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Development of depositions strategies for edge repair using a WAAM process

Francesco Baffa[1,a *], Giuseppe Venturini[1,b], Gianni Campatelli[1,c]

[1] Università degli Studi di Firenze – DIEF, Via Santa Marta, 3 - 50139 – Firenze, Italy

[a] francesco.baffa@unifi.it, [b] giuseppe.venturini@unifi.it, [c] gianni.campatelli@unifi.it

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Abstract. Remanufacturing is an industrial process able to restore a component to at least its original performance, and it is considered one of the key processes to support the transition to circular economy. For restoring a metal component, additive manufacturing processes based on Direct Energy Deposition (DED) techniques are the most widely used, since they can process a damaged part with a complex geometry. Among these, Wire Arc Additive Manufacturing (WAAM) has several advantages including a high deposition rate, lower operative, material, and equipment costs. Nevertheless, it is also characterized by low accuracy and a high risk of defects if the process is not tuned correctly. It is therefore crucial to develop smart deposition strategies to ensure defect-free deposition and high efficiency. This study focuses on the repair of steel edges, and specific toolpaths has been designed and tested for repairing this geometrical feature, both concave and convex, coupled with the selection of proper welding parameters and torch tilting angle.

Introduction

Circular Economy appears to be one of the main approaches adopted to address the issue of sustainability [1]. In addition, Covid-19 pandemic has also highlighted supply chains fragility, especially in Europe, thus the necessity of more resilient supply system [2]. In industry, the issues of sustainability and resilience have found a meeting point in the circular economy, as a possible strategy to simultaneously reduce waste (and therefore reduce the environmental impact) and dependence on external suppliers (increasing resilience of supply chains). Aim of circular economy is to decouple growth and resource consumption and sometimes it is summarized as "doing more with less". In the manufacturing field, it means to keep the product – or at least its material - as much as possible within the boundaries of the manufacturing system Russell and Nasr defined five processes, called Value Retention Processes, which aim to preserve the value that the component has acquired from the extraction phase to the use phase: Direct Reuse, Repair, Refurbishment, Comprehensive refurbishment, and Remanufacturing [3].

Transition to circular economy therefore involves many aspects, from an industrial engineering point of view, these concern mainly supply chain management, product design, and implementation of recovery operations.

This study focuses on remanufacturing, an operation whose objective is to restore (at least) the initial performance of the product. The remanufacturing process involves many stages: disassembly, cleaning, inspection, repair, replacement, reassembly [4]. From a technological point of view, the repair phase presents the greater technical difficulties. This project focuses on the development of repair strategies able to achieve a high-quality repaired part for a metal component through a hybrid process based on Wire Arc Additive Manufacturing (WAAM) and machining. For remanufacturing operations, Additive Manufacturing (AM) technologies are particularly suitable. Among these, the most suitable ones are Direct Energy Deposition (DED) techniques, as they have the possibility of working on the pre-existing part, that it is precluded to powder-bed

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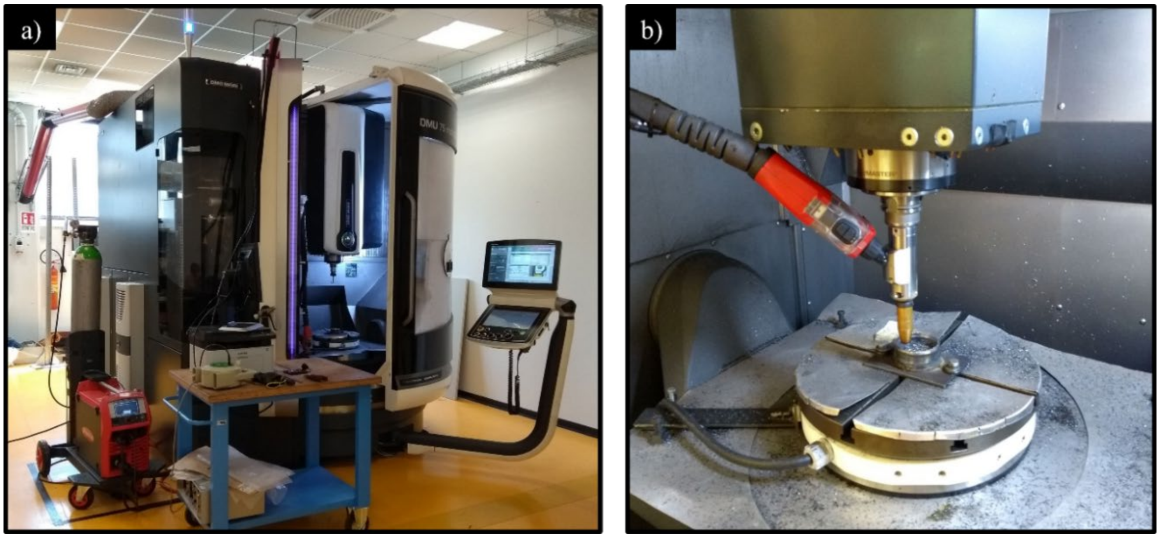

Figure 1 *DMU 75-Monoblock machining center (a) and (b) the welding torch mounted on.*

solutions. WAAM has the advantages of a high deposition rate, a wide choice of materials, an easy management of the filler material, a lower cost of the material, and a low cost of equipment. Moreover, it presents fewer health issues since it uses metal wire instead than metallic powder [5].

In the last years, also another feature of WAAM has increased its interest for the users: its reduced environmental footprint respect to its main competitor, i.e. AM based on laser as source and metal powder as feedstock [6], since both the production of the filler material and the process itself are less energy-intensive. Nonetheless, WAAM has the disadvantage of a lower accuracy and it is characterize by typical defects: porosity, high residual stress levels, and cracking [7]. Since remanufacturing often deals with non-standard components, it is necessary to develop process strategies able to guarantee the correct deposition of the beads of new material. Industrial sectors where repairing process are significantly adopted are turbomachinery [8], dies and molds [9], and marine transportation [10]. However, the most adopted technologies are based on laser and metal powder.

The remanufacturing process of a metal component by means of AM essentially consists of three stages [9]:

i. First machining phase: worn and damaged material is removed, and a geometrically known shape of the surface is obtained.
ii. Deposition phase: new material is added through AM technique to restore the worn features.
iii. Second machining phase: exceeding material is removed, and the final geometry is achieved.

Therefore, additive process is just one of the three main phases of the remanufacturing operation. The significant presence of subtractive phases justifies the adoption of a hybrid process, that integrates in the same machine both machining operations and additive manufacturing. This choice has several advantages, among them the streamlining of setup operations.

Aim of the study

This study aims to develop a remanufacturing strategy for metal components through a hybrid process based on WAAM, including toolpath, torch inclination and deposition parameters.

Material and method

The equipment for repairing operations is a hybrid machine, realized by retrofitting a 5-axis machining center DMG Mori DMU 75-Monoblock (Figure 1a). A special tool that supports a GMAW (Gas metal Arc Welding) torch has been designed and implemented in the automatic tool changer of the machine in order to alternate quickly and smoothly milling and WAAM operations (Figure 1b). The welding machine is a Fronius TPS 320i able to perform GMAW in different modes, e.g. Cold Metal Transfer (CMT) and Low Spatter Control (LSC) [11]. Mild steel has been adopted both for substrate (made by S235JR) and wire feedstock (ER70S-6). Shielding gas mixture is made of 82% Ar and 18% CO_2. Substrate and wire composition are listed in Table 1.

Table 1 *Chemical composition of the wire and the substrate used for the tests; reported data are from producers' datasheets.*

	C%	Mn%	Si%	P%	S%	Cu%	Fe%
Wire	0.08	1.5	0.9	≤0.025	≤0.025	-	Bal.
As deposited	0.08	1.1	0.6	≤0.025	≤0.025	-	Bal.
Substrate	0.19	1.5	-	0.045	0.045	0.45	Bal.

Repairing operations usually involve reconstruction of a solid feature (e.g. a gear tooth) and surface cladding (e.g. in case of a worn mold). WAAM cladding processes are much less studied in literature, and it has a potential risk for some quality issues. Two of the most common defects when cladding a surface are the lack of material in correspondence of the undercut zone of two adjacent layers and the material stacking due to a too low stepover between two layers. To solve this issue, bead modeling has been studied extensively in literature for defining the optimal value to obtain a planar surface [12]. However, most of the results are specific for traditional pulsed GMAW, that is characterized by a high heat input, that usually must be avoided since it is responsible for residual stresses on the component. The optimal solutions for new solutions with lower heat input, like CMT [13], must still be exploited. The presented study wants to take advantage also of the effect of inclination angle of the torch, namely tilting angle, on cladding a surface, since it allows quality improvement [14], and to integrate it in the design of a smart strategy for repairing a surface. The results are summarized in Figure 2. The inclination overcomes the difficulties related to undercut areas of adjacent beads, which also allows easier access to the torch, for filling milled pockets. Current activity is focused on repairing of edges, both concave and convex, since it is a very common feature that could be found whenever repairing a metallic part, i.e., a concave edge can be found on the base of a milled pocket, and a convex edge can be found on a metal sheet punch. Moreover, it is a feature that could be commonly found also after the first preparation (machining) phase to remove the worn material. The edges that have been included in this study are both sharp and chamfered.

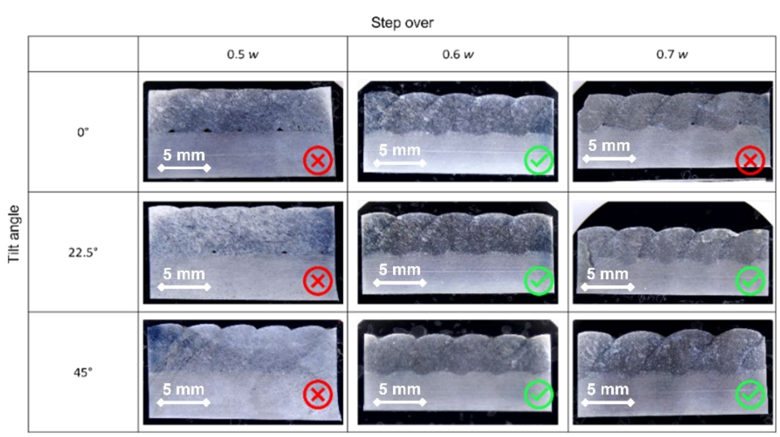

Figure 2 *Overview of material voids assessment. The parameter w is the bead width.*

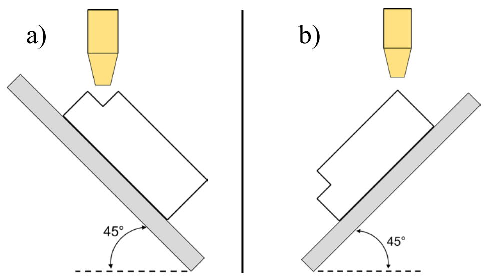

Figure 3 Experimental setup for (a) concave and (b) convex edges.

First, different set of parameters have been tested on a flat surface, and their coverage of the worn surface has been measured to correlate this value when depositing on a plane and on an edge. Then, twelve sets of parameters were selected grouped by similar geometrical dimensions. They are listed in Table 2, reporting the electrical parameters, welding parameters, i.e. Wire Feed Speed (WFS) and Welding Speed (WS), and energy input, i.e. Arc Power (AP) and Heat Input (HI). AP and HI are calculated as follow:

$$AP = \frac{V \cdot I}{1000} \quad (1)$$

$$HI = 60 \cdot \frac{AP}{WS} \quad (2)$$

Numerical coefficients are needed to give AP in kW and HI in kJ/mm.

As shown in Figure 3**,** deposition on the edges is performed rotating – by mean of the tilting table – the workpiece by 45 degrees and putting the welding torch on the bisector of the edge angle. For analyzing concave edges has been measured height (h), bead sides (L_1 and L_2), the bead area (A_b), the area added to the preexisting geometry (A^+), and dilution (D). Similarly, for convex edges has been measured A_b, A^+, and D. A geometric representation of the measures is shown in Figure 4, while the dilution has been calculated according to Eq. 3:

$$D = \frac{A_b}{B} \cdot 100 \quad (3)$$

Where B is the part of the bead penetrated in the substrate (Figure 4b and 4c).

For observing the tests after the deposition, standard metallurgical techniques have been followed. Test specimens were prepared by cutting, mounting in epoxy resin, grinding, and polishing with abrasive paper up to 1200 grit. Nital (1% nitric acid and ethanol mixture) was used as etching solution.

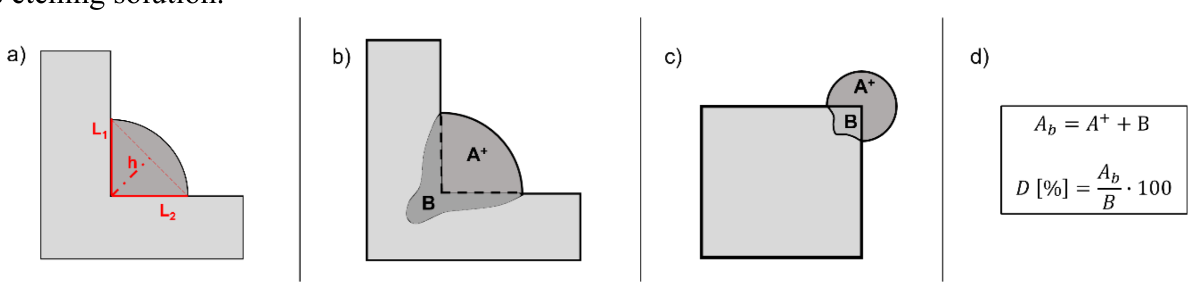

Figure 3 *Measures geometrical representation for (a, b) concave and (c) convex edges and (d) used relations.*

Materials Research Proceedings 35 (2023) 467-475 https://doi.org/10.21741/9781644902714-55

Table 2 *Parameters adopted for tests grouped by the similar bead width.*

Test	Reference width [mm]	Current [A]	Voltage [V]	WFS [m/min]	WS [mm/min]	Heat Input [kJ/mm]	Arc Power [kW]
1	6.5	130	21.1	12	600	0.274	2.74
2	6.7	91	18.9	8	400	0.258	1.72
3	6.7	111	20.2	10	500	0.269	2.24
4	6.8	179	27.4	20	1000	0.294	4.91
5	7.8	114	20.0	10	300	0.456	2.28
6	7.9	119	20.1	10	400	0.359	2.39
7	8.0	150	22.1	14	500	0.398	3.31
8	8.1	92	20.8	8	200	0.574	1.91
9	8.2	138	21.2	12	400	0.439	2.93
10	9.1	152	21.7	14	400	0.495	3.30
11	9.2	117	19.7	10	200	0.691	2.30
12	9.3	124	22.5	12	300	0.558	2.79

Table 3 *Data from deposition on concave edges*

Test	L_1 [mm]	L_2 [mm]	h [mm]	A_b [mm^2]	A^+ [mm^2]	D [%]
1	4.7	4.7	3.5	15.1	11.1	26.1
2	3.7	5.0	2.7	11.5	9.0	21.5
3	4.4	4.1	2.9	10.8	9.4	13.7
4	5.0	4.1	3.0	15.9	10.1	36.4
5	6.1	5.4	4.0	19.8	17.5	11.5
6	4.9	4.5	3.3	17.4	16.3	6.5
7	5.1	5.3	3.6	20.0	17.8	10.9
8	6.1	5.9	4.1	21.0	19.8	5.6
9	5.2	5.3	3.6	17.7	14.2	20.1
10	5.3	5.9	3.9	21.4	17.0	20.6
11	8.2	6.3	4.9	27.7	26.2	5.5
12	5.3	7.8	4.2	26.8	20.6	23.1

Preliminary results

Results of deposition are listed in Table 3 for concave edges and in Table 4 for convex edges. It could be notice that there is not a clear correlation between the value of the reference width of the beads deposited on a plane and the mean value of L_1-L_2, this is probably due to the different heat input that is responsible for a variation in the melting of the substrate and the aspect ratio (width-height) of the bead and different thermal conductivity for convex and concave geometries, as shown in Figure 5. Specimens in Figure 6 show this issue. Nonetheless, this correlation must be further investigated. It could be noted also a relevant variability in the value of L_1 and L_2 both for convex and concave edges. The variability could be assessed by calculating the residuals respect to the mean value, and this assume a value of 0.56 for concave and 0.97 for convex, that is nearly twice the value for concave.

Indeed, the deposition on a sharp convex edge could be source of uncertainty since the bead easily tends to a side or to the other. This would affect the subsequent cladding of the vertical and the horizontal side since the resulting geometry is undefined and this will create a lack or stacking of material with an automatic repairing cycle. This issue could be hardly solved since the instability of the arc on a sharp edge it is difficult to control and the measure of the deposited bead and the following adjustment of the toolpath for the deposition of the next bead is time consuming and avoid the implementation of an automatic repairing cycle. The solution that we are pursuing is to create a geometry before deposition that will reduce the variability of the bead position and geometry. This could be solved by introducing a 45° chamfer of different dimensions on the sharp edge where it is possible to deposit the corner bead on a flat surface. The initial tests had a single parameter set, and the width of chamfers is related to the bead width, as reported in Table 5.

Deposition on chamfers requires one or two beads accordingly with their dimensions. A_b, A^+, and D have been measured for these tests as well.

When two beads are needed for chamfer cladding the stepover was fixed at 0.6*w*. Therefore, set the chamfer width at 1.6*w* means to set chamfer width equal to the overlapped beads width. This seems to partially solve the issue, in fact, the deposition with two beads on a chamfer narrower than the overlapped beads, shows quite promising results, with consistent deposition geometry. On a chamfer characterized by a width of 1.2*w*, deposition is nearly symmetric, and beads cover the whole chamfer (Figure 7).

Table 4 *Data from deposition on convex edges.*

Test	L_1 [mm]	L_2 [mm]	A_b [mm^2]	A^+ [mm^2]	D [%]
1	4.3	4.5	15.6	9.0	42.3
2	2.4	4.8	14.3	9.3	35.0
3	4.8	4.1	16.3	8.7	46.6
4	4.2	4.0	17.6	8.1	54.3
5	4.3	6.0	25.1	14.4	42.7
6	3.2	5.4	20.1	11.2	44.4
7	4.3	5.9	25.0	13.1	47.7
8	5.1	5.3	26.9	17.9	33.4
9	2.4	6.1	19.9	10.9	45.2
10	7.0	4.2	28.7	16.9	40.9
11	5.6	6.7	36.5	23.7	35.1
12	6.8	5.1	32.2	19.6	39.1

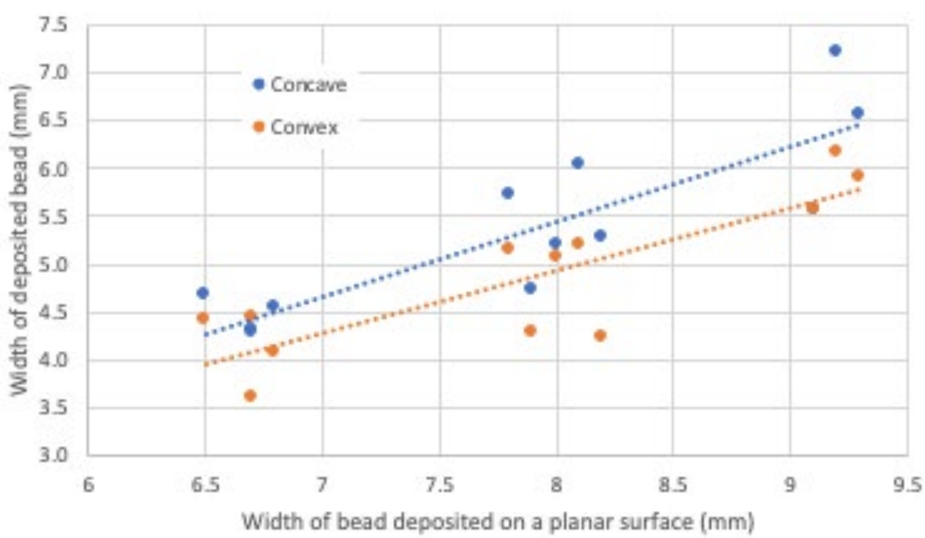

Figure 4 *Correlation between planar and edge bead width.*

Materials Research Proceedings 35 (2023) 467-475 https://doi.org/10.21741/9781644902714-55

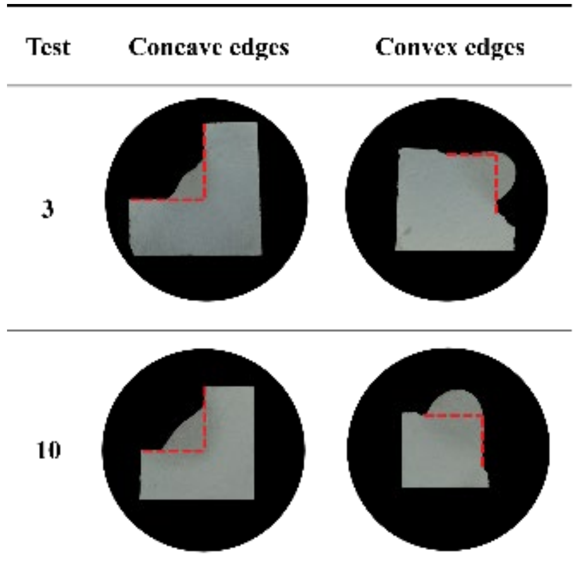

Figure 5 *Uncertainty is more significant in case of convex edges.*

Table 5 *Chamfers cladding tests, d is the chamfer width, w is the bead width.*

Test	d	d [mm]	N of beads
1	$0.8 \cdot w$	4	1
2	w	5	1
3	$1.2 \cdot w$	6	2
4	$1.6 \cdot w$	8	2

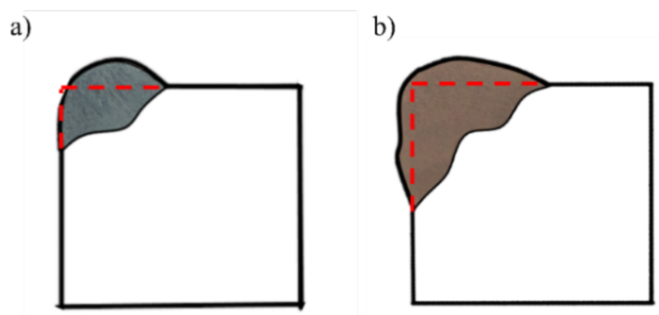

Figure 6 *Chamfers of test 1 (a) and 3 (b).*

Conclusion and future perspectives

The restoring of convex edge is characterized by a high uncertainty of the deposition geometry that is often asymmetric, thus affecting the reliability of the process. A solution is the preparation of the surface by machining a chamfer that enable a more stable deposition process. Starting from these preliminary results, some future actions could be planned, like fillets repair, where also the effect of the corner radius must be considered to predict the coverage of the surface and plan the position of the next beads accordingly. A model for fillets could be extended to repair free-form surfaces, that can be found, for instance, in molds and dies, which are a typical component subject to remanufacturing. Once the approaches to repair the most common geometrical features will be developed, it will be required to solve the issue of the connection of different toolpaths strategies to achieve a single and consistent remanufacturing cycle. In fact, a complex component could require different strategies for each of its features and these must be consistently and smoothly connected to avoid lack or stacking of material. In the meantime, also material tests need to be performed to ensure mechanical properties of the remanufactured parts. These tests could involve hardness test, grain analysis as well as tests for specific application, e.g. corrosion resistance assessment and thermo-mechanical properties. This final result will support a wider adoption of remanufacturing both for standard and non-standard components, ensuring at least the same performance of the original component and lower environmental impact and supporting the introduction of a greener manufacturing cycle.

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