Hybrid/tandem laser-arc welding of thick low carbon martensitic stainless steel plates for hydraulic turbines application

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HYBRID/TANDEM LASER-ARC WELDING OF THICK LOW CARBON MARTENSITIC STAINLESS STEEL PLATES FOR HYDRAULIC TURBINES APPLICATION

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ABSTRACT

The main objective of this research work was to understand the different challenges related to hybrid laser-arc welding (HLAW) of thick gauge section assemblies of low carbon 13%Cr-4%Ni martensitic stainless steel and develop a practical solution by adapting and optimizing this relatively new welding process in order to attain higher processing efficiency through a reduction in the number of welding passes necessary to fill the groove gap. Also a special focus was given to the development of the hybrid and tandem laser-arc welding techniques for the root pass. In this study, the processing methodology using the hybrid/tandem laser-arc welding technology was also adapted based on the thickness of the low carbon martensitic stainless steel plates, namely a single pass HLAW process for a 10-mm thick section and a multi-pass hybrid/tandem laser-arc welding process for a 25-mm thick section. After welding, the joint integrity was evaluated in terms of microstructure, defects and mechanical properties in both the as-welded and post-weld tempered conditions. The effect of different welding speeds on the as-welded joint integrity of the 10-mm thick and 25-mm thick assemblies was characterized in terms of the weld bead geometry, defects, microstructure, hardness, ultimate tensile strength and impact energy. Significant defects such as porosity, root humping, underfill and excessive penetration were observed at a low welding speed of 0.5 m/min. However the welds met the specifications of ISO 12932 at a speed higher than 0.75 m/min. The ultimate tensile strength and Charpy impact energy values of the fully penetrated welds in the tempered condition were acceptable according to ASTM, ASME and industrial specifications, which show good potential for introducing hybrid/tandem laser-arc welding technology for the manufacturing of next generation hydroelectric turbine components.

KEYWORDS

Hybrid/tandem laser-arc welding, Low carbon martensitic stainless steel, Microstructure, Mechanical properties, Post-weld heat treatment

INTRODUCTION

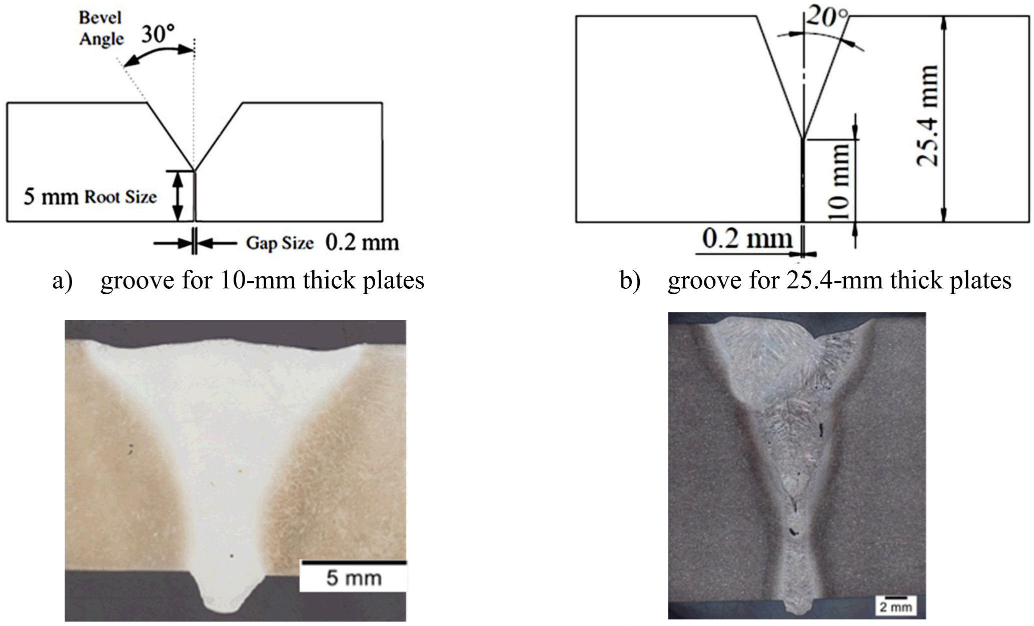
Hydroelectric turbine components are made of thick-walled low carbon martensitic stainless steels. The critical component in hydroelectric turbine systems requires weld assembly between the subcomponents such as the crown, band and blades. The quality of joint assemblies has an important effect on the efficiency and long-term life expectancy of hydraulic turbines. The assembly of large hydroelectric turbine components remains a great challenge and typically involves conventional welding processes and the use of a large groove design with multi-pass welding to fill the groove; this exposes the weld to a high heat input that creates a relatively large fusion zone and several heat affected zones, which distort the assembly and necessitate post-weld re-working to meet the final geometric requirements. As reported by Cao, Wanjara, Huang, Munro, and Nolting (2011) and Bagger and Olsen (2005), the application of a newly-developed hybrid/tandem laser-arc welding technology shows promise as a highly competitive solution to improve the overall hydro-electric turbine performance by combining the high energy density, fast welding speed and narrow heat affected zone characteristics of the laser welding technology with the good gap bridging and filler material feeding ability of the gas metal arc welding (GMAW) process. This technology also enables synergies between the laser and arc that lead to increased productivity and reductions in the consumable material requirements. To date, low carbon 13%Cr-4%Ni martensitic stainless steels, such as grade CA6NM, are mainly used to manufacture hydraulic turbine components, such as turbine runners and guide vanes. For the majority of the assembly and repair work on these relatively large turbine components, conventional fusion welding processes, such as GMAW, are commonly applied presently. However, these conventional arc welding processes involve several welding passes to fill the wide groove and, thus, high heat input, which increases distortion and generates large fusion and heat affected zones. Coupling a laser with arc welding, HLAW (hybrid laser-arc welding) is a relatively low heat input joining technology that combines the synergistic qualities of the high energy density laser beam for deep penetration at high welding speeds with the arc's tolerance for a wide fit-up gap via wire feeding. In the present study, HLAW was applied to butt weld 10-mm and 25-mm thick CA6NM stainless steel plates. The weld geometry, microstructures, and microhardness evolution across the weldment were investigated in the as-welded and post-weld tempered conditions. The ultimate tensile strength and toughness (Charpy impact energy) properties of the joints were also evaluated

EXPERIMENTATION

The 10-mm and 25.4-mm thick CA6NM plates were prepared to form a Y-groove shape butt joint, as shown in Figure 1(a-b). AWS ER410NiMo filler wire with a diameter of 1.14 mm was used for the HLAW trials. A Fronius Trans Pulse Synergic 4000 CMT GMAW power supply was coupled with a IPG photonics 5.2 kW solid-state Yb-fiber. A laser travel speed of 1 m/min was selected as the optimum travel speed. The wire feed speed was adjusted to fill the groove using a single pass for the 10-mm thick joint and five passes for 25.4-mm thick joint. More experimental details related to these welding trials and evaluation of the joints are provided in Mirakhorli, Cao, Pham, Wanjara and Fihey (2016a) as well as Mirakhorli, Cao, Pham, Wanjara and Fihey (2017a).

RESULTS AND DISCUSSION

The weld cross sections after welding are displayed in Figure 1 (c-d). The weld microstructure and microhardness in the as-welded and post-weld heat treated (PWHTed) conditions are displayed in Figure 2. In the as-welded condition, the microstructure consisted of untempered martensite and residual delta ferrite in the fusion zone. This microstructure after post-weld tempering transformed to tempered martensite and retained austenite, which led to a reduction in the microhardness in all regions of the weld, including the fusion zone (FZ), heat affected zones (HAZs) and base metal (BM). The average ultimate tensile strength value for all the welds was 859 MPa. Considering that the minimum ultimate tensile strength requirement in ASTM A743 standard is 755 MPa for CA6NM, the hybrid laser-arc welds in the post-weld tempered condition met quite sufficiently the specification. The Charpy impact energy value of the joints after post-weld tempering was 45 J, while the minimum requirement according to ASME Sect. VIII, Div.1 and industrial hydraulic turbine manufacturing specifications is 27 J and 34 J, respectively. Therefore, all welds exhibited higher Charpy impact energies than the minimum requirements at 255 K (-18 °C). A more detailed description of the microstructural transformations, mechanical properties and fracture surface characteristics are given in Mirakhorli, Cao, Pham, Wanjara and Fihey (2016a-b) as well as Mirakhorli, Cao, Pham, Wanjara and Fihey (2017a-b).



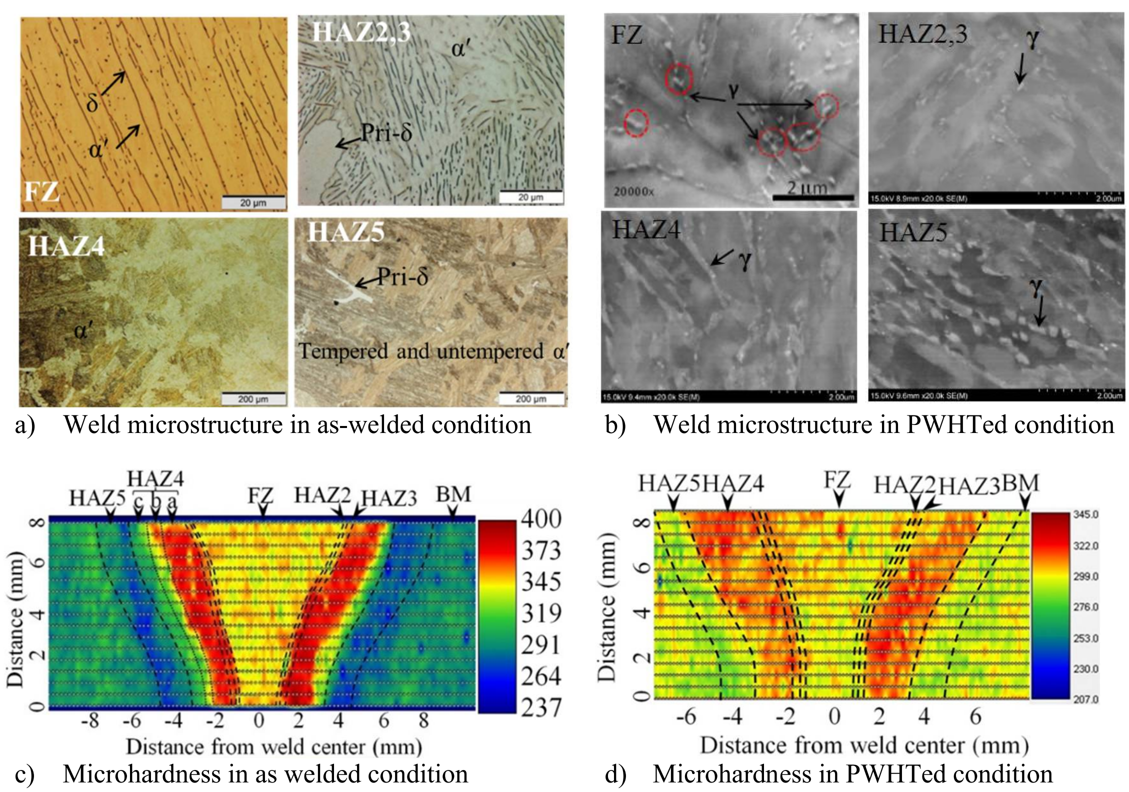
a) groove for 10-mm thick plates

b) groove for 25.4-mm thick plates

c) 10-mm thick weld cross section

d) 25.4-mm thick weld cross section

Figure 1. Groove design and weld cross sections for the two plate thicknesses



a) Weld microstructure in as-welded condition

b) Weld microstructure in PWHTed condition

c) Microhardness in as welded condition

d) Microhardness in PWHTed condition

Figure 2. Microstructure and microhardness in as-welded and post-weld tempered conditions

CONCLUSIONS

This research study involved hybrid laser-arc welding of thick martensitic stainless steels, as applied in hydro-electric turbine manufacturing. The fusion zone microstructure in the as-welded condition consists of untempered lath martensite and residual delta ferrite with different morphology. After post-weld tempering at 600 °C, the untempered martensite changed to tempered martensite in the fusion zone accompanied with the formation of reversed austenite and chromium carbides. After post-weld tempering, the microhardness in both the fusion zone and heat affected zones was reduced. The fusion zone experienced a reduction in microhardness from ~354 HV (as-welded condition) to ~309 HV (in post-weld tempered condition). The ultimate tensile strength both in as-welded (950 MPa) and post-weld tempered (850 MPa) conditions met the minimum requirement of 755 MPa according to the ASTM A743 specification. The Charpy impact energy values were significantly enhanced in the post-weld tempered (45.5 J) condition compared to the as-welded (28.5 J) condition.

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REFERENCES

Cao, X., Wanjara, P., Huang, J., Munro, C. and Nolting, A. (2011). Hybrid fiber laser–arc welding of thick section high strength low alloy steel. *Materials & Design, 32*(6), 3399-3413. https://doi.org/10.1016/j.matdes.2011.02.002

Bagger, C. and Olsen, F. O. (2005). Review of laser hybrid welding. *Journal of laser applications, 17*, 2-14. https://doi.org/10.2351/1.1848532

Mirakhorli, F., Cao, X., Pham, X.-T., Wanjara, P. and Fihey, J.-L. (2016a). Hybrid laser-arc welding of 10-mm thick cast martensitic stainless steel CA6NM: as-welded microstructure and mechanical properties. *Metallurgical and Materials Transaction A*, *47*(7), 3545–3563. https://doi.org.10.1007/s11661-016-3523-6

Mirakhorli, F., Cao, X., Pham, X.-T., Wanjara, P. and Fihey, J.-L. (2016b). Post-weld tempered microstructure and mechanical properties of hybrid laser-arc welded cast martensitic stainless steel CA6NM. *Metallurgical and Materials Transaction B*, *47*, 3245-3256. https://doi.org.10.1007/s11663-015-0578-5

Mirakhorli, F., Cao, X., Pham, X.-T., Wanjara, P. and Fihey, J.-L. (2017a). Technical challenges in narrow-gap root pass welding during tandem and hybrid laser-arc welding of a thick martensitic stainless steel. *Materials Science Forum*, *879*, 1305-1310, https://doi.org/10.4028/www.scientific.net/MSF.879.1305

Mirakhorli, F., Cao, X., Pham, X.-T., Wanjara, P. and Fihey, J.-L. (2017b). Phase structures and morphologies of tempered CA6NM stainless steel welded by hybrid laser-arc process, *Materials Characterization*, *123*, 264–274, dx.doi.org/10.1016/j.matchar.2016.10.029, JA-SMM-2016-0064.