High-strength steel S960QC welded with rare earth nanoparticle coated filler wire

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Abstract

High-strength steel S960 is one of a number of advanced steels able to meet the demands of the shipbuilding, offshore, and construction industries for a favorable good high strength/weight ratio. Gas metal arc welding (GMAW) is commonly used in all structural steel fabrication, and developments in GMAW have removed previous limitations regarding high heat input and have reduced flaws. One solution for controlled heat input while ensuring a stable arc is alloying the welding wire. Usage of nanoparticles as an alloying element in welding wire have shown significant improvements in weld properties. This study investigates an S960QC joint welded with a welding wire having Lanthanum (La) nanoparticles as a coating and examines the influence of La on the welding parameters, arc stability, microstructure formation, and mechanical properties. The results are compared with a weld formed with conventional Union X96 welding wire. The microstructures observed in the weld region were martensite and tempered martensite for both wires. In the heat-affected zone, microstructures of upper bainite, martensite, tempered martensite, and globular bainite were found. The La nanoparticle-coated wire provided a stable arc during welding. However, due to the increase in wire thickness, manual wire feeding was required. The impact toughness was lower in the joint formed with the nanoparticle-coated wire. Additionally, the hardness at the fusion region was higher in the joint welded with the nanoparticle-coated wire.

Keywords High strength steel S960QC · LaB₆ nanoparticle coated filler wire · Robotic GMAW · SEM · Impact toughness

1 Introduction

Fabrication industries are challenged by demands for efficient construction of buildings and infrastructure, offshore platform structures, and high-performance ships and vessel, and a need for product diversification to provide products suitable for harsh and unpredictable environments. Thus far, conventional steels (i.e., steels with yield strength ≤ 300 N/mm²) have not been able to attain the mechanical properties and corrosion resistance required for high-performance ships and structures. To partly address the non-optimal properties of conventional steels, special coatings have been used with steels for harsh

environment, which affects the economic viability of structures made with such steels [1–4].

In recent decades, the steel manufacturing industry has developed upgraded steels such as high-strength steels (HSS) and advanced high-strength steel (AHSS), which have considerably enhanced mechanical properties compared to conventional steels. S960QC steel is a thermo-mechanically processed ferrite structural steel with a yield strength of 960 MPa. The steel is manufactured with direct quenching and is cold formable. S960QC has an excellent combination of toughness and strength, a high strength/weight ratio, and good weldability and machinability, thus meeting key demands of the shipbuilding and offshore industries. Studies have suggested that, without losing structural integrity, construction costs can be reduced by significant reduction in thickness (i.e., 60% thickness reduction) resulting from the improved strength of S960 steel relative to S355 steels [5, 6]. Its good mechanical properties make S960QC steel suitable for many applications in production of pressure vessel components; transportation pipes for the oil, gas, and automobile industries; heavy duty machinery; offshore structures; and shipbuilding [7, 8].

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Fig. 1 Tensile strength reduction in the joint by increased heat input from GMAW process

Although possessing good mechanical properties, some research has suggested that temperature increase during fabrication and heat treatments can reduce the mechanical properties of S960 steels [9, 10]. Consequently, caution is required when welding S960 steels.

GMAW is the most commonly used welding process in the construction of ships, maritime constructions, and offshore platforms, and GMAW is used for structures both above and below water. Traditional GMAW results in a reduction in the mechanical properties of the weld relative to the base metal due to the high heat input. For instance, the high heat input of traditional GMAW processes leads to an increase in the cooling rate and, therefore, softening of the heat-affected zone and lower joint strength [7, 11]. Research has shown that HSS welded by GMAW has significantly reduced mechanical properties in the joint than HSS welded with laser and other welding processes [12]. For example, HSS such as S960, TRIP 900 steel, martensitic DOCOL 1200 steel, and dual-phase steel (DP780) welded by GMAW had broad softening in the fusion zone and heat-affected zone leading to an increase in joint hardness and reduction in tensile strength, whereas joints formed by laser and gas tungsten arc welding (GTAW) had approximately the same mechanical properties as the base metal [12–14]. However, defect formation such as porosity and cracking on thick plates is greater in single pass laser welding and there are difficulties using laser welding offshore and in the shipbuilding industry. In addition to fusion welding processes, research has examined friction stir welding of high-strength steels and aluminum alloys with

incorporation of nanoparticles during welding for improvement of the mechanical properties of the joint [15, 16]. For example, Mirjavadi et al., [17, 18] showed improvement in tensile strength and wear resistance by friction stir welding of AA5083 alloy with TiO_2 and ZrO_2 nanoparticles compared to a joint without nanoparticle addition. These improvements occurred due to reduced grain size and a dislocation strengthening mechanism. The refractory nanoparticle oxide ZrO_2 caused more pinning effects resulting in more refined grain size as well as improved tensile strength with multi-pass welding. However, the hardness increased and the wear resistance decreased significantly with increase in the weld passes because of the load bearing effect of zirconia nanoparticles. In the case of high-strength steels, the friction stir welded joints resulted in high hardness by transforming austenite formation into martensite and upper bainite formation when using high tool rotation speed. Low tool rotational resulted in incomplete consolidation [19]. Moreover, tool wear increases when welding steels with friction stir welding [20].

Recent developments in GMAW welding processes have helped overcome some limitations and have reduced the prevalence of defect formation and flaws compared to traditional GMAW welding methods. For example, modern welding techniques such as pulsed mode, spray metal transfer mode, globular transfer mode, and adaptive welding techniques have improved uniformity and precision in welding performances thereby improving joint properties and reducing joint flaws. Moreover, the usage of robots and adaptive welding methods have improved consistency of weld bead formation and

Table 1 Chemical composition and mechanical properties of S960QC (Wt.%)

C < 0.2	Si < 0.8	Mn < 1.7	Cr < 1.5	Mo < 0.7	Ni < 2.0	Al 0.03	V < 0.12
Cu < 0.5	B < 0.005	P ≤ 0.02	S ≤ 0.01	Zr ≤ 0.15	N ≤ 0.015	Ti < 0.05	Nb < 0.06
Yield strength $R_{p0.2}$ (MPa)			Tensile strength R_m (MPa)			Elongation (%)	
960			980–1250			< 7	

Fig. 2 Schematic of weld groove for S960QC with dimensions (sizes are in mm)

productivity, as well as ease of transportation [21–23]. To obtain flawless joints of thick HSS plates by GMAW, the composition of the base metal and welding wire and the welding parameters have to be carefully considered. Moreover, the weld metal should have low hydrogen content (i.e., hydrogen ≤ 5 ml/100 g) when welding with welding wire, which increases resistance against cold cracking. The welding wire plays a critical role in determining joint strength, and selection of welding wire for S960 high-strength steels can be matching or under matching wire depending on the joint application. Offshore and shipbuilding applications require weld joints with the same properties as the base metal. Union X96 wire has matching properties for S960QC and has good deformability and good resistance to cold cracking, and Union X96 has been widely used in the crane industries and other heavy industries [24–26].

Research conducted on welding S960QC with Union X96 welding wire has found reduction in tensile strength and impact strength within the range of 720 to 810 Mpa. The reduction in tensile and impact strength at the

joint is due to heat input from the GMAW process, as can be seen from Fig. 1 [27]. Similar effects have been found for joints made with laser welding and laser-arc hybrid welding processes [27]. The high heat input from the GMAW process increases the cooling rate, resulting in changes in the microstructural phase and a reduction in mechanical properties at the HAZ region.

The addition of alloying elements in the welding wire is one approach to address heat input limitations and maintain arc stability [28]. Studies suggest that nanoparticles in the welding wire and coating on the weld bead can have significant benefit for the weld joint qualities [29, 30]. There are various ways of introducing nanomaterials into welding processes, for example, as coating on the welding wire, in the form of a composite flux cored wire, as coating on the weld groove, and by injecting nanoparticles in the shielding gas [29–31]. Research has indicated that nanoparticle coating on the welding wire can bring considerable benefits compared to conventional welding wire [32]. For example, Mohan et al. [33] showed that an electrode coated with TiO₂ particles

Table 2 Chemical composition of the Union X96 welding wire (Wt.%)

C ≤ 0.13	Si 0.5–0.8	Mn 1.6–2.1	Ni 2.3–2.8	Cr 0.2–0.6	Mo 0.3–0.65	Cu ≤ 0.3
V ≤ 0.03	P < 0.015	S < 0.018	Ti ≤ 0.10	Zr ≤ 0.10	Al ≤ 0.12	

Fig. 3 **a** Schematic diagram and **b** overview of the electrode coating process setup [41]

Table 3 Chemical composition of different zones of the nanoparticle coated welding wire

ELEMENTS (Weight in %)	Zone 1 (Cross-section)	Zone 2 (Surface)	Zone 3 (Surface)

C	3.9	5.0	22.4 - 25.4
Al	0.3	1.2	1.8
Si	1.0	-	-
Cr	0.4	-	-
Mn	2.1	-	-
Fe	90.0	5.7	3.5 - 4.1
Ni	1.8	87.1	18.0 - 61.9
Mo	0.6	-	-
O	-	1.0	1.4 - 1.5
B	-	-	4.7 - 16.5
F	-	-	0.5 - 3.5
La	-	-	3.3 - 31.3

reduced welding fumes and improved penetration depth as well as resulting in fine grain microstructure and better mechanical properties than with an uncoated commercial welding wire. The presence of nano-powders such as Al_2O_3 , Ti, and W in welding electrodes has also been found to give beneficial results as regards weld formation and the

mechanical properties of the joint [34, 35]. Some research has, however, suggested that nanoparticle inclusion in the weld through electrode coating reduces properties such as tensile strength, impact strength, corrosion resistance, and hardness [31]. The type, quantity, and dispersion method of the nanoparticles have to be carefully considered, and

Table 4 Welding parameters for S960QC with conventional and LaB_6 nanocoated welding wire

Parameters	Experiment 1 (conventional wire)	Experiment 2 (wire with nanoparticle coating)
Current (A)	208	177
Voltage (V)	24	26
Shielding gas	92% Ar and 8% CO_2	
Shielding gas consumption (l/min)	18.93	18.9
Welding wire feed rate (m/min)	9.26	7.81
Welding time (s)	25.84	39.68

selections made should ensure compatibility with the base metal and filler metal composition. For example, Fattahi et al. [29] showed that selection of nanoparticles based on the base metal and filler wire and with a nominal quantity of TiO_2 nanomaterials as an electrode coating resulted in better impact toughness and tensile strength, as well as consistent hardness without softening in the HAZ region, in comparison with welds formed with low and high quantities of TiO_2 nanoparticles as coating on the electrode.

For the nanoparticle selection, refractory element addition such as W, Nb, Zr, Ti has been suggested, which provides an improvement in mechanical properties through the effect of the high temperature strengthening mechanism. Moreover, the usage of refractory nanoparticle elements as surfactant and coating has been found to improve the nucleation ratio in the weld microstructure and reduced surface tension [31, 35, 36]. LaB_6 refractory compounds have a high melting point (2210 °C) and good dispersion and provide good electrical and thermal conductivity with low electron work function as well as having better mechanical properties (high strength and high hardness) than refractory oxide elements [37, 38]. LaB_6 has been used in electron beam welding for its good thermal stability and reduce the carbide formation [38]. Research has shown that the usage of Ce and La as refractory compounds improves hardness, thermal shock resistance, and impact strength through grain refinement and the pinning effect of refractory compounds [13, 34, 39, 40].

This study investigates and compares the properties and microstructural formation of weld joints formed using a conventional Union X96 welding wire and LaB_6 nanoparticle-coated Union X96 welding wire. It is hypothesized that the LaB_6 nanoparticle-coated wire is considered to improve the arc stability and weld properties by the effect of its physical properties on droplet transfer and grain refinement during the

recrystallization process. The research also considers the influence of LaB_6 nanoparticle-coated welding wire on welding parameters and microstructure formation and their corresponding effect on weld properties.

2 Experimental

2.1 Material and groove preparation

The chemical composition and mechanical properties of the S960QC steel base metal is shown in Table 1.

Joint design and groove configuration for 5-mm thickness S960QC HSS plates with specimen size of 230×200 welded by robotic welding are shown in Fig. 2. The GMA robotized welding process was carried out with ceramic backing to avoid joint distortion.

2.2 Welding wire

The chemical composition of the Union X96 (i.e., without nanoparticle coating) filler wire is shown in Table 2. The Union X-96 wire diameter is 1 mm.

Coating of the LaB_6 nanocoated welding wire was performed by electrolytic process, and the coating thickness of the LaB_6 nanoparticles on the welding wire was 15 μm . Layus et al. [41] describe the process for nanocoating the Union X96 wire (8)(10) through a series of containers. The first container, (1) in Fig. 3, contains a cleaning solution of white spirit, sulfuric acid, and sodium salt to cleanse and degrease the wire. In the second container (2), the nanoparticle LaB_6 is deposited on the wire by electrolytic process with a nickel electrode as the cathode, the Union X96 welding wire as the anode, and a water-based electrolytic solution with 50% of $\text{Ni}(\text{BF}_4)_2 \cdot 6\text{H}_2\text{O}$, 4% H_3BO_3 , and

Fig. 4 Schematic representation of the robotic GMAW process for welding S960QC

5% LaB₆. To maintain the temperature at 70 °C and for homogeneous distribution of LaB₆ nanoparticles in the solution, a mixer (11) and heater (7) are placed in the container (2). The last container consists of distilled water to cool down the coated wire.

The nanocoated wire is dried in a drying oven (4), and thermocouples (6) are used to measure the temperature of container (2) and during drying in the oven. As the wire requires winding after the nanocoating, winding to a spool (8) was performed by a motor mechanism (9) with a speed of 3.5 rpm. A schematic diagram and overview of the coating setup is shown in Fig. 3, and the chemical composition of the nanoparticle-coated welding wire is given in Tables 3. To

verify the dispersion of nanoparticles, three different regions on the welding wire were analyzed.

2.3 Welding set-up

The GMAW process was performed by a welding robot consisting of the equipment given below:

- Robot manipulator and robot controller
- Welding torch for the GMAW process and a power supply system
- Wire feeder and wire feed sensor

Fig. 5 Welding parameter with conventional welding wire (Union X96): **a** current, **b** temperature, and **c** voltage, feed rate, and gas consumption in welding of S960QC

- Laser sensors and thermoprofile sensor in the robotic welding head
- Process sensor with current/voltage measurement and an oscilloscope
- Gas sensor
- Data acquisition and control unit connected with a computer.

A schematic diagram of the GMAW process is shown in Fig. 4.

Fig. 6 Welding parameter with La nanocoated welding wire: **a** current, **b** temperature, and **c** voltage, feed rate, and gas consumption in welding of S960QC

2.4 Welding parameters

Three tests were conducted to compare weld joints formed using the conventional Union X96 welding wire and nanoparticle-coated Union X96 welding wire. Welding parameters for the tests are shown in Table 4. The nanoparticle-coated welding wire required manual feeding of the wire due to increase in the thickness of the welding wire resulting from the nanoparticle coating and instability through the welding tip.

Fig. 7 Current and voltage for selected periods for the nanoparticle-coated welding wire. **a** Stable arc during welding. **b** Unstable arc at the start of welding

Fig. 8 Current and voltage for selected periods for the conventional welding wire (Union X96). **a** Stable arc during welding. **b** Unstable arc at the start of welding

2.5 Observation and testing equipment

Energy-dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM) were used to examine the chemical composition of the weld joint, fusion line, and heat-affected zone. The specimens were cut, polished, and etched with a solution of 8% hydro-fluorine and 4% nitric acid and ethanol prior to examination of the microstructure. An oscilloscope, thermoprofile scanner, and process sensor were used to measure and record the current, voltage, temperature, shielding gas consumption, and wire feed rate while welding the S960QC plate.

To evaluate the mechanical properties and strength of the joint, hardness and impact strength were measured with a Vickers hardness test and Charpy pendulum impact test, respectively, according to ISO 6507-1:2018 and ISO 148-1:2016. For the impact test, the specimens were prepared in sub-size test piece with 5 mm from the weld metal (WM) of the joint. The impact energy value for the sub-size and full-size specimen are same till 100 J/cm and the difference in value for the specimen changes from the 100 J.

3 Results and discussion

>The chemical composition of the LaB₆ nanoparticle-coated welding wire given in Table 3 shows that the La and B have been well deposited on the welding wire. Moreover, the La, C, and Ni content is greater at the surface of the nanoparticle-coated welding wire compared to the conventional X96 welding wire.

3.1 Welding parameters

Voltage, current, temperature, shielding gas consumption, and welding wire feed rate for the conventional Union X96 welding wire are shown in Fig. 5 and for the LaB₆ nanoparticle-coated welding wire in Fig. 6.

The temperature graphs in Figs. 5b and 6b show that the nanoparticle-coated welding wire had a high peak temperature unlike the conventional welding wire. This could be due to high heat energy at the arc. The La nanoparticles reduce the electron work function as LaB₆ tends to form only covalent bonds, thereby giving increased heat energy [42].

Fig. 9 SEM microstructure of the joint formed by conventional wire. **a** Fusion line. **b** Formation of M, TM, B in the CGHAZ. **c** M formation in the weld. **d** Magnification of formation of M and Bu in the CGHAZ.

(symbols: M martensite, TM tempered martensite, M-A martensite-austenite, B_u upper bainite, GB globular bainite)

The cooling rate is a critical factor affecting microstructure formation in the fusion zone and heat-affected region. The joint formed with the nanoparticle-coated wire had a shorter cooling time ($t_{8/5}$) (i.e., approx. 7.3 s) than the joint welded with the conventional welding wire cooling (i.e., approx. 11.2 s). The increase in the cooling rate for the nanoparticle-coated wire could be due to the alloying elements in the wire, as an increase in the C and B content reduces the phase transformation temperature as well as cooling time.

The current during welding (i.e., Figs. 5a and 6a) shows greater fluctuation for the nanoparticle-coated welding wire than the conventional welding wire, most likely due to the manual feed of the welding wire. Fluctuation in the current leads to instability in arc length and fluctuation in voltage.

In spite of the current fluctuation caused by manual feeding of the nanoparticle-coated welding wire, the arc was more stable while welding with a steady and uniform wire feed compared to the unstable arc at the start of the weld, which can be seen from Fig. 7. In addition, comparison of Figs. 7a and 8a shows greater arc stability with the nanoparticle-coated welding wire than the conventional welding wire.

3.2 Microstructures

In manufacturing of high-strength steels, the high strength-to-weight ratio and toughness and the microstructure of bainite or ferrite with martensite are formed by reducing carbon content and by the addition of alloying elements. S960QC steels are not tempered and have low alloying elements compared to conventional quenched and tempered high-strength steels. The microstructures and the lack of temper of the steels cause deep and wide softening of the HAZ region while welding, which leads to a reduction in hardness in the coarse-grained heat affect zone (CGHAZ) [27, 43, 44]. In addition, if high heat input is used, as in the GMAW process, a slow cooling rate results, leading to increased softening in the HAZ region and reduced joint strength [11, 45].

The microstructure, observed by scanning electron microscope (SEM), formed with the conventional welding wire and the nanoparticle-coated welding wire is shown in Figs. 9 and 10, respectively. Welded high-strength steels are prone to have bainite and martensite formation, and the joints of both welding wires had upper bainite and martensite as well as tempered martensite. From the figures, the weld metal has fine grain formation in comparison with the heat-affected zone,

Fig. 10 SEM microstructure of the joint formed by nanoparticle coated wire. **a** Weld and CGHAZ region. **b** Formation of M, TM, B_u in the CGHAZ. **c** M and TM formation in the weld. **d** Formation of M and B_u in the CGHAZ. (symbols: M martensite, TM tempered martensite, B_u upper bainite)

due to the high heat of the welding process. Moreover, the joint formed with the nanoparticle-coated wire has more uniform dilution in comparison with the joint made with the conventional welding wire. This occurrence could be the high melting temperature and thermal conductivity of the LaB_6 refractory compound. Retained austenite, martensite-austenite, and globular bainite were found in the CGHAZ of the joint formed with the conventional welding wire. Coalescence of bainite and martensite microstructures led to more softening in the CGHAZ region of the nanoparticle-coated wire weld than the conventional wire weld. In the weld region, lath-like martensite and tempered martensite microstructure were found in the weld metal for both welding wires, which could be due to high heat input.

Studies suggest that alloying elements from the welding wire are one of the factors determining the microstructural formations in the weld [46]. The nanoparticle coated welding wire changed the element content of C, Mn, Ni, and B in the weld metal as seen in the line scanning and shown in Fig. 11.

Research has shown that with increase in carbon (C) content, the time for austenite transformation decreases and the cooling rate increases. Moreover, higher carbon content increases martensite microstructure formation [47]. The nanoparticle-coated wire has higher carbon content on the surface, which could have increased martensite formation in the weld metal, leading to increase in hardness.

In addition to carbon content, increased content of boron, manganese, and nickel were noted in the weld formed with the nanoparticle coated wire. Boron (B) influences the bainite microstructure by retarding the proeutectoid ferrite formation and constraining the range of the cooling rate for bainite formation. Moreover, boron in the presence of a low amount of other alloying elements prevents martensite formation [48]. The Mn and Ni content in the joint is higher for the nanoparticle-coated wire than in the joint formed with the conventional wire. Studies also show that in high-strength steels with weld metal containing more than 1.5% manganese content, the addition of

Fig. 11 Line scanning of element composition from the weld to HAZ region. **a** Weld with conventional wire. **b** Weld with nanoparticle-coated wire

Fig. 12 Hardness measurements for joints made by **a** conventional welding wire and **b** nanoparticle-coated welding wire

nickel improves the coarse grain formation of coalesced bainite and martensite. Additionally, manganese and nickel tend to increase the presence of martensite or bainite within austenite small grain size [49, 50]. As the weld formed using the nanoparticle-coated wire increased the manganese and nickel content, this could lead to the formation of coalesced bainite microstructures resulting in greater softening at the CGHAZ.

As regards grain size, grain sizes are smaller in the CGHAZ region of the joint welded with the nanoparticle-coated wire than in the joint made with the conventional

wire. Moreover, the dilution in the weld formed with nanoparticles were uniform than the weld formed with conventional welding wire.

3.3 Mechanical properties

The hardness of the joints formed with the conventional welding wire shows a hardness increase in the fusion zone, where the hardness is slightly higher than in the base metal. With the joint formed with the nanoparticle-coated welding wire, similar increase occurred in hardness at the fusion zone,

Table 5 Impact strength measured for the joint welded with conventional and nanoparticle-coated welding wires

	Specimens	Impact energy (kJ/cm)	Testing temperature (°C)
Conventional welding wire	1-1	72.2	-20
	1-2	73.6	-20
	1-3	64	-40
	1-4	68.9	-40
	1-5	51.1	-60
	1-6	47.9	-60
Nanoparticle-coated welding wire	2-1	58.1	-20
	2-2	57.8	-20
	2-3	38.6	-40
	2-4	45.1	-40
	2-5	34.3	-60
	2-6	29.7	-60

Fig. 13 Mean value of the impact strength of the joints formed with the two studied welding wires

as can be seen in Fig. 12. However, the hardness of the fusion zone in the joint formed with the nanoparticle-coated wire was higher than in the fusion zone of the weld formed with a conventional welding wire. This greater hardness increase in the fusion region could be due to the heat energy constraint caused by the La nanoparticles leading to the formation of martensite. In addition to the heat energy, the carbon content also plays an important role in hardness properties via martensite formation [48]. Comparing the chemical composition of the welding wires (i.e., from Tables 2 and 3), it can be seen that the carbon content is higher in the nanoparticle-coated wire than in the conventional welding wire, which may have increased the hardness in the weld.

As regards hardness in the heat-affected zone (HAZ), the hardness is slightly lower in the HAZ region of the weld made with the nanocoated welding wire than the weld formed with the conventional welding wire, as can be seen in Fig. 12. This lower hardness in the HAZ region and wider HAZ could be due to softening of the HAZ by the formation of coalesced coarse bainite through increase in alloying contents such as Ni and B. Moreover, Guo et al. [51] have also found reduction of hardness in the HAZ and a wider HAZ in GMAW of S960 steel by the formation of bainite microstructures.

The impact strength of the test specimens welded with the conventional welding wire and nanoparticle-coated welding wire is shown in Table 5, and the mean value for the tested specimens is shown as a graph in Fig. 13.

From Fig. 13, it is clearly seen that the joint made with the nanoparticle-coated wire had significantly lower impact strength than the joint welded with the conventional welding wire.

Studies have also found that in weld metal of high-strength steels containing more than 1.5% manganese content, the addition of nickel reduces the toughness by coarse grain formation of granular bainite and martensite. However, weld metal containing below 1.5% manganese with the nickel addition improves the toughness [49, 50]. The element composition scanning (Fig. 11) shows higher Ni and Mn content in the joint welded with the nanoparticle-coated wire, which promotes the

bainite and martensite microstructure formation in the weld and HAZ region. These higher amounts of granular bainite and island of martensite could lead to low resistance to crack propagation by the large crystallographic packets welded with the nanoparticle-coated wire. Thereby, resulting in impact strength lower than in the joint welded with the conventional wire.

4 Conclusions

The LaB₆ nanoparticle coating on the welding wire was uniform and the La nanoparticle content was higher on the surface of the wire than in the core. The deposition of nanoparticles increased the thickness of the welding wire by 15 μm . Manual feeding was thus required because of the thickness increase and because the wire feed through the welding tip was unstable when using the automated feed, leading to instability in arc length and fluctuation in current and voltage. However, with steady feed of the nanoparticle-coated wire, arc stability was higher than with the conventional welding wire.

A higher peak temperature was noted while welding with the nanoparticle-coated wire than with the conventional wire, which could be due to the La nanoparticles reducing the electron work function aiding in high heat. The high heat concentration could be advantageous when welding in harsh climatic conditions. The cooling time ($t_{8/5}$) in the weld joint is reduced by the alloying elements (C, Ni, Mn, and B) by welding with nanoparticle-coated welding wire than the conventional wire.

The grain size of the joint welded with the nanoparticle-coated welding wire was finer than the grain size of the joint made with the conventional welding wire. Martensite and tempered martensite formation were observed in the microstructure of the weld metal of both joints. However, greater martensite formation was found in the weld formed with the nanoparticle-coated wire because of the carbon and boron alloying elements. In the CGHAZ region, martensite, globular bainite, tempered martensite, and upper bainite were found in the welds for both welding wires. Slightly higher martensite

content was found in the weld made with the conventional welding wire.

The hardness of the joints formed with both conventional and nanoparticle-coated wire had high hardness in the fusion zone. Higher hardness in the joint welded with the nanoparticle-coated wire was found, due to the carbon and boron elements promoting martensite formation. Lower impact strength was found in joints formed with the nanoparticle-coated wire due to the increased content of nickel and manganese from the welding wire resulting in an increase in coalescence of granular bainite formations.

This study shows promising results on arc stability, microstructural formation, and flawless joints using the La nanoparticle-coated welding wire. However, further studies are required to address issues such as smooth and uniform feed of the nanoparticle-coated welding wire into the robotic GMAW system, as well as research of improvement in impact toughness of welds made with nanoparticle coatings. This work used a LaB₆ nanoparticle coating of the welding wire, and further research is required on the usage of other nanoparticles and their effects on joint properties.

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Author's contributions All the authors read, analyzed, approved, and wrote the final manuscript.

Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interest.

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