Thermo-fluid dynamic simulation of hot isostatic pressure quenching (HIPQ) on aircraft blades

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Hot Isostatic Pressing (HIP) is an established technology in the aerospace industry used to develop and produce alloys for high-performance applications such as turbine rotor blades.

HIP is increasingly being used in additive manufacturing (AM) technologies for metallic materials because it reduces the defects typical of these new technologies, thereby significantly increasing the performance of new materials developed for AM. However, HIP systems typically cannot guarantee specific control of the cooling phases and therefore post-HIP heat treatments are commonly used on AM-produced materials to transform their microstructure to the required standards.

This paper studies the latest generation of HIP systems, known as HIP/quench (HIPQ) systems, which combine the HIP process and subsequent controlled cooling in a single system to simultaneously reduce defects and achieve the desired microstructure in a single thermal cycle, with obvious reductions in cost and production time. This paper investigates a combined HIPQ cycle applied to turbine blades produced by additive electron beam melting (EBM) technology for titanium aluminium alloys (Ti48Al2Cr2Nb).

The HIPQ treatment simulation analyses and determines how to optimize the temperature and distribution of airflow within the furnace to ensure a uniform temperature across all blades regardless of their position in the chamber, and to reduce thermal gradients during the immersion and cooling phases. This avoids microstructural variations in the blades as a result of their position in the furnace thus maximizing their mechanical properties.

The study examines a number of design parameters, including furnace geometry, basket and blade arrangement, and the air flow generated by the centrifugal fan. The results show how this simulation approach can analyse the efficiency of the heat treatment process helping to improve the performance and durability of critical aerospace components. Understanding the thermo-fluid-dynamic details also reduces the design of experiments to a minimum while improving the final quality of the material.

This paper discusses the application of computational fluid dynamics (CFD) to the verification of the furnace selected to combine the HIP and controlled cooling process of turbine blades for aeronautical engines produced with additive technology.

The activities described were carried out as part of the SIADD project co-financed by the National Operational Program (PON) "Research and Innovation 2014-2020" with MIUR code no. 1735 of 07/13/2017. We would like to thank all project partners for their fruitful cooperation: DTA– Aerospace Technology District (lead partner), ELFIM, ENEA, EnginSoft, GE AVIO, HB Technology, Ingenia, ITIACNR, CNR, Novotech, Polytechnic of Bari, Polytechnic of Milan, UMBRA Group Cuscinetti, University of Enna "KORE", and University of Salento. SIADD is the Italian abbreviation a Ministry of Instruction and Research-sponsored project focusing on innovative solutions for quality and sustainability in additive manufacturing processes.

Hot isostatic pressure quenching (HIPQ)

Hot isostatic pressing (HIP) is an established technology in the aerospace industry for developing and producing materials for high-performance applications, such as turbine rotor blades. This HIP process combines high temperature and pressure to densify materials, eliminating porosity and other structural defects introduced during the manufacturing process and improving mechanical properties, particularly fatigue strength and ductility.

HIP is proving to be increasingly indispensable, especially in additive manufacturing (AM) technologies for metallic materials where it reduces the defects typical of these new technologies, significantly increasing their performance and making them competitive with conventionally produced products.

In addition to hot isostatic pressing, AM components require heat treatment to further improve their microstructure and hence mechanical properties. At present, HIP systems cannot generally guarantee detailed control of the required cooling rate after heat treatment, which means that the materials require additional specific heat treatment in a different furnace after HIP.

It is therefore essential to investigate the post-processing of AM-produced titanium-aluminium (TiAl) alloy components in the latest HIP systems, namely HIP/Quench (HIPQ), which promise to combine high pressures and controlled cooling in a single system, thus successfully combining the post-production treatment of items currently produced in different equipment and often different facilities.

HIPQ systems could effectively simplify and optimize current AM production processes, significantly reducing existing production cycle times. In addition, the ability to combine pressure and controlled cooling in the same system promises to deliver equal or better results in terms of microstructure and mechanical properties than the separate processes usually used.

This paper focuses on TiAl turbine rotor blades manufactured using the EBM (electron beam melting) AM process and subsequently subjected to the combine HIP and heat treatment (HIP/Quench) process.

CFD simulations of heat flows within a furnace are an established practice for investigating and optimizing the furnace and its potential heat treatment capabilities. Geometrical discretization and material modelling allow the simulation of different usage scenarios, varying the boundary conditions to identify the ideal configuration that provides the most homogenous heating and cooling of the numerous blades arranged on two levels.

This article describes the assumptions used to model argon gas and analyses the results at key points in the process.

In this study, particular attention was also paid to numerically simulating the environment and the HIPQ treatment with CFD techniques in order to facilitate the definition of optimal process parameters and simulate their impact on materials.

This will simplify the transition from laboratory environment to industrial-scale development.

This activity was part of a larger project, SIADD, that not only aimed to optimize the HIPQ process, but also to study different materials and processes that harness additive technology.

The use case

Avio Aero provided low pressure turbine (LPT) blades made of TiAl alloy using EBM additive manufacturing technology to test the HIPQ process on real aircraft components. The nominal composition of

Fig.1. Example of EBM LPT blades before any HT.

the alloy is Ti-48Al-2Cr-2Nb [reference: US patent 4,879,092].

The test case was analysed in terms of microstructure, mechanical properties, thermal distortion, and porosity closure effectiveness to verify the impact of the proposed HIPQ cycle compared to the standard process (separate HIP and HT cycles). The homogeneity of the furnace over the entire working volume was studied at all stages of the HIPQ cycle, demonstrating the ability of the process to produce a uniform alloy microstructure and hence uniform mechanical properties in all positions of the chamber.

Porosity closure efficiency and blade thermal distortion were also studied in comparison with standard HIP and HT cycles in order to exclude any different behaviours when combining HIP+cooling rates in the same cycle (for example, risk of pore reopening during cooling).The simulation of HIPQ cycle allowed us to identify the worst position in the chamber in terms of temperature uniformity, especially during the transient phase, and to selectively study the worst positions in order to define better HIPQ parameters.

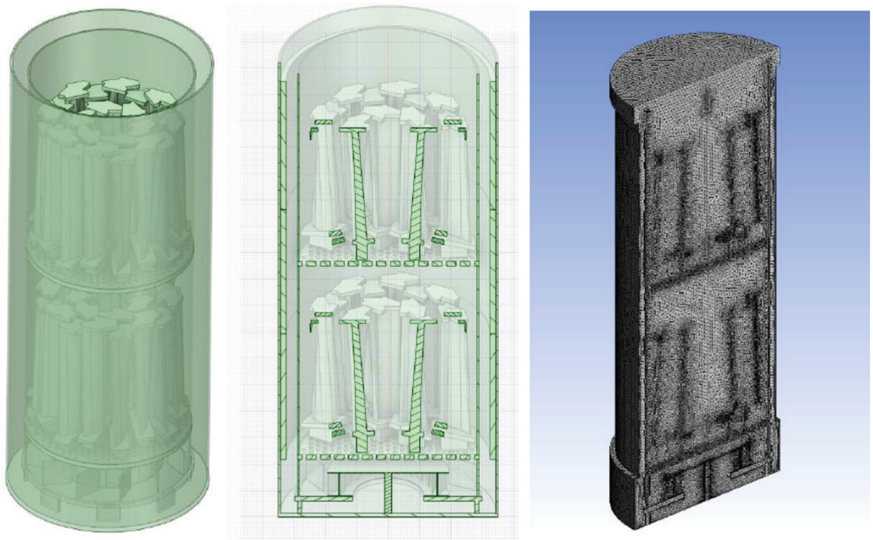


Fig.2. CFD model (left) and vertical section of the mesh including blades (right).

Simulation of HIPQ

Geometrical model and grid

The geometric model of the furnace, shown in Fig.2, represents the actual structure of the treatment system in which the blades are arranged on two levels (upper and lower) of the basket. The accuracy of the mesh in three-dimensional space is essential to capture the flow and temperature variations in the gaps between the different blades. The quality of the overall model developed was confirmed by interpolating virtual sensors and comparing their temperature-time curves with real thermocouple curves.

The virtual sensors for monitoring the temperature in specific areas of the furnace consist of thermocouples inserted in blocks (55mm x13mm x13mm) made of the same material as the blades. These blocks were also faithfully modelled in the numerical simulation. The table shows the positions of the four sensors considered: WL02, WL07, WL08, WL09 (Fig.3)

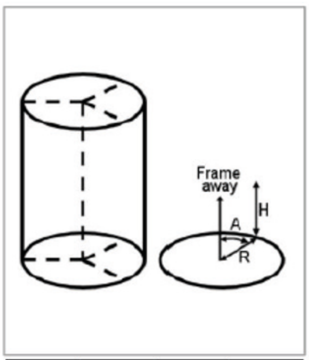
To simulate the thermal cycle under study, the reference curve of the WL08 probe was replicated. The temperature curves collected from the other probes were used to verify the reliability of the replication of the actual thermal cycle. The fan was explicitly modelled using the Frozen Rotor approach, which allows the flow that develops around the fan to be accurately evaluated without simulating its relative movement with respect to the static diffuser. This saves computational time without sacrificing accuracy.

All solid domains inside the furnace (load plates, furnace structure, basket, static diffuser) were modelled taking into account the thickness of each individual component to calculate the thermal inertia.

The electrical resistors that heat the argon for the HIP phase were modelled as heat sources applied to the internal furnace walls. The glycol water flowing outside the furnace for the quench phase was modelled as an energy sink applied to the internal furnace walls. The fluid domain of the furnace coincides with the argon volume.

Material modelling and boundary conditions

The thermo-fluid dynamics analysis was performed using the Ansys CFX 2021 R1 solver [1]. The shear stress transport (SST)



ID	R [mm]	H [mm]	A [°]
WL02	180	965	60
WL07	0	965	90
WL08	10	520	90
WL09	10	35	90

Fig.3. Photo of the oven (courtesy of Pres-X) and the positions of the sensors.

Al	Cr	Nb	Fe	C	O	N	H	Ti
32.0-33.5	2.2-2.6	4.5-5.1	Max. 0.05	Max. 0.025	Max. 0.12	Max. 0.02	Max. 0.003	Bal

Table 1. Chemical composition of aluminium and titanium alloy for the blades.

turbulence model and the discrete transfer model radiation models were used. Energy resolution within the different solid and fluid domains was enabled. For the fluid, argon was modelled as a real gas through the Peng-Robinson equation of state, formulated as follows:

$$p = \frac{RT}{v-b} - \frac{a(T)}{v^2 + 2bv - b^2}$$

where

$$b = 0.0778\frac{RT_c}{p_c}$$

$$a(T) = a_0(1 + n(1 - \sqrt{\frac{T}{T_c}}))^2$$

$$a_0 = 0.45724\frac{R^2T^2{}_c}{P_c}$$

The factor n is calculated as a function of the eccentricity factor w

$$n = 0.37464 + 1.54226w - 0.26993w^2$$

The blade material is an aluminium and titanium alloy as shown in Table 1.

The density of this TiAl material is 0.144lbm/in^3. Specific heat and thermal conductivity vary with temperature.

The furnace material is molybdenum with the following properties:

- Density = 10,200kg/mc
- Specific heat *[Cal/Kmol]* $= 5.69+0.00188T-(50300/T^2)$
- Thermal conductivity *[W/mK]* $= 8*10^{-6}T^2-0.0491T+152.32$

In both phases, the fan does not have a constant speed, but a constant speed assumption was applied in agreement with the partners. The value imposed is the average value calculated for each phase. In the HIP phase, the fan rotates at an average speed equal to 30% of the maximum speed. In the quench phase, the speed increases to 80% of the maximum speed. Since the maximum speed is 900rpm, the fan speed is 270rpm in the HIP phase and 720rpm in the quench phase. The heating elements in the HIP phase and the glycol water in the quench phase were modelled as heat sources and sinks, respectively, associated with the internal furnace walls. Heating and cooling were modulated to follow the temperature trend detected by the WL08 thermocouple positioned in the centre of the furnace during the experimental phase.

Project results

Simulation and actual results

In the present study, a numerical simulation of a typical HIP-Quench cycle is presented. The heat treatment parameters were selected after several laboratory-scale tests. Once the optimized parameters were identified, a new industrial-scale test campaign was carried out to confirm the preliminary results obtained in the laboratory in terms of material properties, porosity closure, and dimensional distortions, which are in line with expectations and comparable to conventional heat treatments.

A numerical simulation was carried out using CFD techniques, focusing specifically on the heating and cooling phases of the entire HIPQ treatment. The output was the thermal distribution inside the furnace to verify the temperature uniformity for each blade. Of interest is the good uniformity observed in the temperature distribution on each component as well as within the entire furnace volume. For example, at the end of the heating phase, a maximum difference of 5°C can be detected between the coldest and hottest point of the blades (Fig.4).

The temperature range during heating corresponds to the minimum and maximum temperature values measured at the time displayed. This range makes it possible to better highlight the temperature gradients that develop on each blade at each instant.

The red areas highlight higher temperatures, while the blue areas correspond to areas with lower temperatures. The cross-sections of the upper basket (Fig.5) show the temperature distribution at 65 and 130 minutes of the heating phase. Six numbered blades were used as a reference to check the temperature homogeneity and the effect on the microstructure.

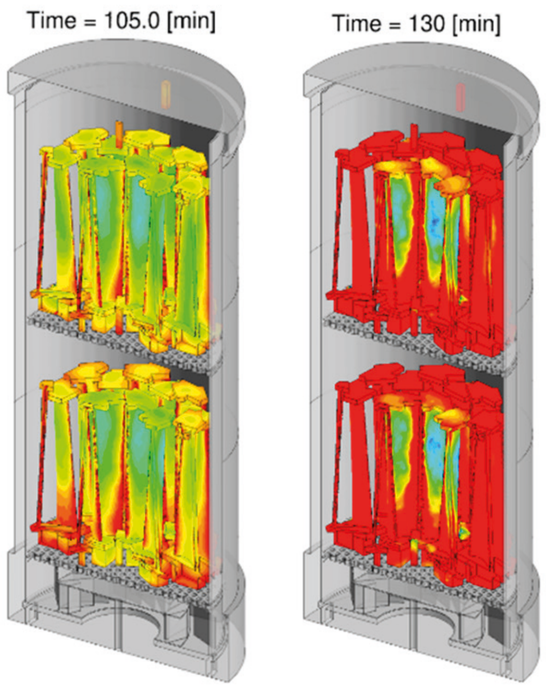


Fig. 4. Heating: Examples of temperature mapping from CFD analysis.

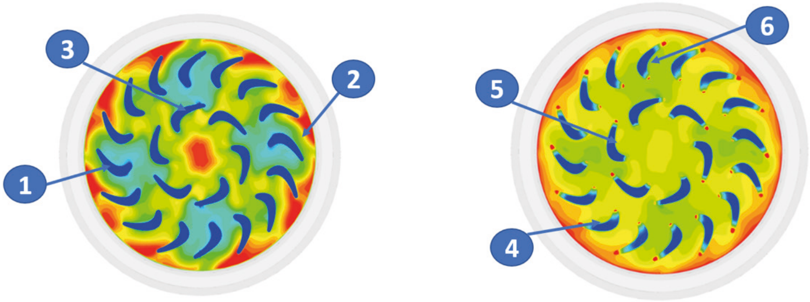


Fig. 5. Heating temperature distribution at 65 min and 130 min in the upper basket; test numbers and locations inside the containers.

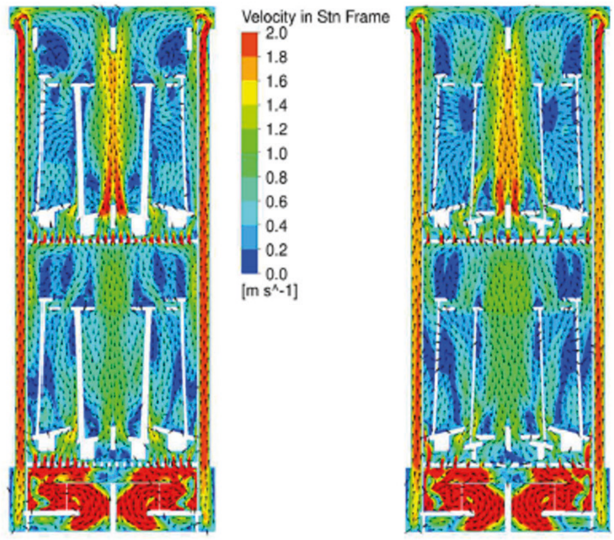


Fig.6. Quench: Flow distribution and velocity vectors.

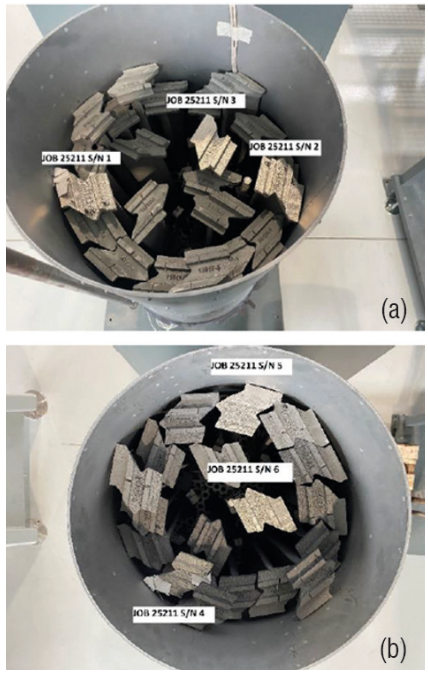


Fig. 7. Example of blades inside the furnace baskets: (a) lower basket and (b) upper basket.

Fig. 6 shows that the areas where the flow recirculates (area under the roof) or the areas in the wake of obstacles such as the dovetail are the areas with the highest temperature. The velocity contour and the velocity vectors are shown on two mid-levels of the oven section. Since the velocity field does not vary during the steady state thermal cycle, a single instant was considered as an example. The velocity in the middle area of the upper basket is higher than any other area of the furnace.

Experimental results

The simulation results were confirmed by the experimental data collected on the test parts treated in this furnace cycle: six out 40 blades, three from each basket, were inspected and tested. Microstructural analysis, tensile tests on specimens taken from blade, porosity and dimensional inspections (both by CT scanning) were performed to verify that the effect of the HIPQ treatment was equivalent to that of conventional heat treatment in terms of mechanical and material properties. This study also demonstrated high temperature uniformity within the furnace (Fig.7). Computer tomography (CT) was performed before and after HIPQ treatment for both dimensional and porosity inspection. No distortion anomalies or typical defects were detected. After CT inspection, cutting showed that the microstructure of each blade examined was the same as the typical microstructure found on the standard material. No anomalies or microstructural differences were detected among the samples analysed. In addition, the data collected is in line with the standard values obtained from the conventional process consisting of two different heat treatments, HIP, and heat treatment (Fig. 8).

A tensile test at room temperature was performed on each blade analysed and the results are shown in the graphs in Fig.9a–c.

The blades show the same behaviour in terms of mechanical properties.

Conclusions

A HIPQ treatment simulation was used to analyse and then determine how to optimize the temperature and distribution of airflow within the furnace to ensure a uniform temperature across the treated components, regardless of their position in the chamber, and to minimize the thermal gradients during the heating and cooling phases. This minimizes the variation in

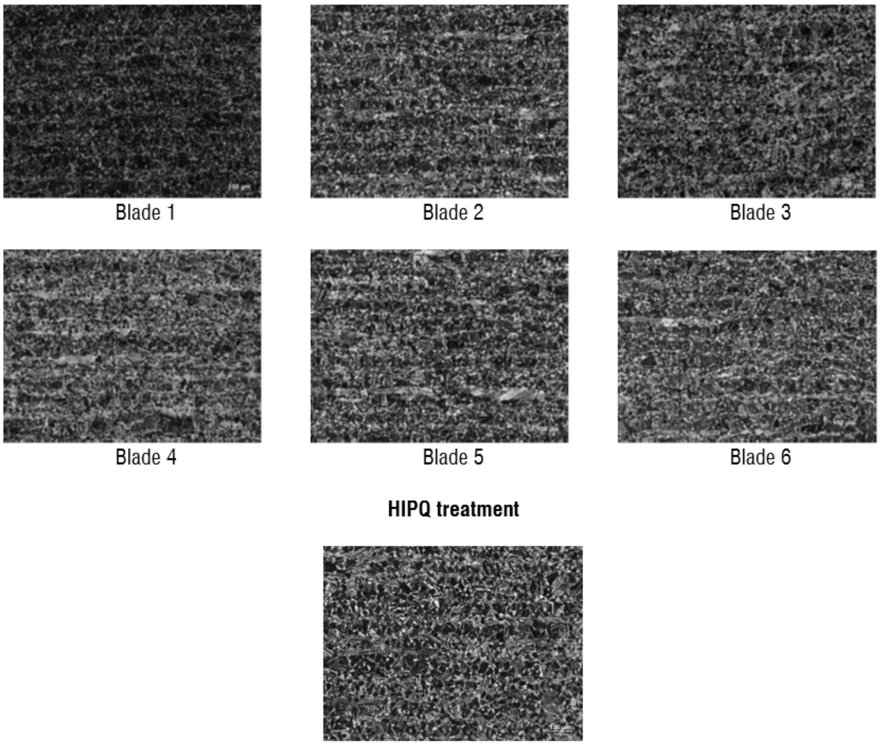


Fig.8. Analysis of six HIPQ microstructures (100x) and comparison with a conventionally produced structure.

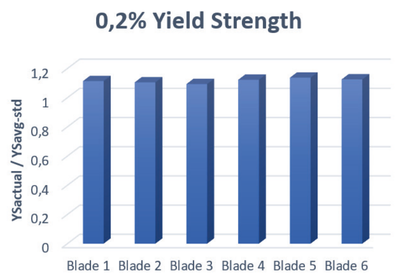


Fig.9 (a). Yield strength deviation for the six blades studied.

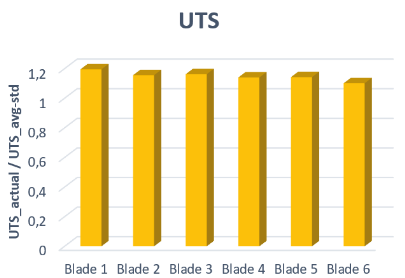


Fig.9 (b). UTS deviation for the six blades studied.

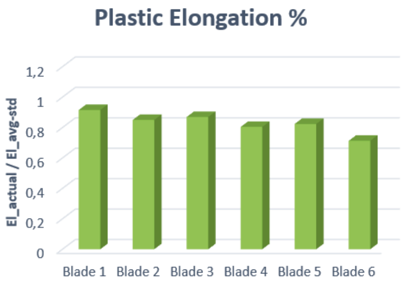


Fig.9 (c). Elongation deviation for the six blades studied.

the microstructure of the blade at different locations and, as a result, maximizes the mechanical properties.

Simulation makes it possible to identify optimized parameters to achieve a uniform temperature inside the furnace, thus avoiding material nonconformity and reducing the number of experimental tests required to achieve the optimal set of parameters. This approach can be useful in reducing the time, and therefore cost, associated with feasibility steps and can accelerate process qualification.

The study demonstrates the importance of processing TiAl AM components with the latest HIP systems, known as HIP/Quench, which combine high pressure and controlled cooling in a single system, reducing the time and costs associated with the need to use different equipment and often different facilities. These systems can effectively simplify and optimize current manufacturing processes for AM components, significantly shortening current production cycles.

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About Avio Aero

Avio Aero is a GE Aerospace company that designs, manufactures and maintains components and propulsion systems for civil and military aviation. Today, the company provides its customers with innovative technological solutions to quickly respond to the continuous changes required by the market: additive manufacturing, rapid prototyping, as well as technologies dedicated to the production of transmissions, turbines, and combustors. The company's head office is in Rivalta di Torino, where its largest production facility is also located. Other important facilities are situated in Brindisi and Pomigliano d'Arco (Naples), with a total of around 4,800 employees employed in Italy.

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