Chapter 5

Optimizing Additive Manufacturing of Superalloys for Sustainable Prototyping

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ABSTRACT

This chapter explores sustainable prototyping through additive manufacturing (AM) of superalloys, particularly in aerospace and energy sectors. It begins with an overview of superalloy material science and its environmental implications, then examines AM technologies that offer efficiency and reduced ecological impact. By customizing AM parameters and applying lifecycle assessments, both performance and sustainability can be optimized. Topology optimization enhances material efficiency, while strategies like waste minimization and powder recycling support circular economy goals. The chapter emphasizes scalability and evolving standards as key factors for broader industry adoption, supported by case studies showing real-world environmental and economic benefits. Future innovation paths, including AI-integrated manufacturing and eco-friendly alloy development, are discussed as part of a holistic approach that unites technical advancement with ecological responsibility.

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INTRODUCTION

In the contemporary landscape of engineering design and product development, prototyping functions not merely as an intermediary step, but as an indispensable phase enabling iterative validation, performance evaluation, and the resolution of complex design challenges prior to full-scale manufacturing (Kubec et al., 2023). The accelerated need for innovation, coupled with the demand for high-performance products, has further accentuated the strategic importance of prototyping (Reeves et al., 2011). However, conventional prototyping methods predominantly based on subtractive manufacturing technique have been increasingly scrutinized for their substantial environmental footprint (Kellens, Mertens, et al., 2017). These methods are inherently resource-intensive, characterized by high energy demand, extensive material waste, and elevated carbon emissions, all of which stand in stark contrast to the overarching goals of sustainable development (Ford & Despeisse, 2016).

In response to global environmental imperatives, there has been a paradigm shift toward sustainable product design and manufacturing, which includes the adoption of environmentally conscious prototyping methodologies (Thompson et al., 2016). The concept of sustainable prototyping entails not only reducing material and energy usage but also integrating principles of circularity, life cycle thinking, and environmental responsibility into the earliest stages of product realization (Bocken et al., 2016). Central to this evolution is the exploration and application of advanced manufacturing technologies such as additive manufacturing (AM), which holds promise for transforming prototyping into a more sustainable practice (Ngo et al., 2018).

Among the spectrum of engineering materials, superalloys occupy a unique and technologically significant niche (Reed, 2006). These high-performance alloys, primarily based on nickel, cobalt, or iron, exhibit exceptional mechanical strength, creep resistance, corrosion resistance, and thermal stability, particularly at elevated temperatures (Sims et al., 1987). As such, they are extensively employed in demanding sectors such as aerospace, energy, and automotive engineering, where component reliability and performance are critical (Pollock & Tin, 2006). Despite their superior properties, the conventional manufacturing of super alloys is associated with substantial challenges both technical and environmental (Rickenbacher et al., 2013). Their complex chemistries and high melting points necessitate energy-intensive processing routes, while machining such materials typically results in considerable material loss and tool wear (Murr et al., 2012).

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