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Hybrid (plasma + gas tungsten arc) weldability of modified 12% Cr ferritic stainless steel

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ABSTRACT

This paper deals with the hybrid (plasma + gas tungsten arc) welding properties of 12 mm thick modified 12% Cr ferritic stainless steel complying with EN 1.4003 and UNS S41003 steels with a carbon content of 0.01% to improve the weldability. The root passes of the butt welds were produced with plasma arc welding (PAW) without filler metal while gas tungsten arc welding (GTAW) was used to accomplish filler passes with 309 and 316 austenitic stainless steel type of consumables, respectively. The joints were subjected to tensile and bend tests as well as Charpy impact toughness testing at −20 °C, 0 °C and 20 °C. Examinations were carried out in terms of metallography, chemical analysis of the weld metal, ferrite content, grain size and hardness analyses. Although 309 consumables provided higher mean weld metal toughness values compared to 316 (90 J vs. 75 J), 316 type of consumables provided better mean HAZ toughness data for the joints (45 J vs. 20 J) at −20 °C. Toughness properties of the welds correspond with those of microstructural features including grain size and ferrite content.

1. Introduction

Mild steels suffer from corrosion, however in many situations galvanic protection or painting of a steel surface is not practical. For long term service, corrosion protection requires maintenance and highly expensive measures to prevent or delay the onset of corrosion with associated expenses. Stainless steels are in many cases a proper option to replace carbon steels for numerous structural applications. They have extensively been used in a variety of industries and environments such as chemical and power engineering, food and beverage industry, health applications, petroleum and petrochemical plants, textile plants, transportation, elevated or cryogenic temperature applications, architecture etc. [1–8]. For most cases, welding is an inevitable production technique in fabrication of stainless steels. In general, most grades are considered as weldable, however many problems are associated with improper control of the weld microstructure and allied properties, or the use of welding procedures that are inappropriate for the material unless some rules have been followed. Good weldability can be effective to determine common application of any alloy and this factor alone has previously restricted the exploitation of ferritic and martensitic grades more than any other mainly due to toughness reduction and high carbon levels, respectively. For instance alloy 420 is one of the few stainless steels with almost no practical arc welding history. Development of new steels inevitably brings new problems in manufacturing and joining. There is a continuous demand for increased productivity in welding, while maintaining the parent metal properties. In almost all cases, welding results in a significant alteration of the weld metal and heat affected zone (HAZ) microstructure relative to the base metal. This can constitute a change in the desired phase balance, formation of intermetallic compounds, grain growth, segregation of alloy and impurity elements, and other reactions. In general, these lead to some level of degradation in properties and performance and must be factored into the manufacture [1–5]. Depending on the life cycle costs analysis and improved steel producing technologies, lean alloyed chromium stainless steels gained a new status based on 10.5–14% Cr system. The reasons for the renewed interest in this group of materials are that these steels can provide good mechanical properties and useful corrosion resistance for many applications and at a relatively low cost. 12% Cr stainless steels are sufficiently corrosion resistant in atmospheric and non-aggressive aqueous conditions in many applications and are widely used as low cost, utility stainless steels. In some predominantly ferritic steels, a small amount of austenite forms at high temperatures and may transform to martensite on cooling. This property has been used to develop 12% Cr transformable stainless steels with better weldability than either fully ferritic or fully martensitic

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steels. They should be produced with close control of the carbon content and martensite/ferrite balance to avoid the extremes of completely ferritic or martensitic structures. The hardness and detrimental effect of the martensite on toughness is limited by the low carbon levels [1,3–5,9–16].

3Cr12 stainless steel which was developed with 0.03% C in the late 1970s making use of the minimum chromium content required to impart acceptable corrosion resistance is known as the first generation of 12% Cr steels. Originally 3Cr12 is a trademark and was not included in any international specifications. However a 12% Cr steel developed from 3Cr12 has been designated DIN type 1.4003 and ASTM/ASME 41003. 3Cr12 now appears in ASTM A240 as UNS S41003 and in Europe as Material Number 1.4003, although the two specifications are not exactly the same. In particular, conformance to S41003 does not require nickel as an alloying element, although it is permitted, while conformance to 1.4003 does require some nickel. In addition to the composition ranges of S41003 and 1.4003, some suppliers, but not all include a deliberate addition of titanium. Because of the low alloying content, 1.4003 alloys may lie in the dual phase region consisting of a mixture of untransformed delta ferrite, alpha ferrite which transformed from austenite on cooling and martensite depending on the cooling rate, consequently they are variously described as ‘‘ferritic" or ‘‘ferritic–martensitic" 12% Cr stainless steel. In comparison to fully ferritic grades like 409 and 430, 3Cr12 is considered to have better weldability and HAZ toughness in thick as well as thinner gauges, and it is supplied in thicknesses up to 30 mm. Relatively low fracture toughness of the HAZ has restricted their use where dynamic loads are concerned. Although 5Cr12HT was developed later as a second generation to give better toughness, weldability remained limited due to the carbon content [5,11,16–28].

It is clear from the previous published literature and industrial applications that the 12% Cr type of steels had not achieved its full potential so far, because the possible alloy combinations were not fully understood. And usually weldability is not concerned a lot, since 3Cr12 was mainly used for applications without welding. There is limited weldability data in the published literature. EN 1.4003 steel is modified from conventional 3Cr12 stainless steel by decreasing the C content to well below 0.03% which is regarded as the limit for low carbon steels to improve the weldability. Also, the amount of titanium is limited, because titanium tends to form brittle carbide phases in the HAZ of a welded joint. Advanced steel making technology now enables tight control of composition and can provide extremely low levels of carbon and nitrogen with significant improvement in the as welded HAZ properties, as well as the reduction of chromium carbides which degrade corrosion performance. Modified X2CrNi12 stainless steel still conforming to grades 1.4003 in EN 10088-2 and EN 10028-7 and UNS S41003 in ASTM A240, with a quite low carbon level of 0.01% enhancing the weldability and mechanical properties has recently been produced. This modified 12% Cr low carbon ferritic stainless steel provides an alternative which displays both the advantages of stainless steels and engineering properties of carbon steels. In case attention is paid for using the correct welding parameters to ensure good joint integrity, this combination opens up a wide range of applications. Initial applications of these 12% Cr stainless steels were consisted of materials handling equipment in corrosive environments, but the 1.4003 type of steels are now extensively used in the coal and gold mining industry, for sugar processing equipments, road and rail transport, power generation, for petrochemical, metallurgical, pulp and paper industries and in aerospace engineering. Although it has higher initial cost, modified X2CrNi12 stainless steel provides lower total life costs due to longer life with less coating renewals and lower maintenance offering significant economic and environmental advantage with regard to carbon steels. For other applications, it would be more economical compared to higher alloyed stainless steels [3,14–18,22,29–49].

Recent years, the interest has been increased in applying plasma arc welding (PAW) process in industry due to the higher welding speeds providing improved productivity and producing welds with high penetration/width ratios [48]. Since modified X2CrNi12 stainless steel is relatively new, plasma arc or hybrid weldability or welding properties of this modified 12% Cr stainless steel grade has not been well determined yet. Taking into account of the increasing interest in demands of using this steel as high strength structural stainless steel and hybrid welding for industrial applications, this study focused on hybrid (plasma + gas tungsten arc) welding of modified X2CrNi12 ferritic stainless steel plates.

In this study, properties of hybrid (PAW + GTAW) welded joints of modified 12% Cr stainless steel conforming to EN 1.4003 and UNS S41003 steels using austenitic stainless steel type of consumables such as 309 and 316 have been investigated. Mechanical and impact toughness testing and microstructural examinations including macro-microstructures, grain size and ferrite content analyses were carried out to evaluate the welds. Effect of consumable type on the properties has been discussed. In addition, property-microstructure relationship was analyzed and explained.

2. Material and experimental studies

Chemical composition data obtained from chemical analysis and transverse tensile properties provided from the steel producer for the 12 mm thick modified 12% Cr stainless steel conforming to grades 1.4003 and UNS S41003, respectively in EN 10088-2 and EN 10028-7 and in ASTM A240 are given in Table 1.

To ensure tougher weld metal yielding adequate properties required for structural purposes and to minimise the risk of heat affected zone (HAZ) hydrogen cracking, austenitic stainless steel filler metals are generally recommended in producing arc welds of 1.4003 type of grades in applications where dynamic loading is anticipated. [3,5,14,15,39]. Hybrid welded joints of modified 12% Cr stainless steel were obtained by hybrid (plasma + gas tungsten arc) welding process. Two types of hybrid welded panels were produced with 309L and 316LSi type of austenitic stainless steel consumables. The chemical composition of the filler metals are given in Table 2. First welded joint-named as L9 was produced with an ER309L wire of 1.2 mm diameter protected by Ar as plasma gas and 30He/70 Ar as shielding gas. Y groove preparation with an opening angle of 90° was used. Similar conditions were used with an ER316LSi wire of 1.2 mm diameter to produce second welded joint-named as L6. Root passes were produced with plasma arc welding (PAW) in one pass while multi passes with gas tungsten arc welding (GTAW) were used for filler passes for both joints, The total heat input varied from 4.1 kJ/mm to 4.3 kJ/mm for each weld.

Transverse tensile specimens were prepared with respect to EN 10002-1-EN 895 from both welds and tested at room temperature by a servohydrolic tensile test machine at room temperature. Face and root bend test specimens removed from both welds transverse to the weld seam were prepared with a nominal specimen width of 30 mm, a mandrel diameter of 55 mm. Bending test was executed till 180° according to EN 910 unless severe cracking was observed before. Notch impact test samples were extracted transverse to each weld and notched at the weld metal centre (WM), the fusion line (FL), at the heat affected zone 2 mm from the fusion line (FL + 2 mm). Testing was performed due to EN 10045-1 at −20 °C, 0 °C and 20 °C. Cross-sections from both welds were prepared, polished and etched with proper reagent for metallographic examination. Macro- and micrographs of the weld zones were obtained. Complete HV5 traverses were made according to EN 1043-1