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Mitigating distortion and residual stress by static thermal tensioning to improve fatigue crack growth performance of MIG AA5083 welds

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ABSTRACT

The demand for lightweight structures in ship fabrication to improve performance and fuel savings has led to increasing use of thin-section structures. However, welding such structures often produces problems such as distortion and residual stress. The present investigation is aimed to mitigate distortion and residual stress using static thermal tensioning (STT) to improve fatigue performance in AA 5083 metal inert gas (MIG) welded joints. The STT treatments were performed by cooling the weld zone and its adjacent area during welding whereas both sides away from the weld were heated at various temperatures of 100, 200 and 300 °C to generate thermal gradient. Subsequent experiments including distortion measurements, microscopical examination, hardness and tensile tests, measurements of residual stresses using neutron diffraction method and fatigue crack growth tests combined with SEM fractography were conducted. Results showed that an increase in heating temperature reduced convex longitudinal out of plane distortion. The minimum longitudinal out of plane distortion was achieved at a heating temperature of 200 °C owing to the balance between buckling distortion induced by welding and that generated by static differential heating which opposed the weld distortion. Under such condition, fatigue crack growth performance was improved.

1. Introduction

Aluminium-magnesium alloys designated as 5xxx series alloys have been widely used in marine applications such as ship structure and superstructure of ocean-going vessels due to their lower weight, relatively high strength and excellent corrosion resistance. One of these alloys is AA5083 that is Al-4.5%Mg-1%Mn alloy where its strength is resulted from solid solution strengthening due to magnesium additions and strain hardening [1]. Moreover, this alloy is considered to have good weldability since it has hot cracking resistance and meets required mechanical strength at the weld joint [2].

Welding is one of the most critical manufacturing processes in modern ship fabrication since a ship construction today consists of many structural elements that are welded during assembly. Among fusion welding processes, a metal inert gas (MIG) welding is the most common joining process for aluminium alloys [3]. To date, a trend in design and manufacturing practice is to use thin-plate structures to reduce product weight but welding such structures tends to increase distortion and residual stress. Buckling distortion often referred to out of plane distortion causes some problems, i.e. it reduces dimensional accuracy, it can cause loss of structural integrity and it increases manufacturing cost due to additional correction works [4].

A number of works has been carried out to study weld distortion and residual stress. It is known that weld heat flow studies which were initially treated using analytical approach [5–7] have become increasingly important as basic principles for understanding weld distortion and residual stress. Recently, the increase in computational power has enabled researchers [8–13] to apply finite element (FE) model to gain better quantitative understanding of distortion and residual stress which are important to develop distortion-controlled methods [14–15]. A particular attention is paid to in-process methods since they have advantages over conventional post weld correction techniques, i.e. the elimination of distortion takes place prior to and during welding process hence avoiding costly reworking operation after welding [16]. Currently, thermal-based in-process control methods which employ additional heating with and without cooling sources during welding are more desirable than those based on mechanical techniques. This is because thermal stretching generated by differential heating is more efficient compared to mechanical stretching which requires complex setup and large forces for large structures.

The application of thermal effect for mitigating weld distortion and residual stress prior to and during welding was first reported by Burak et al. [17,18] who developed thermal tensioning method, often known as static thermal tensioning (STT). This technique involves resistive heating bands located at both sides away from the weld whereas the weld zone is quenched simultaneously. The effectiveness of static thermal tensioning has been evaluated by Michaleris and Sun [19] using

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finite element analysis. According to the authors, thermal tensioning technique is able to reduce residual stress below the critical buckling level hence avoiding structural buckling. Consistent with this finding, Guo and Li [20] have reported that STT reduces longitudinal plastic compression in the weld resulting in lower distortion and residual stress.

Another approach known as transient thermal tensioning (TTT) has also been developed as an alternative distortion control technique [21–23]. Unlike STT, the TTT technique employs movingly localised heating sources to generate tensioning stresses without quenching. Furthermore, Guan [24] has categorised effects of thermal tensioning into two different types, namely the overall cross-section thermal tensioning and the localised thermal tensioning. In the former, the thermal tensioning which consists of preset cooling and heating is applied along the cross section of welded plates. This method is the modification of STT technique by employing 'two-point' finger clamping system termed as Low Stress No Distortion (LSND) whereas the latter is carried out by locating a cooling source following the moving weld torch to locally cool the weld. This new developed technique is known as Dynamically Controlled Low Stress No Distortion (DC-LSND). Recent investigations conducted numerically and experimentally have shown that DC-LSND is proved to be effective for control of distortion and residual stress [25–26].

In modern engineering practice, welded structures are often subjected to dynamic or fluctuating loads during service. Under such condition, the presence of tensile residual stress in the welded joints can promote fatigue failure at a stress below its static strength [27–29]. Current researches on thermal tensioning are mostly focused on mitigation of distortion and residual stress and there have been limited data on how these techniques, in particular static thermal tensioning (STT) to affect mechanical properties and fatigue performance of the welded structures. Therefore, it is the subject of the present investigation.

2. Experimental procedures

2.1. Welding conditions

In order to obtain experimental data with greater consistency, an automatic MIG welding equipment was employed in this investigation. The materials used were aluminium alloy AA5083 plates welded using a filler metal of ER5356 and their chemical compositions are given in Table 1. Two AA5083 plates having dimension of 400 mm × 100 mm × 3 mm were butt welded along 400 mm. The plates were clamped using simple supports as reported by Gray et al. [13]. Details of the filler material data and welding parameters used are given in Table 2.

The STT treatments were carried out by locating a cooling system underneath the weld zone and simultaneously, both regions away from the weld zone were heated using resistive heating bands at various temperatures of 100, 200 and 300 °C to generate thermal gradient as shown in Fig. 1. The cooling system was made of copper backing bars having drilled water passages to provide quenching. Three thermocouples, designated as TC1, TC2 and TC3 were attached to the welded plates at the distances of 10, 20 and 30 mm respectively from the weld centreline to monitor temperatures during welding. The STT-free welded plate specimens (as welded condition) and the specimens with quenching only were also produced for the reference welds.

Of note is that the cooling intensity should be carefully controlled to reduce out of plane distortion and residual stress effectively. Therefore, it is necessary to analyse heat energy source, heat loss and heat sink. In the case of welding with quenching only (heat sink welding), the heat energy transferred from the heat source to the cooling system as shown in Fig. 1 could be analysed as follows. Due to heat losses, the net heat energy (Q_{net}) during welding is given by:

$$Q_{net} = \eta Q_{in} = \eta EI \tag{1}$$

where Q_{in} is heat generated by welding (Watt), η is heat transfer efficiency, E is welding voltage (V) and I is welding current (A). A portion of the net heat energy is transferred to heat sink (Q_s) and the remaining heat energy (Q_r) is lost to the surroundings so that:

$$Q_{net} = Q_s + Q_r. \tag{2}$$

The heat transferred to heat sink is given by:

$$Q_s t_{weld} = \int_0^{\infty} mc[T_{out}(t)\text{-}T_{in}]dt \tag{3}$$

where m is mass flow rate of water (g/s), c is specific heat of water (J/(g.°C)), T_{in} is inlet water temperature (°C), T_{out} (t) is temperature of water leaving the copper baking bars which varies with time (°C) and t_{weld} is welding time (s). If the net heat energy (Q_{net}) is transferred completely to heat sink then the energy balance is given by:

$$Q_{net} t_{weld} = \eta EI t_{weld} = \int_0^{\infty} mc[T_{out}(t)\text{-}T_{in}]dt. \tag{4}$$

Referring to Eqs. (3) and (4), the cooling intensity could be determined by controlling mass flow rate and temperature of cooling water.

2.2. Distortion and residual stress measurements

The longitudinal out of plane distortions (displacement in Z-direction) in Fig. 2 were measured at the edge of the welded plates along a longitudinal direction (X-direction) using dial indicators.

Longitudinal and transverse residual stresses were measured using neutron diffraction technique at middle part of the welded plate length. The measurements were taken along transverse distance, starting from the weld centreline to the edge of the welded plate as indicated by the plane A-B in Fig. 2. The neutron beam with the wave length of 1.83375 Å was diffracted on (311) reflection at the diffraction angle (2θ) of 96.5°. Lattice parameters were measured in the x (longitudinal), y (transverse) and z (through-thickness) directions using a gauge

Table 2
Materials and welding parameters.

Filler material	:	ER5356
Wire diameter	:	0.8 mm
Wire speed	:	9 m/min.(150 mm/s)
Shielding gas	:	Argon (Ar)
Gas flow	:	14 l/min
Voltage	:	20 Volt
Current	:	100 A
Welding speed	:	10 mm/s
Water flow	:	1200 l/h

Table 1
Chemical compositions of AA 5083 plates and ER 5356 filler metals (wt%).

Material	Mg	Mn	Si	Fe	Cr	Cu	Zn	Ti	Al
AA 5083	4.5	0.65	0.26	0.22	0.09	0.09	0.06	0.03	Bal.
ER 5356	4.5–5.5	0.05–0.20	0.25	0.40	0.05–0.20	0.10	0.10	0.06–0.20	Bal.