Chapter 3
Additive Manufacturing of Nickel-Based Superalloys Used in the Aero-Engines:
SLM of Inconel

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ABSTRACT

Aero-engines contains parts that are generally lightweight, subjected to high performance at high temperature. Ni-based superalloys are widely used in engine turbines. Manufacturing these parts by additive manufacturing (AM) methods provides researchers a lot of creative space for complex design to improve efficiency. Powder bed fusion (PBF) and direct energy deposition (DED) are the two most widely-used metal AM methods. Both methods are influenced by the source, parameters, design, and raw material. Selective laser melting is one of the laser-based PBF techniques to create small layer thickness and complex geometry with greater accuracy and properties. The layer-by-layer metal addition generates epitaxial growth and solidification in the built direction. There are different second phases in the Ni-based superalloys. This chapter details the micro-segregation of these particles and its influence on the microstructure, and mechanical properties are dependent on the process influencing parameters, the thermal kinetics during the process, and the post-processing treatments.

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INTRODUCTION

Superalloys, as its name implies, are special class of metallic materials that exhibits stable microstructure, good mechanical strength, toughness, resistance to degradation in corrosive environment at a temperature more than 80% of the melting point (Pollock et al., 2006). It is because of the superalloys, which mostly encompassed in aero engine gas-turbines, humans able to fly in the skies. The aero-engine, operates according to the Newton's third law of motion. The fans at the front of the engine sucks the air in, the compressor squeezes the air and sprayed along with fuel in to the combustion chamber. The air-fuel mixture is then ignited by an electric spark, the burning mixture will expand and leave the exit nozzle, after passing through the turbine blades, with a thrust that propels the engine. The cycle would continue, as the bursting out gases push the turbine blades to rotate the shaft which in turn rotate the compressor and fan at front to bring more air into the system. The cold air temperature rises to 600 °C during compression and can reach 1500 °C during combustion and drops down to approximately 800 °C after expansion, around the turbines, and before leaving the exhaust nozzle. Superalloys are used to withstand such high temperature for long operating hours. The world's first successful axial compressor turbojet engine, the Junkers Jumo 004, with a pull starter, run first during the world war II in 1940s to power Messerschmitt Me 262 fighter and the Arado Ar 234 reconnaissance/bomber. The Jumo 004 engine was made up of steel stator, aluminium coated mild steel combustion chamber, hollow turbine blades of Cromadur alloy (12% chromium, 18% manganese, and 70% iron) and cast magnesium engine casing (Kay & Couper, 2004). The usage of superalloys in aero-engine increased from about 10% in 1950 to approximately 50% in 1985 (Akca & Gursel, 2015).

There are three kinds superalloys classified based on the major element present in the alloy. They are Iron (Fe)-based, Cobalt (Co)-based and, Nickel (Ni)-based superalloys. Fe-based superalloys are cheaper amid the three superalloys. The Fe-based superalloys, such as, Cr-Mo-V stainless steel and Maraging steels are used as shaft material due to its good high temperature fatigue strength and they are less prone to segregation. Co-based superalloys are not as strong as Ni-based superalloys but retain their properties at temperatures as high as 1100 °C, therefore, they are used in low stress and high temperature applications such as stationary vanes in the gas-turbine. Ni-based superalloys are most complex and interesting among all the three because it can withstand applications at higher fraction of the melting temperature of the material. Ni-based superalloys contain γ-phase with face cantered cubic structure which precipitates out γ'-phase (a primitive cubic structure (Al, Ti) with Ni at face centre to strengthen the γ-matrix. While Fe-based superalloys required at least 25% Ni to stabilize γ–phase (austenite) and Co-based superalloys depends on carbide precipitates for strengthening. The γ'-precipitates may have one of the chemical formula; Ni_3Al, Ni_3Ti or $Ni_3(Al, Ti)$. When γ' precipitates out of γ matrix, they exist in coherent cube-cube relationship. A small negative misfit (γ' has a smaller lattice parameter than γ) between γ and γ' phase generates rafts in the microstructure that prevents climb which improves the creep property. The misfit can be controlled by changing the Al/Ti ratio or by the addition of rhenium (Re). With the addition of niobium (Nb), the superalloy called IN 718, the low temperature yield strength can be increased further due to the formation of γ'' phase in the form of discs with orientation relationship of $(001)\gamma''\|\{001\}\gamma$ and $[100]\gamma''\|\langle 100\rangle\gamma$. The composition of γ'' phase is Ni_3Nb, with a crystal structure of body-centred tetragonal lattice (Sun et al., 2015). The elements Cr and Al are added to prevent oxidation. The metal carbides (MC) precipitates at grain boundary which reduces the tendency of grain boundary sliding (Tytko et al., 2012) at high temperatures. Re and Ru are used to develop single crystal superalloys. However, all the precipitates that form in superalloys are not beneficial as precipitates such as Laves and σ phases