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Reviewed Paper

DEVELOPMENT OF NOVEL HIGH TEMPERATURE LASER POWDER BED FUSION SYSTEM FOR THE PROCESSING OF CRACK-SUSCEPTIBLE ALLOYS

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Abstract

In the industrial panorama, Laser Powder Bed Fusion (LPBF) systems enable for the near net shaping of metal powders into complex geometries with unique design features. This makes the technology appealing for many industrial applications, which require high performance materials combined with lightweight design or conformal cooling channels. However, many of the alloys that would be ideal for the realisation of these functional components are classified as difficultly weldable due to their cracking sensitivity. Currently, industrial SLM systems employ baseplate preheating to minimise these effects although this solution is limitedly effective along the build direction and often does not achieve high enough temperatures for the realisation of crack-free specimen. In this work, the design and implementation of a novel inductive high temperature LPBF system is presented. Furthermore, preliminary results regarding depositions of Titanium Aluminide alloy with and without preheating are reported, showing the potential of the solution developed.

Keywords: Laser Powder Bed Fusion, High Temperature, Preheating, TiAl

Introduction

Laser Powder Bed Fusion (LPBF), also known as Selective Laser Melting (SLM), employs a highly energetic laser beam to selectively melt a layer of metallic powder feedstock which is laid upon a substrate material. The process is thus repeated layer-by-layer as typically done in other Additive Manufacturing (AM) processes. In order to obtain stable processing conditions and high part density, full melting of the powder bed is required. Hence, for the processing of metallic powders, LPBF requires the use of a beam with elevated energy density which has been enabled by the development of high brilliance fiber laser sources in recent years [1]. Although, the Laser Powder Bed Fusion technology has been witnessing an increasing interest on behalf of the industrial world, its applicability is mainly restricted to the processing of weldable alloys. The main reason behind the limitation in the range of materials processable is linked to the elevated thermal gradients and cooling rates that are experienced locally during the fusion process and are intrinsic to the technology due to the concentrated energy beam that is required to melt the powder bed. Cooling velocities greater than 10^6 K/s have been measured experimentally by Scipioni *et al.* [2] while Shi *et al.* estimate values of thermal gradients above 10^4 K/mm [3]. As clearly explained by Hagedorn *et al.* these values are critical when processing metallic powders, due to the elevated stress concentrations generated as a consequence [4].

Powder bed preheating has thus been extensively employed since the onset of the laser powder bed fusion technology [5]. Initially, its role was that of lowering the energy density required to achieve full melting of the feedstock material but with the introduction of high brilliance fiber lasers the main scope became the minimisation of thermal tensions which form locally. As a matter of fact, all of the industrial systems are equipped with preheating systems that allow the reduction of thermal stresses in the first layers of the building process. In the initial depositions of the AM process, the reduction of thermal stresses is essential due to the presence of the substrate base which acts as a heat sink and thus causes the formation of higher thermal gradients and cooling rates.

Different techniques of substrate preheating have been applied to the laser powder bed fusion technology, namely IR heaters [5], preheating or remelting strategies through fast scanning of the laser beam [6,7], use of a second defocused laser beam [8], substrate resistive heating [9,10] or baseplate induction circuit [4,11,12]. The greater part of industrial selective laser melting systems employs resistive heaters [10], which typically allow preheating of the baseplate up to 200°C while the most recently developed systems enable to achieve up to 500°C. Although these systems are particularly effective in reducing local stresses near the base plate, they lose their effectiveness when a full-scale component must be manufactured since their effect remains limited to the lower parts of the build (due to the inherent nature of the process which relies on the lowering of the base plate). A similar preheating concept was developed by Hagedorn *et al.* which on the other hand employed a pancake induction heating circuit capable of achieving up to 1000 °C [11,12]. IR heaters have been applied for the preheating of the top layer of the powder bed, however these systems are not energetically efficient [5,13].

Alternatively, the use of a second defocused laser beam may be effective in reducing residual stresses as estimated by Aggarangsi *et al.* [14] and demonstrated experimentally Wilkes *et al.*[8]. Although, this approach is effective when processing non-metallic materials, it implies a higher capital cost of the AM machine since a second optical set up and laser source must be equipped for this solution. Preheating or remelting strategies employing the same process laser can be effective in reducing porosity as demonstrated by Demir *et al.*[7] and Aboulkhair *et al.*[6]. However, these imply a notable increase in terms of production time due to the double scanning of the powder bed required. A competing technology which relies on a similar preheating concept is Electron Beam Melting (EBM) which is capable of achieving powder bed temperatures in the order of 1000°C whilst maintaining high build rates due to the higher scanning velocities enabled by the magnetic coil deflection system [15]. For this reason, the EBM technology is capable of processing γ-TiAl alloys. However, a downside of the EBM is that the minimum feature achievable is limited by the melt pool dimension which is typically greater in comparison to laser powder bed fusion systems [16].

Taking into consideration the available technologies and the need for uniform high preheating temperatures for the processing of crack susceptible alloys, the aim of the present work was the development of a novel high temperature laser powder bed fusion (HT-LPBF) system, namely project *Grisù*. The preheating system chosen for this purpose was an induction coil with a different geometry with respect to that implemented by Hagedorn *et al.*[4]. The EBM technology or IR heating systems are capable of heating the last few layers of the powder bed. On the other hand, baseplate inductive or resistive heating systems are effective only for low build heights. The solution developed in the current research enables a constant preheating temperature throughout of the whole build. Instead of employing a pancake coil, the novel HT-LPBF was designed with a helical coil which contains the substrate base as it is lowered during the building process. The use of this innovative system architecture might not only open the road for the processing of crack-susceptible alloys but also for the realisation of in-situ heat treatments during the freeform fabrication process.

The scope of this article will therefore present this new conceptual AM system and is structured as follows: the design of project *Grisù* is presented and the testing of the induction system to achieve preheating temperatures above 800°C is reported. Eventually a demonstrator build using a TiAl alloy prone to crack formation is realised with and without the use of the preheating system. Results show that the prototypal system designed is effective in suppressing crack formation and acts as a proof of concept of the novel HT-LPBF system architecture.

Design of a novel high temperature LPBF system

Design of the inductive preheating system

Project *Grisù* was born with the aim of developing an innovative additive manufacturing system whilst maintain the advantages of an open-ended laboratory set-up. For this reason, the prototypal system was designed to operate with low quantities of powder, similarly to its predecessor, project *Powderful* which consisted in a basic automated powder deposition system[17]. The novel conceptual design of the preheating system compared to the classical resistive baseplate heating is schematically shown in Figure 1.

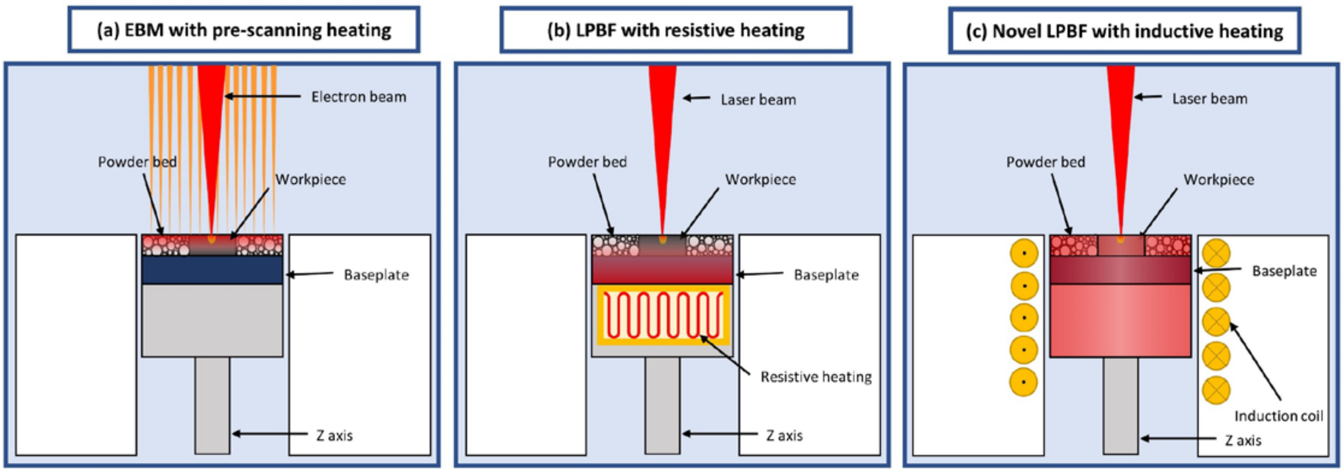


Figure 1. Conceptual layout design of (a) EBM with pre-scanning heating (b)LPBF with standard resistive preheating system and (c) novel LPBF with inductive heating system

A critical aspect of the design of this prototype was the choice of materials for the different components. It was essential that the most stressed components of the system could sustain temperatures up to 800 °C whilst not being influenced by the strong magnetic field generated by the induction coil. For this reason, quartz glass was selected for the cylinder containing moveable part of the z-axis. The piston was realised in *Cerastil* (Formenti, Milano, Italy) a poly-silicate material capable of withstanding up to 1100°C. Accordingly, the gasket of the piston which prevents powder infiltration in the Z-axis was realised in *Paperseal* (Formenti, Milano, Italy) a mineral fibre material. The fixed plane of the powder bed was designed to be in ceramic glass whilst the helical coil for the preheating system was of pure copper.

Within the piston, a small steel cylinder was located which inductively heats up during the printing process and contributes to the preheating of the metallic substrate by means of conduction. In case the prototypal system is employed to study the processing of non-metallic materials which must thus be deposited upon non-metallic substrates, the steel cylinder will act as the heat source for the preheating system. In the present work, for the testing of project *Grisù* the substrate material chosen was Ti6Al4V. Titanium alloys although they are light non-ferrous materials tend to behave similarly to steel when heated inductively (since they possess analogous values of electrical resistivity and thermal conductivity) [18]. Hence, the whole substrate base can be expected to be effectively heated up by means of the inductive preheating system. On the other hand, during the printing process the induction field will also have an influence over the powder bed. Although, the effect in terms of inductive preheating on metallic powders is unclear in literature and will be the focus of future studies, the system will still be effective in preheating the solidly deposited material.

The "heart" of project *Grisù* was designed with three water heat exchangers in order to contain the elevated temperatures being generated from the induction heating system. An adequate cooling system is fundamental to avoid distortions of other mechanical parts and in particular the accuracy of the Z-axis movement system. The first heat exchanger is the induction coil itself which is composed of copper tubes where water is forced to flow. This acts not only as a barrier for the heat flow with respect to the rest of the machine but also plays an important role in maintaining the copper tubes cooled. A second flat water-cooled heat exchanger is located in a fixed position beneath the heart of the induction system. The third water-cooled component translates along the Z-axis as it is lowered during the build job and is responsible of maintaining at a low temperature the motor transmission.

Temperature sensors were placed on these components in order to monitor their temperature and avoid them from achieving excessive values. The components and their respective materials are listed in Figure 2, alongside with a side view of the design of the preheating system and Z-axis. T_{max} refers to the maximum operational temperature of the different components (depending on their material). These were indicated within the specifications given by the part producers or providers. Although, relatively high values of T_{max} are indicated for the mechanical components the heat exchangers design is supposed to maintain these values below 100 °C.

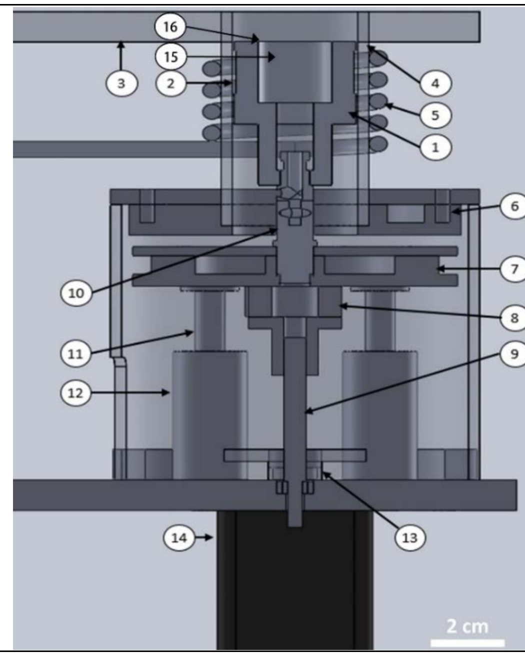
#	**Component**	**Material**	**T_{max} [°C]**	**System design**
1	Piston	Cemestil	1100	
2	Gasket	Paperseal	1100	
3	Plane	Ceramic glass	800	
4	Cylinder	Quartz glass	1250	
5	Induction coil	Pure Cu	250	
6	Fixed heat exchanger	Al-alloy	400	
7	Moving heat exchanger	Al-alloy	400	
8-9	Nut and screw	Carbon steel	500	
10	Piston-Heat exchanger connection	Carbon steel	500	
11	Rebored bar	Carbon steel	500	
12	Linear bearing	Steel	500	
13	Motor transmission	Elastomer	70	
14	Stepper motor	Mixed	70	
15	Steel insert	Carbon steel	1000	
16	Thermocouple position			

Figure 2. List of materials and their maximum operational temperature T_{max} and design of the preheating system

The final design and realisation of project *Grisù* is shown in Figure 3. The recoater blade was realised in stainless steel in order to withstand the elevated temperatures of the powder bed. The system is equipped also with a fan which provides a gas flow above the build area. The whole prototypal system can be placed within an inert gas chamber (analogously to the previous prototypal system developed [17]). Before each processing the powder bed and activating the preheating system, an inertization procedure of the closed chamber was conducted, applying a vacuum down to 50 mBar and then filling the process chamber with high purity Ar gas. The whole mechanical control of the system is conducted with a self-developed LabVIEW code (National Instruments, Austin, TX, USA).

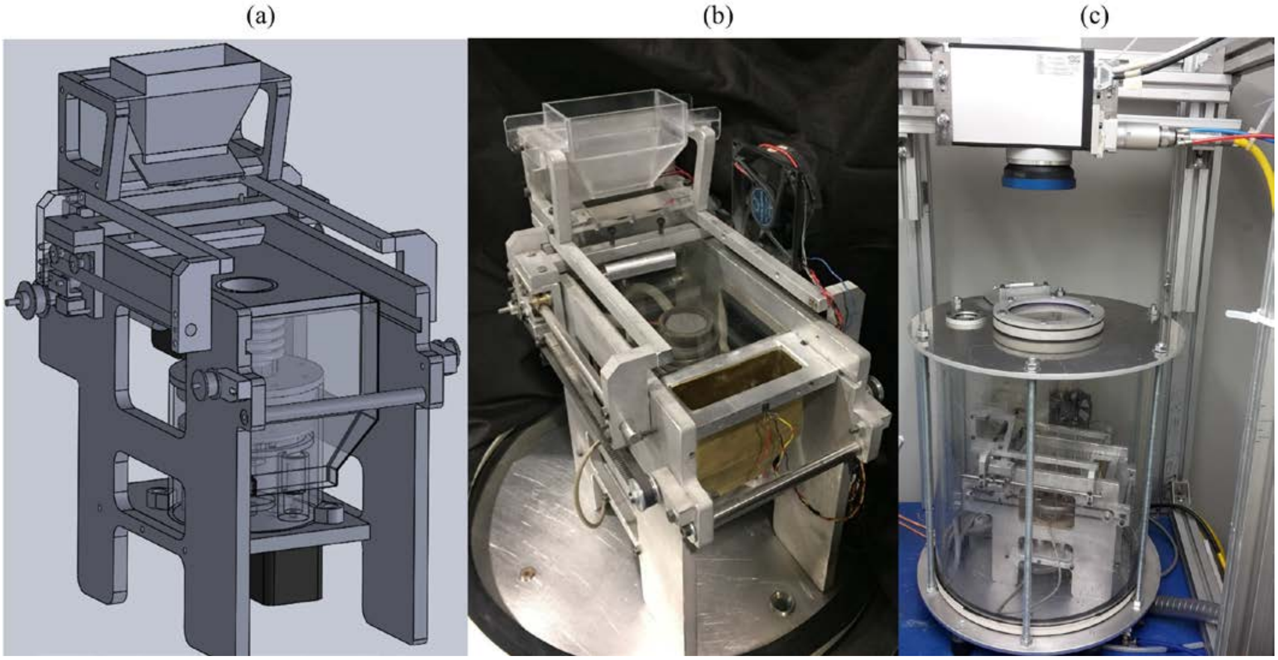


Figure 3. Project Grisù (a) CAD design (b) assembled prototype system (c) final set-up

Laser optical delivery system

For the present research, a 1000 W single-mode fibre laser source (n-Light, Vancouver, WA, USA) was employed as a light source to process the powder bed. The beam path was controlled with a Smart Scan SH30G-XY2 scanner head (Smart Move GmbH, Garching bei München, Germany), whereby the laser emission was collimated with a 75 mm lens and focused onto the substrate using a 420 mm F-theta lens. The beam diameter on the focal plane was determined from theoretical calculations as d_0= 78 µm. Overall, the principal features in terms of optical and mechanical parameters of project *Grisù* are reported in Table 1.

Table 1. Characteristic parameters of project Grisù, the HT-LPBF system

Parameter	**Value**
Laser source	nLight Alta Prime
Laser max. power, P_{max}	1 kW
Beam quality factor, M^2	1.19
Max. scan speed, $v_{scan,max}$	5 m/s
Spot diameter, d_0	78 µm
Layer thickness, z	30 to 100 µm
Process atmosphere	Ar; N_2
Max preheating temperature, $T_{preheat,max}$	>800°C
Build plate diameter, ϕ	38 mm

Testing of the high temperature preheating system

In order to verify the functionality of the high temperature preheating system a measurement chain to keep track of the temperature variations within the powder bed had to be designed. A K-type thermocouple was employed for this scope (TERSID, Milano, Italy) which is indicated for use in these processing conditions by the producer. The measurement point was selected just beneath the substrate position such that the actual temperature of the baseplate could be measured (as indicated in Figure 2). Although this configuration does not allow to monitor the temperature of the whole system, given the reduced dimensions of the powder bed it might be taken as representative of the effective thermal history of the build. An alternative solution for the temperature control could be the use of a pyrometer but this equipment has higher capital cost and was therefore not taken into consideration as an option during the realisation of a prototypal system whose main objective is the proof of concept of a novel preheating system. Future developments of the system could also attempt at using more thermocouples to monitor the temperature along the build direction.

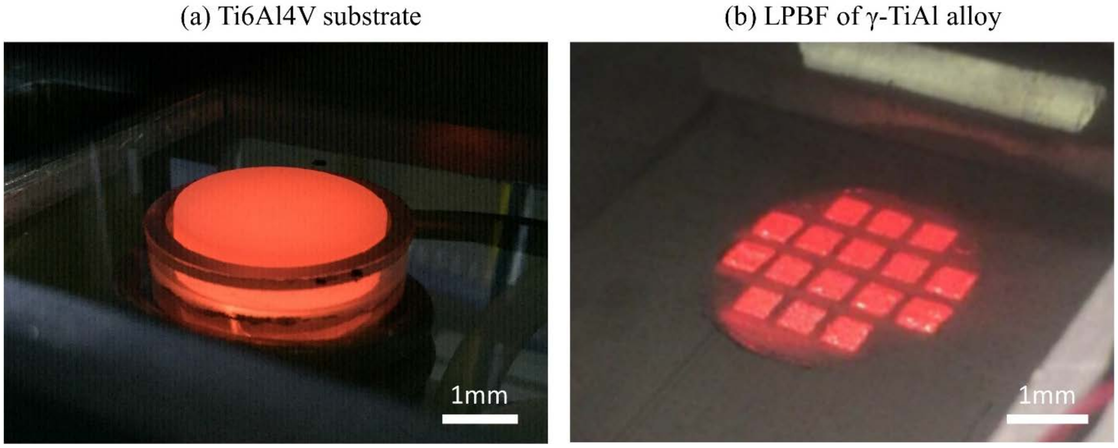


Figure 4. (a) Incandescent Ti6Al4V substrate during the testing of the high temperature induction preheating system and (b) HT-LPBF of a γ-TiAl alloy on project Grisù

The control of the powder bed temperature was obtained through an ON/OFF solution, whereby the magnetic field was switched on and off. A Zero Voltage Switching (ZVS) circuit was employed to generate the current that was fed to the helical coil to generate the magnetic field. A 48V-20A DC power supply (Mean Well, New Taipei, Taiwan) was employed to power the ZVS circuit. A switch to achieve the ON/OFF control was interposed between the power supply and the ZVS circuit in order to avoid the transient behaviour of the power supply. The resonating frequency of the inductive circuit was estimated as 100 kHz.

In order to verify the functionality, the inductive preheating system was tested initially up to 200°C, 500°C and 700°C. The maximum temperature achievable by the inductive preheating system was in excess of 840°C so the final temperature testing condition which simulated printing conditions and times was conducted at 800°C. In all tested conditions the power input to the induction system corresponded to maximum power output of the DC supply which is 960 W. Figure 4 (a) shows an incandescent Ti6Al4V substrate during one of the testing phases while Figure 4 (b) depicts the powder bed at 800°C during the deposition of a γ-TiAl alloy. Each of the preheating temperature tests consisted of four phases: heating, maintenance, controlled cooling and convective cooling. The heating phase must avoid excessive thermal shock on the system components but in any case results less critical since the component of a crack susceptible alloy is yet to be built. The time to achieve the operating temperature value of the system was set at 30 minutes. The maintenance phase at 800°C was tested for a 450 minute duration whereby the temperature oscillated with a ±10°C margin of the target temperature. Finally, the controlled cooling phase is shown, whereby the system was tested to maintain a cooling ratio of 5°C/min (always controlled using the ON/OFF control logic previously reported). Finally, a convective cooling of the system was experimented in order to view the behaviour of the system. This was arbitrarily tested from 450 °C downwards.

In Figure 5, the temperatures recorded by the thermocouple system are reported during the different phases of the testing at 800 °C (selected time instants are reported). Although, the ON/OFF control introduces an error into the powder bed temperature with respect to the target temperature, it is also true that this simple control logic system is functional for the aim of the present work. The largest errors with this control logic may be witnessed at temperatures below 500°C since even if the induction circuit is switched on for a very brief period it rapidly raises the temperature of the system. At higher temperatures, however the error reduces and may be considered as acceptable.

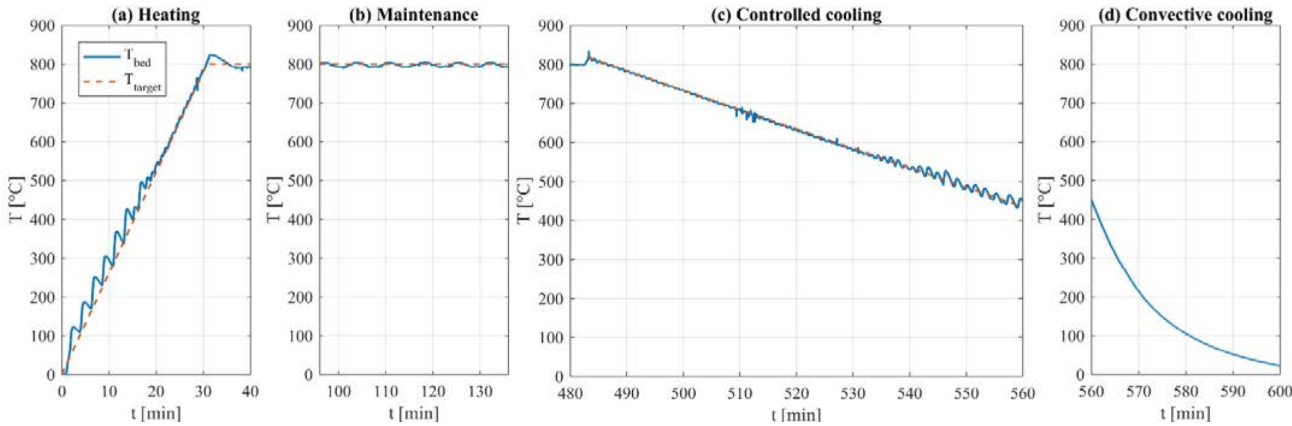


Figure 5. Testing of the inductive preheating system up to 800°C. Powder bed temperature measured by thermocouple, T_{bed} in blue whilst target temperature, T_{target} when present in orange. Different phases are shown: (a) heating (b) maintenance (c) controlled cooling (d) convective cooling.

Testing of the high temperature laser powder bed fusion system

Material

In order to verify the functionality of the novel HT-LPBF, testing of the system was conducted with a γ-TiAl alloy. As can be evinced by the literature on the laser melting of titanium aluminide alloys, this material is prone to crack formation due to the elevated temperature gradients and cooling rates of the process as well as the ductile-brittle transition of the alloy (which tends to occur around 750°C as stated by Vilaro *et al.*) [19]. Löber *et al.* witnessed the presence of cracking already during single track deposition of a γ-TiAl alloy [20]. Similarly, Doubenskaia *et al.* with a preheating up to 450°C witnessed cracks during the realisation of cubic specimen of Ti–48Al–2Cr–2Nb [21].

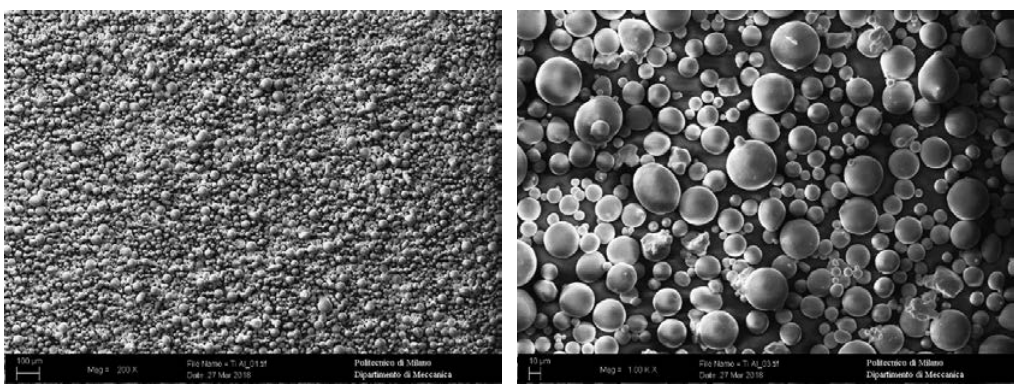


Figure 6. Scanning Electron Microscope images of Ti-48Al-2Cr-2Nb gas atomised powder low magnification (left) and high magnification (right).

Since Project *Grisù* was successful in maintaining temperatures of the powder bed around 800°C it should be apt for the processing of γ-TiAl alloys. Specifically, Ti-48Al-2Cr-2Nb gas atomized powder (LPW Technology, Runcorn, UK) was tested on the novel HT-LPBF system. The chemical composition of the feedstock material as declared by the producer is reported in Table 2 while the size distribution parameters are: d_{10}=16 µm, d_{90}=45µm. Scanning electron microscope images of the γ-TiAl powder are visible in Figure 6.

Table 2. Chemical composition of Ti-48Al-2Cr-2Nb declared by the producer

Element	**Ti**	**Al**	**Cr**	**Nb**	**Fe**	**Si**	**C**	**O**	**N**	**H**
Wt %	Bal.	34.4	2.58	4.74	0.04	0.006	0.007	0.12	0.006	0.001

Measurement apparatus

Qualitative evaluation of the top surface and of the polished cross-sections of the specimen deposited was done through optical microscopy images, acquired with a 2.5X objective (Quick Vision ELF from Mitutoyo, Kawasaki, Japan).

Experimental conditions

Laser powder bed fusion of the Ti-48Al-2Cr-2Nb powder was investigated into two different experimental conditions (i.e. at ambient temperature and at $T_{preheat}$=800 °C). Preliminary experimentation led to the choice of different laser energy density delivered to the powder bed, respectively corresponding to 357 J/mm^3 for the print at ambient temperature and 119 J/mm^3 in the case of $T_{preheat}$=800 °C. For both experimental conditions, laser power was fixed at 150 W, scan speed at 200 mm/s and hatch distance at 70 μm. Energy density variations were controlled processing the powder bed with different the layer thicknesses whilst the preheating contribution was not taken into account since its effect is two orders of magnitude lower (i.e. 2 J/mm^3). In the case of the laser deposition with high preheating temperature, once the build was completed a controlled cooling rate, $\Delta\dot{T}$=5 °C/min was applied as indicated by Gussone *et al.*[12]. Within both configurations, the inertization gas employed was high purity Argon and the substrate material was made of Ti6Al4V. 4x4 mm^2 square hatched laser trajectories were projected on to the powder bed in order to realise cubic specimen layer-by-layer.

Results

Both experimental conditions, with and without the high temperature preheating of the powder bed it was possible to deposit material onto the Ti6Al4V substrate. However, in the case of the ambient temperature printing of the γ-TiAl alloy the process had to be interrupted after 10 layers of material had been deposited due to powder bed instabilities and protruding parts which impeded the correct deposition of successive layers. Contrarily, the high temperature preheating at 800°C was capable of maintaining a stable powder bed and 50 layers were successfully deposited. These instabilities can be clearly viewed from the top surface finish of the specimen realised, shown in Figure 7.

(a) *No preheating* (b) $T_{preheat}$ = 800 °C

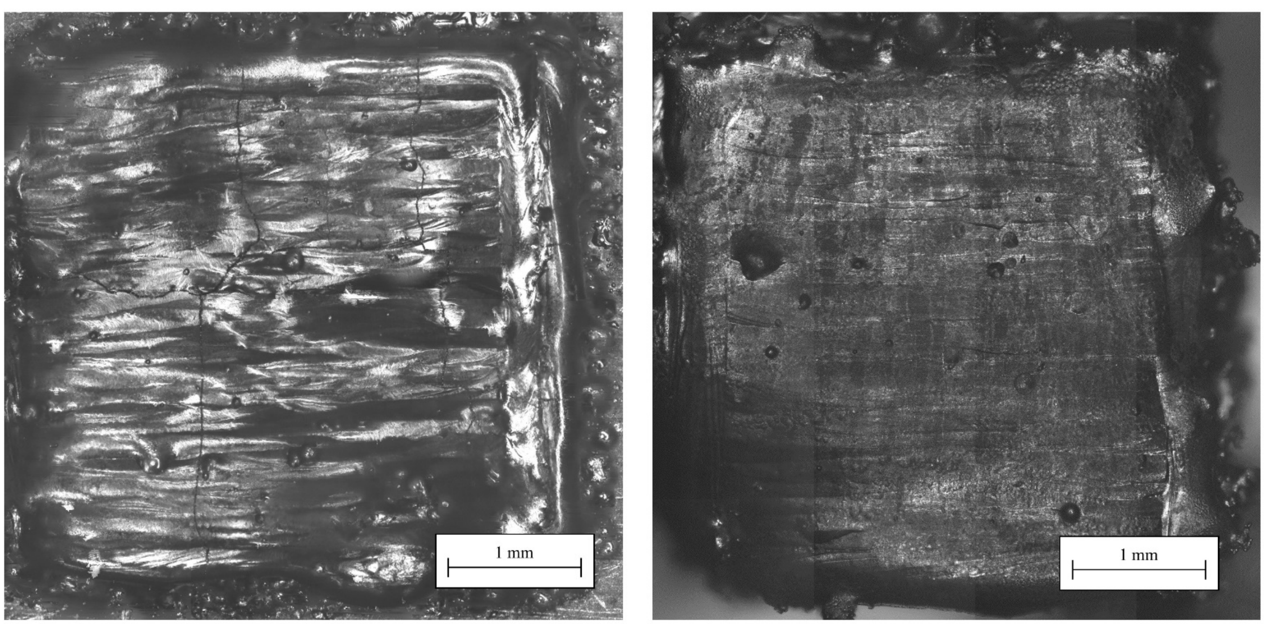


Figure 7. Top view of specimen acquired with optical microscope (a) no preheating (b) with preheating at 800°C

Furthermore, it is possible to denote the extensive presence of cracks in the specimen realised at ambient temperature, clearly evident in the top view of Figure 7 (a) and also confirmed by the cross-section of the specimen shown in Figure 8 (a)). The crack density for the specimen realised was measured to be from the metallographic analysis as 4.23 mm/mm^2 which indicates that without the high temperature preheating system, it is impossible to realise components in γ-TiAl since the presence of defects highly compromises the structural integrity of the components realised. During the present experimentation cracking occurred predominantly perpendicularly to the scanning direction of the laser beam. This is in agreement with the findings of Löber *et al.* whom identified the cracking always perpendicularly to the scanning direction during the single track deposition of a γ-TiAl alloy [20]. Furthermore, the formation of cracks transverse to the advancement of the heat source has been reported for process to laser powder bed fusion (i.e. electron and laser beam welding) [22,23].

(a) *No preheating* (b) $T_{preheat}$ = 800 °C

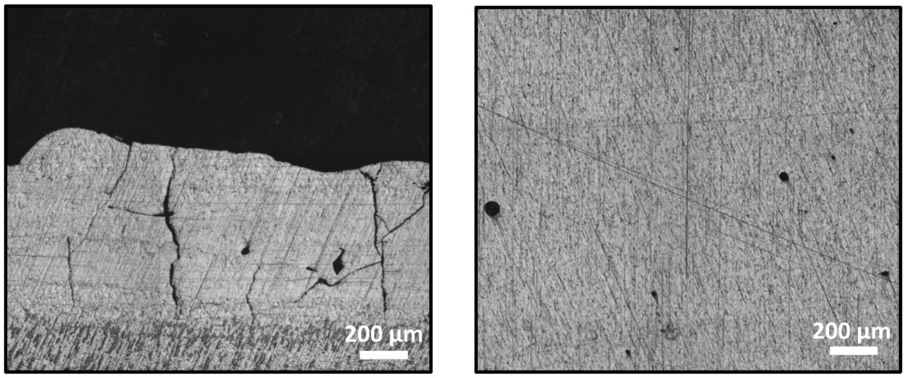


Figure 8. Cross section along build direction of specimen acquired with optical microscope (a) no preheating (b) with preheating at 800 °C

The reason for the formation of such defects can be related to the ductile to brittle transition which occurs around 750 °C and with the local strong thermal stresses generated by the process. γ-TiAl alloys are known to be susceptible to this phenomenon, often referred to as "cold cracking" [24]. The use of local preheating to minimise thermal stresses has been identified as a solution for the defect-free processing of Titanium-Aluminides [22–24]. The absence of cracks in the cross-section of the specimen deposited with high temperature preheating confirms results coming from previous literature studies and shows promising results for the development of industrial systems capable of realising fully functional γ-TiAl components.

Conclusions and future developments

The main objective of the present work, namely the realisation of a novel high-temperature laser powder bed fusion system, was achieved. Project *Grisù* was successfully tested to preheat the powder bed up to 800 °C. A demonstrator print of Ti-48Al-2Cr-2Nb was conducted both with and without preheating in order to verify the functionality of the system in processing crack-susceptible alloys. The temperature control implemented was effective in maintaining the temperature within the desired range and in controlling the cooling rate such to prevent crack formation of the deposited samples. Specimen processed without the use of the inductive system presented severe cracks. The defects developed perpendicularly to the scanning direction of the laser beam and are related to the cold cracking formation mechanism. On the other hand, components realised at $T_{preheat}$=800°C, did not show the presence of cracks under optical microscope inspection. Further characterisation of the deposited specimen is required in order to confirm the absence of cracks although preliminary analyses are promising.

The potential of the system developed principally relies upon its ability of uniformly heating up the powder bed and the component being realised. This opens up the barrier for in-situ heat treatment of the component during its freeform fabrication which is not possible within the technology currently available. Nonetheless, it must be taken into consideration that project *Grisù* is a prototypal system with reduced powder bed dimensions and this greatly simplifies the management of the heat input. In the case a full-scale industrial system should be designed a much greater attention should be directed towards the containment and distribution of temperature within the system. Furthermore, open questions remain with regards to technological limitations of the process and mechanical properties of components realised as well as the effect of the inductive field on the process dynamics. This technological development has the potential of enabling a whole new perspective in the freeform fabrication of materials which to the present moment could only be processed with conventional technologies or complex manufacturing routes yet many unanswered queries remain open for research.

Acknowledgments

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