POLITECNICO
MILANO 1863

Modeling of a blow-down propulsion system

Course of Space Propulsion
Academic Year 2023-2024

Lockheed Martini Group

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Notation

SYM	Description of symbol	**AM**	Additive Manufacturing
SYM	Description of symbol	**LPBF**	Laser Powder Bed Fusion
SYM	Description of symbol	**BJ**	Binder Jetting
SYM	Description of symbol		

1 Introduction and literature overview

1.1 Blow-down heritage

1.2 Additive manufacturing state of art

Additive manufacturing technologies in aerospace industry is rapidly spreading thanks to the offered advantages with respect to traditional production techniques. Among the benefits provided by AM there are weight and time savings, cost reductions and the possibility to optimize components creating more complex geometries[1]. Various technologies for AM have been developed for different fields, in particular, the most used in this sector is Laser Powder Bed Fusion (LPBF), which utilizes a laser beam to melt successive layers of metal powder. Binder Jetting (BJ) is also a feasible technology although still under development, as it requires post-processing procedures to obtain better finished components than LPBF, making it less attractive for the general industry. A focus on this technology will be carried on in the following pages. Different types of alloys can be processed through both technologies, among which there are nickel-based superalloys, such as Inconel-718. This materials offers excellent mechanical properties under extreme temperature conditions and, for this precise reason, suits perfectly the role of injectors, manifolds and turbomachinery elements in general. Inconel-718 is also characterized by a considerable corrosion resistance, that allows it to be used in concomitance with an oxidizer such as liquid oxygen[2].
The finishing of a component created with AM depends on several parameters:

- **Temperature**: the laser's power and thus the powder's melting temperature selection is crucial in order to avoid performance losses due to stress induced by heating and cooling cycles. The calculation of this parameter is important to prevent overflowing from the meltpool, convective transport of the liquid and nonmetal particles to be blown away from vapors. Cracks and curling, caused by uneven shrinkage during production can also damage surface quality[3].
- **Powder dimension and morphology**: the mechanical properties of the component are significantly influenced by the dimensions and shape of the powder. Coarse and irregular particles result in inefficient packing and higher porosity of the powder bed. This, in turn, makes it challenging for the molten material to fill all the interstices, especially due to the rapid solidification in the LPBF process. The mechanical properties of the component decrease due to its porosity[4].
- **Deposition method**: powder deposition direction directly affects the superficial finishing of the material as dross or deposits from the process can be present: the angle of deposition directly influences the roughness and the accuracy of the produced parts. Staircase effects is related to the discretization of the different layers: the bigger the layers the less smooth the surface will be. In general, it can be observed that the more the build direction α of a generic piece shifts from perpendicular ($\alpha = 0°$), to parallel, ($\alpha = 90°$), the roughness increases and accuracy lowers[tesi_dottorato].

BJ is a technology firstly developed during the nineties and consists in a deposition of a polymeric liquid binder onto successive layers of powder. The whole process takes place at ambient temperature and pressure. No controlled atmosphere is required as phase changes are not involved in this process. The binder bonds the different layers together without needing of supports, resulting in a box of powder with a 3D component built inside. Post processing treatments, such as sintering and infiltration, are performed to improve its properties[5]. On the contrary, LPBF technology uses an high power laser beam to melt the different layers of powder together. A more controlled ambient and atmosphere are required as thermal stresses play a major role during the production of different items[1].
BJ technology technology brings advantages and disadvantages with respect to LPBF:

- **Material compatibility**: BJ is potentially compatible with any material, metallic and non metallic, allowing to build complex components, unfeasible with LPBF process capabilities.
- **Roughness**: BJ technologies require a significant amount of post processing treatments to improve both superficial finishing and mechanical properties, reaching lower values of roughness with respect to LPBF. In general, fewer superficial treatments are required by LPBF as the layer stratification could lead to more accurate roughness. Refinement is instead necessary with BJ-made components to obtain lowest possible values of roughness, even better than the ones LPBF could reach. BJ components show average roughness of $\approx 6\ \mu m$, lower than the one obtained with LPBF printing, spacing between 70 and 10 μm[tesi_dottorato]. It's important to note that the roughness of BJ-made components is less dependant on the build direction α.

- **Density drawback**: BJ-made component show lower relative densities leading to possible distortions of the printed elements. Again, post-processing is required with sintering at temperatures of $\approx 1300°$.
- **Mass production**: Production of components via BJ is more cost and time effective in case of batches of multiple parts.
- **Shrinkage**: metal parts produced with BJ can shrink by up to 2 % for smaller items and by more than 3% for larger items as a result of infiltration. Sintering can cause average shrinkage of 20% and also lead to warping caused by friction between the furnace plate and the bottom surface of the part. The heat used in sintering can also soften the part and cause unsupported areas to deform under their own weight. While these problems can be compensated for in the build, non-uniform shrinkage can be more difficult to account for[6].

Even if BJ is a promising technology, more sustainable as it produces less wastes and requires less energy in the production of different pieces, it lacks a solid mathematical modelling[5] as the research dedicated to this technology is still in its infancy. LPBF is thus the technology of choice to build the systems of DRY-1.

1.3 Analysis of losses

Real life is far from an ideal world, and this is also true for propulsion systems, especially around the nozzle. The modelling considered is based on some ideal assumptions of the propulsion process, but in the nozzle some irreversibilities and losses have been analyzed and compared with the ideal case. The losses considered are specifically those caused by throat erosion and boundary layer thickness[7]. The throat erosion of a nozzle is mainly caused by the fact that the propellant passes through the throat at a high velocity and at an elevated temperature, causing the material around it to erode and fail more easily. This effect causes an unwanted increase in the throat area of the nozzle during propulsion, increasing the rate at which the combustion chamber's pressure decreases and as a result, provoking a loss of power of the system. The second irreversibility analyzed is that caused by the viscosity between the propellant flow and the nozzle surface. As the nozzle is stationary and the flow is moving, a boundary layer is created which causes a slight decrease in the average exit velocity. This can be simplified by saying that the effective throat area through which the flow can pass is reduced, and therefore the actual flow rate through is not the ideal one, thus worsening the merit parameters[8].

2 Modeling of propulsion system

Initial considerations (req + hyp / assumptions + constraints + criteria)
Flowchart

2.1 Tanks sizing

2.2 System dynamics

3 Results analysis

4 Nozzle losses

5 Additive manufacturing influences

6 Cooling analysis

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