Selective laser melting for heat exchanger

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***Abstract*—Selective laser melting (SLM), a powder-bed based Additive Manufacturing (AM) technology, has been used to fabricate a compact counter-flow heat exchanger from Inconel 718 powder. Compact heat exchangers have found application in highly specialized areas such as microelectronics cooling, aerospace, micro-fabricated fluidic systems, biomedical processes, and energy applications where lightweight, small volume heat exchangers are required. Historically, specialty heat exchangers have been made through traditional computer numerical control machining. This limits the shape of the internal passageway to planar arrays of cross-drilled holes. More complicated 3D devices can be made with a series of interlocking machined components using brazing and diffusion bonding. However, these are expensive and time consuming to produce and assemble. With SLM technology, new shapes and forms that would dramatically decrease the weight while, at the same time, increase the overall performance of the heat exchanger are now achievable. In this paper highlights on manufacturing concerns encountered during SLM of a compact heat exchanger (HX) are reported, such as orientation of the part, support structures, process parameters, post-processing and de-powdering. Furthermore, the results of the simulation and the experimental test of the heat exchanger produced by SLM are reported in order to analyze and validate its performances.**

Keywords-selective laser melting (SLM); compact heat exchanger (HX); orientation; support structures; process parameters; Inconel 718.

1. INTRODUCTION

Additive manufacturing (AM) is a production method that is attracting interest in many industrial sectors such as that of the heat transfer equipment due to the need to have innovative designs able to accommodate demand for increased performances with minimum pressure loss, reduced size (volume, envelop dimensions, aspect ratio) and weight, affordable, modular and/or scalable. Novel compact heat exchangers (HXs) solutions are needed in aerospace (environmental control, avionics and engine oil cooling systems), automotive (waste heat recovery and exhaust gas recirculation system), power (thermal management for microturbine and fuel cell systems), and process (heating/cooling and waste heat recovery systems). Traditional methods of production of HXs typically require the assembly of laminar pre-formed elements often referred to as shims, sheets, or platelets produced with a series of holes, slots, channels, or other shapes created in the face of the element (Fig. 1). In these structures, each layer of the stack is configured to a pre-determined shape and precisely aligned with other elements in the stack. Alignment is achieved with mating holes or channels (or other voids) in adjacent elements. By carefully controlling the relative position of each layer, intricate three-dimensional channels and passages may be created within the stack structure.

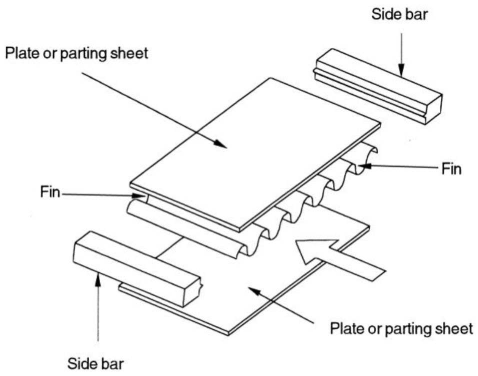

Figure 1. Basic components of a plate-fin heat exchanger [1].

The laminar element may be produced by sawing, punching, fine-blanking, coining, and water-jet or laser cutting or other means of material removal [2]. Another method of producing very precise and complex through-hole and grooved-channel metal sheet laminar elements employs photochemical machining. In this process, acids or other chemicals are used to etch away material from a solid, thin plate to produce the desired holes and other shapes. When a series of these plates are stacked, a three-dimensional structure replete with complex fluid flow channels may be realized. Joining the plates together may be accomplished by the use of adhesives, brazing or welding or other bonding methods. A preferred bonding method, particularly for severe service structures which must operate under extreme temperature, pressure and corrosive environments, is that of diffusion bonding or variants such as transient liquid phase diffusion bonding or diffusion brazing. These traditional production methods require complex and expensive special tooling. Additionally, a number of unrelated fabrication and assembly processes must be employed. Since the tooling and processes required are often highly specialized in the creation of heat exchangers, it can be very expensive and time consuming to implement even a small design change. Moreover, since the production process usually relies on material removal, a considerable amount of waste material is created which must be recycled or discarded, potentially creating environmental issues. The process of using stacked, as for the tools, is often specific to a particular part and is not readily re-purposed. If photochemical machining is employed, less purpose-built tooling may be required. However, the etching process employed uses corrosive materials, typically strong acids or bases. Furthermore, this process generates waste whose recycling/disposal is often complex and expensive.

The AM process overcomes many of the shortcomings of previous processes, particularly with respect to costly dedicated tooling and the generation of toxic waste materials. AM technologies provide maximum freedom of design, and so open up new paths for the geometrical layout of HXs. Although AM has existed since the early 1980s, its application was initially limited to creating visualization prototypes which were primarily utilized to accelerate the product development cycle. This role changed with the advent of AM technologies capable of processing advanced metallic materials and alloys [3] such as stainless steel, titanium alloys, aluminum alloys and nickel-based alloys (e.g. Inconel 625 and 718). The adoption of powder-bed based AM processes such as selective laser melting (SLM) and electron beam melting (EBM) has contributed to the increasing adoption of AM in production of HXs. These technologies do not need any tools, so single, individual items can be produced requiring almost no additional costs. Although there have been previous works [4, 5] on the design of HXs for AM technologies, there are still few studies on manufacturing feasibility through SLM. The main SLM process parameters (e.g. laser power, scanning speed, layer thickness, etc.) and build strategy (e.g. part orientation, scanning pattern) determine the porosity, microstructure, surface quality and mechanical behavior of the produced parts as they act on the laser-to-powder heat transfer, powder melting, melt pool behavior, layer-to-layer adhesion, cooling rates [6-8]. Hence, SLM parameters must be carefully selected for a given material and part geometry/size. The orientation of parts during SLM can also impact on final part quality and mechanical properties. For heat transfer equipment, the porosity and surface quality are very important as they have effects on the overall heat transfer capability, resistance to fouling and sealing.

In this paper the fabrication concerns that occur during the fabrication of a counter-flow heat exchanger in Inconel 718 by SLM, such as orientation on the building platform, support structures needed, main process parameters, dimensional limits of the internal channels, post-processing and following removal of the residual powder are reported. Moreover, the produced HX is analyzed and validated through the results of the simulation and experimental testing.

2. MATERIALS AND METHODS

The heat exchanger was designed considering the operating conditions necessary to fulfill the requirements of the HELMETH FP7 Project, that is to work at high temperature and under high pressure in a severely aggressive ambient (with H_2 and O_2). Each side of the heat exchanger has three channels and inside the channels longitudinal triangular fins have been inserted in order to act as fins for the enhancement of the heat transfer and in order to act as structural support for the plates. Each channel of the HX is sandwiched between two cold side channels and vice versa, except for the external ones. The geometrical data for the HX are reported in Table I. The design of the HX is represented in Fig. 2.

TABLE I. HEAT EXCHANGER GEOMETRICAL DATA

Parameters	***Values***
Length x width x height [mm]	80 x 38 x 19
HX total volume [cm^3]	5780
Inlet manifolds depth [mm]	15
Outlet manifolds depth [mm]	5
Plate thickness[mm]	1
Channels height [mm]	2
Hydraulic diameter [mm]	1.13
Total heat transfer surface [cm^2]	39900

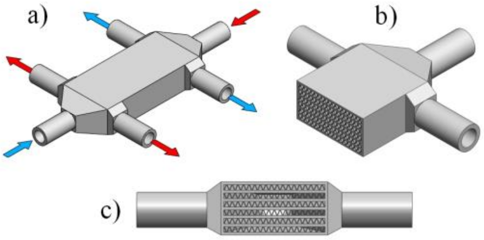

Figure 2. HX design: a) Isometric Projection and flow fields (Hot side: red – Cold side: blue); b) Cross-section with internal channels; c) Internal channels

In order to resist to severely aggressive ambient, Inconel 718 (a trademark of Special Metals Corporation [9]) has been chosen as material for the construction of the HX. This kind of precipitation-hardening nickel-chromium alloy is characterized by having good tensile, fatigue, creep strengths at high temperatures, and it has also outstanding corrosion resistance in various corrosive environments. Therefore this material is ideal for applications such as gas turbine parts, power and process industry parts. The powders (EOS GmbH, Germany) are produced by gas atomization: they are spherical, with a with a particle size between 2 and 40 µm.

The HX was fabricated using an EOSINT M270 Dual mode machine, equipped with 200W Yb fiber continuous laser beam with a focused diameter of 100 µm and layer thickness of 20 µm. Specimens of 20 x 15 x 30 mm were used to optimize the support structures and process parameters. The experimental scheme was designed based on Design of Experiments (DoE). Table II shows the process parameter investigated in this study to obtained parts with highest density and with support structures able to anchor them to the building platform.

TABLE II. PROCESS PARAMETERS VALUES INVESTIGATED

Process parameters	***Values***	
	Core and up-skin[a]	***Down-skin (3 layers)[a]***
Laser power [W]	175, 185, 195	50, 80, 120
Scan speed [mm/s]	600, 900, 1200	400, 600, 1200
Hatching distance [mm]	0.07, 0.09, 0.11	0.07, 0.08, 0.09
Support scan speed [mm/s]	400, 600, 800	
Support laser power [W]	50, 80, 120	

a. [10]

Furthermore simulations and tests with different operating conditions have been run in order to validate the HX behavior using computational fluid dynamics (CFD).The flow fields inside the heat exchanger have been studied in the laminar regime because of the low mass flow rates involved. The simulation has been performed using the commercial software Comsol Multyphisics®. The tests have been made using H_2 in the hot side and air (79/21 N_2/O_2) in the cold side. Two tests were performed at almost perfect adiabatic conditions toward the external ambient; in these two cases the thermal balance was fulfilled. It was then possible to evaluate the global heat transfer coefficient (HTC) using the logarithmic mean temperature difference method (LMTD).

3. RESULTS AND DISCUSSION

3.1. Orientation and support structures

One of the major limitations in the geometrical freedom offered by SLM is the overhang surfaces: they are a part of the component that is not supported during building by solidified material or a substrate on the bottom side [11]. Consequently, the melt pool created by the heat input from the laser is supported by powder material that can lead to dross formation, distortions, curling, etc. The orientation of the part on the building platform is crucial to reduce or even eliminate overhanging surfaces. Considering the HX of this study, while the internal channels are designed to be self-supporting [11], there are overhanging areas that cannot be avoided (Fig. 3). But supports in these areas cannot be used because they are impossible to be removed being in internal passages.

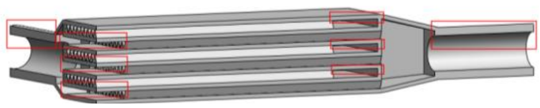

Figure 3. Overhanging areas of the HX highlighted with rectangular boxes (in red).

The orientation was chosen taking also into account to reduce the surface roughness of self-supporting surfaces due to the staircase effect [11]. Fig. 4 shows the part orientation and support structures for the manufacturing of the counter-flow HX adopted.

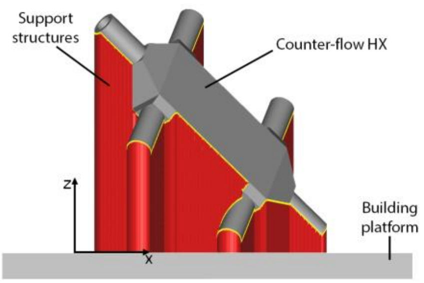

Figure 4. Part orientation adopted for the HX manufacturing and support structures (in red and yellow).

External support structures during the construction used to fix the part to the building platform, help also to conduct excess heat away from the part and to prevent the warping and/or collapse [10]. A support structure may be decomposed into three functional areas: the lower, connecting to the platform, providing a stable base support; the middle, strong enough to withstand both the vertical weight and other horizontal disturbances; the higher, connecting to the part surfaces, also known as teeth, that should be easily removable. The optimized configuration of these three areas depends on the material employed. Support structures play an important role in resisting the thermal stresses typical of the SLM process [8]. Thermal stresses can cause huge deformations to the part and can lead to process failure due to delamination of the part from the building platform (Fig. 5a). In some cases, they are so high that can also induce cracks in the parts during processing before that it is completed.

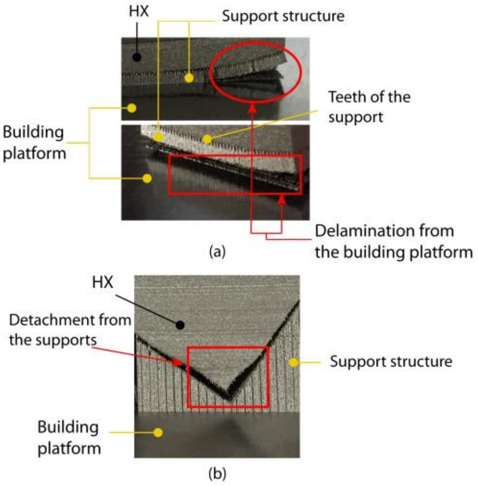

Figure 5. Detachments and distortions arised during the manufacturing of the HX in Inconel 718.

It was noticed that the difference of the laser power between the last layer of the support (teeth) and the first layer of the part (down-skin), created a narrowing of the melting region with consequent deformation and detachment of the part from the supports (Fig. 5b). For this reason, newly designed teeth supports (Fig. 6) were adopted together with a value a power laser value equal to that of the down-skin of the part.

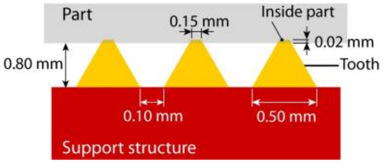

Figure 6. Design optimization of the upper areas of supports (teeth) for the building of the HX.

3.2. Process parameters and internal channels

Fully dense heat exchangers, with minimized porosity, should have a better ability to maintain vacuum pressures in evacuated two-phase heat spreaders, as well as combat against leaks driven by high vapor pressures during high heat flux operation [12]. Hence is fundamental to use parameters that assure the highest final density. The amount of energy absorbed is determined by various process parameters (laser powder, scanning speed, hatching distance, layer thickness [10]), and affects the melting and the process stability of the melt pool and therefore the layer beneath [13]. Table III summarizes the process parameters used for the production of the counter-flow HX. These parameters have permitted the creation of well-defined and full dense parts. Fig.7 shows the walls cross-sectional area of the internal channels of the HX: they were built before (Fig. 7b) and after (Fig. 7c) process parameters optimization.

TABLE III. PROCESS PARAMETERS VALUES USED FOR HX

Process parameters	***Values***		
	Core	***Up-skin (2 layers)***	***Down-skin (3 layers)***
Laser power [W]	195	195	80
Scan speed [mm/s]	1200	1200	1200
Hatching distance [mm]	0.09	0.09	0.08
Layer thickness [µm]	20		
Substrate temperature [°C]	80		
Stripe width [mm]	5		
Overlap stripe [mm]	0.12		
Contour scan speed [mm/s]	1400		
Contour laser power [W]	140		
Support scan speed [mm/s]	400		
Support laser power [W]	80		

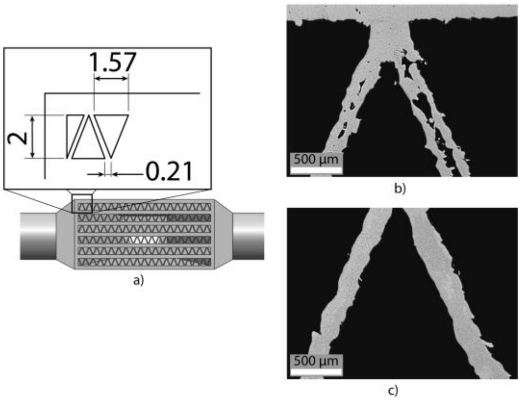

Figure 7. Internal channels walls in cross section: a) geometrical dimensions [mm]; macrographs of manufactured walls b) before and c) after process parameters optimization.

3.3. Post-processing and de-powdering

After the SLM process and before detaching the HX from the building platform, it is fundamental to perform a stress-relieving treatment to avoid bending or distortion of the parts. Firstly, the part was subjected directly to a solution annealing at 980°C for 1h in vacuum, and then cooled in air, as suggested by the powder supplier. This treatment, followed by ageing, should ensure the precipitation hardening of the alloy. But due to the very small size of the cross-section of the channels, while they are several centimeters long, the powder remained entrapped within the internal cavities. The heat treatment compacted the trapping powder, making it impossible to be removed (Fig. 8).

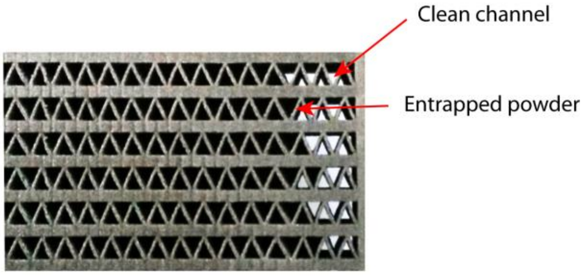

Figure 8. Cross-section of the HX after direct solution annealing at 980 °C.

Therefore, in order to solve the problem, the HX has been re-manufactured and subjected first to a stress relieving heat treatment at 450°C for 2h. Then, once removed the residual powder, the HX was solution treated at 1065°C for 2h in vacuum and subsequently quenched in Ar. In this way it was possible also to take advantage of the precipitation hardening and on the protective oxide that form on the channels surface.

3.4. Simulation and test

The simulation results and the experimental data of the adiabatic tests are reported in Table IV. The same conditions of the experimental test have been used in the CFD model considering a perfect insulation and thus adiabatic conditions towards the ambient. From what can be seen from the simulation results the CFD model correctly predicts the performances of the HX. Moreover, the HX built via SLM demonstrates performances that are slightly better than traditional gas-gas counter-flow heat exchanger with a global HTC around 50 [W/m^2/°C], while the typical value for this type of heat exchangers is between 10 and 40 [W/m^2/°C] as reported by [14].

TABLE IV. SIMULATION RESULTS AND EXPERIMENTAL DATA FOR THE CFD MODEL

Simulation results	***Model 1***	***Model 2***
HS outlet temperature [°C]	139.1	111.4
HS pressure drops [mbar]	≈ 0.1	≈ 0.1
CS outlet temperature [°C]	224.5	179.8
CS pressure drops [mbar]	≈ 2.1	≈ 2.8
Heat Exchanged between HS and CS [W]	≈ 58.36	≈ 60.98
Heat losses toward the ambient [%]	0.00	0.00
LMTD [°C]	84.7	76.8
Global HTC [W/m2/°C]	49.09	56.56
Experimental conditions	***Test 1***	***Test 2***
Reference pressure	Ambient	Ambient
HS flow rate [Nl/min]	5	5
HS inlet temperature [°C]	679.7	675.2
CS flow rate [Nl/min]	30	40
CS inlet temperature [°C]	136.9	110.6
Experimental results	***Test 1***	***Test 2***
HS outlet temperature [°C]	140	112
HS pressure drops [mbar]	≈ 0.3	≈ 0.2
CS outlet temperature [°C]	225.4	178.9
CS pressure drops [mbar]	≈ 4.9	≈ 6.6
Heat Exchanged between HS and CS [W]	≈ 58.4	≈ 60.3
Heat losses toward the ambient [%]	0.25	1.92
LMTD [°C]	90.7	83.9
Global HTC [W/m2/°C]	45.89	51.24

4. CONCLUSION

In this work the design, manufacturing and testing of a gas-gas counter-flow compact heat exchanger for high temperature application in highly aggressive atmospheres has been described. The manufacturing has been performed using the AM technique knowns as SLM. Firstly it was fundamental to study and optimize the orientation of the component in the building chamber, in order to avoid supports structures in internal passages, impossible to be removed, and to reduce the surface roughness due to stair-case effect. Then the process parameters for both support structures and the part were investigated and optimized, to have the highest density without detachment and deformations. The supports were also re-designed in the upper areas, the so-called teeth. Finally, a specific thermal treatment was adopted for stress relieving and to ensure the removal of un-melted powders, followed by solution annealing to take advantage of the Inconel 718 precipitation hardening alloy. A CFD model has been developed to model the behavior of the HX and it has been validated with experimental data. The results demonstrated that, optimizing the SLM process, it is possible to obtain a HX

in Inconel 718 with performances comparable or better with respect to the one obtainable with traditional processes.

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