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Research Paper

Thermo-Mechanical Analysis and Microstructure of Steel Weld

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Abstract
The study focused onthermos-mechanical properties of steel weld. A mild steel stock selected from the SAE10XX class was used to fabricate four pairs of rectangular plates, each measuring 200 mm by 100 mm by 6 mm.The mechanical testing analysis were conducted on the samples after welding process and the microstructure of the all the welded samples were analysed with the help of scanning electron microscope. The results suggest that a good combination of the operational variables guarantees stable welding operation which in turn assists in achieving a quality welded joint. Moreso, it is recommended that maintaining low but sufficient high welding power helps to minimize excessive temperature rise in the base metal and improves stress distribution along the welding line, which in turn mitigates degradation of mechanical properties. The result also shows that the coarse structure is formed in fusion zone and fine structure is formed in heat affected region.

Keywords: *Steel, Weld joint, Mechanical properties, Heat transfer, Welding parameters, Thermal analysis, Temperature distribution.*

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I. Introduction

In metal joining, welding creates a permanent joint between two or more base metals.American Welding Society (AWS),defined the phenomenon as the coalescence of metals or nonmetallic produced by heating the materials to a specific temperature without applying pressure, or by applying pressure alone, with or without using filler metal.Thermally, the base metals and the filler material are melted while in contact with one another, then cooled and bonded together. Research in welding processes is primarily driven by the need to overcome defects in welds as well as other limitations associated with welding as an important metal joining process. In many cases, welding conditions and subsequent cooling of metals cause the material to degrade mechanical properties at the weld region because of residual stresses and other factors associated with material microstructure changes (Holovento et al. 2013; Hu et al. 2013).Weld induced residual stresses can greatly affect the mechanical behavior and response of structures, for instance they may enhance occurrence of brittle fracture, fatigue, structural buckling and stress corrosion cracking (Azimi et al. 2018; Dias & Chuvas, 2016; Grajcar et al. 2014). The problem of material microstructural change is inevitable in welding since the process necessarily involves heating the weld materials beyond equilibrium melting temperature. For instance, in the arc welding process, the energy required for metal fusion is produced by the Joule effect which produces the energy required to melt the base and filler metals, forming what is known as the liquid pool whose temperature varies from 1700 K to 2500 K, depending on the material. In the liquid pool, convective effects take place that improve the heat transport. When the heat sources are removed, the metal solidifies on cooling (Khan et al. 2008; Bringes, 2012). During the cooling process, temperature changes in the alloy produce solid state transformations. These microstructural transformations cause changes in the material properties during the evolution of the process. The thermal strains that occur in the vicinity of the welding zone are elasto-plastic and the resulting stresses react, causing permanent distortions which also affect the dimensional integrity of the joint. At present, evaluation of weld joint requires mechanical testing and detailed metallographic examination of the microstructural differences at the weld region (Grajcar et al. 2014; Holovenko et al., 2013; Hu et al. 2013; Khan et al. 2008). Therefore, the proposed study on thermo-mechanical analysis of steel weld and microstructure represents an important research problem.

Critical monitoring of welding process is central to achieving high strength permanent weld joint in metals. Previous studies assisted in rapid development of welding processes, proper welding skills, appropriate welding technologies for the various types of metals/alloys, and some practical solutions to weld defects which helped to minimize the most fundamental problems (Calik, 2009; DeCost et al. 2019). The present study noted that the most reliable suggestions to a specific weld problem are those based on detailed consideration of the thermo-mechanical properties of the weld materials such as; heat capacity, thermal conductivity, rheological properties, thermal expansion, strength, fracture, melting/freezing point, latent heat, thermal durability, hardness, resistance for abrasion and surface energy (Kou, 2003; Li et al. 2019; Merchant, 2015). Heat capacity and thermal conductivity are the main properties characterizing heat transfer in materials. Heat capacity is a measure of the ability of a material to absorb heat energy under the heating and to emit heat energy under the cooling while; thermal conductivity is heat flux through material layer with unit thickness when the temperature of the material opposite sides of the layer differs by 1 K (Ohkita& Oikawa 2007; Papa et al 2011). Rheological properties describe relations between internal stresses of materials and their deformations or strains. The most popular ones include; elasticity, viscosity and plasticity. Weld problem is somewhat complicated when the base metals (or alloy) show regional diversity in the chemical compositions (as in dissimilar metals/alloys, or different alloys of the same metals) due to differences in these thermo-mechanical properties (Azimi et al. 2018 Elangovan et al. 2013).

II. Experimental Procedures

A mild steel stock selected from the SAE10XX class was used to fabricate four pairs of rectangular plates, each measuring 200 mm by 100 mm by 6 mm.Prior to welding, the samples were analyzed for their chemical composition and relevant mechanical properties. The chemical composition of the specimen was analyzed using OES after a thorough polishing. For the thermal process, one pair of steel samples was utilized to analyze each of the four demarcated heat transfer zones (BM, WL, BL and HAZ). An arc welding machine (Fronius Model- NW2200) was used for the welding operation and the welding was carried out along the 200 mm edge in a butt joint squared groove. The surface of the plates was cleaned with a cotton ball dipped in acetone before welding to remove any stains and dirt on the surface. At every step, each pair was arranged on a workbench with a 1 mm gap between the segments. Only one part of the pair was clamped to monitor natural distortion and material distortionin the second segment which was free throughout the welding period. The machine is equipped with voltage (23 V)/current (90A) regulators and a multi-meter display that allowed the welding power to be prescribed appropriately. Three sets of high configuration digital optical thermometers were focused at the three marked points in the fusion zone (FZ) at a distance of about 2 m from the back of the specimen. While three sets of thermocouple devices strongly clamped at the back of the specimen were used in the other zones of heat transfer for convenience. To start the welding the electrode was placed at the origin (0,0,0) for a few seconds to ensure complete joint penetration and then moved forward along the welding direction using the specified welding speed of 1 mm/s. The process was monitored over the entire welding duration of about 180 s. During the welding, the instantaneous temperature readings recorded by the infrared (IR) thermometer or thermocouple devices were captured using a high-speed video camera (Panasonic Full Hd Camcorder-50x) focused on the digital display screens. After welding, the samples were allowed to cool under the prevailing environmental condition. Visual inspection was used to monitor macro defects and material distortion after deslagging. After allowing the specimen to cool down to room temperature the maximum distortion of the free steel segment was measured using a verniercalliper. Tensile testing of the samples (before and after welding) was conducted following the ASTM E8 standard with a gauge length of 25 mm. The hardness values of the samples before and after welding was determined using a Brinell Hardness Tester on the BM and WL using ASTM E10-14 standard testing procedure carried out in the Mechanical Engineering Workshop Nnamdi Azikiwe University.

III. Results and discussion

Mechanical and chemical characterization of the steel plate

The mechanical test results obtained are presented in Table 1. To quantify the effects of welding on tensile strength and hardness, Table 1 presents the properties of the alloys studied. These properties are affected by welding by increasing the hardness and decreasing yield strength (YS), ultimate tensile strength (UTS) and breaking strength (BS). The hardness of the material increased after welding, which means that other mechanical properties were degraded.

Table 1: Mechanical test results of the steel sample

Description	Elastic load	Yield load	Maximum load	Breaking load	Hardness (HB)
Load (N)	6500	7554	9767	9067.4	$BHN = {}^{2P}/_{\{\pi D[D^2 - (D^2 - d^2)^{1/2}]\}}$
Extension (mm)	1.30	2.40	5.30	6.50	
Initial length (mm)	30.45	30.45	30.45	30.45	
Final length (mm)	32.32	32.87	36.34	38.42	
	Elongation (%)	**YS (N/mm^2)**	**UTS (N/mm^2)**	**BS (N/mm^2)**	
Before welding	25.42	275	360	330	106
After welding	20.4	243	314	-	140

In addition, the chemical composition of the specimen was also analyzed using OES after a thorough polishing. Table 2 summarizes the chemical composition test results for the steel sample. These results led to an AISI–SAE classification of the steel sample as SAE1017. The material is considered mild steel because it has a low carbon content and is generally used in structural applications. There is no doubt that mild steel is one of the most popular types of steel for structural applications due to its important properties

Table 2: Average chemical composition (%) result for the steel sample.

Element	Carbon	Manganese	Silicon	Sulphur	Phosphorus
Percentage	0.18	0.67	0.4	0.06	0.04

Microstructural Analysis

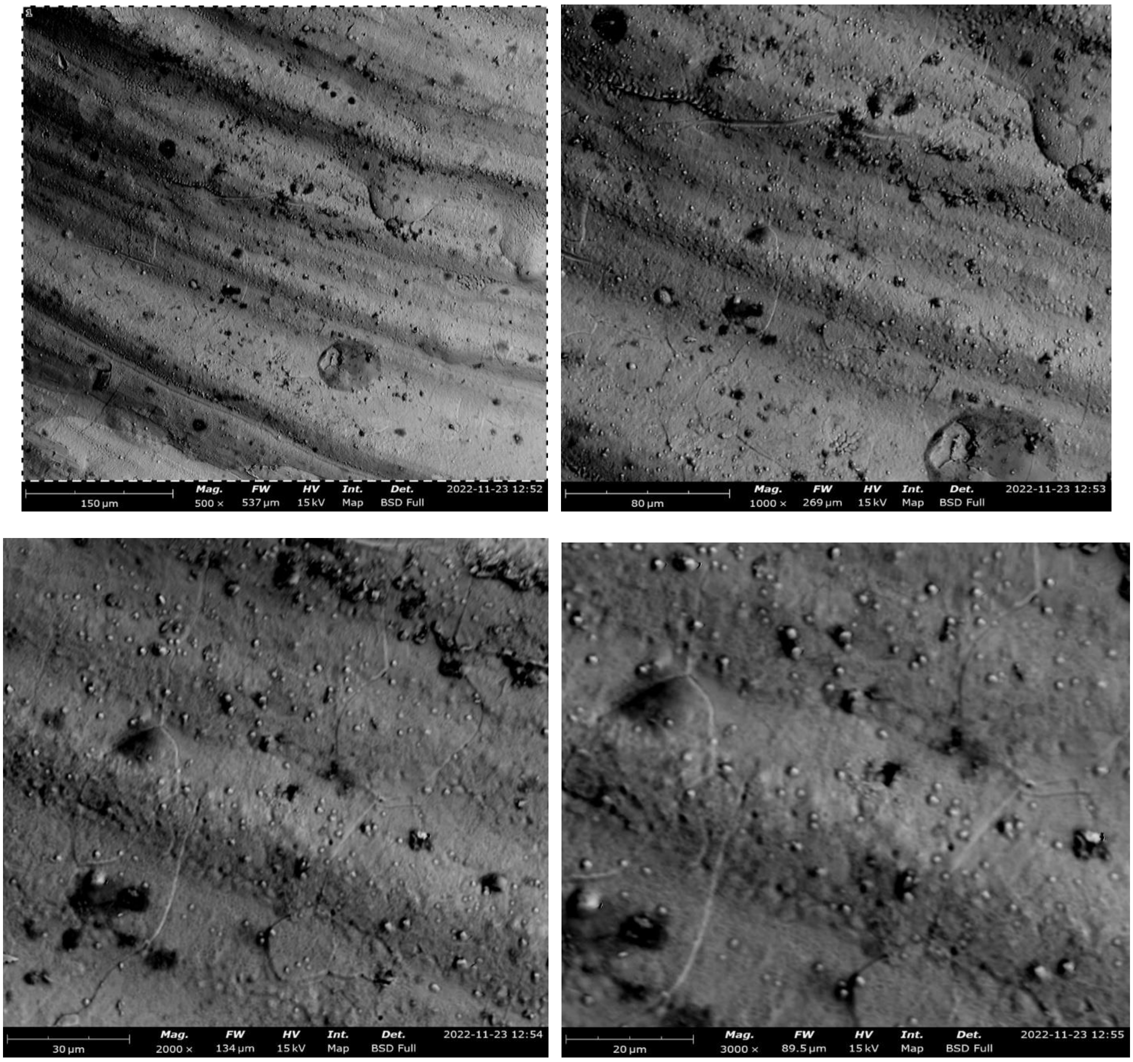

Figure 1: Microstructure of weld zone (a) 500x, (b) 1000x, (c) 2000x and (d) 3000x

The microstructure investigation of the welded mild steel plates has been performed by the help of scanning electron microscope. The microstructure study was done as shown in the Figure1to show the heat input increases resulted in formation of more grain in difference magnifications. From the figure, it can be clearly seen that the coarser grain structure is formed in fusion zone. The temperature in the fusion zone is having more than the melting temperature of the metal so a new coarse grain is formed after welding. As a result of high temperature recrystallization, fine grains are formed in the HAZ, which have a high hardness and toughness value.Consequently, there is drop-in cooling rate that produces coarse grain. The lower hardness and low strength and increase in porosity of the weld bead are caused by the coarse grain in the microstructure.

IV. Conclusion

The results of this research helped the research team to arrive at the following conclusions: Mild steel workpieces will be permanently distorted when joined using the arc welding method.Arc welding distortion is a function of the power of the heat source, the welding speed, clamping conditions, and the cooling rate of the welded workpiece after welding.Degradation of important mechanical properties such as; yield strength, ultimate tensile strength and breaking strength associated with steel weld is predominant in the weld area including the weld line (WL), the fusion zone (FZ) and the heat-affected zone (HAZ).

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