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Review of the fatigue strength of DED- and casting iron-based alloys

Pengfei Guo, Alexander Kaplan

1. Motivation and scope

Iron-based alloys, having a long history of more than 3000 years since the start of the Iron Age, are widely used in all aspects of our daily life and industry owing to their high output, moderate price, and satisfactory performance [1]. Casting, an even older method being used at least 6000 years ago during the Bronze Age, has developed as one of the most mature and effective methods to process iron-based alloys. Until now, the relatively complete theorical system of casting iron-based alloys in terms of casting process, microstructure and service performance has been developed basically [2].

Directed energy deposition (DED) technology, exhibiting the advantages of flexibility, no die, full density, and near-net-shape forming, has been extensively utilized in the fabrication of large-scale and complex-structure metal components. In recent years, with the increasing requirements of the high-performance, large-structure, lightweight, and complex iron-based components from industry, DED technology has been rapidly introduced to fabricate iron-based parts. It is worth mentioning that the iron-based alloys with high carbon level present low cost and poor weldability with pores, cracks, and undesirable microstructure [3], and thus only the low-carbon or free-carbon iron-based alloys were fabricated using DED for the actual production and most of the research. Owing to the rapid solidification of the melt pool (cooling rate of 10^5-10^9 K/s) during DED process, the microstructure size is smaller than that of the conventional castings. As a result, the static mechanical properties (e.g., tensile strength) of DED iron-based alloys are better than the castings, such as, austenitic stainless steel (316L [4], 304L [5]) and martensitic steel (18Ni300 [6], 4-17PH [7, 8]), etc. However, little attention is received regarding the dynamic mechanical properties (e.g., fatigue strength), which are the remarkable reliability indexes for a structural component.

To understand the fatigue strength difference between deposits and castings systematically and comprehensively, we summarized and reviewed the high cycle fatigue (HCF) at room temperature and high temperature, and the low cycle fatigue (LCF) behavior of the iron-based alloys based on the existing literature. Afterwards, the related fracture and failure mechanism was discussed based on the microstructural features and defects. Note that the introduced iron-based alloys mainly include martensitic steel (18Ni300 and 17-4PH) and austenitic stainless steel (316L and 304L). The normal compositions of the related iron-based alloys are listed in Table I. In addition, considering the available literature on the fatigue strength of DED iron-based alloys is limited, other additive manufacturing (AM) methods were also involved, such as, the powder bed fusion (PBF) and wire arc additive manufacturing (WAAM).

Table I

Nominal compositions of iron-based alloys

Element	C	Mn	P	S	Si	Ni	Cr	Mo	Ti	Co	Al	Fe
18Ni300	<0.03	<0.1	<0.01	<0.01	<0.01	17-19	<0.25	4.6-5.2	0.6-0.8	8.5-9.5	0.05-0.15	Bal.
316L	≤0.030	≤2	≤0.045	≤0.03	≤1	10-14	16-18	2-3	-	-	-	Bal.
304L												
17-4PH												
…												

Microstructural features directly determine the mechanical properties, and thus the microstructural features and strengthening mechanism should be clear. Table II presents the strengthening types and associated microstructure of the iron-based alloys.

Table II

Strengthening types and associated microstructure of the iron-based

	Heat treatments	Constituent phases	Strengthening mechanism
18Ni300	Solutionizing (820°C×1h, air cooled) and aging (550°C×3h, air cooled) [9]	Martensitic phase (α’) and intermetallic precipitates ($\mathrm{NiTi_3}$)	Martensite and precipitation hardening
316			
17-4PH	Solutionizing (1038°C×4h, air cooled) and aging (482°C×1h, air cooled) [10]	Martensitic phase (α’) and Cu-precipitates	Martensite and precipitation hardening
…			

2. Fatigue and fracture

2.1. High cycle fatigue at room temperature

Table III shows the room temperature HCF behavior of the casting and AM 18Ni300 (we are searching for the related data and perfecting the table). The as-built 18Ni300 with aging heat treatment exhibits inferior room temperature HCF strength (440 and 358 MPa) to the casted 18Ni300 with solutionized heat treatment (617 MPa). Seen from the crack initiation site, the more surface defects decrease the HCF strength of the deposit. Further, the HCF strength along the vertical direction of the deposit (440 MPa) is better than that along the horizontal direction (358 MPa). For the aged castings, the HCF strength is even better than the solutionized castings. Similarly, the deposit without heat treatment exhibits even worse HCF strength than that with heat treatment. This tendency is caused by the fact that the heat treatment leads to the formation of the strengthening phases.

Table III
Room temperature (20°C) HCF strength of iron-based alloys, produced by casting and additive manufacturing (AM).

Material	Process/Condition	Orientation	R	f (Hz)	HCF (MPa)	Crack initiation site	Defect size (μm)	Ref.
18Ni300	Cast (Vacuum-melting)/Solutionized	-	-1	50	617	Surface (roughness, inclusions)	10	[11]
	LB-PBF/490°C×6h (aging)	V	-1	50	440	Surface (oxide inclusion, pores, matrix defects)	10-40	[11]
	LB-PBF/490°C×6h (aging)	H	-1	50	358	Surface (oxide inclusion, pores, matrix defects)	10-40	[11]
	Cast (Vacuum-melting)/ 820°C×1h, air cooled (Annealed)	-	-1	30	483 (70 ksi)	Surface (probably Ti(C,N) inclusions)	-	[12]
	Cast (Vacuum-melting)/ 480°C×3h, air cooled (Aged)	-	-1	30	689 (100 ksi)	Surface (probably Ti(C,N) inclusions)	-	[12]
	LB-PBF/As-built	V	-1	10-30	182*	Surface or subsurface lack of fusion defects or cluster of defects	200-700	[13]
	LB-PBF/As-built	H	-1	10-30	91*	Surface or subsurface lack of fusion defects or	200-700	[13]

						cluster of defects		
…								

* Run out at 2×10^6 cycles.

2.2. High cycle fatigue at high temperature

Table IV presents the high temperature (400 ℃) HCF strength of the 18Ni300 fabricated by casting and LB-PBF. The casted 18Ni300 exhibits a better HCF at 400 °C than LB-PBF samples. It is the sub-surface matrix defects that worse the high temperature HCF of the deposit. Furthermore, the intercellular crack initiation makes the vertical direction of the deposit exhibiting a higher high-temperature HCF than the horizontal direction.

Table IV
High temperature HCF strength of iron-based alloys, produced by casting and AM.

Material	Process/Condition	Orientation	R	Frequency (Hz)	HCF at 400°C (MPa)	Crack initiation site	Defect size (μm)	Ref.
18Ni300	Casted (Vacuum-melting)/Solutionized		-1	50	650	Surface matrix defect	10	[11]
	LB-PBF/490°C×6h (aging)	V	-1	50	440	Sub-surface (oxide inclusion, lack of fusion pores, **matrix defects**)	10-40	[11]
	LB-PBF/490°C×6h (aging)	H	-1	50	312	Sub-surface (oxide inclusion, lack of fusion pores, **matrix defects**)	10-40	[11]
…								

2.3. Low cycle fatigue at high temperature

Table V presents the high temperature LCF strength of the casted and LB-PBF 316. Roughly, the deposit exhibits inferior high temperature LCF strength to the castings. (The data are being searched and the table is being perfected.)

Table V
High temperature LCF of iron-based alloys, produced by casting and AM

Material	Process/Condition	Orientation	R	Strain rate (/s)	LCF (N_f−Strain amplitude)	Crack initiation site	Defect size (μm)	Ref.
316 (Material 58)	Cast	-	-1	$2\text{-}6\times10^{-4}$(625°C)	3161-0.34% 2488-0.33% 478-0.6% 287-0.8% 211-1% 162-1.5%			[14]

				$2-6\times10^{-4}$(570°C)	16157-0.25% 4526-0.35% 1215-0.6% 480-1%			[14]
316L	LB-PBF/As-built	H	-1	5×10^{-4}(550°C)	1035-0.4% 740-0.5% 480-0.6% 121-0.8% 110-1.0%			[15]
	LB-PBF/1060-1110°C×5.5 h (aging)		-1	5×10^{-4}(550°C)	2190-0.4% 1518-0.5% 915-0.6% 442-0.8% 269-1.0%			[15]

2.4. Fatigue crack initiation and growth

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