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Technical Paper

Investigations on the impact toughness of HSLA steel arc welded joints

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ABSTRACT

The impact toughness of HSLA steel weld joints fabricated by arc welding processes was studied. The influence of inclusions and microstructural characteristics of SMAW, SAW, FCAW and A-GTAW on the toughness of the weld metals were investigated. The inclusion size, area fraction and number density were analyzed using image analysis software. The area fraction and the number of inclusions per mm^2 indicated maximum inclusions in SAW followed by FCAW, A-GTAW and SMAW. It was observed that finer inclusion size and lower inclusion content can be related with higher impact toughness of the weld joints at room temperature. At sub-zero temperatures, the impact toughness of the weld metals of various arc welded joints was found to be influenced by the weld metal grain size, chemical composition of weld metal, acicular ferrite and inclusion content.

1. Introduction

The shipping construction, offshore and land-based structures use high strength low alloy (HSLA) steel. HSLA steel exhibits equiaxed fine grain ferritic steels with good yield strength and weldability. The HSLA steels are generally Mn alloy grades with approximately 0.2%C and grain-refining elements, such as V, Nb, and Ti contributing towards enhanced resistance to brittle fracture [1–3]. The required yield strength levels are obtained with alloying elements such as Si, Ni, Cu, Cr, and Mo. HSLA used for experiments is low carbon (0.08 wt.% C) steel, with additions of micro-alloying elements viz., V (0.03–0.05), Nb (<0.05) and Ti (0.01–0.06). The steel is designed to have a predominantly ferritic microstructure, with pearlite content less than 10% by volume [4,5]. This structural grade steel is standardized by the American Bureau of Shipping for shipbuilding and being widely used in the construction of the hulls of vessels and ships.

Conventional arc welding process (fusion welding) is extensively used for joining HSLA steels during construction of bridges, ships and various machineries including space vehicles. Submerged arc welding (SAW) and flux cored arc welding (FCAW) are commercially preferred automated welding processes in ship building industry. Shielded metal arc welding (SMAW) is used for onsite manual welding and repair works for sea going vessels, ships and off shore structures and, in general, is the most common welding process. Innovative welding processes have been developed to optimize the welding cost and increase weld productivity [6,7]. The process called activated flux gas tungsten arc welding (A-GTAW) enhances the productivity and also increases the depth of penetration uses the activating flux during GTAW.

The inorganic oxides like Al_2O_3, SiO_2, MnO, TiO, Ti_2O_3, $CaCO_3$ etc. are known to exist in weld metal in the form of inclusions. The inclusions in weld metals can be due to the entrapment of slag or flux in the weld metal (can be termed as primary inclusions) or due to the formation or entrapment of deoxidizers like aluminum, silicon, manganese, and titanium present in base metal or added for deoxidation and alloying of weld metal (can be termed as secondary inclusions). The primary inclusions can be associated with the welding technique and process employed for welding and usually occur as defects in welding processes that use flux, such as shielded metal arc welding, flux-cored arc welding, and submerged arc welding, but can also occur in gas metal arc welding. The secondary inclusions exist as integral part of weld metal irrespective of the welding process and depend on the weld chemistry, heat input, number of passes and weld metal solidification behavior.

Austenite grain size, cooling rate and distribution of nonmetallic inclusions are the dominant factors in acicular ferrite nucleation, which has a significant influence on the impact toughness of weld

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metals [8–11]. Amongst these factors, the intragranular nucleation of acicular ferrite on the non-metallic inclusions is extensively reported. Also, the potential nucleation sites for the formation of acicular ferrite are strongly controlled by the inclusion size distribution, density and chemistry. Kanazawa et al. [12], Koukabi et al. [13] and Ito et al. [14] suggested that during the austenite decomposition, TiN was an effective nucleating agent for acicular ferrite. The observation that TiN acted as a weld metal grain refining agent and that the effectiveness of titanium addition is enhanced in the presence of aluminum and boron was also reported by Heintze and McPherson [15]. Mori et al. [16] showed that an increase in nitrogen in the weld metal did not bring any microstructural change except for an increase in proeutectoid ferrite. Instead, they demonstrated that titanium containing oxides can nucleate acicular ferrite within the austenite grains. Pargeter [17] and Devillers et al. [18] reported that grain boundary ferrite and ferrite side-plates are usually associated with inclusions with manganese and silicon, with or without sulfur. Acicular ferrite appeared to be associated with aluminum-bearing particles. Cochrane et al. [19] and Saggesse et al. [20] observed that the effectiveness of inclusions on phase transformation behavior may depend on tramp elements (either in the form of surface coating or other ways) rather than on the macroanalysis of the inclusions. The removal of inclusions from a weld deposit, with other features constant, causes a change in the microstructure from acicular ferrite to bainite [21]. An increase in the number density of austenite grain surface nucleation sites (relative to intragranular sites) causes a transition from acicular ferrite to bainite [22]. But the number of inclusions in a weld joint is not conclusive evidence of higher acicular ferrite content. Depending on the size distribution, the partition of the inclusions to the boundary and to the interior of the grains may be different. An optimum inclusion size distribution to obtain a large volume fraction of acicular ferrite is the one that contains a low percentage of fine size particles, with the inclusion population sizes resembling a normal, or close to normal, distribution. The combination of large austenite grains and high intragranular inclusion density is the key to obtaining a refined microstructure.

The objective of the present investigation is to study the impact toughness of HSLA steel weld joint fabricated by arc welding processes. The inclusions and microstructure of the weld metals of SMAW, SAW, FCAW and A-GTAW were investigated. It was observed that finer inclusion size and lower inclusion content can be related to higher impact toughness of the weld joints at room temperature. At sub-zero temperatures, the impact toughness of the weld metals of various arc welded joints was found to be influenced by the weld metal grain size, chemical composition of weld metal, acicular ferrite and inclusion content.

2. Experimental details

2.1. Material and welding processes

The chemical composition of base metal is given in Table 1. For each weld joint, two plates of dimensions $300 \times 120 \times 10\,mm^3$ were welded to make a weld joint of $300 \times 240 \times 10\,mm^3$ (Fig. 1) (welding parameters are given in Table 2). The square butt joint for A-GTAW and 70° V-Grove for SMAW, SAW and FCAW processes were used. The standard filler wires commercially available for the base steel were used for SMAW, SAW and FCAW processes. The chemical composition of the filler wires is given in Table 3. Based on the expertise and experience of the authors on success of A-GTAW welding for 304LN and 316LN steels [23], the activated flux for the steel was developed to enhance the weld penetration, weld efficiency and productivity. The developed flux consisting of SiO_2, TiO_2 and other combinations of oxide powders was used for A-GTAW process [24]. The chemical analysis of the weld metals was carried out using Jobin Yuon Make (JY 132F) spurt atomic emission spectrometer.

Table 1
Chemical composition (wt.%) of DMR 249A steel:.

C	Mn	Si	Ni	Al	Nb	V	S	P	Ti	Cu/Cr	N (ppm)
0.09	1.14	0.18	0.62	0.026	0.039	0.02	0.006	0.14	0.019	<0.020	56

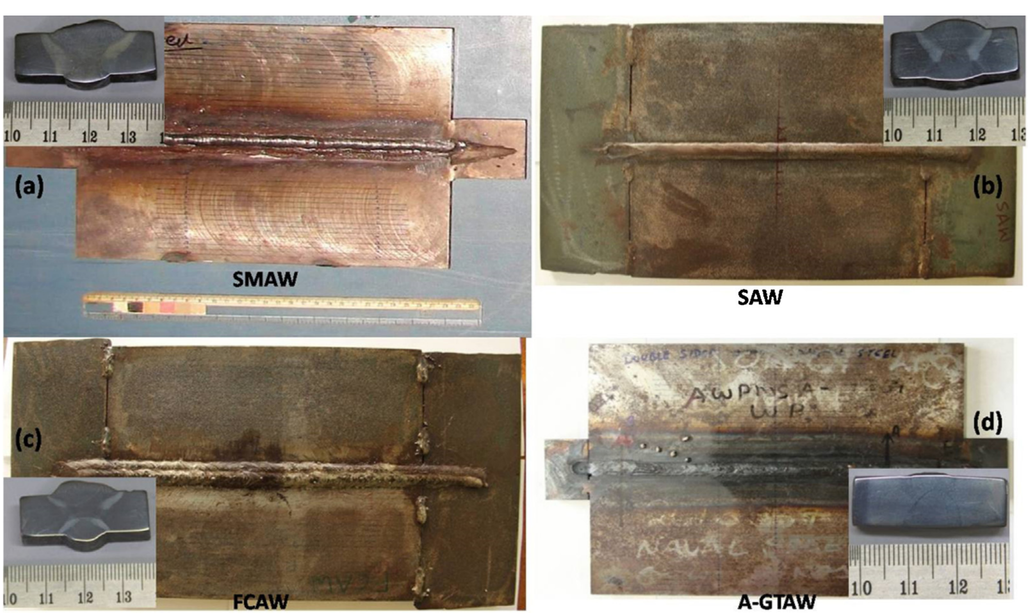

Fig. 1. Macrostructure photos of HSLA steel arc welded joints—SMAW, SAW, FCAW and A-GTAW.