Effect of Carbon Content on the Printability and Mechanical Properties of Ni-based Superalloy in Laser Additive Manufacturing

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Abstract: The role of trace elements such as C, B, Zr, and Hf in additive manufacturing of superalloys remains a subject of debate. This study aims to analyze the impact of carbon content on the printability and mechanical properties of a specialized additive manufacturing superalloy. The findings indicate that the cracking susceptibility of the alloy initially increases and then decreases with rising carbon content. The porosity gradually decreases with the addition of carbon. However, as the carbon content increases, the stress rupture properties of the alloy progressively deteriorate. The mismatch in deformation between the carbides and the matrix triggers crack initiation and propagation at the carbide interface, resulting in diminished property. These results elucidate the influence of carbon content within a specific range on both printability and mechanical properties of the alloys, thus providing valuable guidance for regulating carbon content in future alloy designs.

Keywords: Additive manufacturing; Superalloy; Carbon; Printability; Mechanical properties

1 Introduction

Additive manufacturing technology offers a promising solution for the production of complex superalloy parts with advantages such as short production period, high precision and good formability [1,2]. However, grain boundaries with severe elements segregation and high internal stress are more susceptible to crack initiation. Carbon is the most common grain boundary strengthening elements in superalloys, typically added in the range of 0.06-0.15 wt.%. Carbon plays a complex role in nickel-based superalloys, and properties can be improved if the appropriate proportion of carbon is present [3]. In the field of additive manufacturing, carbides are considered to be one of the causes for crack formation [4]. However, recent studies have shown that even with a high carbon content of 0.6%, good formability can still be achieved in the additive manufacturing process, leading to a controversy surrounding the role of carbon [5]. In addition, in the performance research of additively manufactured superalloys, the main focus is on room temperature tensile properties, and there is little research on high temperature tensile and rupture properties.

In conclusion, further investigations are required to explore the roles and mechanisms of trace elements in AM superalloys. This study aimed to examine the relationship between varying carbon content in additively manufactured printability and properties. The results of this study can serve as a reference for determining the optimal carbon content for additive manufacturing of superalloys in the future.

2 Experimental procedure

In this study, an alloy specifically designed for additive manufacturing was utilized. Four different levels of C content (0 wt.%, 0.05 wt.%, 0.1 wt.%, 0.15 wt.%) in the alloy powders were prepared through gas atomization of the as-cast alloys. Directed energy deposition (DED) equipment was used to prepare the sample. The substrate was GH3536, and the samples size were 16×16×60 mm. Uniform laser power (2000 W), scanning speed (1100 mm/min), layer thickness (0.167 mm), spot diameter (2 mm), and powder feeding volume (11 g/min) were employed for all specimens.

3 Result and discussion

Alloy printability

Table 1 shows the statistics of some microstructure characteristics of as-built samples. The crack density did not show a linear relationship with carbon content. Instead, it increased initially, peaked at 0.06 wt.%, and then decreased significantly. Cracks were classified according to their causes, and the crack density was calculated separately. The statistical results were compared with the results of thermodynamic calculations, which well explained why the crack density first increased and then decreased. Owing to the rapid cooling rate in DED, carbides have limited time for growth following nucleation, resulting in minimal changes in carbide size with increasing carbon content. These finely granular carbides are expected to exert minor impact on liquid phase feeding. The reduction of porosity can be examined from two complementary perspectives. Firstly, during the inherent heat treatment process of additive manufacturing, carbides gradually grow and fill existing pores. Secondly, thermodynamic calculations indicate that the carbon lowers the pressure drop within the mushy zone, promoting the closure of pores.

Table 1 As-built sample microstrcture characteristics statistics

Alloy	Crack density ($\mu m/\mu m^2$)	Porosity (%)	Carbides Size (μm)
0C	2.48×10^{-4}	0.36	—
0.05C	3.27×10^{-4}	0.19	1.12
0.1C	5.32×10^{-4}	0.14	1.58
0.15C	3.22×10^{-4}	0.13	1.96

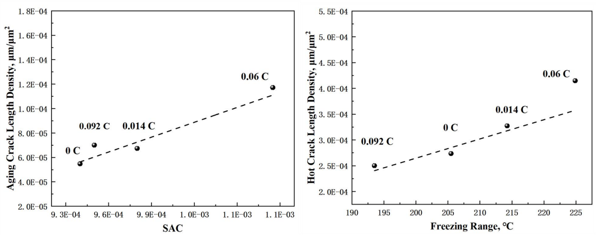

Figure 1 Relationship between aging crack density and SAC and between hot crack and solidification range.

Stress rupture properties

The stress rupture properties of the alloys under different conditions are presented in Table 2. It is evident that the alloys experience a decline in rupture properties as the carbon content increases. Since the size and volume fraction of the γ′ phase are minimally affected by the addition of carbon, the main source of performance degradation is likely the increasing presence of carbides. EBSD analysis reveals a notable stress concentration at the carbide interface, along with observations of dynamic recrystallization in the vicinity of the carbides. The large difference in thermal expansion coefficients and deformation coordination ability between carbides and the matrix lead to high stress levels at the interface. Furthermore, an excessive quantity of carbides tends to deplete solid solution elements, further diminishing the alloy's solid solution strength and facilitating dislocation movement within the matrix.

Table 1. Alloy rupture life under different conditions

Alloy	760°C/800MPa (h)	980°C/260MPa (h)
0.05C	132±15	26±4
0.1C	57±10	21±3
0.15C	15±5	12±4

4 Conclusion

Carbon can influence various factors including the solidification interval of the alloy and the precipitation rate of desired phases, thereby aiding in the prevention of crack initiation and reduction of porosity. However, excessive carbon content can significantly impair the stress rupture properties of the alloy. This deterioration is attributed to the high interface stress between the carbide and the matrix, which promotes microcrack formation. Therefore, when designing the alloy composition, a comprehensive consideration of printability and mechanical properties is essential, with careful control of the carbon content playing a crucial role.

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