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Wire arc additive manufacturing of thin-wall low-carbon steel parts: Microstructure and mechanical properties

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Wire arc additive manufacturing (WAAM) has received much attention for manufacturing metal parts with medium and large dimensions because of its high deposition rate and low production costs. In this study, the effects of the heat input on the microstructure formation of thin-wall low-carbon steel parts built by a WAAM process were addressed. The mechanical properties of built materials were also studied. The results indicate that the heat input significantly influences on the shape of built thin walls, but has slight effects on the microstructure evolution of built materials. The WAAM thin-wall low-carbon steel presents suitable microstructures and good tensile strengths (YS: 320 – 362 MPa, UTS: 429 – 479 MPa) that are adequate with industrial applications.

Keywords: Wire arc additive manufacturing; low-carbon steel; microstructures; mechanical properties.

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1. Introduction

Wire arc additive manufacturing (WAAM) has appeared as the most promising additive manufacturing (AM) technology for manufacturing metal components with large dimensions because of its high rate of material deposition and low costs of investment.[1,2] WAAM uses the electrical arc as a heat source to melt the metal wire and fabricates metal parts layer-by-layer.[1] Upto now, considerable studies on microstructure and mechanical properties of WAAM-built parts have been carried out

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in the cases of titanium, nickel and aluminum alloys.[3,4] However, studies concerning microstructures and mechanical properties of WAAM-built steel components are still limited.[3]

In this study, the effect of the heat input on the microstructure evolution of thin-wall low-carbon steel components built by a WAAM process was firstly addressed. The mechanical properties of WAAM thin walls were then investigated.

2. Materials and Methods

The commercial low-carbon steel wire (ER70S-6) with a diameter of 1.2 mm and several low-carbon steel plates (SS400) with dimensions of 200 × 100 × 10 mm were used. The thin-wall components were built by an industrial robotic gas metal arc welding system (Panasonic TA 1400) according to the alternating deposition direction strategy.[5,6] During the WAAM process, the CO_2 gas with a flow rate of 18 L/min was used for the shielding.

To observe the effect of heat input on the microstructure evolution of built walls, four thin-wall samples were built on a substrate [Fig. 1(a)] with four sets of process parameters, as presented in Table 1. A specimen was cut from four thin-wall samples and the substrate in the middle region for investigating the microstructure

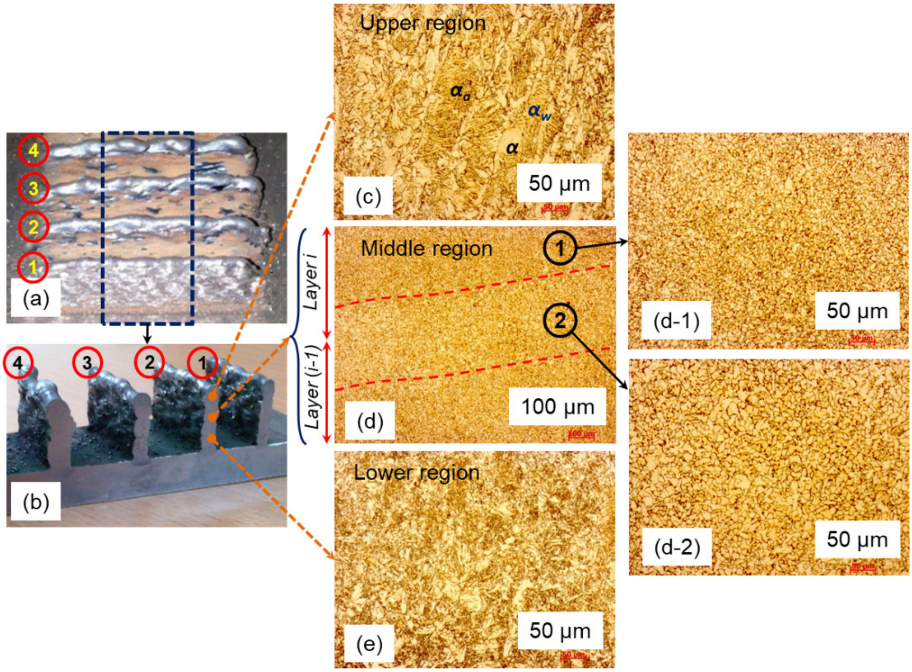


Fig. 1. (Color online) Four thin-wall samples (a), specimen for observing microstructure and hardness (b), microstructures in the upper region (c), in the middle region with lower magnification (d) and higher magnification for the nonoverlapped zone (d-1) and overlapped zone (d-2) of the middle region, and in the lower region (e).

Table 1. Process parameters used to build the thin walls.

Parameter	Welding current, I (A)	Voltage, U (V)	Travel speed, v (mm/min)	Heat input, Q (J/mm)
Sample 1	50	18	300	144
Sample 2	70	18	300	202
Sample 3	90	18	300	259
Sample 4	110	18	300	317

[Fig. 1(b)]. The microstructure of built samples was observed by an optical microscope on a grinded and chemically etched surface of the specimen [Fig. 1(b)]. The microhardness of built thin walls was measured by using a digital microhardness tester.

Another thin wall (100 mm in height and 130 mm in length) was built with $I = 70$ (A), $U = 18$ (V) and $v = 300$ (mm/min) for investigating tensile properties. Three tensile specimens in each vertical direction (vTS) and horizontal direction (hTS) were then extracted from this thin wall. All tensile tests were performed by a tensile test machine at room-temperature.

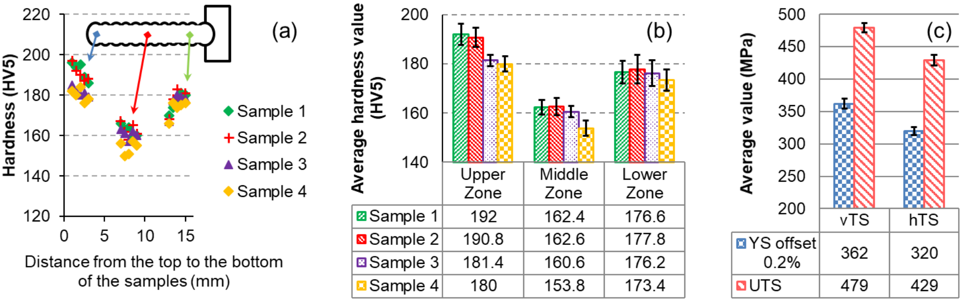
3. Results and Discussion

From scanned images of microstructures, it was firstly observed that all thin-wall samples present similar microstructure evolution in three regions: the upper region, the middle region, and the lower region [Figs. 1(c)–1(e)]. The microstructure type in each region is mostly identical for all samples. The heat input only has effect on the size of grains in each region and the shape stability of built thin walls [Fig. 1(b)]. The samples built with higher heat inputs reveal coarser grains in microstructures. For each sample, the microstructure types in three regions were presented, as follows:

The upper region shows lamellar structures composed of primary austenite dendrites that distribute along the cooling direction and ferrites. The ferrite reveals three morphologies: allotriomorphic ferrite α, Widmanstätten ferrite α_w, and acicular ferrite α_a [Fig. 1(c)]. The microstructure evolution in this region is due to the effect of air cooling and heat conduction from the upper to the bottom of the walls.

The middle region reveals granular structures of ferrites with small amounts of pearlites at grain boundaries [Fig. 1(d)]. Equiaxed grains with a dense distribution in the nonoverlapped zone [Fig. 1(d-1)] and granular grains in the overlapped zone with a relatively large size [Fig. 1(d-2)] were also found. This is due to the fact that the heat of molten pool that formed the layer (i) reheated and partially remelted the previous layer (i-1), resulting in the solid-state phase transformation in the overlapped zones.[7]

The microstructure in the lower region consists of equiaxed ferrites and thin lamellae of pearlites [Fig. 1(e)]. The lower region undergoes a slower cooling rate when compared to the upper region, thus generating the ferrite phases.[7,8] The grain



	Upper Zone	Middle Zone	Lower Zone
▨ Sample 1	192	162.4	176.6
▨ Sample 2	190.8	162.6	177.8
▨ Sample 3	181.4	160.6	176.2
▨ Sample 4	180	153.8	173.4

	vTS	hTS
▨ YS offset 0.2%	362	320
▨ UTS	479	429

Fig. 2. (Color online) (a) Microhardness distribution, (b) average hardness values in each region of four thin-wall samples, and (c) tensile properties of WAAM-built low-carbon steel walls.

size of the lower region is also finer than that of the middle region, because the lower region contacts the cold substrate at room-temperature, while the middle region contacts warm deposited layers.[9]

The microhardness of four thin-wall samples is revealed in Figs. 2(a)–2(b). For each sample, the microhardness was measured at five positions in each region, which distribute on the centerline of the cross section. The hardness value at each position is the average value of three different indentations on the polished surface [Fig. 1(b)].

It was found that all the built samples reveal the same hardness evolution. The upper region of the samples presents the highest hardness value, while the middle region has the lowest microhardness value. This observation is in line with the microstructure observation. For instance, the microhardness of the upper region is higher than that of other regions due to the presence of Widmanstätten structures [Fig. 1(c)]. Because of the presence of lamellae structures [Fig. 1(e)], the lower region has the microhardness values higher than that of the middle region.

The average yield strength (YS) and ultimate tensile strength (UTS) of WAAM low-carbon steel walls in both vertical and horizontal directions are shown in Fig. 2(c). The average values of YS and UTS in the vertical direction (362 ± 8 MPa and 479 ± 7 MPa, respectively) are higher than those in the horizontal direction ($\mathrm{YS} = 320 \pm 6$ MPa and $\mathrm{UTS} = 429 \pm 8$ MPa). The difference of YS and UTS values between two directions may be due to the anisotropy of microstructures of WAAM thin-wall materials.[10]

4. Conclusions and Future Works

In this study, thin-wall low-carbon steel components were built by a WAAM process. The main conclusions can be drawn as follows:

(i) The heat input in the WAAM process has slight effects on the microstructure evolution of built thin walls. The increase of heat input only leads to coarser grains in microstructures.

(ii) The microstructure of built thin-wall materials varies from the top to the bottom. The microstructure formation of WAAM thin-wall low-carbon steel is mainly due to the reheating and remelting effects of the successive layer deposition and the cooling cycles.

(iii) The tensile properties of WAAM-built low-carbon walls presented anisotropy characteristics in the vertical and horizontal directions of thin walls (YS: 320–362 MPa, UTS: 429–479 MPa).

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