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Investigation of mechanical properties for hybrid deposition and micro-rolling of bainite steel

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ABSTRACT

Wire and arc additive manufacturing (WAAM) with a high efficiency and a low cost, is a novel technology for mass popularity. However, a relatively low deposition accuracy and lack of microstructure performances limit the further development of this method. In this paper, the hybrid deposition and micro-rolling (HDMR) process has been used to eliminate the ubiquitous anisotropy in the WAAM bainitic steel samples. To overcome the problems of deficient deformation and large remelted area resulting from the deep penetration and high temperature gradient, an initially optimized micro-rolling morphology based on decreasing the depth of penetration and increasing the ratio of width to reinforcement has been used. Besides, the rolling method with a rapid cooling rate near the temperature for austenite non-recrystallization region, has been used to increase the crystallinity. The results are shown below: the tensile strengths for the optimized sample are 1275 MPa, 1256 MPa, and 1309 MPa, corresponding to the transverse (X), longitudinal (Y), and perpendicular (Z) directions, respectively. The elongations for these three directions are 17.4%, 16.6%, and 17.7%. The average impact toughness is 99 J/cm^2, and the average grain size is about 7 μm. As compared with the traditionally heavy rolling equipment, the new micro roller technology has been indicated as a lower cost method, for achieving outstanding mechanical properties.

1. Introduction

Bainite steel is a type of structural material, which has been widely used in many major industries of the national economy such as railway, oil pipeline, engineering machinery, bridge, vehicle, architecture and aerospace areas, due to its low cost, perfect weldability and excellent comprehensive mechanical properties (Yang et al., 1992). There is no doubt that bainite steel represents the development direction of modern high-performance steel.

As one of the techniques based on the dispersion-deposition principle, the additive manufacturing (AM) processes using the data taken from the CAD model, taking layer by layer overlapping manner to achieve a “bottom-up” freeform fabrication. Due to the feasibility of the near-net successive shape fabrication, AM has been indicated as one of the most powerful processes with the potential of reducing material cost and lead-time (Frazier, 2014). In addition, powder bed, blown powder and wire feed are the main AM feeding components, and the common heat sources are laser, electron beam and electric arc.

The wire and arc Additive Manufacturing (WAAM) is one of the AM techniques using electric arc as heat source and wire as feedstock, has been initiallyinvestigated for large scale deposition of metallic components (Kazanas et al., 2012). The typical WAAM can also be divided into gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) processes. The high efficiency, combined with the relatively low cost and good structure integrity make WAAM rapidly develop, especially for the deposition of large thick-walled parts, which have low or medium complexities on morphology (Williams et al., 2016). Among another two promising AM techniques, selective laser melting (SLM) is sensitive to a part of the alloys, such as aluminum alloy and copper alloy; the part size of the samples underwent the electron beam melting (EBM) process is determined by the equipment forming cylinder and the vacuum chamber. Both SLM and EBM have a high manufacturing accuracy and cost more as compared with WAAM. Moreover, the lack of fusions, cracks, pores, residual stresses and distortions limit most of the AM techniques for the wide applications. Nevertheless, these problems have been gradually solved by using a series of actively thermodynamic controlling methods with subsidiary processes like milling and electromagnetic stirring. As demonstrated by Tammas-Williams et al. (2016), the hot isostatic pressing (HIP) can remove gas pores and reduce fusion defects as well as large

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scale internal porosities from the AM components upon non-optimized conditions. Wu et al. (2014) reported that the residual stress can be diminished by decreasing the scan island size, and increasing applied energy per unit length. Song and Park (2006) elucidated that a hybrid approach called 3D welding and milling can fabricate the functional parts and tools with a sufficient accuracy and surface roughness. Zhou et al. (2015) showed the WAAM with external longitudinal magnetic field can induce the tangential stirring force in molten pool and move the molten metal to the edge, further improve the surface quality.

Due to the rapid heating and cooling speed, the columnar grains are growing and the anisotropic properties have been found in all kinds of AM parts. This process can significantly affect the reliability and quality of the critical components upon complex conditions. As it is widely known, the equiaxed grains have excellent mechanical properties which can efficiently hinder the expanding of cracks, due to the increased density of grain boundaries. As reported by Dinda et al. (2009), the full recrystallized equiaxed structure can be obtained in Inconel 625, by annealing the as-deposited sample at 1200 °C for 1 h, following by cooling in air. Meng et al. (2014) found that using the electromagnetic stirring effect of longitudinal dc magnetic field in molten pool can break the dendritic crystal and refine the crystal grain. However, the distribution of grain sizes is inhomogeneous and the grain refining efficiency is still limited with the above methods.

Rolling is found to be a dramatic method of transforming the dendritic structures into equiaxed grains, which is commonly applied to welding (Li et al., 2015). A few AM publications have reported that rolling could not only significantly reduce the distortions and residual stresses, but also refine grains and improve mechanical properties (Colegrove et al., 2013). Among these work, Martina et al. (2016) illustrated that high-pressure interpass rolling is effective in reducing the longitudinal residual stress, and the distortion has been reduced to less than half of the untreated level in the WAAM components. Besides, microstructure refinement converts the deposited anisotropic properties into isotropic (Martina et al., 2015). However, the “profiled” and “slotted” roller used by them cannot carried out in the non-linear depositing, especially for the samples with intersecting features. Meanwhile, due to the relatively low rolling temperature, the separated casting and rolling processes have a lot of limitations because of the heavy equipment tonnage, large tendency of cracking, and inhomogeneous distribution of grain sizes, especially for the metal parts with poor toughness. For the parallel activity, hybrid deposition and micro-rolling (HDMR) as one kind of the novel AM processes was first reported by Zhang et al. (2013), realized the integration of casting and rolling. This technique can fabricate large thin-wall metal components directly, and further deposit an eligible aircraft metal part (Zhang et al., 2016). Compared with the high-pressure interpass rolling process, the HDMR can obtain finer equiaxed grains by using smaller devices. However, the mechanisms for the grain refinement have not been analyzed deeply, and the HDMR was only used for manufacturing wall components before.

In this paper, the HDMR process has been used to eliminate the significant anisotropy for the bainitic steel WAAM part upon the multi-layer and multi-pass welding. In addition, the strengthening mechanism for mechanical properties improvements of the refined crystalline has also been discussed. Fig. 1 shows the detailed sections of the WAAM/HDMR process.

2. Experimental works

2.1. Material and procedure

A commercial bainite steel has been selected for this study, which is used as wire and substrate for the WAAM and HDMR samples. The chemical compositions of bainite steel are listed in Table 1, and the continuous cooling transformation (CCT) curves of bainite steel modeled by using the JmatPro software, are shown in Fig. 2.

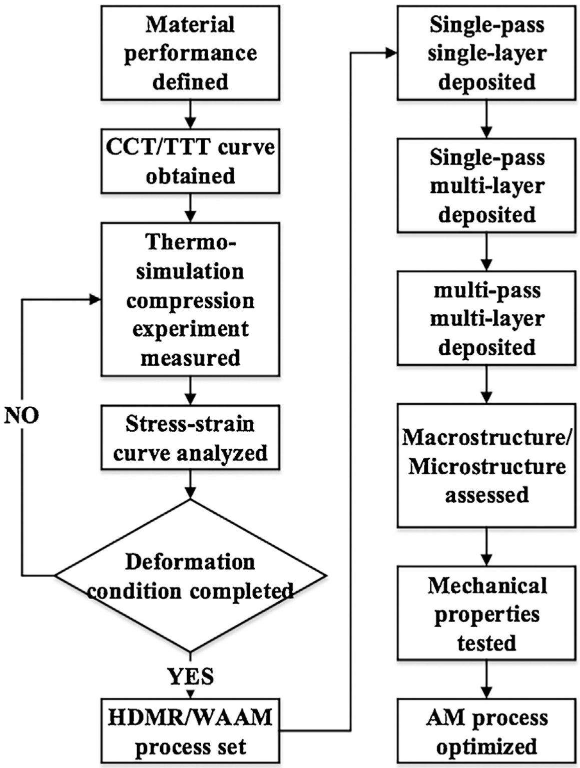

Fig. 1. The flowchart of the optimized AM processes.

Table 1
The chemical compositions of substrate metal and filler wire (wt.%).

C	Si	Mn	S	Mg	Cr	Ni	Mo
0.2310	1.9180	1.6510	0.0120	0.0005	1.2940	0.3600	0.4330
Cu	Ti	V	Nb	W	Co	Zr	B
0.1100	0.0890	0.0100	0.0030	0.0400	0.0220	0.0010	0.0004

Fig. 3 shows the schematic diagram of the HDMR process, and it was performed on a custom-made flat rolling rig, with the supply of a SAF•FRO DIGI@WAVE™ 280 metal inert gas (MIG) welding machine. Moreover, a three-axis computer numerical control (CNC) machine was used for the motion platform, whereas the industrial personal computer (IPC) was to process the signals. The roller moves with the torch, and rolls on the surfaces of the samples according to the prescribed trajectory based on the arc striking signal. Therefore, metal samples would be fabricated by the deposition led by hot rolling immediately because of the short distance between torch and roller, and the rolling force can be modified by the force sensor located between the screw rod and the roller rack.

To understand the different microstructures and properties between the WAAM and HDMR, three kinds of samples with approximately 80 mm length have been prepared, they are single-pass single-layer (Fig. 4), single-pass multi-layer, and multi-pass multi-layer. All samples were produced in similar welding process and deposited on rolled structural substrates with dimensions 100 mm × 40 mm × 10 mm. Before the deposition process, the substrate surfaces were preheated to 250 °C and ground to remove oxide scales and rusts. The sample temperature was allowed to reduce below 250 °C but not less than 200 °C before the new layer was deposited. To achieve the quick and stable clamp, the bench clamp has been used. The original welding conditions for the WAAM and HDMR were listed in Table 2.

2.2. Thermo-simulation compression experiment

To reveal the connection between the HDMR process and the