The production of high-performance heat exchangers for aerospace applications

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Abstract

The use of additive manufacturing (AM) of heat exchangers is growing in popularity due to the possibility to produce thin-walled structures with excellent heat-transfer performance. Common aerospace materials are in focus, including stainless steel, titanium, aluminium, copper, and nickel base alloys.

Along with the opportunities, there are also challenges which are being addressed by suppliers, OEMs (original equipment manufacturers), and research institutes.

Hot Isostatic Pressing (HIP) is a key post process that has been used to remove shrinkage porosity and internal defects in cast products for many years, with improved mechanical properties and fatigue resistance. The application of this process to AM thin-walled structures is key to achieve desired properties, with modern HIP technology now offering opportunities for improvement in productivity, processability, and performance.

Recent advancements in HIP equipment offers the ability to perform argon gas quenching as part of the HIP cycle during the processing of thin-walled heat exchanger structures. This technology facilitates combined HIP and in-situ solution heat treatment (SHT) and aging for improved productivity and mechanical/physical properties. This processing route has also been shown to reduce distortion, mitigate corrosion, and improve surface finish for enhanced product quality.

In this whitepaper, solutions for various aerospace alloys as well as recent results from trials and studies will be discussed.

Keywords: Heat Exchanger, Additive Manufacturing, Heat Treatment, Aging, HIP, Hot Isostatic Pressing, Mechanical Properties, Combined HIP and Heat Treatment, Post processing, Quality Assurance

Introduction

There are many heat exchanger applications on in the aerospace industry, including everything from APU heat exchangers, to rocket engines. The use of additive manufacturing (AM) is increasing rapidly for these types of applications, to increase heat transfer, reduce weight and thereby fuel consumption. A rule of thumb for the effect of weight reduction on fuel consumption of passenger aircraft is that at weight reduction of 1 kg results in a fuel saving of 20-30 grams of fuel per 1000 km. [1] and every gram is of interest.

For space, the ability to pre-heat fuel in rocket engines whilst at the same time cooling the combustion chamber increases fuel efficiency. This allows for reduced rocket size for the same payload, or large payloads for the same size of rocket. Re-usable boosters are an area of great interest, and of course, a critical application for the AM components. [2]

Figure 1: Multi-engine booster using AM technologies

Structures and designs

The use of complex geometries enables the reduction of the total size of heat exchangers through increased surface area and thin sections. Reduction in size, automatically leads to reduced weight, which is of key interest for aerospace applications. Gyroid structures are becoming an increased focus areas for heat transfer applications [3]. AM enables printing in almost any geometry and topography often referred to that a triply periodic minimal surface (TPMS) structure, which is a mathematically defined smooth surface. The concept is not new and was defined by Schwartz in 1885, with two inter-dependent volumes separated by material. [4].

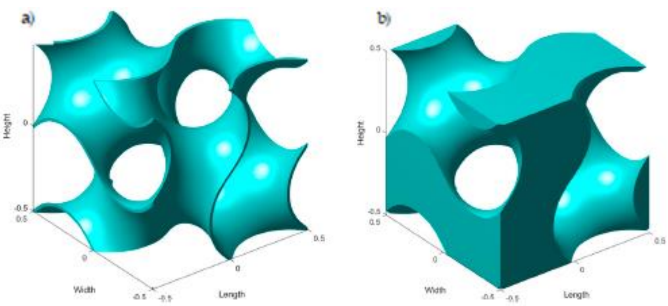


Figure 2: Example of TPMS structure that are made possible using additive manufacturing. [4]

This kind of high-surface area can therefore be used for forced-convection heat exchangers and are of great interest for aeronautical application.

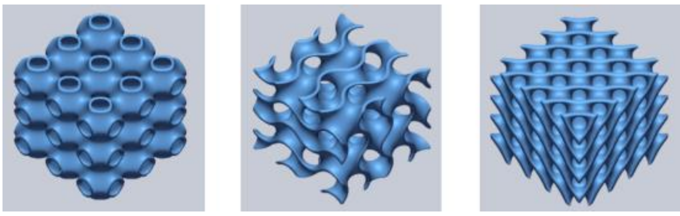


Figure 3: Examples of high surface area designs for heat exchanger internals [5]

Careful design and choice of structure is needed to ensure that pressure drop across the heat exchanger is managed as well as the volumetric flow rate [6]. The increased surface area of TPMS structures, increases heat transfer surface area by as much as 61% compared with a traditional heat exchanger [4].

Printing is not a perfect process, there are issues

Although AM is an enabler for very complex designs, with high thermal transfer efficiency, the thin wall, complex structures pose challenges from production and operation perspectives. Typical issues centre around powder removal after printing, surface integrity and material performance.

Powder removal is a challenge, but can be overcome through careful rotation, tapping, and emptying of channels followed by blowing with compressed air. Due to safety concerns, handling of the removed powder may involve manual gloveboxes or inert environments. Powder must be removed prior to heat treatment to avoid agglomeration and fixation of granules on critical surfaces or in fine features. X-Ray Computer Tomography (CT) scanning is often used to ensure that powder-free cavities are achieved, but this is often seen as a costly operation for larger structures, especially when attempting high resolution scanning of dense materials.

Following powder removal, further operations usually include stress relief and support removal prior to further heat treatment procedures and surface finishing. Stress relief is essential for PBF-LB produced components, due to the large temperature variations are seen during printing, leading to excessive stresses. These can cause cracking and distortion, and thin-walled structures are especially vulnerable due to the limited heat-sink behaviour through the minimal printed structures. Variation of microstructure over build height is often seen for the same reason [6].

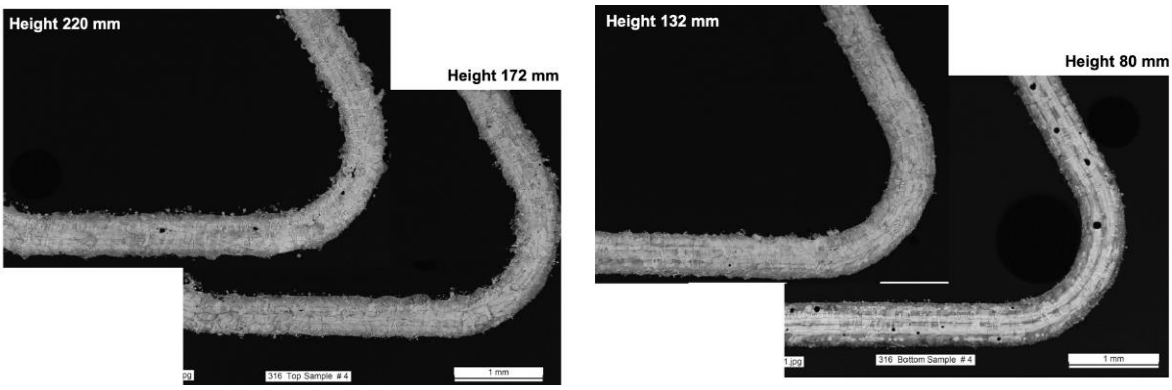


FIGURE 4: Variation of porosity levels witnessed at different build heights [6]

Although thin-wall structures are possible to print, there are risks or defects that can lead to leaks or potential corrosion initiation points. Surface finishing using chemicals and/or abrasives also removes some of the material, so sufficient wall thickness needs to be planned for prior to production.

The use of Hot Isostatic Pressing (HIP) to heal defects

HIP has been used for many decades to close defects in castings and other wrought materials. The advent of additive manufacturing and the production of increasingly complex structures has led to increased demands on HIP processing to heal defects and improve material integrity [7]. Heat treatment can now be done in modern HIP equipment, using High Pressure Heat Treatment (HPHT™) in a controlled argon atmosphere immediately following the densification process. As argon gas is used for the HIP densification process, all internal channels and surfaces in AM heat exchangers receive the same pressure. Forced convection of the gas in the HIP ensures uniform heating of the components and as heat exchanger surfaces are naturally designed to allow flow of gas and liquids and are ideal candidates for extremely uniform heat treatment in Quintus HIP equipment.

HPHT™ comprises several key technology areas including steered heating profiles, densification, solution heat treatment and aging using Steered Cooling™ profiles. A recent addition is the ability to limit surface oxidation using the patented Quintus Purus® clean HIP solutions.

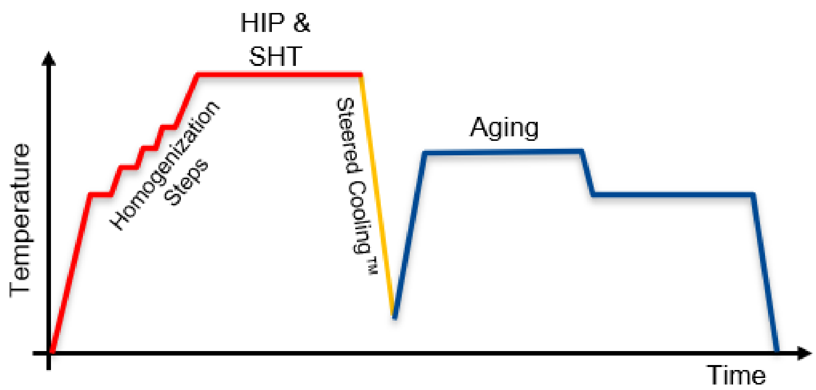


Figure 5: showing a typical HPHT cycle for a typical nickel base alloy ©Quintus Technologies, 2024

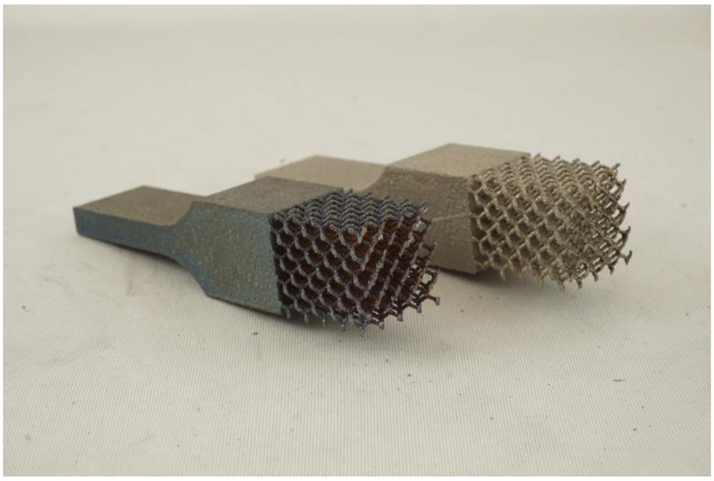
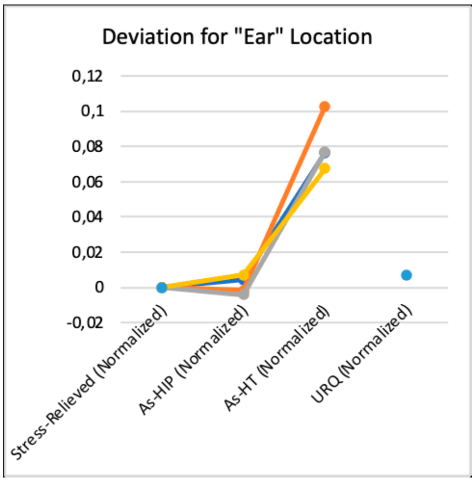


Figure 6: Example of complex structures with traditional HIP (left) vs HPHT with Quintus Purus® (Right) ©Quintus Technologies, 2024

Traditional heat treatment processes often include high speed cooling and may involve water, oil, or polymer quenching. These operations are usually performed on the stress relieved parts or after HIP densification. Of course, in the HPHT process, similar steps can be done in the one machine. Parts are sometime left on the build-plate to avoid cracking or tolerance shifts during the heat treatment steps. Recent publications have demonstrated that tolerances of Aluminium alloy F357 AM parts can be retained using in-HIP quenching, with significantly improved tolerances compared with water quench [8]. This is due to the use of high-pressure argon gas as the cooling medium that is in contact with the component and the cooling surfaces of the HIP equipment. In this example, the material was cooled in the HIP using URQ® (Uniform Rapid Quenching) technology to mimic T6 heat treatment, directly from the densification temperature at the chosen HIP pressure of 170MPa (24,646 psi). For this alloy heat treatment is essential after stress relief.



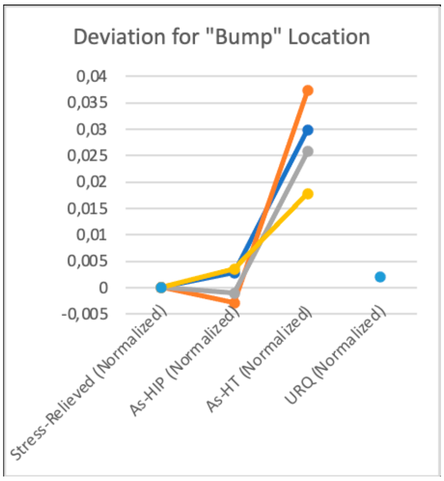


Figure 7: tolerances for F357 AM aerospace components. Distortion measurements for a representative geometry, Two Benchmark Part Locations “Ear” and “Bump” [8]

Hot isostatic pressing is positive for heat exchanger materials in several ways

With improved heat transfer performance and optimized metallurgy come improvements in in-situ performance. Key benefits can be seen in leak tightness, corrosion resistance and fatigue behaviour. Thin wall printing often leads to porosity in the bulk material and struts are more difficult to print with thin section than walls [9]. Repeatable feasible limitations in minimum thickness have been reported down to minimum 0.3mm using PBF-LB with a relatively high risk of defects, although guidelines usually recommend minimum 1.0mm thickness and tolerance and thickness deviations often require a minimum thickness of 2.0mm [10]. The limits can be exasperated by variations between printers, powders, recoater blades, bed thickness and feature orientation [11].

The directionality of PBF-LB printed microstructures is well known [12], with higher strength in the Z direction (build direction). Complex structures therefore have challenges when it comes to design strength and tolerance control. Not only the TPMS morphology is an issue, but the build direction must also be considered. The surface texture will automatically vary in a TPMS build as there are sections with all possible orientations. It is well documented that down-skin areas give rise to rougher surfaces [11][13] which often require support structures. These down-skin areas are generally rougher which may potentially lead to more active corrosion sites.

Porosity is also an issue, which has a negative effect on heat transfer since heat must pass through the material surrounding the pore. A “fully dense” material with 99.5% density, still has 0.5% porosity that prevents optimal heat transfer. This can be an added challenge for thin-section materials where printing is more of a challenge [9]. Hydrogen porosity (blistering) from low pressure or vacuum heat treatment is commonplace in aluminium alloys which can be avoided through in-HIP heat treatment under pressure [12] [8]. HIP is effective at closing porosity and can help thermal conductivity [15].

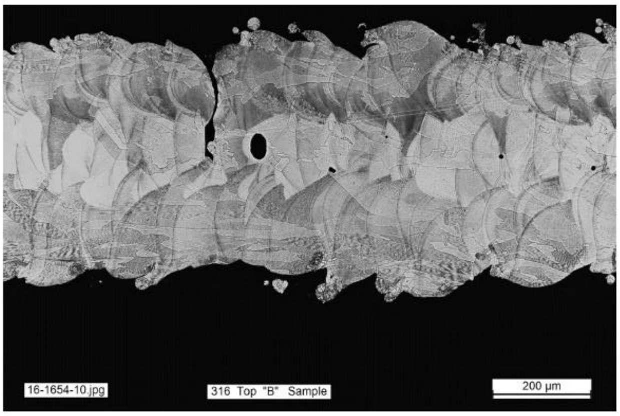


FIGURE 8: defects in thin-wall printed structure with potential corrosion initiation site [6]

It is common to perform surface finishing to reduce roughness and improve corrosion resistance which is a major concern for heat exchangers where chlorides are present in service which can accelerate degradation of materials [7]. Rough surfaces and fouling of heat exchangers can lead to under-deposit corrosion or pitting corrosion, which in turn can lead to leakage. Surface finishing is often used and leads to smoother surfaces, less fouling and improved flow characteristics.

Surface finishing should be conducted after HIP, to ensure that unwanted sub-surface pores are closed prior to surface adjustment. This helps ensure removal of surface anomalies such as roughness, loosely attached powders or tight crevices [16]. Figure 8 (above) shows a potential crevice corrosion site and porosity in a thin-wall structure. The effect of polishing before or after HIP for a Ti6Al4V component can be seen in Figure 9. The left picture shows surface finishing of non-HIPed material, and the right picture shows surface finishing after HIP [17].

Figure 9: Typical surface finish of AM as-built material (Centre), with surface finishing. Surface after finishing on non-HIPed material (Left), and surface finishing after HIP (Right). [17]

Image courtesy of REM Surface Engineering.

Improved surfaces lead to a reduced number of sites where corrosion can initiate, often through pitting corrosion attack or potentially crevice corrosion under fused powder grains or fouling products, leading to under deposit corrosion. They also significantly improve fatigue performance and reduce scatter in mechanical properties as demonstrated in Figure 10 below, where HIPed material was subjected to different surface finishing alternatives. [16]

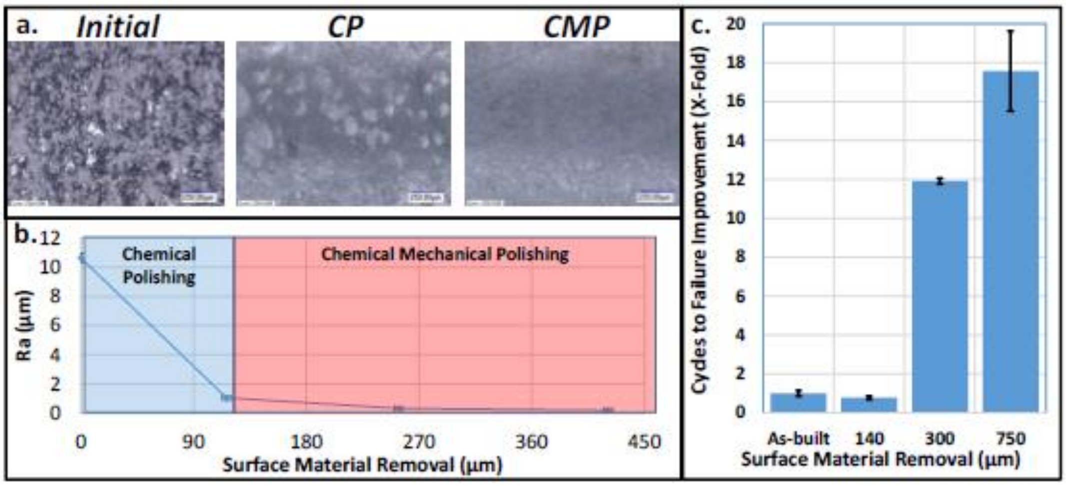


Figure 10: Effect of surface finish on high cycle fatigue performance of IN-625 PBF-LB REM [14] (a)Microscope images at 100X magnification of To-6al-4V L-PBF as built, CP and CMP surface progression. (b)Average surface roughness progression per surface material removal (SMR) through surface finishing operation. (c)Uniaxial tensile high cycle fatigue cycles to failure at 650MPa, RT, R=0.1 and 60Hz, at different SMR.

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Summary and Conclusions

Powder bed fusion is being applied increasingly to the production of aerospace heat exchangers. It is possible to produce very thin and highly complex heat exchangers with high thermal efficiency. To ensure robustness of these solutions in service modern HIP technologies are being utilised for densification and heat treatment in a single thermal processing cycle, leading to improved tolerances and mechanical properties. Surface finish and device robustness is guaranteed with the use of further post-processing technologies following HIP.

As a result, the production of high-performance heat exchangers can be manufactured with a combination of powder bed fusion production and rationalized post processing routes using High Pressure Heat Treatment, HPHT™ and subsequent surface finishing.

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Quintus Technologies is the global leader in high pressure technology. The company designs, manufactures, installs, and supports high pressure systems for sheet metal forming and densification of advanced materials. Quintus has delivered over 1,900 systems to customers within industries such as aerospace, automotive, energy, and medical implants. The company is headquartered in Västerås, Sweden, with a presence in 45 countries worldwide.

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