a Milling Machine

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Abstract: Repairing, remanufacturing, and refurbishing high value metal components are crucial to move towards a more sustainable economy. Nowadays, repairing operations on high value parts, such as dies, are generally performed using time-consuming manual approaches that rely on the operator's expertise. The research idea of this paper is to develop a retrofit kit to provide additive capabilities to an existing milling machine, allowing automatic repairing of components thanks to a fast switch between additive and machining operations without a relevant economic investment such the acquisition of a brand-new machine: the final cost of the solution is lower than 10% with respect to the mean cost of a 5-axis milling machine. The additive technology used in this work is Wire Arc Additive Manufacturing (WAAM) that is characterized by a higher deposition rate and a simpler and cost-effective equipment with respect to other techniques (e.g., laser cladding). The design of the system is illustrated in the paper together with the analysis of the results achieved repairing a test case: a die casting mold made of AISI H13 tool steel.

Keywords: WAAM; milling; repairing; hybrid manufacturing; green manufacturing

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1. Introduction

In many leading-edge industrial sectors, there are components suffering damages or wear during their service life and for which repair or restoration could be very advantageous due to their high value in terms of materials used, production cost or complexity. The repairing of metallic parts is an important step to limit the energy and material use in industrial production, by extending the service life of a part by recursive repairing [1]. As an example, EU defines the circular economy as "an economy, where the value of products, materials and resources is maintained in the economy for as long as possible" [2]. EU is very committed in pursuing a circular economy to improve industry and society sustainability, by means of regulations aiming at reducing the wasted materials volume and limit primary material use [3]. In this context, repairing, remanufacturing or refurbishing metal high added value components represents an effective action to move towards a circular economy [4,5]. This practice is already used in many applications such as to eliminate the service flaws from turbine blades or to repair the manufacturing errors or the worn features on molds and dies. These components involve high-cost materials together with long and complex manufacturing processes, making the extension of their service life mandatory for cost effectiveness. It is expected that many companies will increase the number of parts repaired in the next years [1,6]. Some relevant examples of metal components for which repairing is already a well-established practice are: turbomachinery parts [7], dies and molds [8,9], pressure vessels [10] and marine propulsion engines [11]. Such damaged components are critical for the machine's life since, due to the harsh operating conditions, they could lead to severe failures. An example of worn turbomachine blade before and after restoring is shown in Figure 1 [12].

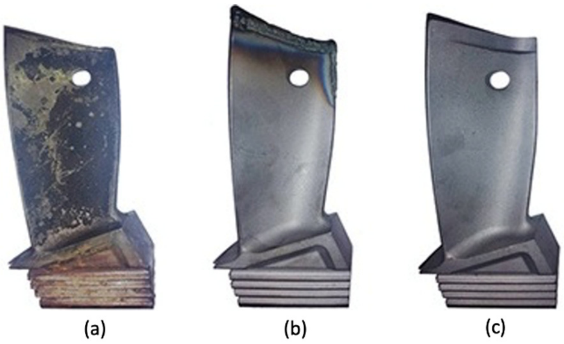


Figure 1. An example of worn turbomachine blade (**a**) as is (**b**,**c**) after restoration.

Due to the harsh operational environment and their design philosophy, turbine blades and vanes shall be periodically substituted. However, replacing worn blades with brand new ones is a demanding operation in terms of manufacturing cost. Indeed, such components are usually manufactured with expensive materials (e.g., alloy steels, nickel-based alloys) and by complex and time-consuming processes. The same considerations are valid in the case of molds and dies, where damaging and wear phenomena are critical [13]. Indeed, a worn die could compromise the quality of the produced part, resulting in a significant cost. Furthermore, repairing operations on molds and dies are carried out even in the production stage, to correct machining errors or to modify their geometry [14]. Therefore, the possibility of repairing components flaws or to regenerate worn features is a convenient approach, already applied in the cited industrial sectors. Furthermore, repairing over manufacturing brand new parts allows for significantly reducing the environmental footprint [15].

In general, the operations required to repair flaws on worn components are summarized by Figure 2: first, the damaged surfaces must be prepared for the subsequent processes, then the lacking material must be added through an additive manufacturing or a welding process. Finally, the filler material is machined to meet the dimensional and surface finish requirements. This is usually done using a NC milling machine. The most used available technologies to repair a part are Gas Tungsten Arc Welding (GTAW, especially for manual operation), Gas Metal Arc Welding (GMAW, both for automated and manual operations) and Direct Laser Metal Deposition (DLMD, used for reporting a small volume of worn metal by melting a flow of metal powder using a high-power laser) [16]. The GTAW is probably the most widespread, but it is often used manually with consequent constraints about the repeatability of the process and its productivity, since it relies on the operator's expertise.

The same considerations apply to GMAW, when manually adopted. More recently, automatic GMAW solution, e.g., robotic welding or Wire Arc Additive Manufacturing (WAAM) machine, are introduced, but they require the acquisition of a new machine and trained operators (e.g., machine programmer). DLMD is arising on the market, especially for high complexity parts where the worn surface is small, like for turbine blades, where it is widely adopted thanks to the development of very specific machines, for example, with OptoMec LENS® declares that more than 10 millions of turbine blades have been already repaired [17]. These machines are very specific and expensive, hence not affordable for small and medium enterprises that need to perform such repairing operations on different components and infrequently.

Figure 2. Flowchart of repairing operations.

In this paper, we decided to investigate the use of a WAAM retrofit kit to be integrated on NC milling machine (including 5-axis) in order to provide a solution able to repair a part on an existing machine. This allows us to avoid time-consuming and operator-dependent manual operations, without the need of a dedicated machine. The possibility of converting a machining center into a hybrid repairing center by means of retrofitting is very advantageous, especially for small companies that cannot afford the costs of a brand-new equipment. Furthermore, such an approach is intended to bring the advantage of the reduction of operation time, since no repositioning of the part is required, and achieving a higher accuracy, since no error is introduced by the change of fixture on a different machine. WAAM has been selected instead of DMLD for this application since it is characterized by lower acquisition and operational cost, enabling us to create a solution that could be cost effective. Moreover, the number of materials and the knowledge of their use in production companies is far more widespread than the possible materials and process setup of DMLD; lack of knowledge about a new process could be a constraint for the introduction of a new technology, especially for small companies.

Since the possibility to repair a part is quite appealing, many companies have already started to create hybrid solutions based on WAAM, like Mazak and Hybrid Solutions [18]. In the scientific literature, several works have been dedicated to hybrid metal additive/subtractive technologies [19]. However, most of them are not focused on the design and realization of machines or retrofit kit, but rather on product quality [20] or process planning [21]. Jones et al. [22] presented a hybrid machine that combines DLMD and machining, the proposed DLMD head for deposition can be located in the tool magazine, and thus take advantage of the Automatic Tool Change. Designing a similar retrofit for WAAM is more complex since it requires us to consider the electrical insulation of both the torch and the table. Therefore, there are several approaches preferred to implement a WAAM-milling hybrid solution on robots, already configurated for robotic welding [23–25]. However, robotic milling is far from being as efficient and effective as milling performed on a dedicated milling machine, because of stiffness loss and vibrations issues [26]. Therefore, WAAM technology should be included on the milling machine. In this scenario, the proposed solutions are generally tailored to three-axis milling machines [27] and the few for 5-axis machines (e.g., [28]) are designed to include WAAM to a machine with both rotary axes on the tool head (i.e., tilting/swiveling head). Although 5-axis machine tool with rotary table are very common, no proposed solution can be applied to this configuration, since a dedicated design of the insulated rotary table is required.

In this paper, we will present a solution that could be applied to a general milling center, including 5-axis machine with rotary table, through a simple retrofitting operation. Moreover, it will be shown how a repairing process could be performed to achieve optimal results. After the description of the developed hardware, including the torch holder and the insulated rotary table, the initial setup of the process parameters to achieve a defect free and fully dense repaired layer will be presented. Subsequently, how a toolpath for repairing purpose could be planned is shown, and the results of the repair operation of a die made of AISI H13 tool steel are presented.

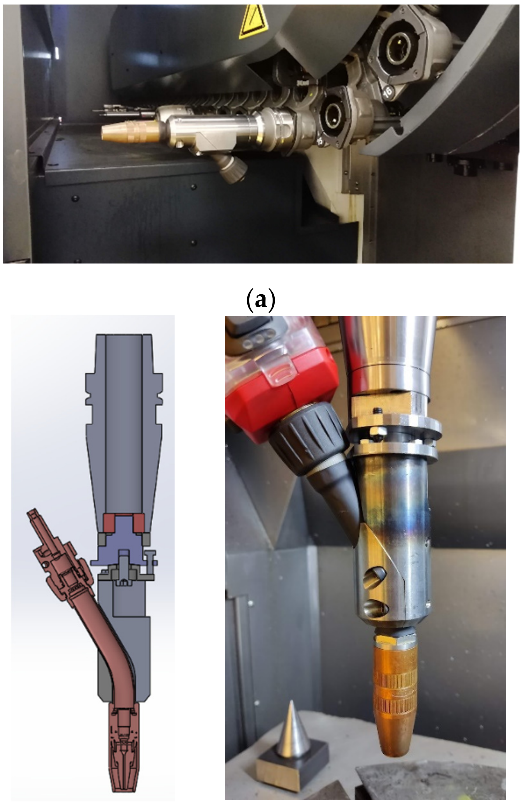
2. Materials and Methods

2.1. Design of the Hardware

The design process for the kit able to convert a traditional machine tool in a hybrid solution for repairing purpose has been based on the following requirements:

- The retrofit kit must be compatible with most of the machine tools;
- Initial setup and tuning of the solution must be simple and fast;
- The solution must be cost effective;
- Integration with the NC is mandatory to control both the deposition and the machining phases using the same NC program;
- The switch from the deposition tool to the machining tools must be automatic and fast;
- The machine tool must be protected by possible damage caused by the deposition process;
- The use of the retrofit kit must be safe for the operator.

Given these design requirements, an analysis of the possible systems has been carried out, and it led to a design solution that is different from the one adopted by the currently market-available WAAM-based hybrid machine (i.e., the one developed by Mazak). In fact, in that case, the deposition torch is installed on an additional axis that is usually parallel to the spindle axis. When deposition operations need to be performed, the axis is activated, and it slides down to a level usually lower than the spindle nose. This is not acceptable for a solution that must be as general as possible and must require few interventions to enable the integration on an existing machine. Definitively, the introduction of a new axis is a complex, costly solution, not feasible for most of the machines. In the proposed system, the design solution adopted is to create a new torch support that will have a standard interface with the machine tool. The torch is mounted directly on the spindle and managed as an additional tool. To achieve this, a specific torch support has been designed, integrating on it a standard toolholder (in our case with HSK 63 dimension). The use of a standard toolholder implies that the torch support must be treated as a tool by the NC of the machine and could be called for operation like any other tool. Such a configuration allows us to design the torch holder in a way that makes it possible to host it in the tool magazine of the machine (eventually classifying it as a large tool, depending on the tool magazine allowance). Moreover, for safety reasons, the tool should be considered as a trigger probe, so that rotation of the spindle is disabled. These possibilities are offered by the most common NC, like the ones produced by Fanuc or Siemens. Furthermore, the torch holder must be easily adjusted, and the tooltip of the deposition torch must be as collinear as possible with the spindle axis. This is mandatory when 5-axis toolpaths are programmed to repair a part, since a misalignment of the torch tip with respect to the spindle axis during a movement of the rotary axes could lead to errors in the deposition. In addition, high precision is required for repairing components with thin-walled geometries, for instance the tip of the compressor blades. However, achieving this result could not be trivial, since the most common torches are not designed for granting high precision in the tooltip position with respect to the torch clamping system or body. Therefore, the correct collinearity between the torch tip and the spindle axis has been achieved by integrating in the torch holder a micrometric regulation to meet the necessary precision requirements. The micrometric regulation enables us to adjust possible errors in the tooltip position with respect to the spindle axis by allowing a controlled rotation of the torch lower part with respect to the spindle coupling. Two different releases of the torch holder have been designed and produced, with and without microregulators, as reported in Figure 3.



(**a**)

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

Figure 3. (**a**) Torch without micro-regulations in the tool magazine; (**b**) torch with micro-regulations, design; and (**c**) picture of micro-regulations torch installed on the spindle.

The one without micro-regulation is more compact and could be used when using a torch with good geometric tolerances between tip and holder, or when depositing using a 3-axis toolpath, the second solution is mandatory when performing a 5-axis toolpath.

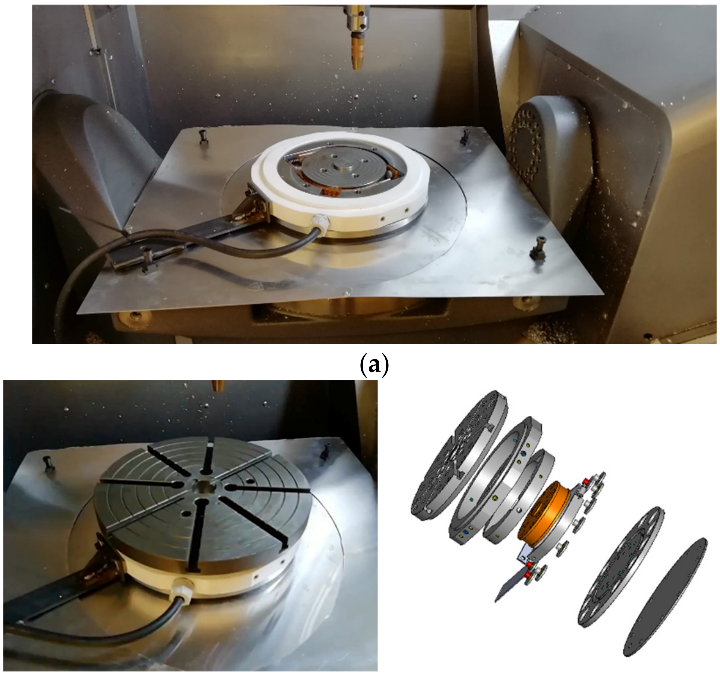
The connection of the cabling to power up the torch and to feed the wire and shielding gas for the deposition process are manually attached to the torch after the torch holder has been mounted on the spindle by automatic tool change. This operation requires less than 30 s. The cabling must be disconnected before calling again an automatic tool change and must be stored in the machining chamber without interference with the working area of the spindle or other moving parts. The choice of the cabling position depends on the specific machine architecture.

A safe operation of the machine is achieved thanks to the introduction of an electrically insulated table for the fixturing of the part. Such specifically designed table is applied on the original table of the machine, is connected to the ground of the welding unit, but is electrically insulated from the machine itself: this allows to avoid any discharge of current thought the motors, sensors, and electronics of the machine during the welding process. The table must be also able to connect the ground to the part without twisting of the ground cable during 5-axis deposition operations that implies the use of two rotating axes of the machine. It must be possible to install the table on a large variety of machine tools, hence a general interface has been designed for its base. The system is constituted by different parts:

- An insulating layer;
- A ground plate;
- A rotating ring connected to the welding unit ground;
- A retaining system;
- An external insulation;
- A machining table with T grooves;

- Additional welding spatter shields.

At the base of the system an insulating plate made of 10 mm thick plate is installed, made of Teflon® with fiber reinforcement to grant both insulation and high stiffness. On the top of this, there is the ground plate, housing several holes for the installation of the table with standard screw on a large variety of machine tool tables. The screws are installed in specially designed insulating washers, made of the same material as the insulating plate. The rotating part of the system is installed on the ground plate, thus allowing a sliding contact with the welding unit ground. This is achieved thanks to two copper braids that are retained in position by a spring system and a groove created on the ground plate. The external part of the rotating ring is created using nylon to avoid any electrical connection with external components of the machine tool. On the rotating ring, some threaded holes are included to be used to block the anti-rotation bar in position. On top of the rotating ring, a standard round machining table with 400 mm diameter is installed, with tight tolerances to avoid the entrance of cutting fluids, metal chips and other pollutants. The dimension of the table is selected to house a large variety of components and fit for most 5-axis machines available on the market. The table must be installed with its rotation axis collinear with the rotation axis of the machine tool. However, the collinearity tolerance is not tight (around 1 mm) since the contact among the rotating and fixed part is also assured by the two counterposed copper braids pre-tensioned by metal springs. In Figure 4a, a picture of the insulating table is reported, together with an exploded view showing all its components.


(**a**)

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

Figure 4. (**a**) Ground table with the internal sliding copper braids; (**b**) assembled ground table; and (**c**) components of the ground table.

To assure the safety of the operations, strategies to comply with the welding fumes and UV radiation have been implemented. For the first aspect, the aspirator of the machine has been connected to a welding fume aspirator and filter. For the second, a screen made by a thin layer of aluminum and a self-obscuration LCD screen for welding operations has been installed on the machine door. The welding unit selected is a Fronius® (Austria) model TPSi320, with the option of CMT deposition strategy. CMT has been selected since it allows a very low heat input during the deposition phase, that facilitates the continuous deposition of the material without requiring pauses to cool down the part to avoid excessive remelting of the substrate.

CMT achieves a low heat input by coupling a pulse of the welding current with a micromovement of the welding wire, that is quickly pushed in the welding pool as soon as the wire tip gets melted and then retracted to an upper position to start again the creation of a melted drop of material on the tip of the welding wire. The integration of the welding source with the numerical control (NC) of the machine (NC produced by Fanuc®, Japan, model: 31 iB5) has been achieved by activating one of the additional outputs of the NC and connecting it with the control board of the welding unit. The output is activated and deactivated using specific M functions; hence the welding process could be controlled by simply introducing a M function to turn on the process and another to turn off the arc. The possibility to control a welding source by means of an analogical or CAN bus signal is a standard feature for all the robotic wielding source and could also be achieved for manual sources by adding an interface board, usually supplied from the manufacturer as an optional. This implies that the approach adopted could be replicated on a large variety of different welding sources and NCs, expanding the possibility to use the kit in a very general operational background and with existing machines, both for welding and machining. The advantage of an integration between the NC and the welding source is that all the programming and control activities for the repairing process could be managed by programming a working cycle using standard GCODE commands. Theoretically all the operations, including both deposition and machining, could be carried out in a single GCODE command file. This allows an easy manual programming of the deposition toolpath or the use of dedicated CAM that uses the same logic and language of standard machining CAM software. The result is that no new software skills are required to the operators to program and use the developed kit.

The possibility to potentially integrate any milling machine and welding source to create a hybrid machining center, results in a dramatic drop of the solution cost. Existing machines could be used for this purpose with a minimum investment, mainly related to the manufacturing of torch holder and rotating welding table, since only few operations must be carried out on the hardware and software of the machine to enable the integration of the two processes. In case of a permanent installation of the kit on the machine, a dedicated welding source would be required. In this case, considering the cost of the source and the material to be manufactured, the overall cost is generally lower than 10% respect to the cost of the milling machine. This means that the developed solution is accessible also for small and medium enterprises that have reduced capability to sustain significant investment.

2.2. Test Case

To test the developed approach and validate the capabilities of the repairing kit, an AISI H13 steel die has been repaired, the CAD model of the die is presented in Figure 5, while in Table 1 is reported the chemical composition of AISI H13 substrate and the composition of the welding wire, produced by Bohler-Udderholm. The surface to be repaired is highlighted in the figure and is generally the whole surface that is in contact with the melt aluminum. In this case, the repair operation aims to replace the upper layer of material that presents small cracking and increased roughness.

Table 1. Nominal chemical composition of wire and substrate used for the tests (data from producers' datasheets).

	C%	**Si%**	**Mn%**	**Cr%**	**Mo%**	**V%**	**Fe%**
Mold Insert	0.39	1.10	0.40	5.20	1.40	0.95	Bal.
Wire	0.39	1.0	0.40	5.3	1.3	0.9	Bal.

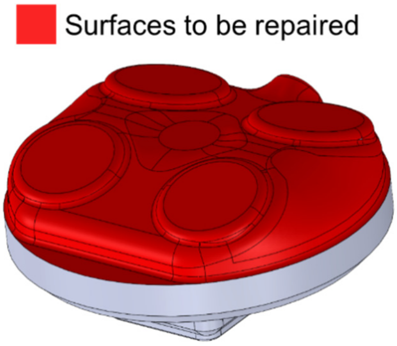


Figure 5. Geometry of the selected use case.

One of the main criticalities of AISI H13 is its susceptibility to cracking. Rajeev et al. [29] studied the hardfacing of AISI H13 tools with nickel based (Stellite) electrodes using CMT. Different welds were deposited using different heat treatment conditions. It was found that the only situation where cracking could be avoided was to apply a pre-heating and a post-weld annealing. Legesse et al. [30] used a hybrid CMT-milling approach to manufacture an AISI H13 die. It was found that the workpiece could be manufactured avoiding cracks by using a pre-heating system. Wang et al. [31] deposited H13 samples using a standard GMAW process. They performed both tensile and hardness tests. As welded, samples showed microhardness values of the substrate of about 276 HV and 356 HV in the deposit. The increment was explained by the high presence of fine martensite and carbides dispersed in the grain boundaries. Significant anisotropy was found in the mechanical properties (both yield and tensile strength) for the as welded samples. Annealing was then performed to reduce it, but it resulted in a significant reduction of the mechanical properties: tensile strength in the deposition direction decreased from 1085 MPa for the as welded samples to 536 MPa for the annealed one. It must be highlighted that this result was achieved using a regular GMAW power source and that the annealing time was 4 h at 830 °C. Therefore, it is expected that by using a CMT and a different heat treatment, better results can be achieved. In the specific case, a preheating till 300 °C has been performed and a slow cooling rate has been achieved by covering the part with vermiculite sands.

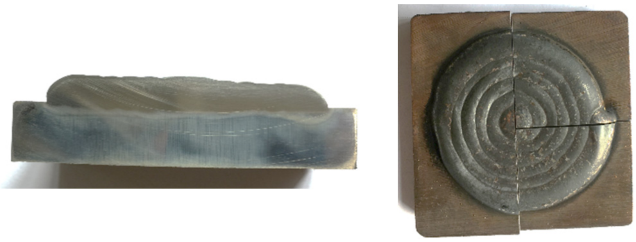
2.3. Deposition Parameter Setup

The first step for a high-quality repairing process is to find the optimal process parameters able to avoid the occurrence of the most common multi-bead welding defects, such as porosity, lack of material and lack of penetration. To find the optimal process parameters, a Box–Behnken Design of Experiment (DoE) test campaign has been carried out on a simplified geometry. The parameters considered in the tests are reported in Table 2. The dynamic correction is a parameter of the adopted welding unit (Fronius®, Austria, model: TPSi 320) that affects the geometry of the plasma created by the welding current: a lower correction factor decreases the aperture of the plasma cone and increases the bead penetration. The other deposition parameters, such as the welding current and voltage, are automatically calculated by the synergic logic of the welding unit, using a CMT welding program specific for steel with high nickel content. At this stage of the study, the determination of the correct process parameters was conducted only through the assessment of possible lack of material and penetration depth. For analyzing the quality of samples after the deposition, they were prepared by cutting, mounting in epoxy resin, grinding, and polishing up to a 6 µm diamond suspension. Nital (5% nitric acid and ethanol mixture) was used as the etching solution to highlight the depth of penetration. The resulting samples have been analyzed using a metallurgical microscope (Nikon Eclipse LV150) while the microhardness Vickers tests have been carried out using a Shimadzu HMV 2000 system.

Table 2. Parameters for DoE tests.

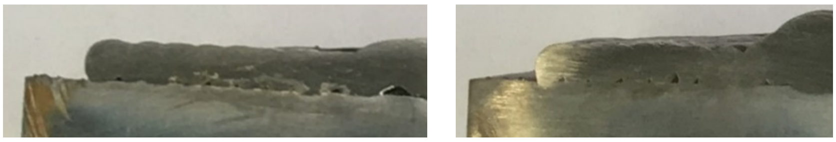
Parameters	**Level**		
	−1	**0**	**+1**
Wire Speed (m/min)	3	4	5
Deposition Speed (mm/s)	240	300	360
Dynamic Correction Factor	−5.0	−2.5	0.0

The best results in terms of quality of the deposited layer has been achieved with wire speed of 5 m/min, deposition speed of 360 mm/min and dynamic correction of −2.5. The result of this setup is reported in Figure 6, where a fully dense layer with enough penetration depth could be appreciated. A couple of examples of not satisfactory setup are shown in Figure 7. The first case is related to a wire speed of 3 m/min, deposition speed of 360 mm/min with zero dynamic correction, while the second the travel speed has been lowered to 300 mm/min. In both cases, it is possible to evaluate how the depth of penetration is too low and some voids are visible at the base of the beads. In the process with the lower heat input, in the first, these voids are quite evident and there is a nearly complete lack of fusion of the substrate. The second sample has a higher heat input and the presence of voids and reduced fusion of the substrate, although present, are less evident. To achieve a good penetration and remove the voids at the base of the beads has been necessary to increase the heat input of the process, mainly increasing the wire speed and introducing an arc correction. The negative arc correction has the effect to increase the arc voltage. Too high correction is responsible for spatter and should be avoided.



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

Figure 6. (**a**) Section of the specimen; (**b**) top view of the specimen.



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

Figure 7. Tests with low depth of penetration and lack of fusion at the base of the beads.

2.4. Preparation of the Sample

The repairing procedure is composed by three main operations: firstly, the component must be machined in order to remove worn material and, optionally, to obtain a geometry easier to repair; then a layer of fresh material is deposited, and finally the part needs to be machined again for finishing operation. Regards to the first machining phase, called here "preparation phase", an accurate planning is required to achieve better results in terms of lack of material (usually caused by small recesses and sharp changes in the surface of the part). This allows us to avoid the cited sharp corners, recesses and abrupt changes in the surface that are usually hard to fill by the new layer causing quality defects in the part. An example of how the surface has been smoothed on the test case is reported in Figure 8. The machining phase has been carried out in two steps: one for roughing using a

3 flutes 10 mm end mill tool from NS tools (code MSE345 with cutting speed of 60 m/min, feed speed of 300 mm/min, depth of cut of 2 mm and radial engagement of 0.5 mm), and one for the finishing using a 4 mm ball end mill from NS Tools (code MACH225SF with cutting speed of 60 m/min, feed speed of 1200 mm/min, depth of cut of 0.2 mm and radial engagement of 0.7 mm).

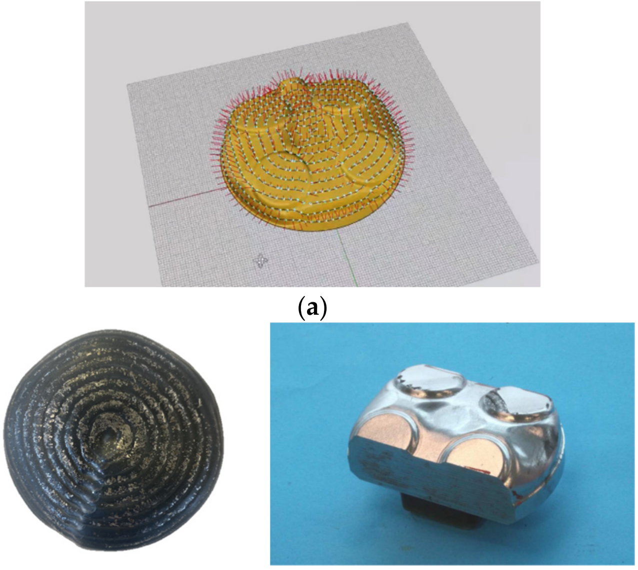
Figure 8. Surface smoothed before the new layer deposition.

The degree of smoothing required to avoid the defects next to the most complex geometrical features has been determined experimentally for the specific test case by testing different options. However, a more general approach must be developed yet. Regarding the deposition process, as preliminary considerations, it has been noted that two significant factors that could affect the result are temperature and bead dimension. On one hand, temperature should be checked both at the beginning of the process and during the process itself, and it can affect the component metallurgy and the geometry of the deposed layer. On the other hand, the dimension of the deposited bead, which depends mainly on the wire feed speed, wire diameter and deposition speed, is crucial for programming the toolpath, because the stepover values are commonly related to the bead width. The optimal stepover has been analyzed in numerous studies, each determining a different ratio of stepover to bead width. Stepover values reported in the literature range from 0.6 to more than 0.7 times the bead width [32]. To comply with temperature requirements, as suggested by the analysis of the scientific literature on the use of CMT for depositing H13, a preheating of the part has been performed through an industrial heater on the component fixed on the welding table. Heating required about 30 min and the temperature of the part was about 300 °C. After the deposition, the part has been cooled down using an insulating sand and then the part has been machined and removed from the machine for metallurgical analysis. However, the best efficiency of the developed hybrid solution could be achieved using materials that would not require controlled heating and cooling at the beginning and end of deposition cycle.

2.5. Design of the Depostin Toolpath

To obtain a complete cladding of a complex surface without the occurrence of lack of material, excessive refusion and other characteristic defects of the multi-bead welding process, it is mandatory to define a toolpath able to maintain both constant step over between adjacent beads and the correct angle between the torch and the surface. In most of the cases, this will require a 5-axis toolpath. A vertical CAM for the repair of dies has been developed to quickly compute a reliable toolpath. The software provides different toolpath planning strategies, and for the specific use case, a concentric constant-stepover toolpath was selected due to nearly axial symmetry of the part.

The designed toolpath optimized after preliminary experimental tests, and the repaired part after deposition and machining are shown in Figure 9. The use of the CAM is quite simple and only the geometry file is required to start the toolpath planning process. Second step is the definition of the surface to be repaired and the selection of the best strategy (e.g., spiral) and associated process parameters (e.g., stepover, angle respect to the surface). The software produces as output a GCODE file that could be used on the NC of the milling machine. The same results could also be achieved using commercial CAM software, taking care to remember that toolpaths generated for machining operations could not be directly used for deposition, since the stepover in some areas of the geometry could be not constant. Any CAM and manual programming are possible with this solution, also allowing an easy and low-cost implementation in small and medium enterprises.


(**a**)

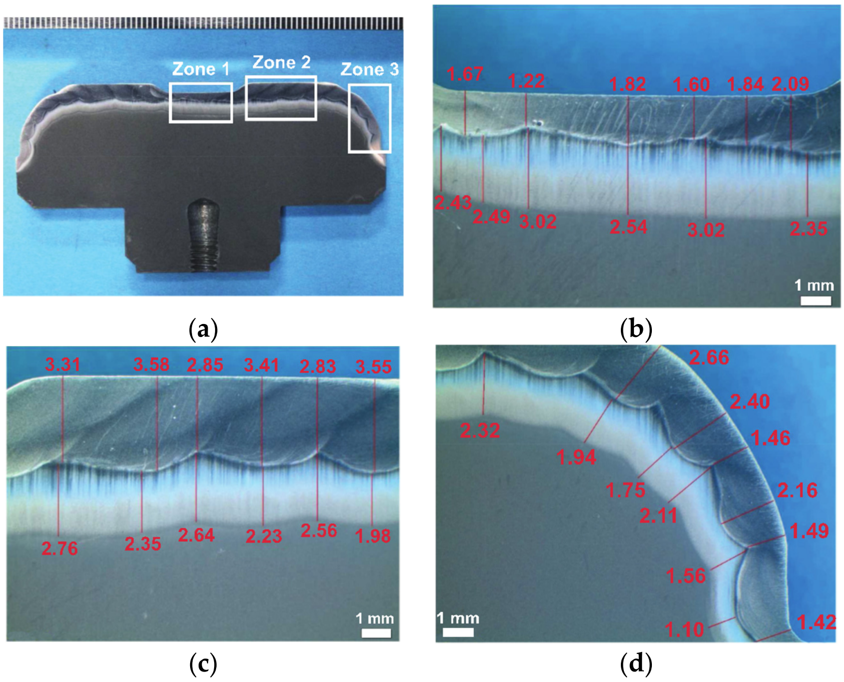
(**b**) (**c**)

Figure 9. (**a**) Developed toolpath for surface cladding; (**b**) top view of the deposited repairing layer; and (**c**) section of the part repaired after machining.

3. Results

The quality of the repaired part is assessed analyzing the microstructure, the level of hardness reached after the repairing process, as well as the entity of the Heat Affected Zone (HAZ). The samples have been prepared as described in the previous section and depth of the HAZ and the thickness of the layer has been measured with an optical metallurgical microscope (Nikon Eclipse LV150). In Figure 10 the analysis of one section of the repaired part is reported, where it is possible to assess the homogeneity of the deposited layer and the presence of no porosity nor lack of material at the interface between the substrate and the new layer. Several measuring points have been selected along the whole profile to evaluate the HAZ and fused layer thickness. A value able to provide a continuous boundary between the substrate and the fused material is mandatory to have a functionally acceptable repair.

No significant welding imperfections, such as lack of fusion and cracks, are observed on the conditioned test specimen. The thickness of the fused metal varies between 1.22 mm and 3.58 mm, while the thickness of the HAZ varies between 1.10 mm and 3.02 mm. It is possible to notice that the thickness of fused layer varies along the profile of the part. This is due mainly to the process adopted to repair the die, since the preliminary machining has created a smooth surface where more material has been removed in the convex zones of the component, while less material has been removed from the planar ones. Hence, at the end of the last machining phase after the deposition, a higher thickness of material is found in convex zones. An example of this behavior could be found comparing zone 1 and zone 2. Considering how was programmed the deposition toolpath (Figure 9a), nearly a constant thickness of material has been deposited on the surface of the repaired part. This is evident also looking at the HAZ thickness that, apart when the surface become nearly vertical at the border of zone 3, has a nearly constant value; this is an indication of the low variability of both the heat transfer and the material deposition rate along the toolpath. A metallographic analysis has been carried out on different areas of the repaired part in order to assess the difference between substrate, HAZ and repaired layer. These results are reported in Figure 11. The substrate microstructure shows the effects of quenching and tempering of the material, and it is composed by tempered martensite, while fields with reticular segregations or globular carbide clusters are not observed. In the transition area that constitutes the HAZ, needles of martensite are showed, with grain characterized by a dimension similar to the base metal. Finally, the added layer is composed of needles of martensite and segregated zones of dendritic morphology.



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

(**c**) (**d**)

Figure 10. (**a**) Analysis of the depth of penetration of the repaired part; thickness of the deposited layer and HAZ in (**b**) zone 1, (**c**) in zone 2, and (**d**) in zone 3.

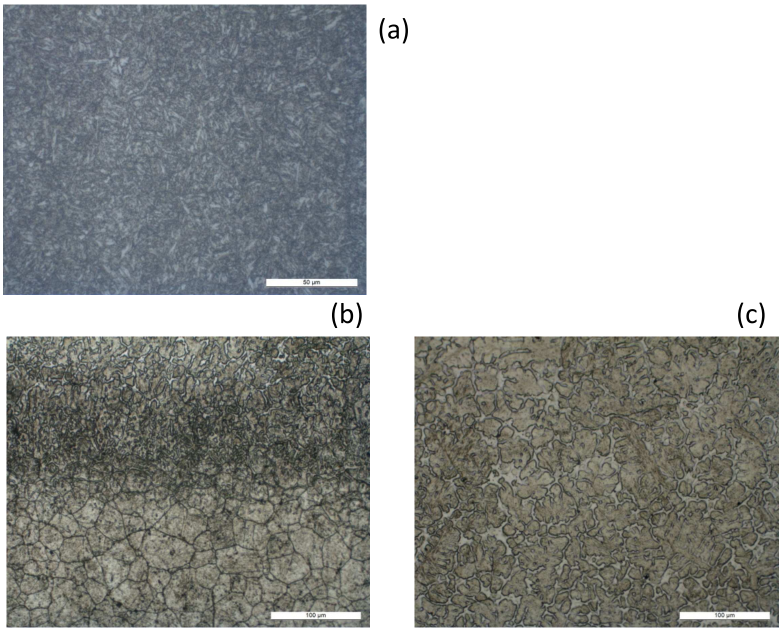


Figure 11. Metallographic analysis of (**a**) base metal, with tempered martensite; (**b**) HAZ, with needles of martensite; and (**c**) deposited layer, with needles of martensite and segregated zones.

Vickers HV10 hardness tests have been carried out to evaluate the need for additional heat treatment after the repairing using a Shimadzu HMV 2000 microhardness test equipment. The results of the tests are reported in Table 3, while the locations of the tests are presented in Figure 12. The hardness measured in the overlay and in the HAZ is higher than required; the mean value is around 660 HV, while an acceptable value for the specific application is 560 HV. A following heat treatment is required to reduce the hardness of the overlay to an acceptable level.

Table 3. Microhardness of the repaired part (HV10).

Vickers Hardness Test—HV10														
Overlay					**HAZ**					**Base Metal**				
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
677	658	663	669	661	696	684	692	688	717	364	361	361	369	370

Figure 12. Locations of the hardness control points.

4. Discussion and Conclusions

In this work, a retrofit kit enabling existing milling machining centers to perform deposition operations using WAAM technology has been presented. Moreover, all the other ancillary elements such as software and a structured approach to component repairing have been described. All such infrastructure has been installed on a DMU 75 MonoBlock 5 axis milling machine in order to be tested. The validation of the developed system (hardware, software, and manufacturing guidelines) has been carried out repairing a mold made of AISI H13 tool steel.

The developed system is innovative with respect to the state of the art, since it enables the use of WAAM for a hybrid machine instead of other laser-based solution. This implies a more difficult solution for the insulation of the machine from the electric discharge of the welding arc and the possibility to maintain a good ground connection when using a roto-tilting table. The achieved result is not only the system developed, but also the procedure to be used to set up the deposition process for different materials and dimension of the part, since some preliminary experiments are mandatory to achieve a defect free deposition. The manufacturing and installation of the developed kit proves that the integration of WAAM technology in an existing machining center is feasible on a large variety of milling machines, since the approach adopted for the integration is quite general and could be adapted to different tool holder dimensions (both HSK and ISO) and numerical controls. Moreover, the developed solution is characterized by a low production cost, lower than 10% with respect to the cost of the machine, a value acceptable for most of the users, including small and medium enterprises with low investment capabilities. This will allow a potentially large market for this solution, enabling the possibility for many companies to acquire a solution to also easily repair complex metallic parts, supporting the shift toward a greener production.

The possibility to repair complex and high-valued component like molds and dies in a single machine is possible since pre-machine, re-coat and post-machine operations of a component to be repaired are carried out with a single fixturing. To achieve this goal, several challenges have been faced and solved. The first is the development of a solution to allow the welding torch to be managed as a machining tool, assuring a precise collinearity between the torch tip and the spindle axis. This allows us to host the additive tool in the tool magazine and mount it automatically in the spindle by the activation of the ATC system. To achieve a good collinearity, required to program 5-axis cycles using the RTCP system of the NC control of the machine, a micro-regulation system has been implemented in the developed torch-holder. A complete integration of the control of the deposition source with the NC of the milling machine has been carried out in order to program both deposition and machining cycle using standard GCODE language. With the solution adopted, turning on and off the deposition source is controlled directly by the NC thanks to additional M functions.

Moreover, all the precautions to achieve a safe deposition operation for both the machine and the operator have been faced and implemented. Therefore, the specially designed table to host the part is electrically insulated from the original table of the machine and a special metal shield including and auto-obscuring LCD welding screen has been installed on the door of the machine. The system has been tested on a mold for the automotive sector, the surface of which had to be rebuilt, adding on it a new fresh layer of material. Analyzing the quality of the performed restoration, it can be stated that the metallurgy of the new layer is compatible with the requirements of a repaired die.

To support the widespread of such a solution, more structured guidelines must be developed for the preparation and repairing of worn surfaces. However, these guidelines are strongly dependent on the kind of part to be repaired, and even if a general approach could be given in the future, each company could develop its own approach to the restoration of a component, once the retrofit kit is installed on one or more of its machines.

Concluding, we can state that the initial objective of creating a system to easily repair a worn component using WAAM technology and milling integrated in a unique (already existing) machine has been achieved, and the measured results are satisfactory. The developed and presented system can be installed in new and old machines in a short time, and its cost makes it attractive even for small enterprises. The NC control of the whole process allows us to reach a higher degree of quality and lower the cost of a repairing operation. The process parameters found for the optimal deposition of AISI H13 are not applicable to other materials, and this constitutes a limitation of the presented study since experimental tests will be required for the definition of the process parameters for any other material. However, the approach depicted to find this set of parameters could be replicated for additional materials and constitutes a sound and efficient approach for this selection.

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