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Impact of iron composition on the properties of an additively manufactured solid solution strengthened nickel base alloy

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ABSTRACT

The impact of changes in Fe content from 1 wt% to 4 wt% on the properties of additively manufactured (AM) Inconel® 625 fabricated using laser-based directed energy deposition (DED) is investigated in both the as deposited and post processed hot isostatically pressed (HIP) conditions. While similar solidification structures and microhardness values are observed, the low Fe content build displayed higher yield (520 MPa ± 12 MPa vs. 450 MPa ± 27 MPa) and tensile strengths (860 MPa ± 27 MPa vs. 753 MPa ± 25 MPa) and lower elongations (36% ± 5% vs. 44% ± 9%) in the as-deposited condition. Differences in mechanical properties are connected to differences in the grain size produced with the different Fe contents. In the as deposited condition, fine grains less than 500 µm in size with low aspect ratios were observed with the low Fe content, while large elongated grains in excess of 1 mm in length were observed with the high Fe content. After HIP, the yield strengths for both Fe contents decreased by 14%, while elongation increased similarly. On the other hand, tensile strengths after post processing changed by only 3%, which were correlated to higher levels of strain hardening for the higher Fe content. These differences in behavior can be attributed, in part, to changes in precipitate morphologies. After HIP post processing, the low Fe content build displayed Nb and Mo rich precipitates, while spherical Ti rich precipitates are present in the high Fe content build.

1. Introduction

Inconel® 625 is a solid-solution strengthened Ni-base alloy with high strength, outstanding corrosion resistance, and excellent fabricability. These properties make Inconel® 625 an attractive candidate for use in cryogenic and high temperature ($> 980\,^{\circ}C$) environments [1,2]. The versatility of this alloy system is derived from the combination of its primary alloying elements, which include Ni and Cr for high oxidation resistance, Mo for corrosion resistance, and Nb for stiffness. Table 1 provides a summary of the allowable composition limits for this alloy system [3]. While originally designed for high temperature environments characteristic of steam and gas turbines [4], its corrosion resistance has allowed its application space to be expanded into marine environments [5].

This alloy is widely used in the cast and wrought forms, but its good weldability also makes it an attractive material for clad overlays in steel structures and other applications where it can be used in an as-solidified condition [6–12]. In conventional arc welding and overlay processes, Inconel® 625 displays a columnar dendritic structure, with secondary phases forming in the interdendritic regions. These ordered secondary phases, which include various carbides (MC, M_6C, and $M_{23}C_6$) and Laves phase, are shown to have a detrimental effect on mechanical properties [8,13]. Laves phase, which is a brittle microconstituent, in particular, adversely affects ductility and acts as a crack initiation site [13–19]. Formation of the Laves phase is typically limited by controlling composition, with previous work directed at tightly controlling the Si, C, and Nb compositions. It has been observed that Laves phase formation was promoted [7,8] with high Si and low C compositions. Increased levels of Nb were also shown to increase secondary phase constituents as well as the solidification temperature range, resulting in increased crack susceptibility [8].

As shown in Table 1, there are rather large ranges of allowable alloying element compositions for several alloying elements in Inconel® 625. For example, Fe has a wide allowable range (0–5 wt%) [3], but the impact of large changes in the Fe content has not been specifically investigated. Most existing work dealing with changes in Fe content has been primarily directed at the dilution of the weld metal in clad overlays fabricated on steel structures [6–11]. In these applications, the weld metal becomes significantly enriched in Fe due to dilution from the carbon steel substrate, causing the Fe content to reach levels much

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Table 1
Summary of standard chemical compositions [3] and measurements of these compositions in low and high Fe content Inconel® 625 powder feedstock and as-deposited structures.

Element	Alloy Compositions (wt%)				
		Low Fe		High Fe	
	Standard	Powder	Deposit	Powder	Deposit
Ni	> 58.0	64.8	64.06	61.3	60.62
Cr	20.0 – 23.0	21.0	21.59	21.3	21.46
Fe	< 5.0	1.02	1.07	4.34	4.14
Mo	8.0 – 10.0	8.73	8.83	8.70	8.96
Nb	3.15 – 4.15	3.43	3.47	3.83	4.11
Si	< 0.50	0.37	0.39	0.035	0.051
Mn	< 0.50	0.31	0.28	0.010	0.085
C	< 0.10	0.008	0.009	0.005	0.006
Ti	< 0.40	0.019	0.033	0.19	0.21

higher than the allowable Fe range and altering the solidification path [6]. Dupont et al. found that the solidification temperature range in the deposited Inconel® 625 was suppressed because of the transfer of significant amounts of Fe to the overlay from the substrate [6].

Weldability and solidification studies of Inconel® 625 have been limited to the deposition of a small number of layers on both matching Inconel® 625 and steel substrate materials [6–11]. Additive manufacturing (AM) technologies, however, are capable of producing complex 3-dimensional components over a wide range of size scales [20–24]. Dilution of the deposited metal composition combined with the complex thermal cycles created by the continuous layer-by-layer melting and remelting are factors that influence the solidification path and final microstructure of the material [25]. When the deposition process is scaled, the governing process-structure-property relationships can change in unknown ways [26].

For larger scale applications, directed energy deposition (DED) AM processes are commonly used. In the case of Inconel® 625, several areas, including the role of powder feedstock size distributions [27], processing parameter control [28–30], microstructural impact [13,19,25,31,32], post processing [31], and mechanical properties [13,19,33] have been investigated. Additional AM work with the powder bed fusion (PBF) process, which is primarily used to fabricate smaller scale structures, has concentrated on microstructural characterization and the impact of hot isostatic pressing (HIP) on mechanical properties [34,35]. With the addition of this post processing step, the promotion of secondary phase formation is readily observed [16,36–39].

The Fe content in these previous AM studies was typically held constant at levels either below [19,25,27,40] or above [13,30,31,33] 3 wt%, which is at approximately the mid-level of the allowable composition range. The microstructures formed in these builds were characterized primarily by the presence of a $NbCr_2$ Laves phase, γ' (Ni_3Al), δ (Ni_3Nb), or one of several carbide phases. Little additional characterization of the impact of these different Fe levels on other microstructural and mechanical properties, though, is available.

In order to determine the impact of changes in the Fe content, laser-based DED Inconel® 625 builds were fabricated using powder feedstocks with 1 wt% and 4 wt% Fe levels. The resulting microstructural and mechanical properties were characterized in both the as deposited and post-processed HIP conditions. Even though the differences in Fe content are near the extremes of the allowable composition range, similar solidification microstructures, as characterized by secondary dendrite arm spacing (SDAS) and secondary phase volume fraction measurements, are observed along with similar microhardness levels across the height of the as-deposited builds. However, the lower Fe content builds displayed higher strength but lower elongation than the higher Fe content builds in the as deposited condition. These differences in as deposited mechanical properties correspond to differences in grain morphologies, with the low Fe content builds having a fine grain structure, while the high Fe content builds display large grains. After a post-process HIP treatment, the mechanical properties for both Fe contents decrease, but differences in the composition and morphology of secondary phases present in the structures lead to differences in the strain hardening behavior.

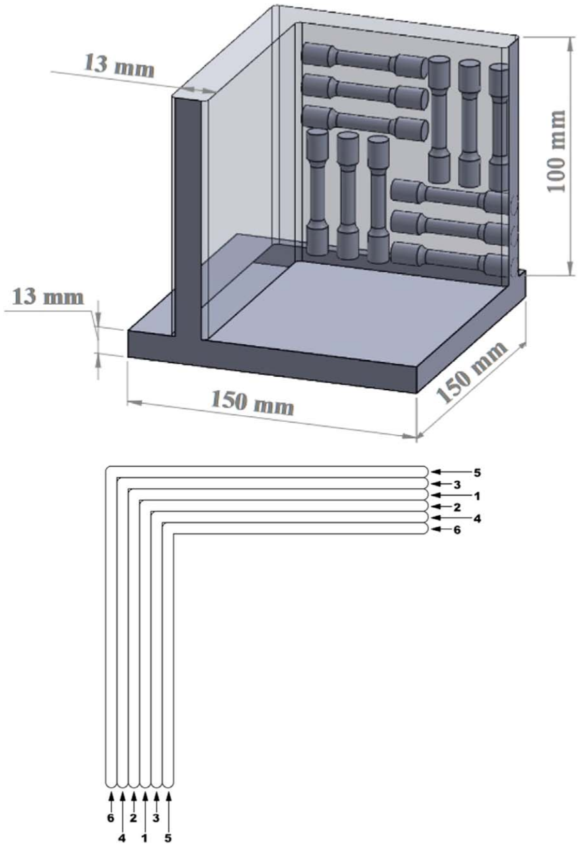

Fig. 1. Schematic diagram showing the solid model isometric view of the L shaped builds fabricated using a laser based DED AM process and the corresponding build path plan. Locations where tensile specimens were extracted from the fabricated structures are also shown. Longitudinal specimens are oriented parallel to the substrate, and transverse specimens are oriented perpendicularly.

2. Experimental

A series of L-shaped Inconel® 625 builds, schematically shown in Fig. 1, were fabricated using a laser based DED system on 150 mm × 150 mm × 13 mm thick Inconel® 625 substrates.[1] An IPG Photonics® YLR-12000 ytterbium fiber laser system operating at a near-infrared wavelength between 1070 and 1080 nm was used as the energy source. The laser was delivered through a 600 µm diameter fiber to a water-cooled copper reflective optics system, which consisted of a 49.5 mm diameter collimator with a 125 mm focal length lens and focusing optics with a focal length of 600 mm. The powder feedstock was delivered through a Powder Feed Dynamics Mark XV Precision Powder Feeder to a custom coaxial, four nozzle powder delivery system, with each nozzle having an orifice size of 2 mm and located 10 mm above the deposition surface. At this stand-off distance, the beam is operated in a defocused condition to ensure efficient powder consumption. The beam diameter was measured using a PRIMES® Focus Monitor and confirmed to be approximately 4 mm with a Gaussian energy density distribution [41].

Nitrogen atomized powder feedstocks[2] with a low Fe content (1 wt

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[2] Carpenter Powder Products (Bridgeville, PA).