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Hybrid laser/arc welding of advanced high strength steel in different butt joint configurations

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ABSTRACT

An experimental procedure was developed to join thick advanced high strength steel plates by using the hybrid laser/arc welding (HLAW) process, for different butt joint configurations. The geometry of the weld groove was optimized according to the requirements of ballistic test, where the length of the softened heat affected zone should be less than 15.9 mm from the weld centerline. The cross-section of the welds was examined by microhardness test. The microstructure of welds was investigated by scanning electron microscopy and an optical microscope for further analysis of the microstructure of fusion zone and heat affected zone. It was demonstrated that by changing the geometry of groove, and increasing the stand-off distance between the laser beam and the tip of wire in gas metal arc welding (GMAW) it is possible to reduce the width of the heat affected zone and softened area while the microhardness stays within the acceptable range. It was shown that double *Y*-groove shape can provide the optimum condition for the stability of arc and laser. The dimensional changes of the groove geometry provided substantial impact on the amount of heat input, causing the fluctuations in the hardness of the weld as a result of phase transformation and grain size. The on-line monitoring of HLAW of the advanced high strength steel indicated the arc and laser were stable during the welding process. It was shown that less plasma plume was formed in the case where the laser was leading the arc in the HLAW, causing higher stability of the molten pool in comparison to the case where the arc was leading.

1. Introduction

The application of the advanced high strength steel (AHSS) exposed to the extreme loading conditions (e.g. ballistic impact) in a number of structures poses a substantial challenge. This kind of problem may raise more in joining of the structures by fusion welding processes, especially when the thickness of the plates is noticeably high. The advanced high strength steels are characterized with the microstructure that consists of fine martensite whose mechanical properties can be easily changed by exposure to the elevated temperatures during the welding process. This could be more pronounced in the case of welding thick plates. Among the welding processes, it was reported that the hybrid laser/arc welding (HLAW) of the different grades of steels can provide a reliable joint for the thick plates with different joint configurations [1]. The HLAW process takes the benefits of the laser's deep penetration and high speed, while the arc assists to bridge gaps, slow weld cooling rate, and changes the metallurgical and mechanical properties by using the filler wire. However, similar to the acceptance of any new manufacturing technologies, the HLAW process has been also experiencing reluctance in its acceptance and adoption by the industries. In this welding method, two heat sources are used to control the heat input into the weld area. One of the heat sources could be gas metal arc welding (GMAW) in the spray-transfer mode, which enhances the stability of chemical composition and reduces the distortion-related problems of the welding process [2,3]. The possibility of using CO_2 laser-GMAW hybrid welding process was studied for the stainless steel ASTM: A240/A240M-14 and influence of the shielding gas was overseen as the potent factor in the weld quality [4]. The microstructure of the mild steel after the HLAW showed coarse columnar dendrites and fine acicular dendrites in the heat affected zone (HAZ) and fine equiaxed dendrites and columnar dendrites in the weld zone. Laser zone showed the finer grain size and higher microhardness in the fusion zone and narrower heat affected zone in comparison to the arc weld [5].

It was reported that the HLAW process can lead to the lower residual stress and as a result less thermal distortion [6]. This method also gives more freedom for the structural designers to use larger gaps and have lower amount of porosity inside the weld bead, if the stand-off distance between the heat sources is carefully controlled [7,8]. There are many physical evidences for the

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interaction of the arc and laser when they are in the close range. The first benefit of having simultaneous arc and laser is the stability of the arc, because the vaporization of the elements from the keyhole in the laser side will help in the formation of arc plasma. The second important perspective is the plume provided by combining the plasmas of arc and laser [9]. If there is not enough large stand-off distance the vaporization of the elements would not lead to the bending of the arc towards the keyhole. In the case of HLAW of stainless steel with the laser leading it was reported that increase in the stand-off distance caused the keyhole to be collapsed [10]. An experimental-three dimensional finite element method was also presented and it was demonstrated that the shared molten pool can have a prominent effect on the residual stress and the molten pool shape in a butt joint configuration of a structural steel with the standard specification of ASTM: A1018/A1018M-10 [11]. A control volume method was developed, where the combination of the solidification rate and compositional variation have been linked by new analytical models of the weld pool dynamic, final bead geometry and cooling rate [12]. It was numerically and experimentally demonstrated that the stand-off distance between arc and laser in the HLAW of aluminum alloys can effectively determine the final properties of the welds, specifically the bead appearance and microhardness of the joints [13].

The hardness of the material is highly dependent on the welding temperature history. It was reported that the zone close to the weld bead can experience a high peak temperature gradient, exceeding the AC_3 line in the steel phase diagram. This can be a key factor to control the grain size and amount of softening in the heat affected zone [14]. The control of the temperature history ($T_{800-500}$) and volume of the deposited material helps to retain the material against the ballistic impact, which is a cause of different types of cracking. The heat treatment of the AHSS by oil quenching from 900 °C and air tempering at 200 °C produces a tempered martensite microstructure [15]. The control of the heat input should be in a way that the width of the heat affected zone does not exceed the value of 15.9 mm counting from the weld centerline. This rule of thumb was indicated in the standard MIL-STAN-1185 [16]. The sensitivity of the material to the heat input can lead to a disaster response to the ballistic impact [17].

The influence of the joint geometry and beam alignment relative to the center of the groove with respect to the laser power and welding speed on the properties of the welds was aimed at this study. The main objective of the investigation was to keep the length of the softened zone in the HAZ below 15.9 mm as indicated in MIL-STAN-1185 [16]. The present work provides high quality joints of the AHSS using the HLAW process. The joint properties and metallurgical characteristics of the welds were investigated by microhardness test and optical microscopy.

2. Experimental procedure

The chemical composition and mechanical properties of the base metal (BM) and filler wire are shown in Tables 1 and 2. The steel is categorized into the high hardness, high strength martensitic steel and air-quenched self-tempered AHSS. The as-received coupons were produced by a hot rolling after the casting while during the casting process the steel was homogenized in order to remove the defects via the bilateral process; e.g., vacuum degassing and deoxidization by argon. The filler metal used for this study was ER100S-G AWS. The filler wire encounters a minimum tensile strength of 852 MPa and minimum yield strength of 764 MPa. It contains 0.25 wt.% Molybdenum and 1.5 wt.%. Nickel, making it an outstanding choice for welding of the high strength steel. The hot-rolled AHSS with the density of 7850 kg/m^3, has the yield strength of 1034 MPa, ultimate tensile strength of 1690 MPa and Charpy test response of 25–30 J.

The carbon equivalence (CE) of the steel was calculated by the following equation according to the ASTM: A6/A6M-14; standard specification for general requirements for rolled structural steel plates:

$$CE = C + [Mn/6] + [(Cr + Mo + V)/5] + [(Ni + Cu)/15] \tag{1}$$

where for the plates with the thickness of 12.5 mm the CE was almost 0.75 wt.%. However, the advanced steel was heat treated (426 °C) after the production to create the higher hardness. The austenitizing temperature was varied within a range of 10 °C below 926 °C. The stress was also relieved after the final quenching and tempering at a maximum temperature of 10 °C below the tempering temperature (200–230 °C). The high hardness gives the AHSS enhanced resistance to the ballistic penetration. The surface conditions of the specimens were also within the requirements of ASTM: A6/A6M-14, meaning that the surfaces of the plates were basically free from the surface defects such as seams, laps, snakes, blisters, cracks, cold shuts, burning, laminations and mechanical gouges. The steel was machined by the heavy-duty CNC milling machine to have different groove geometries and sizes with the variation in the shoulder size, from 0.0 mm to 6.5 mm. For the protection of the molten pool from the atmosphere a combination of the 92% argon and 8% CO_2 was used. The real specimens (as-received without any post processing; e.g., heat treatment and preparation) were used for the welding purpose. The specimens were griped in a clamping fixture. A fiber laser of 4 kW in power with continuous wavelength of 1070 nm, delivered by an optical fiber with a core diameter of 400 μm was used for the welding process. The laser welding head had two lenses including a 200 mm focusing lens and a 150 mm collimating lens, providing a size of the spot at the focal point of 0.6 mm. A CLOOS power source (Quinto GLC 403) was used for the GMAW process. In the GMAW CLOOS machine all the connections were available by a Plug and Weld (PAW), and a monitoring of the process was performed by Software Versions Management (SVM).

The distance between the tip of the wire and laser beam was also varied to explore the optimum conditions for the positioning of the laser beam with respect to the arc. The distance between the arc and laser was changed from 1 mm to 14 mm. The welding torch was tilted relative to the vertical axis to an angle of 20° and the laser head was tilted 5° relative to the vertical axis, making the total angle between the welding torch and the laser head about 25°. The experimental work was based on a full factorial design of experiments. The welding parameters with the main concern

Table 1
Chemical composition (wt.%) of the AHSS and filler metal (ER100S-G) [16,18].

Material	Composition (wt.%)																				
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	B	Ti	Zr	Al	Sn	Pb	Sb	As	Fe	Mg	Zn	V
Advanced High Strength Steel (AHSS)	0.28	0.9	0.02	0.001	0.53	0.18	0.19	0.28	0.24	0.003	0.10	0.10	0.01	0.02	0.01	0.02	0.02	Bal.	–	–	–
Filler metal (ER100S-G (0.9 mm in diameter))	0.098	1.6	0.005	0.009	0.5	0.04	1. 5	0.3	0.25	-	0.0025	0.0025	0.004	–	–	–	–	–	0.8	0.25	0.09