Influence of Post-Heat Treatments on Fatigue Response of Low-alloyed Carbon-Manganese Steel Material Manufactured by Direct Energy Deposition-Arc Technique

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Abstract

The main idea of this paper is improving fatigue response of a low-alloyed carbon-manganese steel material manufactured by Direct Energy Deposition-Arc technique using post-heat treatments. Four series of fatigue specimens are machined from a 3D printed wall. The machined samples are austenitized following a direct quenching and tempering processes at two different temperatures. All samples are subjected to rotating bending fatigue loading conditions. Next, microhardness, microstructures and fracture surfaces of the fatigue samples are analysed. Despite of very low carbon content, a full martensitic transformation was observed after the post-heat treatments which resulted in considerably higher fatigue lifetimes compared to non-treated ones. The quenched samples gave the best improvement when compared to as-printed and tempered samples.

Keywords: DED-Arc, WAAM, Fatigue Fracture, Heat Treatment, Steel

1. Introduction

Direct Energy Deposition-Arc (DED-Arc) Additive Manufacturing (AM) technique, which is also known as Wire and Arc AM (WAAM), uses an electric arc as heat source to melt a filler wire and build a component in layer-by-layer way, which allows producing near net shape parts [1]. In general, DED-Arc AM is very beneficial for medium to large metal parts and recently gaining more attentions by many industrial sectors. However, successful construction of metallic components using DED-Arc method, for many safety-critical applications, requires a thorough understanding of associated mechanical properties, such as fatigue.

Fatigue fracture assessment of DED-Arc manufactured parts, reported in literature, can be divided in two main groups, namely stress/strain based fatigue tests [2] and fatigue crack growth studies [3, 4]. In respect to the surface quality, the research works mainly focus on post-machined [2, 5] and as-built surface conditions [6, 7]. Some researchers have investigated the influence of different printing parameters on fatigue fracture of as-built AM materials [8-10]. For example, Gordon et al. [11] have studied the impact of strain accumulation, porosity, and microstructural features on fatigue response of as-built metastable 304L stainless steel. They have reported that fatigue behaviour of as-built metastable DED-Arc-304L material was exceptional compared to wrought material. It is well known that fatigue response of AM parts could be

enhanced using post-heat treatments [8]. Recently, Nemani et al. [12] have investigated the effects of post-printing heat treatments on microstructure and tensile properties of low-carbon low-alloy steel material manufactured using DED-Arc technique. In this study, effects of post-printing heat treatments on fatigue response of a low-alloyed carbon-manganese steel, manufactured using DED-Arc technique, is investigated.

2. Materials and Testing Methodology

The DED-Arc AM wall, as shown in Figure 1(a) was built up using Gas Metal Arc Welding (GMAW) process [13]. Standard industrial 6-axis welding robot arm CLOOS QRC320H was used as a motion system for the DED-Arc process. The wall was deposited using Qineo pulse 450A welding power source with synergic control in a standard GMAW mode. The EN ISO 14341-A (G 42 4 M21 G 3Si1), hereafter G3Si1, filler wire ($\varnothing 1.2\text{mm}$) was used as printing material and S235 steel as the base plate. The chemical composition and mechanical properties of the filler wire can be found in Table 1. The shielding gas was 85% Argon and 15% CO_2 mixture at a constant flow rate 15 l/min. The wire feed speed and travel speed of the robot were set to 4.5m/min and 0.34m/min, respectively [13]. The resulting welding voltage and current were equal to 19V and 174A. Contact tip to workpiece distance was kept constant during the process and equal to 15mm. Except for the first two layers which had a height of 2.3mm, 90 layers of 2mm high were printed. Two passes were applied for each layer and resulted in a 12mm wall thickness.

Table 1. Chemical composition and mechanical properties of the G3Si1 filler material.

Material	Element (wt%)					
	C	Si	Mn	P	S	Cu
	0.088	0.9	1.51	0.012	0.012	0.19
G3Si1	σ_y [MPa]		σ_{ult} [MPa]		ε_{fr} [%]	
	420		500-640		20	

Twenty fatigue samples were machined from the DED-Arc-G3Si1 wall along the vertical direction, as schematically shown in Figure 1(a). All samples, with a diameter of 4mm at the minimum cross section, were polished to reach a roughness value of $R_a = 0.4\mu\text{m}$. Fatigue tests were performed under rotating bending loading conditions to obtain fatigue lifetimes between 10^4 to 10^6 cycles, as shown in Figure 1(b).

Three post-heat treatments were performed on 15 fatigue samples which were compared against non-heat-treated machined samples (DED-Arc-M). The first set (DED-Arc-MQ) consists of five samples which were austenitized at 950°C for 30 min, following a direct quenching in water. The second (DED-Arc-MQT@T1) and third (DED-Arc-MQT@T1) sets were also austenitized at 950°C for 30 min and quenched in water, followed by tempering for two hours at $T_1 = 180^\circ\text{C}$ and $T_2 = 220^\circ\text{C}$, respectively.

3. Results and discussions

Figure 1(b) compares the fatigue lifetimes of DED-Arc-G3Si1 subjected to different post-heat treatments. The fatigue lifetime of DED-Arc-M was used as the baseline to evaluate the effects of the applied post-heat

treatments. Moreover, the fatigue response of DED-Arc-M is compared to as-built DED-Arc-G3Si1 material taken from the literature [7].

Figure 1. (a) printed DED-Arc-G3Si1 wall, (b) stress amplitude vs fatigue cycles plot for DED-Arc-G3Si1, (c) FAT-class design curves plot for different steel grades printed using DED-Arc method, and (d) microhardness measurement plot through the cross section.

Figure 1(b) reveals that fatigue behaviour of as-built G3Si1 is significantly lower compared to DED-Arc-M samples. For as-built condition a fatigue limit of 149MPa can be obtained at 10^6 cycles. By applying machining this fatigue limit is increased to 206MPa (*ca.* 0.39% higher). Figure 1(b) shows that the fatigue behaviour of the DED-Arc-M samples can be improved using all three post-heat treatments. The DED-Arc-MQ samples give the best results which leads to 61% higher fatigue limit (331MPa) at 10^6 cycles compared to DED-Arc-M samples. It can be seen that the results for DED-Arc-MQT samples are scattered, when compared with the DED-Arc-M and DED-Arc-MQ samples. It was observed that, applying tempering

process on such miniaturized fatigue samples caused undesired deformations which resulted in residual stresses. These stresses lead to out of plane loading conditions for some of the samples.

A FAT-class design curve represents the stress range that corresponds to a 95% survival rate after 2×10^6 cycles which can be utilized to design a DED-Arc manufactured structure using steels such as G3Si1, 304L stainless steel [11] and ER70S-6 [5], as plotted in Figure 1(c). It can be seen that for a very conservative design a FAT 100 curve with a slop 3 can be used. However, a higher FAT class of 300 with a slop of 5 can be considered for G3Si1 (DED-Arc-M, DED-Arc-MQ and DED-Arc-MQT) and 340L materials. To include as-built G3Si1 and ER70S-6 materials, a FAT 200 design curve with a slop of 5 is suggested.

To understand the effects of post-heat treatments on fatigue response of DED-Arc-G3Si1 material, microhardness (HV) of DED-Arc-M, DED-Arc-MQ, DED-Arc-MQT samples were measured from $L = 150\mu\text{m}$ to $L = 4.5\text{mm}$ ($L =$ distance from surface), as plotted in Figure 1(d). As can be seen, the microhardness value of non-heat-treated sample is *ca.* 157HV and almost constant through the printed material. By applying the post-heat treatments, the microhardness value of the DED-Arc-MQ sample is the highest, nearly 500 HV, close to the surface of the material ($L = 150\mu\text{m}$) and gradually decreases to 313 HV at $L = 2\text{mm}$. This hardening is the main reason for the lifetime improvement of DED-Arc-MQ samples. For DED-Arc-MQT samples, at both temperatures, the microhardness values are quite similar to each other with a value of *ca.* 254 HV at $L = 150\mu\text{m}$ which slightly raises to *ca.* 300HV at $L = 4.5\text{mm}$ and remains steady through the cross section. The main cause of the hardening behaviour of DED-Arc-G3Si1 material can be explained by looking at the microstructure evolution after the post-heat-treatments, as shown in Figure 2.

The G3Si1 welding wire has a carbon percentage of 0.06% – 0.14%, which can be categorized as very low carbon steel grade. Figure 2(a) shows the microstructure of as-printed G3Si1 material which consists of primary ferrite grains (α) and pearlite ($\alpha + \text{Fe}_3\text{C}$). The carbon content of 0.15% was measured for as printed material. Interestingly, despite very low carbon percentage of DED-Arc-G3Si1 material, a full martensitic transformation can be achieved through the entire cross section for all post-heat-treated samples (DED-Arc-MQ, DED-Arc-MQT@T1 and DED-Arc-MQT@T2), as illustrated in Figure 2(b) to (d). Figure 2 (e) to (h) depict variation of the grain sizes from the surface through the cross section for DED-Arc-M, DED-Arc-MQ, DED-Arc-MQT@T1 and DED-Arc-MQT@T2 samples. Except for the DED-Arc-MQ sample, the rest of samples show a uniform grain size distribution through the cross section. As indicated in Figure 2(f) for DED-Arc-MQ sample a finer microstructure is formed after the direct quenching process on the surface up to *ca.* $350\mu\text{m}$ beneath the surface. This is the main reason for the high microhardness value of *ca.* 500HV at $L = 150\mu\text{m}$ for the direct quenched samples, as shown in Figure 1(d), which resulted in higher fatigue lives compared to other post-heat treatment conditions shown in Figure 1(b).

Figure 2. Microstructures of DED-Arc-G3Si for M DED-Arc-M, DED-Arc-MQ, DED-Arc-MQT@T1 and DED-Arc-MQT@T2 samples.

Figure 3 (a) to (d) show the fracture surfaces of DED-Arc-M, DED-Arc-MQ, DED-Arc-MQT@T1 and DED-Arc-MQT@T2 at the stress amplitude of 424MPa, 480MPa, 485MPa and 450MPa, respectively. From all the fracture surfaces it can be noted that, due to rotating bending loading conditions, multiple fatigue cracks initiate from the surface and propagate through the cross section till final tensile rupture. Figure 3-I shows a zoom view of the fatigue crack initiation. Figure 3-II and III show typical striation lines associated with the fatigue crack propagation. Figure 3-IV depicts the dimples which happens due to rapid tensile fracture.

4. Conclusions

The main goal of this study was utilizing post-heat treatments to improve the fatigue lifetime of a low-alloyed carbon-manganese steel material (G3Si1) manufactured by DED-Arc technique. To do so, the machined fatigue samples were austenitized following quenching (DED-Arc-MQ) and tempering processes at two different temperatures, namely $T_1 = 180^\circ\text{C}$ and $T_2 = 220^\circ\text{C}$ (DED-Arc-MQT@T1 and DED-Arc-MQT@T2). All samples were subjected to rotating bending fatigue loading conditions and the results were compared against the non-treated samples (DED-Arc-M). Based on the observed results, it can be concluded that the fatigue lifetimes of DED-Arc-MQ samples are improved considerably at different stress levels when compared to DED-Arc-M and DED-Arc-MQT samples. Despite of very low carbon content, a full martensitic transformation was observed after the post-printing heat-treatments. The DED-Arc-MQT

specimens also showed an improvement regarding fatigue life, but the results were more scattered, due to the undesired deformations in the specimens.

Figure 3. Fracture surfaces of (a) M DED-Arc-M, (b) DED-Arc-MQ, (c) DED-Arc-MQT@T1 and (d) DED-Arc-MQT@T2 at different stress amplitudes.

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