International Journal of Pressure Vessels and Piping 209 (2024) 105171

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Microstructure, mechanical properties, and corrosion behaviour of wire arc additive manufactured martensitic stainless steel 410 for pressure vessel applications

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ARTICLE INFO

Keywords:
WAAM
Martensitic stainless steel
Welding
Microstructure
Mechanical properties
Corrosion

ABSTRACT

High-strength martensitic stainless steel 410 (MSS 410) was successfully fabricated without defects via wire arc additive manufacturing (WAAM). The microstructural features, mechanical properties, and corrosion performance of WAAM-processed MSS 410 were examined. Microstructural analysis revealed the existence of equiaxed and coarse columnar dendrites and the formation of residual delta-ferrite and retained-austenite (RA) was confirmed within the martensitic matrix. The fraction of residual ferrite and RA varied along the building direction due to complex thermal cycles. Uni-axial tensile results exhibited anisotropic behavior and are related to layered microstructure. Microhardness values varied from bottom to top (384–460 HV). Ductile mode of failure was noticed, and the existence of RA influences the ductility. The corrosion behaviour of the WAAM 410 specimens in 3.5% NaCl solution was considerably acceptable, and the corrosion rate ranged between 0.05 and 1.37 mpy. This shall be attributed to the absence of defects, microstructural features, and ferrite fraction in the WAAM 410 samples. The mechanical properties and corrosion behaviour of the WAAM 410 were comparable to the wrought grade and are suitable for pressure vessel applications with adequate corrosion resistance.

1. Introduction

Martensitic stainless steels (MSS) are chromium stainless steels with a low carbon content, higher chromium concentration, and a body-centered cubic crystallographic structure. MSS are generally employed in automotive components, turbine blades, hydro-turbines, cutting tools, cutlery, valve parts, bearings, razors, offshore platforms, surgical, and dental instruments because of their combined corrosion resistance and mechanical properties [1,2]. MSS primarily comprises tempered martensite, retained austenite (RA), delta-ferrite, and carbides in the martensitic matrix [3]. The microstructure of MSS is metallurgically complex, and appropriate heat treatment should be carried out to obtain a fully martensitic structure by avoiding the formation of RA, and delta-ferrite. MSS parts can be manufactured with additive manufacturing (AM) process, and it offers great potential in fabricating new parts and restoring service-exposed components with difficult-to-machine materials. AM is a promising manufacturing technology for achieving custom-made and tailored near-net-shaped components with less secondary machining in various industrial sectors, including marine, energy, aerospace, transportation, and chemical processing plants [4,5]. MSS is preferred for applications requiring mild corrosion resistance and higher mechanical properties. MSS has been fabricated with AM processes such as laser powder-bed fusion, laser-engineered net-shaping, and wire arc additive manufacturing (WAAM) [6]. The residual stress, dendritic microstructure, and defects considerably decrease mechanical properties. The AM-processed MSS, on the other hand, is more susceptible to localized pitting corrosion because various microstructural flaws, including pores and non-metallic inclusions, frequently serve as pathways for erosive anions to deplete the metal ions [7]. These problems have prevented AM processed MSS parts

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https://doi.org/10.1016/j.ijpvp.2024.105171
Received 27 November 2023; Received in revised form 1 March 2024; Accepted 11 March 2024
Available online 12 March 2024
0308-0161/

from reaching their maximum development. WAAM has drawn broad interest from industries in manufacturing medium-to-large metallic structures because of its production flexibility, unrestricted deposition capability, higher deposition rate, comparatively lower cost, and eco-friendliness [8–10]. WAAM's higher deposition rates make it ideal for printing large components and have become one of the most effective alternatives for the current hybrid metal AM approaches [11,7]. Li et al. [12] reported that the scale and features of the WAAM process could provide a thermal environment sufficient for the nucleation of equiaxed grains during solidification. Gas metal arc welding (GMAW) is widely preferred for manufacturing near-net-shaped structures because of simple equipment, higher deposition rate, and reduced forming ability.

In rough working environments like steam turbines, MSS 410 (AISI 410) is a preferred material for fabricating turbine blades & blisks, and these high-value blades are subjected to different damages like wear, mis-machining, corrosion, and fatigue [13]. As an integral part of the turbine, the production time and cost are very high with MSS. In this regard, the WAAM process is an alternative to reducing manufacturing costs by repairing the damaged part. The damaged part should be pre-processed to deposit or refill the material in a layer-by-layer pattern with the same or different filler materials to improve the component life. If the consistency of the AM based repair or remanufacturing process is approved, then the remaining component life can be successfully increased with a considerable reduction in manufacturing cost. GMAW-based WAAM process can be used as a remanufacturing technique due to its lower operational cost, easy adaptability by the shop floor workers, and its use for welding different materials. Vishnukumar et al. [14] reported the feasibility of using the WAAM process as a repairing technique to restore marine components made of AA5052 with ER4043 filler material. The corrosion rate of WAAM printed 4043 specimens was in the range of 0.18–0.20 mm/year compared to wrought AA5052 (0.19–0.21 mm/year). Lee et al. [15] repaired a damaged cross slide using the WAAM process by making a flat slot followed by the deposition of ERNi-1 filler wire. Priarone et al. [16] established a remanufacturing procedure to repair an H13 steel mold insert for casting aluminium alloys via the WAAM process using H13 filler material and performed carbon footprint savings and life-cycle energy analysis.

In contrast to the present work, there are few works on the fabrication of MSS via the WAAM process. Ghaffari et al. [17] examined the microstructure and mechanical properties of WAAM-processed PH 13–8Mo MSS. They reported the presence of lathy and vermicular residual δ-ferrite within the martensitic matrix, along with a small amount of RA. Zou et al. [18] developed a super-MSS with less carbon content ($\leq$0.04%) and reported the enhancement of tensile properties in heat-treated specimens due to grain refinement along with an increase in austenite (10%). Ge et al. [19] fabricated the MSS 420 (2Cr13) part and reported the existence of elongated ferrite dendrites and equiaxed acicular martensite within the matrix, while tensile strength was higher with reduced ductility. Lyu et al. [20] studied the effect of post-tempering on the microstructure and mechanical properties of WAAM-processed MSS 420. In addition, reported that a tempering at 600 °C eliminated anisotropy with comparable microstructure and mechanical properties to that of wrought counterparts. Ghaffari et al. [21] examined the metallurgical bonding at the interface between wrought MSS and WAAM processed MSS 420 part. Also, reported a higher volume fraction of carbides in heat affected zone and a higher fraction of retained austenite (RA) in the fusion zone within the martensitic matrix. Zhu et al. [22] fabricated an SS410 wall having considerable mechanical properties along with 100% evenly distributed martensite, and the absence of δ-ferrite was confirmed. Singh et al. [23] optimized the WAAM process parameters using Analysis of Variance (ANOVA) and response surface methodology (RSM) techniques by considering the wire feed speed, welding speed, and gas flow rate. The produced wall comprised martensite and δ-ferrite, while comparable tensile properties were obtained compared to the wrought SS410 alloy. Subramanian et al. [24] performed optimization studies for fabricating SS420 alloy via WAAM by controlling parameters such as welding current, arc voltage, and welding speed using RSM. Also, examined the effect of process variables on the weld bead geometry. MSS components can be successfully deposited using GMAW with less or no pores and cracks due to its lower fraction of carbon. This research investigates the microstructural features, mechanical properties, and localized corrosion performance of MSS 410 produced with GMAW-based WAAM. The current work's outcomes will help demonstrate how effective WAAM technology is for producing MSS components.

2. Materials and methods

A commercial MSS feedstock, ER410, having a 1.2 mm diameter conforming to AWS A5.9/ASME SFA 5.9 standard and AISI 316L substrate having a size of 360(L) × 50(W) × 10(H) mm was employed for fabricating the wall. The nominal composition of the feedstock material in weight percentage is presented in Table 1. The wall component was manufactured using an OTC Daihen robotic welding system with a Welbee P500L power source. The total number of layers was 64, and the deposition path was alternated. Manual programming was done with the help of a teach pendant. Each deposited layer has a height of approximately 2.5 mm. Initially, iterative trials were carried out to determine the process parameter range, and the optimal process parameters for wall fabrication were identified with the help of macrographs from single-layered weld bead trials (refer to Table 2). The heat input was calculated using the guidelines mentioned in ISO/TR 18491:2015 and ISO/TR 17671–1:2002 standards. As per ISO/TR 17671–1:2002, the efficiency of the GMAW process is 0.8. The interpass temperature of 200 °C was maintained to avoid the formation of cracks and was monitored with the help of an Amprobe IR-750 infrared thermometer, while the dwell time varied between 30 and 90 s.

The size of the fabricated wall before and after face milling were 315 × 160 × 8 mm (L × H × W) and 300 × 150 × 6 mm, respectively. The samples for microstructural analysis were sectioned from the top, middle, and bottom regions along the building direction (BD), followed by electrolytic etching with 15 vol% HCl, 80 vol% H_2O, and 5 vol% HNO_3. Microstructural features and elemental distribution were analyzed with electron back-scattered diffraction (EBSD) and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) attachment. Microhardness mapping was subjected to an applied load of 500 g and a dwell time of 10s with Struers Duramin-4 Vickers Hardness Tester in accordance with ASTM E92-17 standard. A total of 30 readings were taken and the distance between adjacent indentations is 0.5 mm. The samples for uni-axial tensile test were prepared from horizontal (WAAM 410-HD) and vertical direction (WAAM 410-VD) along the BD using wire-electric discharge machining. Sub-sized specimens having an overall length of 100 mm, grip section width of 10 mm, gauge length and width of 25 mm and 6 mm, respectively was considered as mentioned in ASTM E8/E8M − 22 standard. Tensile tests were repeated thrice with a 1 mm/min loading rate using an Instron 8801 Servo Hydraulic testing system at room temperature. SEM was employed to examine the fractured surfaces of tensile-tested specimens.

Potentiodynamic polarization (PDP) tests were performed to evaluate the electrochemical behavior of WAAM 410 specimens from top, middle, and bottom regions in aerated 3.5 wt% NaCl solution at room temperature. PDP was performed under a scan rate of 1.33 mV/s starting from −1.5 to 1.5 V. A classical three-electrode cell system was employed, and the tests were performed thrice to verify the repeatability and to average the corrosion results. A platinum plate was used as the counter-electrode, saturated calomel electrode (SCE) served as the reference electrode, and the working electrode was the WAAM 410 sample. SEM and EDS were utilized for examining the corroded specimens to understand the pit morphologies in WAAM 410 specimens.