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ORIGINAL ARTICLE

An adaptive laser cladding methodology for blade tip repair

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Abstract Worn-out blade geometries differ from the nominal geometry. Studies about numerical control tool path recalculation or control processes at constant melt pool are the most used approaches to generate a good repair process, but they use the same parameters for all parts, in spite of the different thermal behavior due to the difference in thickness. This paper presents an innovative based adaptive laser cladding methodology for obtaining the optimal process parameters taking into account the real geometry of the part, providing a unique solution to solve the part-to-part variation repair problem in blades. This solution can be implemented on its own or combined with monitoring and control process techniques. Laser power was identified as the most effective process parameter that permitted to modify and adapt the obtained width to the presented in a blade different from the nominal. The study of the obtained width when varying laser power on machined thin wall of different widths showed that MetcoClad718 and Ti6Al4V clad width behavior exhibited three phases. From the comparison of experimental data with programmed overwidths, it was possible to determine equations that related the required power for variable widths. Results show that it is not necessary to know the nominal input power to repair blade tips with variable geometries. The required power is directly obtained from the methodology equations. The performance of the proposed methodology was validated by laser cladding on machined MetcoClad718 mock-up blades and by means of the repair of Ti6Al4V compressor blades. Good agreement between experimental and programmed widths was obtained.

Keywords Laser cladding · Adaptive methodology · Variable geometry · Aero engine repair

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1 Introduction

Blades are subjected to several damages during engine service, but its replacement for a new one, especially in blisks, is extremely costly, limiting the overall life of the component. One way to reduce costs is to carry out repair of these single components, but after a certain number of hours of working, the geometries for worn-out blades differ significantly from the nominal geometry. Denkena et al. [1] presented a literature review that collect published information on common technologies regarding the regeneration of blades.

The conventional option was to create a new numerical control (NC) code adapted to the new geometry because the optimization of the generated tool path is especially critical to ensure the deposition quality. Reverse engineering (RE) technology has been widely recognized as a crucial role in the NC machining [2], permitting the creation of innovative strategies for reconstructing actual profiles from measured data. Sheng et al. [3] reported on results using an integrated mechatronic system with the capability of generating NC paths adaptively for turbine blades based on a reconstruction and extrapolation algorithm that automatically reconstructs the ideal geometric model of blades. Ren et al. [4] developed a strategy to find the shortest, and therefore the most efficient, path to cover the area to be machined. Gao et al. [5] proposed a defects-free model-based repair strategy to generate correct tool paths for build-up process and machining process adaptive to each worn component through the reverse engineering application based on 3D scanning data, transferring the tool paths to a CNC machine for the repairing trials. Cerit et al. [6] introduced a new method based on computer numerical controlled milling operation for path generation.

Regarding the deposition process itself, Simhambhatla et al. [7] used hybrid layered manufacturing (HLM), a synergic integration of material addition (arc welding) and substraction (CNC machining) processes, to develop build strategies for rapid manufacturing of components of varying complexity. Zheng et al. [8] utilized reverse engineering techniques to capture the geometric shape of the worn area by digitized point cloud and nominal geometry, leading to the automation of laser welding and cladding. Calleja et al. [9] developed an algorithm to resolve non-uniform motions in machines that perform 5-axis continuous interpolation, resulting in a homogeneous material deposition process.

But as in NC tool path recalculations, a nominal deposition process from a component designer is different from its corresponding worn one, and therefore, its use directly for build-up repair processes can bring thermal problems associated with the different geometry. These differences with the original geometry make each repair process a "unique" one with its own parameters and restrictions. Current blade repairing processes do not take into account the required variation in process parameters. They look for a process window that works for different geometries, implying to limiting the valid parameter values that can be used in the repair process. Thus, the resulting repaired geometries of the worn blades are poor and the consequence is a high waste for blades and a reduction for the performance of the engine. Monitoring and control process techniques provide flexible capabilities to restore damage blades. Song et al. used a heat input on-off controller as the most simple and efficient way to limit the layer growth, avoiding both overbuilding and under-building and thus guarantee the dimensional accuracy. Rodriguez-Araujo et al. [10] demonstrated the suitability of field programmable gate arrays (FPGAs) for optimizing the monitoring and control of a laser cladding process. Bi et al. [11] adopted the infrared temperature signal emitted from melt pool for process control in the restoration of nickel-base turbine blade knife edges. Literature control processes usually maintain constant melt pool size along the blade repair but depositing on blade geometry requires variable bead widths adaptively produced along the chordwise deposition tool path in order to minimize the thermal problems that are typically associated with constant bead width deposition, such as overheating at thin edges or undercut at thick sections. Furthermore, tunable overwidths depending on the blade size are desired in order to fulfill required tolerances for the machined blade operation that is carried out after the deposition process step. Moralejo et al. [12] developed a feed forward proportional-integral (PI) controller to effectively control and tune the laser cladding melt pool geometry online taking advantage of the concept of variable set point at different positions or time and providing the opportunity to apply it in applications that require variable geometry. The use of a suggested power close to the real displayed a remarkable improvement of the system behavior.

As alternative, Qi et al. [13] developed a geometry-based adaptive tool path laser powder deposition method based on a quadratic regression transfer function that predicted the deposition bead width as a function of the dominating processing parameters identified. However, the performance of the method is verified generating blade external profile first and then filling with adaptive widths, masking any defect in cladded track precision.

The aim of this study is to develop a geometry-based adaptive laser cladding methodology that determines the local power required to obtain a desired overwidth taking into account the real thickness of the blade in each point. Furthermore, combined with control techniques, this proposal will improve the efficiency of control process systems providing an advanced solution to solve the part-to-part variation repair problem in blades. The performance of the methodology is demonstrated by laser cladding on MetcoClad718 mock-up blades and by means of the repair of Ti6Al4V compressor blades. The obtained measured width along the blade chord is in agreement with the target value, within the experimental error.

2 Experimental procedure

The experimental setup consisted in a high Yag BIMO laser processing head and an IWS COAXpowerline laser cladding nozzle situated into a six-axis machine tool, combined with a Rofin FL020 laser fiber of 2 kW. A fiber of 150 μm diameter went through the optical path, obtaining a final spot diameter of 860 μm at the working position. The powder was stored in a Sulzer Metco Twin-10C powder feeder, and argon 99,991% was used as carrier gas.

Laser cladding experiments were carried out on MetcoClad718 and Ti6Al4V substrates using MetcoClad718 and Ti6Al4V powder as cladding material, respectively. Compositions are shown in Table 1. The powders had a granulometry of −90 + 44 and −125 + 45 μm, respectively, and were manufactured by gas atomization. During the tests, the substrates were fixed and the cladding head was moved perpendicularly to them, depositing monolayer tracks of 25 mm length. Cladded tracks were cut with an automatic precision cut-off machine and the dimensions were determined by an optical microscope.

3 Adaptive laser cladding methodology

The goal of this work is to develop a methodology that enables to determine the process parameters that lead to a desired

Table 1 Chemical composition of the powders (wt%)

Material	Ni	Ti	Cr	C	Al	Fe	B	Nb	Mo	V	H	O	N
MetcoClad718	Bal.	1	19	0.05	0.5	18	0.01	5	3	–	0.5		
Ti6Al4V	–	Bal.	–	0.03	6	0.1	0.1	–	–	4	0.003	0.15	0.01

geometry in top of a thin wall of variable thickness. The methodology involved firstly the determination of the key process parameter that permitted to modify the clad width efficiently. The defined dependence enabled to determine at each point the required parameter value to clad the desired track width, allowing to obtain a constant overwidth on top of a wall with variable thickness. The methodology was verified over MetcoClad718 mock-up blades and by means of the repair of Ti6Al4V compressor blades.

3.1 Adaptive parameter determination

First experiments for developing the adaptive laser cladding methodology consisted in determining the key process parameter that permitted to modify and adapt the obtained width to the new one presented in a blade different from the nominal. Laser power, cladding speed, and powder feed rate were tested. In that sense, a battery of tests was carried out varying these parameters in order to study the behavior of the clad width and to define a working process window.

Figure 1 shows the evolution of width when modifying process parameters. When laser power increased maintaining constant of the other two parameters, track width increased linearly. When increasing the cladding speed, a width decrease was exhibited but not in a sufficient percentage for using it as adaptive control parameter (i.e.,, track width increased 1.7 μm/W and 0.19 μm/[mm/min] for MetcoClad718). For powder feed rate, same conclusion was drawn due to the slight variations in widths and its longer reaction time. Thus, laser power was selected as the appropriate parameter for the development

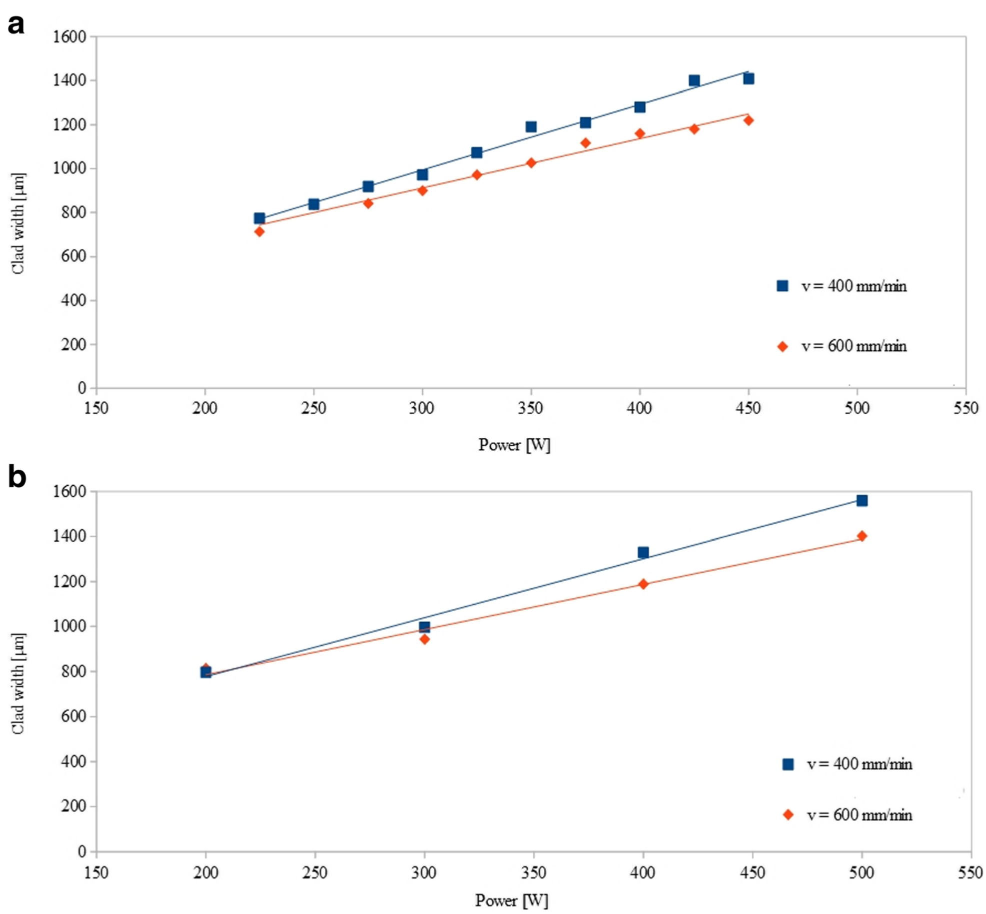


Fig. 1 Clad width evolution at different powers and cladding speeds for **a** Ti6Al4V and **b** MetcoClad 718

a

Power [W]	Metcoclad 718 machined wall width [mm]														
	0,45	0,55	0,65	0,75	0,85	0,95	1,05	1,15	1,25	1,35	1,45	1,55	1,65	1,75	1,85
100	■	■	■	■	■	■	■	■							
150	■	■	■	■	■	■	■	■	■						
200	■		■	■	■		■	■	■						
250	■		■	■	■	■	■	■	■	■					
300	■		■		■	■	■	■	■	■	■	■			
350			■		■		■	■	■	■	■	■		■	
400			■		■			■	■	■	■	■	■	■	■
450					■			■	■	■	■	■	■	■	■
500					■			■	■	■	■	■	■	■	■
550								■	■		■	■	■	■	■

b

Power [W]	Ti6Al4V machined wall width [mm]									
	0,45	0,65	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,70
250	■	■	■	■	■	■				
300	■	■	■	■	■	■				
350	■	■	■	■	■	■	■	■	■	
400	■	■	■	■	■	■	■	■	■	
450		■	■	■	■	■	■	■	■	■
500					■	■	■	■	■	■
550						■	■	■	■	■

Fig. 2 **a** MetcoClad718 and **b** Ti6Al4V laser cladding tests carried out over the machined thin wall widths related to the used laser power, at 600 mm/min and 4.4 and 11 g/min, respectively

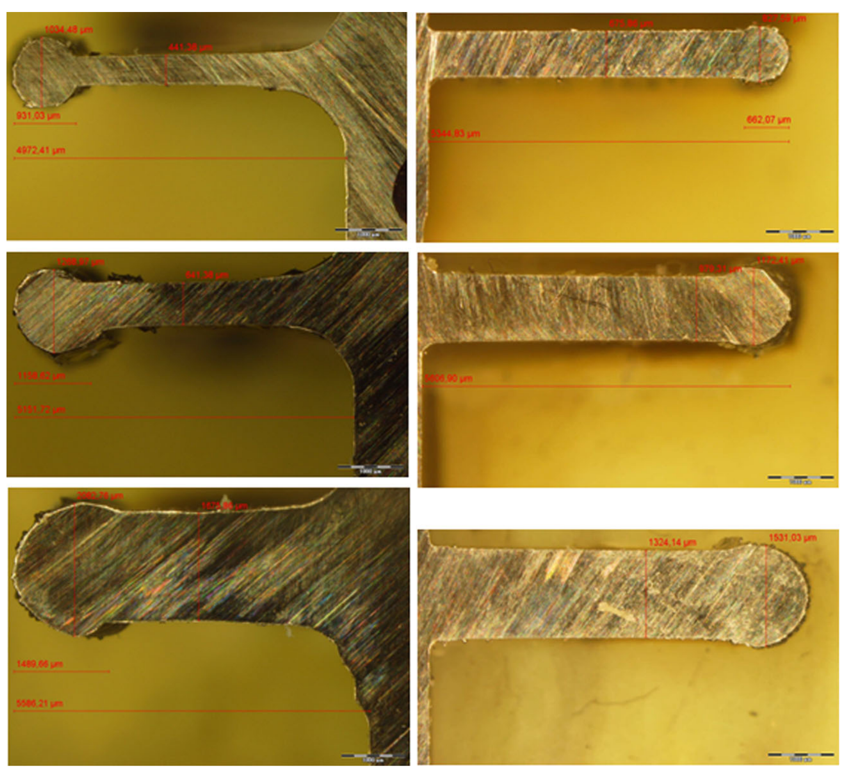
of the geometry-based adaptive methodology because of its high influence over the width and for showing the quickest reaction time faced with the required modifications.

3.2 Analysis of width track variation

The influence of laser power over the obtained width was studied using as substrates machined thin walls with widths in a range of 0.45 to 1.85 mm. The processing parameters used in this study, represented as dark rectangles, are shown in Fig. 2a for MetcoClad718 and 2-b for Ti6Al4V.

A fix feed powder rate (4.4 g/min for MetcoClad718 and 11 g/min for Ti6Al4V) and cladding speed (600 mm/min) were selected from the previously obtained working window, and power was varied as the adaptive control parameter. For these experiments, it was taken into account that above 550 W plasma was generated, making the melt pool difficult. Figure 3 shows optical microscope images of the resulted tracks cladded on different machined thin wall widths. Depending on the used laser power, variations in the obtained width were appreciated. Figure 4a presents the evolution of the clad width with the machined thin wall width and the laser power. For each power, as the wall width increased, the obtained clad width exhibited a similar behavior that was divided into three phases (Fig. 4b). In phase I, clad width tended to decrease with the increase in thin wall width. The increase of the surface in which the clad material was deposited caused a quick heat evacuation, avoiding the melting of the whole base material and generating a track with less width that the corresponding thin wall width. In phase II, the clad width tended to be equal to the thin wall width because the present energy permitted to melt the edges of the machined surface but was not enough to

Fig. 3 Microscopic optical images of MetcoClad718 cladded tracks on thin machined walls



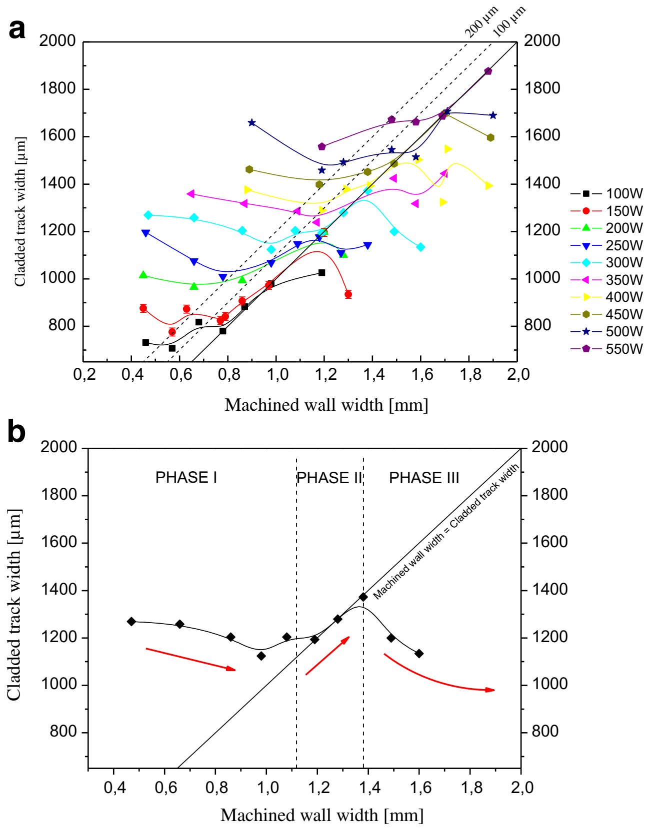


Fig. 4 **a** Evolution of MetcoClad718 cladded track width with the machined wall width and the laser power. **b** Schematic overview of the cladded track width behavior with 300 W laser power

make possible an overwidth. In phase III, the involved energy was not able to melt completely the base material, producing a decrease in the cladded track width. In this figure, the continuous line appeared representing the points where both widths coincided. The two discontinuous lines made reference to overwidths of 100 and 200 µm, ideal for near-net-shape blade repair. The intersection of these three lines with the lines corresponding to the experimental data provided the required power for obtaining a customized cladded track.

Figure 5 gathers the deduced width values from analyzing the intersection points. A linear relationship was observed (eq. 1 for MetcoClad718; eq. 2 for Ti6Al4V), indicating the required power for each desired width so that a mathematical function for each overwidth was determined. Thus, these equations allowed to select an overwidth and calculate the needed power in function of the new blade width. Standard deviations were 17.59 and 16.62 W for 100 and 200 µm overwidth, respectively. Analogous study was made for Ti6Al4V observing a similar behavior.

(1) 100 µm: power = −259.35 + 0.517 * wall width
200 µm: power = −177.29 + 0.508 * wall width

(2) 100 µm: power = −95.28 + 0.413 * wall width
200 µm: power = −123.24 + 0.489 * wall width.

3.3 Determination of the associated error

In this methodology, two experimental errors must be taken into account: (i) the variability of the process, due to the difference in the obtained track dimensional measurements in spite of using the same process parameters. In each constant, machined thin wall tests were carried out at constant power. Two width measurements in two positions were compared, indicating an average of 33 µm process error; (ii) adjustment error, defined as the caused error for using the obtained geometry-based adaptive equations instead of experimental data. To estimate this error, differences between experimental used power (points) and calculated required power (line) are analyzed in Fig. 6. In this figure, all tested powers were drawn, obtaining a slope of 1.89 µm/W, which indicated that the calculated deviation of 17 W will cause a difference of 33 µm, which was considered as the adjustment error. Therefore, as both errors were similar, 33 µm was estimated as the error methodology.

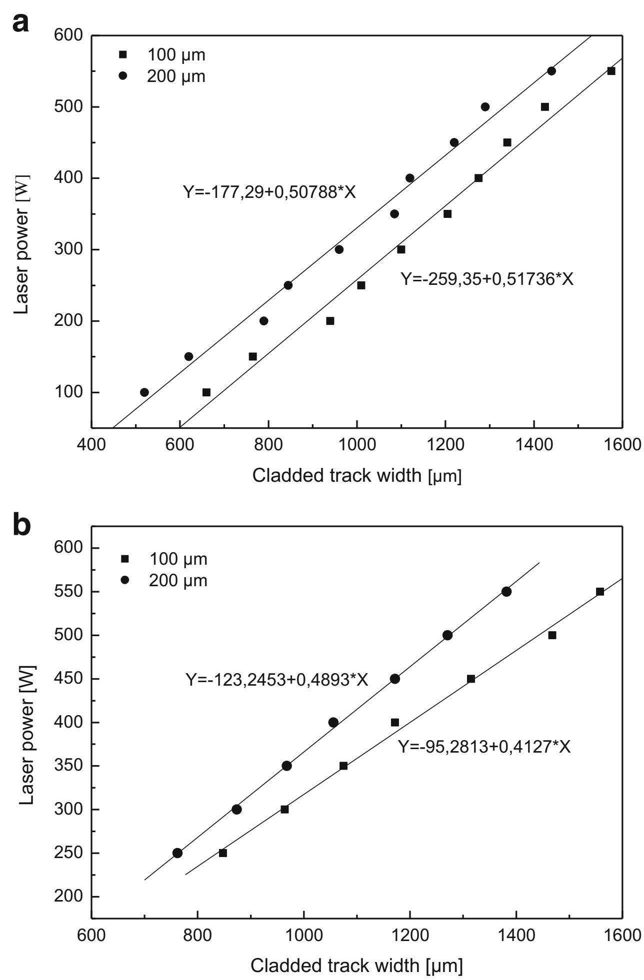


Fig. 5 Required laser power for each machined wall width for **a** MetcoClad718, **b** Ti6Al4V

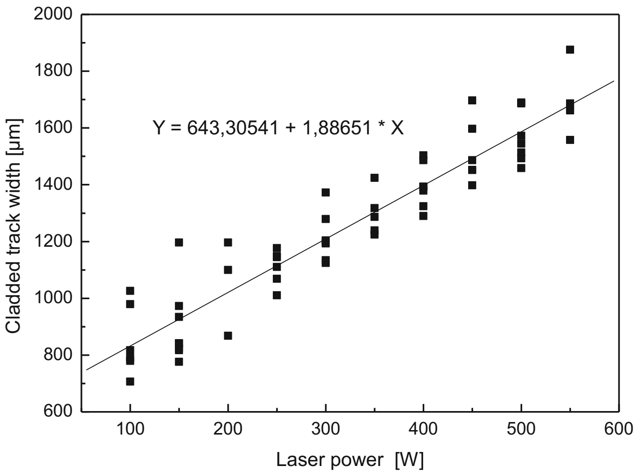


Fig. 6 MetcoClad718 cladded track width variation with laser power, independently of the machined wall width

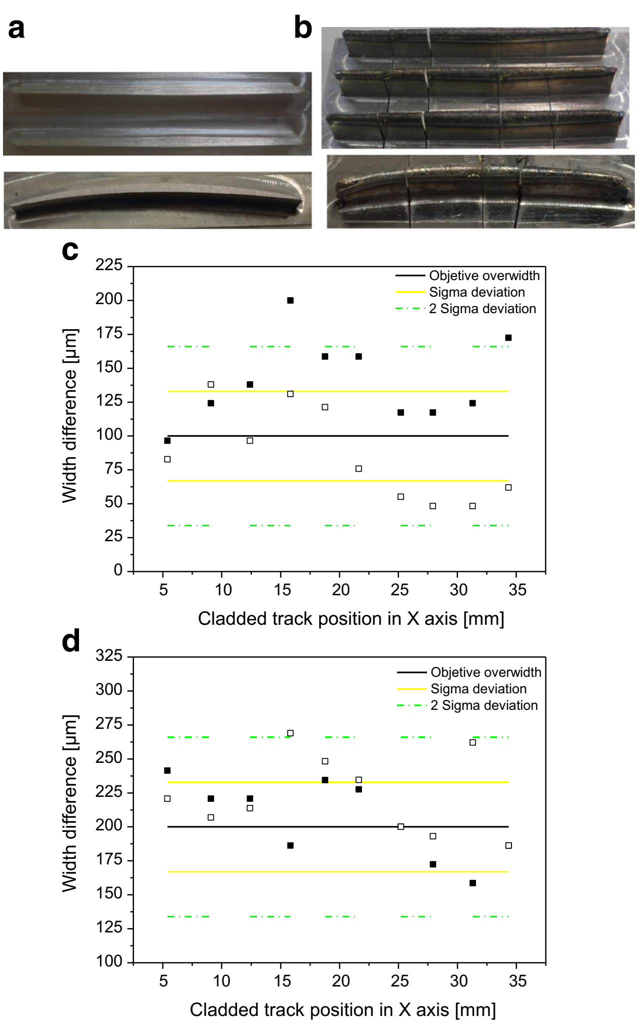


Fig. 7 **a** Machined MetcoClad718 thin walls and Ti6Al4V blade tip profiles, of 35 mm long. **b** Cut-off of cladded tracks over the profiles. **c** Obtained overwidths for MetcoClad718 using the proposed methodology and with reference to 100 and **d** 200 μm. *Dark and open rectangles* corresponded to two different experiments

3.4 Methodology validation

For the validation, MetcoClad718 thin walls with variable width and Ti6Al4V compressor blade tip profiles were machined. The dimensions were selected in order to be close to the blade tip size. A CNC program was created taking into consideration the different machined widths and programming the required laser powers in function of the calculated equations. Figure 7c, d shows the obtained widths for both overwidths for two different experiments (open and dark rectangles) carried out with the same process conditions. Results were in good agreement with the expected ones, observing that the behavior was slightly better for 200 μm than for 100 μm due to be more far away from the transition between the defined phase I and phase II and consequently in a more stable area.

4 Conclusions

This paper presented an innovative strategy for obtaining a geometry-based adaptive laser cladding methodology that, as individual solution or combined with monitoring and control process techniques, will provide the required power for repair blade tips, turning into an advanced solution to solve the part-to-part variation repair problem in blades. First experiments determined that laser power was the key process parameter that permitted to modify and adapt the obtained width to the new one presented in a turbine blade different from the nominal.

MetcoClad718 and Ti6Al4V tracks were cladded on thin walls with constant width in a range of 0.45 to 1.85 mm. Track dimensions were determined with an optical microscope, revealing a width behavior that can be divided into three phases. The intersection of the experimental data with the lines corresponding to theoretical overwidths permitted to determine equations that related the required power with the new width. Results show that it is not necessary to know the nominal input power value to repair blade tips with variable geometries. The required power is directly obtained from the methodology equations. Finally, the performance of the proposed methodology was validated by laser cladding on MetcoClad718 mock-up blades and by means of the repair of Ti6Al4V compressor blades. Good agreement between experimental and programmed results was obtained.

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