On the Laser Powder Bed Fusion based processing route for hard to weld Nickel Superalloys

Summary

Nickel superalloys are crucial materials for developing high-performing aero-engine turbines. These alloys can be shaped via specific primary processes, i.e., forging, casting powder metallurgy, to obtain the required geometries e specific properties. Laser powder bed fusion is a process belonging to additive manufacturing (AM) that manufactures complex components due to the near net shape capacity.

The technology is characterised by rapid melting and cooling of the material, the processing of Ni superalloys is critical due to many issues arising during and after the processing. Typical issues are volume defects, i.e., pores, cracks, residual stresses, and microsegregation. These issues may intensify when processing hard to weld superalloys, which, thanks to the high fraction of hardening phases, have better mechanical performances at high temperatures. Hence a specific manufacturing sequence must be adopted to process such alloys safely.

The thesis goal is to find a reliable route to manufacture hard to weld superalloys through the L-PBF technique, considering the ultimate scope of producing blades for Low-Pressure Turbines (LPT). Therefore, a processing route was defined to guarantee a microstructure equivalence with the cast's traditional processing route. The likeness is intended for microstructural features, such as grains, precipitate, and volumetric defects, to guarantee similar or better mechanical performances. Therefore, several criteria were considered for the design of the processing route: material soundness, reduction of residual stress and metallographic matching. The steps adopted were tailored to manufacture two hard to weld superalloys, CM247 LC and Rene 80, operating in temperature ranges, i.e., 927-982°C and 871-927°C.

The processing route was defined by analysing the conventional processing route and the literature finding on superalloys' L-PBF processing. This innovative route is characterised by three steps L-PBF processing, post-print condition and heat treatment. Lastly, the mechanical properties of the component produced with this processing route were primarily characterised by tensile tests.

Initially, the powders batches of the two alloys were characterised in composition, size distribution, and rheology. These properties influence the

processability of the material and the component quality. Then, the raw material was processed via L-PBF to produce specimens. This step creates massive components affected by critical features, volumetric defects, residual stresses, and a micro-segregated and anisotropic microstructure. The printing parameters were adjusted to lower the number of critical defects, such as cracks and pores found in the internal region of the component. The defects were evaluated via automated image analysis to reduce the measurements biases and compare the results of different parameter combinations. The optimal parameters were determined by refining the processing window and assessing the repeatability of the defect level. The two alloys responded differently to the optimisation procedure due to different amounts of γ' phase. Indeed, Rene 80 was easier to process compared to CM247 LC. Indeed, indeed the optimisation path and achieved defect level is different. For Rene 80, the optimisation procedure consisted of three steps in which the initial set of 18 combinations was reduced to 5, and the inter and intra-print repeatability was evaluated. The optimal combination of parameters led to a crack density of 45±20μm/mm² and a slightly below 0.06% porosity fraction. Although this alloy has no AM references in the literature, the achieved crack density is very low and promising for optimal L-PBF processing outcome. CM247 LC followed a similar procedure with the addition of further refining of the scanning strategy to reach a lower fraction of crack density. The final values achieved are 170±5μm/mm² crack density and 0.15% for porosity fraction, which are among the best values found in this alloy literature.

After print optimisation, the components are conditioned to mitigate the residual stresses and lower the volumetric defects. The sequence adopted includes Sand Blasting (SB), Stress Relieving (SR), and Hot Isostatic Pressing (HIP). SB and SR were performed to reduce the residual stresses and prevent macrocrack formation on the components. The HIP was carried out to heal the volumetric defects created during the previous processing steps. The CM247 LC stress relief recipe was changed to avoid the macro cracking of the components. The optimisation was driven by the SAC theory and empirical observation, leading to a two-step treatment. The conventional HIP recipe lowered the mean crack density to almost 0μm/mm² (always considering the limits of the assessment method applied) and the max crack length to 25μm. Similarly, the porosity fraction to 0.05% and the max pore diameter to 25μm. Conversely, the SR of Rene 80 was not changed, while the HIP soaking temperature was increased to heal the volumetric defects efficiently. The HIP reduced the defects fraction in the specimens for both the alloys to almost 0μm/mm² and the max crack length to 10μm. Similarly, the mean porosity fraction was lowered to 0.005% and the max diameter to 26μm.

The last step of the proposed processing route consists of the heat treatment and is intended to define the microstructural features ultimately. The conventional recipes were modified by changing the solution temperature and the second ageing soaking time. The target was the formation of cuboidal γ' particles and peak harness. For the two alloys, the solution temperature was risen to induce a considerable dissolution of γ' into the matrix. The dissolution is mandatory to promote the formation of cuboidal precipitates. Conversely, the second ageing soaking time was reduced to 6hr. The transformation involving other microstructural features has been mapped, such as grains and carbides. The execution of the heat treatment at temperatures higher than HIP provoked a slight re-opening of porosities. For Rene 80, the increase is comparable with the as-built level, whereas CM247 LC is considerably lower than the as-built.

Lastly, the mechanical properties of the alloys processed with this new processing route were preliminarily tested via tensile experiments. The yield strength and ultimate tensile strength have similar values for both the alloys compared to the literature findings. Conversely, the elongation to fracture is much higher than the typical values. Over these assessments, the tensile behaviour was investigated deeply via stress-strain curves, the fracture surfaces, and cross-sections. This defined a baseline for the material failure mechanisms. One specimen per alloy showed an anomalously low elongation to fracture. The causes of this phenomenon were addressed to the presence of brittle particles, i.e., oxides for Rene 80 and carbides cluster for CM247 LC. The oxides in Rene 80 were probably inherited from the raw material; in CM247 LC, the carbide cluster originated from the particles ripening during the heat treatment. However, the phenomenon occurred only once per alloy; therefore, these specimens were not considered representative of the whole production.

The major result of the current thesis is the demonstration of the possibility of processing and post-process in tight synergy of two Ni alloys that were considered hard to process via additive manufacturing route. Microstructure and mechanical properties were optimised within the framework of this thesis project. Milestone achieved is the potential application of two very high performing Ni alloys in the AM fabrication of complex and hollow turbine blades to be used in the next generation of aero-engines.