

Application of Local Mechanical Tensioning and Laser Processing to Modify the Residual Stress State and Microstructural Features of Multi-Pass HSLA Steel

Jibrin Sule and Supriyo Ganguly
Cranfield University

ABSTRACT

In a multi-pass weld, the development of residual stress to a large extent depends on the response of the weld metal, heat affected zone and parent material to complex thermo-mechanical cycles during welding. Previous investigations on this subject mostly focused on mechanical tensioning or heat treatment to modify the residual stress distribution in and around the weld. In this research, microstructural refinement with modification of residual stress state was attempted by applying post weld cold rolling followed by laser processing. The hardening of the weld metal was evaluated after welding, post weld cold rolling and post weld cold rolling followed by laser processing. The residual stress was determined non-destructively by using neutron diffraction. Hardness results showed evidence of plastic deformation up to 4 mm below the weld surface. In residual stress analysis, the result indicated that, up to 4 mm below the weld surface, post weld cold rolling was effective in changing the longitudinal residual stress distribution, modifying the stress state from tensile to compressive across the weld center line. Post weld cold rolling followed by laser processing was carried out to induce recrystallization of the cold rolled grains. Microstructural characterization indicates some grain refinement near the capping pass, however, laser processing reinstated the as-welded residual stress distribution and profile. The stress variation in as-welded state, showed diminishing longitudinal peak stress magnitude through the thickness from cap to root pass.

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INTRODUCTION

Multi-pass fusion welding by a filler wire is normally carried out to join thick steel sections used in most engineering applications. Multiple thermal cycles from a multi-pass weld, creates a graded structure with a newly formed weld metal and heat affected zone where the microstructural features and mechanical properties are significantly different from the parent metal. This also resulted in a variably distribution of residual stress field across the weld and through the thickness.

Welding residual stresses are thermal stresses which are primarily cooling stresses with possibly superimposed transformation stresses [1, 2]. These transformation stresses are formed as a result of volumetric mismatch which occur during transformation of austenite to ferrite during the cooling cycle.

Residual stresses can be beneficial or detrimental depending on whether it is tensile or compressive and its magnitude and distribution with respect to the service induced stresses. Weld thermal cycle induced residual stresses are tensile in nature in the weld metal and near heat affected zone which becomes compressive near the far heat affected zone and the parent metal. The peak magnitude of such stress is observed in the longitudinal direction which is along the

length of the weld. Evaluation of residual stresses is essential for the structural integrity of an engineering or structural component. The presences of tensile residual stresses have been reported to accelerate stress corrosion cracking and fatigue crack growth rates [1], [3, 4, 5]. Therefore, the knowledge of the nature and magnitude of residual stresses in a weld joint is important in avoiding distortion, and to prevent premature failure due to in-service degradation mechanisms such as fatigue and stress corrosion cracking.

Fatigue and stress corrosion cracking are surface sensitive phenomena [6] and often initiation of such crack depends on surface residual stress state and therefore, evaluation of surface residual stress is considered adequate. However, in multi-pass welds which has relatively thick thickness; the concept of fracture mechanics [7] necessitated the understanding of complete through thickness stress profile as understanding crack propagation in the variably distributed residual stress state is vitally important to assess the service life of a component. As for example, cracks generated on the surface of a component will not propagate through the thickness, if compressive stresses are present below the surface. However, in case of tensile residual stress field, the crack propagation will hasten and therefore, an accurate knowledge of the stress magnitude and distribution is important in assessing the service life.

A number of methods have been used to mitigate the effects of residual stress. These include; post weld heat treatment, shot peening, and modification of the structural configurations and the implementation of thermal tensioning techniques [8, 9, 10]. The application of post weld cold rolling to reduce weld residual stress and distortion for a thin plate is in practice for many years [11, 12, 13]. Recent works by Coules et al [14] and Altenkirch et al [15] have shown that the post weld rolling methods was effective in reducing residual stresses in single pass welds. However, application of this technique on multi-pass welds is not yet reported.

Post weld heat treatment (PWHT) is used on welded components to reduce the tendency of catastrophic failure through its effect on microstructure and phase composition, residual stress or a combination of both [16]. Post weld cold rolling followed by laser processing presented in this paper is to see the possibility of recrystallization and formation of new set of strain free high angle grains with random orientation. Generation of such microstructure would increase the strength and toughness of the material which is lower in as-welded state due to the formation of dendritic grain structure.

There are no reported works in the literature concerning the application of post weld cold rolling followed by laser processing of weld metal in a multi-pass weld. The aim of this research is to apply a novel technique of local mechanical tensioning (post rolling method) followed by laser processing to modify the stress field and refine the microstructural constituents in a multi-pass high strength low alloy (HSLA) steel weld.

EXPERIMENTAL PROCEDURES

Material

The material used for this study is API 5L X100 pipeline steel plate and the filler wire used is Union MoNi (1.0 mm diameter). Table 1 shows the chemical compositions of the pipeline steel plate. Table 2 shows the chemical compositions of the filler wire. The shielding gas used was 92% Ar and 8% O₂ at flow rate of 30 l/min.

The dimension of the test piece is (300 × 150 × 20) mm which was machined out from the X100 pipeline steel plate. A narrow groove edge preparation of 5° angle with backing bar was made as shown in Figure 1. The gap between the two plates was kept at 5 mm as shown in Figure 1. The bevel was filled with six (6) welding passes.

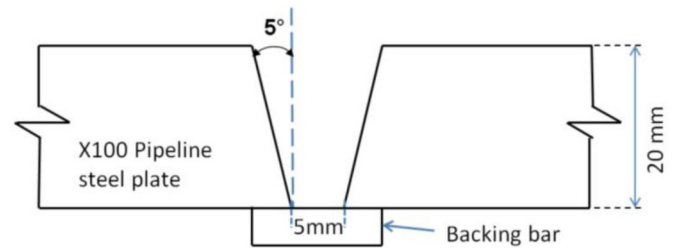


Figure 1. Pipeline steel plate set-up with backing bar

Experimental Method

Welding

An optimized Tandem Gas Metal Arc Welding torch as shown in Figure 2 was used for welding. The contact tips were fed by two independent power sources and two independent wire feeding units. During welding the lead arc determines the depth of penetration while the trail arc controls the final weld bead shape and reinforcement [17]. Significant research on this welding process has been reported and can be found in [18, 19]. The welding parameters are shown in Table 3.

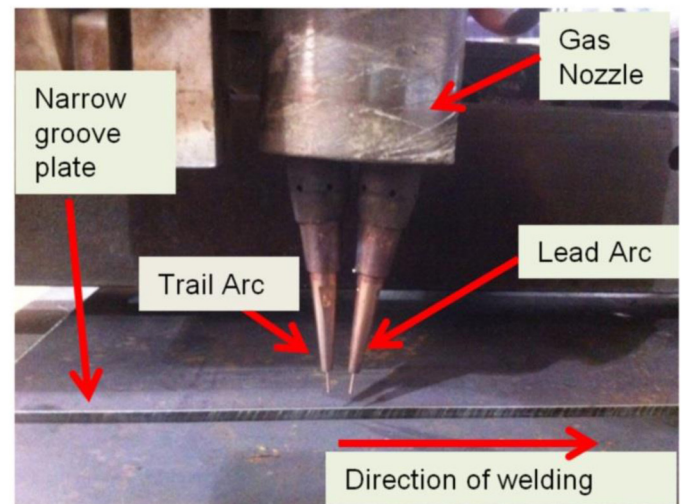


Figure 2. Typical tandem GMAW torch

The heat input in table 3 was calculated using equation 1.

$$\text{Heat input} = \left(\frac{\text{current} * \text{voltage} * \text{efficiency}}{\text{travel speed}} \right)$$

(1)

An efficiency factor of 80% was used [1].

Table 1. Composition of the pipeline steel plate

C	Si	Mn	P	Mo	Ni	Al	B	Cu	Nb	Ti	V	Cr	S
0.06	0.25	1.79	0.016	0.16	0.13	0.03	<0.0005	0.27	0.03	0.01	0.04	0.03	<0.003

Table 2. Composition of the filler wire.

C	Si	Mn	P	Mo	Ni	Cu	Cr	S	Others
0.12	0.4 - 0.8	1.3 - 1.9	0.015	0.25 - 0.65	0.8 - 1.3	0.3	0.15		



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Table 3. Welding parameters on narrow groove welds.

Passes	Travel speed (m/min)	Lead			Trail			Heat Input		
		Wfs (m/min)	Av. Current (A)	Av. Volts (v)	Wfs (m/min)	Av. Current (A)	Av. Volts (v)	Lead Heat input (kJ/mm)	Trail Heat input (kJ/mm)	Total Heat Input (kJ/mm)
Root pass	0.9	11	193.3	20.3	11	116.2	44.5	0.24	0.14	0.38
Fill 1	0.9	12	191.9	21.5	12	177.7	21.7	0.26	0.24	0.50
Fill 2	0.9	13	209.3	22.21	13	192.3	21.7	0.29	0.26	0.55
Fill 3	0.9	14	226.6	21.9	14	195.6	21.3	0.31	0.26	0.57
Fill 4	0.9	15	231.7	23.9	15	184.4	22.9	0.34	0.27	0.61
Cap pass	0.7	13	215.0	21.5	13	168.7	21.4	0.37	0.29	0.66

Local Mechanical Tensioning (Rolling)

The rolling machine is capable of rolling with a constant force. The principle of operation of this machine is that, the hydraulic cylinder applies a vertical force through a single roller supported in a fork assembly. The roller is made from hardened BS 4659 BH13 tool steel. It has an effective width of 30 mm and its diameter is 100 mm. The welded plates were firmly clamped on the base plate of the rolling rig as shown in Figure 3, while the crossbeam with the roller, is translated by a linear drive system. Post weld cold rolling was carried out on the capping pass of the multi-pass weld using a rolling load of 150 kN with constant travel speed of 0.7 m.min^{-1} . A flat roller was used and under all rolling conditions, the rolling force was applied on the top of the weld metal. The roller did not touch the plate surface on either side of the weld.

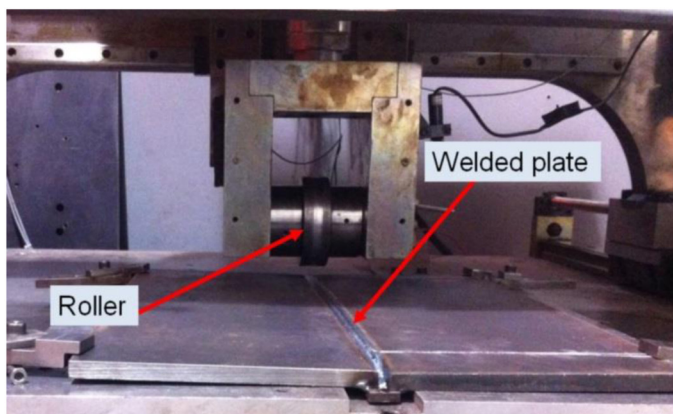


Figure 3. Photograph of the rolling set-up

Laser Processing

An IPGYLR-8000 fibre laser machine was used for laser processing. The laser beam was transmitted to the laser head through an optical fibre of 300 μm diameter. Laser beam was collimated using a lens of 125 mm focal length. After collimating, focusing lens of 250 mm focal length was used to focus the beam. This would produce a spot size of 0.61 mm at the focal point. However, the laser in this specific experiment was used to increase the temperature at a controlled rate and a defocused beam of 20 mm spot size was used on the sample surface as shown in Figure 4. The vertical distance for defocussing was determined using a beam diagnostic system. The laser head was positioned at 10° angle to avoid any back reflection which could

damage the lens. This laser processing parameters viz. the laser power and travel speed was designed to ensure that the weld metal was heated to a pre-determined temperature to avoid excessive input of thermal energy and to avoid re-melting. As mentioned in the introduction section, the purpose of laser processing is to induce recrystallization after cold rolling the weld metal. Localized cold rolling of the weld metal resulted in local plastic deformation which not only introduces strain energy but also relaxes the tensile residual stress state that formed from the thermal energy applied during welding. Application of laser on the other hand was to induce recrystallization; however, excessive application would result in reinstating the residual stress state which was removed during cold rolling. Therefore, application of laser needed to be precise to achieve a controlled rise in temperature.

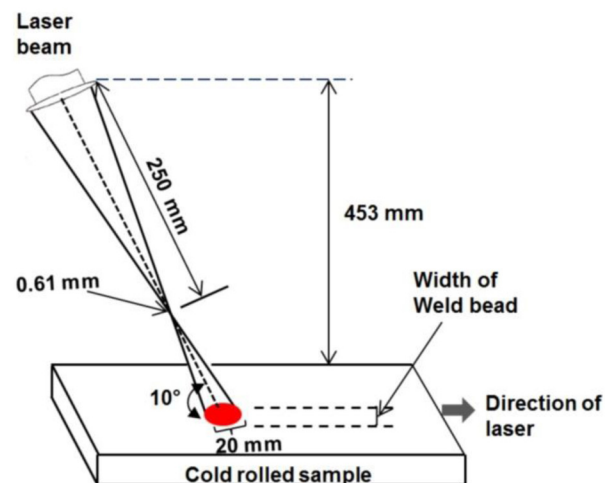


Figure 4. Schematic set-up of laser

Experimental Measurement

Weld Thermal Cycles Determination

Thermocouples were used to measure the temperature-time relationship of the weld metal with the aid of a Scopecorder 750 instrument. Three holes were drilled through the plate thickness (from backing bar) to the weld metal into which K-type thermocouples were placed. The thermocouples were placed at 0.5 mm, 2.0 mm and 3.5 mm below the weld surface respectively. Laser travel speed of 0.3 m.min^{-1} was used in combination with laser powers of 1.5, 3.0, 4.0 and 6.0 kW.