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The Influence of GTAW Parameters on Micro-structure and Mechanical Behaviour of Austenitic Weldments—A review

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Abstract— In pressure vessel, there is a large need for joining austenitic stainless-steel weldments. These applications are mainly in fabrication of pressure vessels and several industries due to good beneficiary high strength at different temperature and excellent corrosion resistance. Nowadays, there is a great demand for austenitic welding practices due to its performance and economic benefits. Therefore, it is important to optimise the various welding parameters. In order to develop sound welds and achieve the optimum ultimate tensile strength and minimum heat input, the GTAW technique is considered as one of the most suitable process. Additionally, the microstructure also influences both the corrosion resistance and the mechanical properties to a significant degree. The aim of this paper is to review the efficiency of various GTAW parameters and their consequences on the properties of the weldments and heat affected zones, which if uncontrolled, could lead to mechanical failure and corrosion attack.

Index Terms— Austenitic stainless steel; GTAW parameters; heat affected zones (HAZ); heat input; microstructure; mechanical behaviour; ultimate tensile strength.

1 Introduction

The present paper surveys research work conducted on Gas Tungsten Arc Welding (GTAW) of austenitic stainless steel. Different welding parameters such as welding current, voltage, polarity, gas flow rate, welding travel speed and arc length change the properties of weld produced through GTA welding. Major areas of research have been in the characterisation of the weld, dissimilar welding, parameter optimisation. This paper provides the review of literatures provided by different researchers in context to the topic by highlighting the important conclusions and results. In the first section, the process description and materials selection will be discussed in details. After that, the main parametric effect of GTAW process on weldment will be discussed in detail.

1.1 Process Description

Gas Tungsten Arc Welding (GTAW), also identified as He-Arc Tungsten Inert Gas (TIG). In the late 1930s GTA welding was created when the need to weld particular material. Welding method is developed to fuse magnesium using the inert gas helium and a tungsten electrode. Argon gas soon became the most widely used shield gas because of its lower cost and smoother arc. This joining process replaced riveting as a process of constructing aircraft with parts made from aluminium and magnesium. To this day, the He-Arc welding has persisted with many refinements and name changes, but without any alteration in the fundamentals as reported by Olson et al. [1].

GTA welding provides a clean, durable weld joint that makes it suitable for assembling and repairing various special materials as high-quality welding aircraft components. in plain terms, it can be said that if the product has to be budget limited and long lifetime is desired, gta welding may be preferred as reported by devendran et al. [2]. GTAW is the most common welding technique that used to weld an austenitic stainless steel using a created arc between a non-consumable tungsten electrode and the base metals, as shown in fig1. the torch holding shown in fig1(b), tungsten electrode is connected to a shielding gas cylinder as well as one terminal of the power source. the tungsten electrode is normally linked from the terminal to the welding cable (cable 1). the work-piece is connected to the other power source terminal by an individual cable (cable 2). the shielding gas passes through the body of the torch and is directed by a nozzle to the weld zone for protection from the air. for this reason, gtaw looks a more appropriate fitting name for this welding process.

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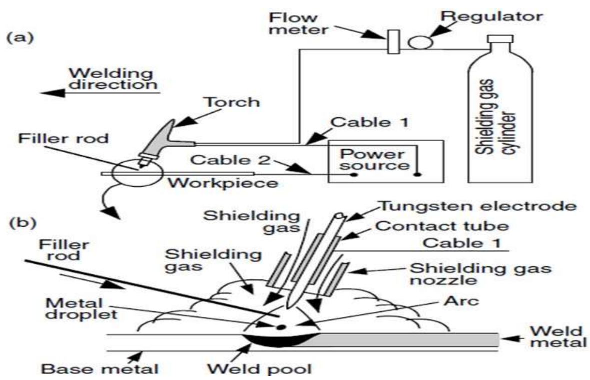

Fig. 1. GTAW: (a) Overall process; (b) Welding area enlarged

1.2 Stainless steel welding

Stainless steel is designated for corrosion prevention due to reactions with its surroundings which affect the essential properties in materials. Brien [3] recommended that majority of stainless steels can be joined by several welding processes such as arc welding processes, resistance welding, electron and laser beam welding, friction welding and brazing. Dawes [4] found that the coefficient of thermal expansion of austenitic steel is 50% higher than that of carbon steel which means that the expansion rate of stainless steel is greater than that of carbon steel which allows welded joints to deform. In general terms, the low thermal and electrical conductivity of austenitic stainless steel in GTA welding is desirable to reduce the probability of deformation. In this case, the final selection will be made based on the lowest cost material that will accomplish the service requirements of the company. Consequently, that austenitic types and higher grades of chromium typically have more resistant to corrosion than martensitic as reported by Kotecki and Armao [5]. Austenitic stainless steels are a category of steels that contain technically 19% chromium and 9% nickel. This category of steels exhibits a highly desirable combination of high strength, good ductility, excellent resistance to corrosion and a rational weldability as stated by Mirshekarni et al. [6]. Kumar et al. [7] recommended following the specified welding guidelines such as the steel grades, e.g. austenitic Stainless steel, chemical compositions and thermal elongation. Such parameters can increase weld deformation, depending on weld metal microstructure, that might be a potential chance of hot cracking and intermetallic precipitations compared to mild steels. The most common types of austenitic stainless steels used within this temperature range of nearly 600 °C (1110 °F) are the AISI 200 and 300 series. The alloying elements such as, chromium, nickel and silicon are selected to provide the desired properties and reasonable cost. Furthermore, specific alloy composition could have a significant influence on weldability and weld grain structure as reported by Olson et al. [1]. Apart from this, one of the key distinctions between ferritic stainless steels and austenitic stainless steels is in its structure because austenitic steels have FCC structure and ferritic steels have BCC crystal structure which obviously affects their mechanical and metallurgical behaviour.

2 THE MAIN PARAMETRIC EFFECT OF GTAW PROCESS ON WELDMENT

The sum of energy released by the arc is correlated to current and voltage. The amount of energy transferred per length of weldment is inversely proportional to the weld travel speed. In this way, as all of these variables firmly react with each other, they are difficult to manage as autonomous variables when designing welding method for construct specific weldments as reported by Brien [8]. Besides that, the microstructure, which is primarily responsible for the physical and mechanical properties of the metals, is influenced by the chemical composition and the heat input of welded joints. Additionally, alloy microstructure is characterised by the overall arrangement in a metal alloy of grains, grain boundaries, and phases occurring. The thermal and mechanical effects of welding will also alter the microstructure and may affect the service life of weld as found by Brien [3]. This section will discuss the main GTAW process parameters that affect the quality of welded joint. These parameters are; welding current, welding voltage, welding travel speed, shielding gas and microstructure.

2.1 Welding Current

Current is a flow rate, current is defined by the amount of electricity that flows through a cable in one second. The term ampere is the sum of current flowing in a circuit per second and the letter I is used to designate current ampere as reported by Helzer and Cary [9]. With conventional power sources, it is common practice for the GTA welding process to use constant-current static characteristics which are required for optimum striking and current stability as stated by Norrish [10]. The effect of welding current (as a heat input parameter) on the microstructure, could be create a coarse grain structure in HAZ, which negatively affect the mechanical properties as reported by Kurt and Samur [11]. Several researchers have studied the tensile properties, microstructure and fracture of welded joints of austenitic stainless steel to achieve optimum welding current setting; Singh [12] concluded that, based on the formula, as in (1) of the effect of joule, heat is directly proportional to current, resistant and time. The following equation is the effect of joule.

$$H = I^2 x R t \qquad (1)$$

Where (H = heat, I = current, R = resistant, t = time).

Moslemi et al. [13] explained how welding current effects on depth and width of welded metal by applying different welding current settings to an austenitic stainless-steel plate single V Butt weld joint, which reveals the macro morphology of welding joints under the different welding current. Obviously, increasing the arc welding current increases the depth and width of fusion weld metal. Ultimate tensile strength (UTS) and yield strength (YS) properties are typically influenced by welding parameters including welding current, Okonji. et al. [14] demonstrated that by using an austenitic stainless steel as a base metal and (GTAW) process with specified welding currents and austenitic stainless-steel filler metals, the final results show that for, higher strengths (UTS and YS) than that of the base metal for all the joints. However, for all filler metal types, the UTS and YS decreased with an increase in welding current parameter. In micro structure point of view, and as the current is a factor of Heat Input Formula, it is found that maximum tensile strength and ductility are regulated by the weld joints produced using low heat input. As heat input increases, the fusion zone and HAZ area also increase. Significant coarsening of grain is observed in the HAZs of all the joints (see fig 2-3). It is also observed that as Kumar and Shahi [15] achieved, the size of grain coarsening increases with increasing heat input during their experimentation.

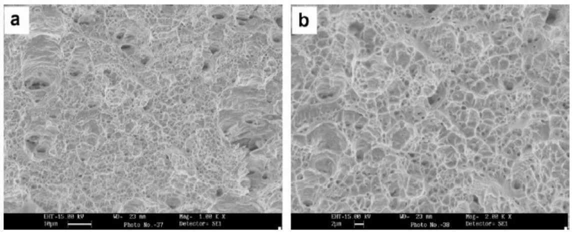

Fig. 2. SEM fractography of the tensile specimen welded at low heat input (a) at 1000X (b) at 2000X

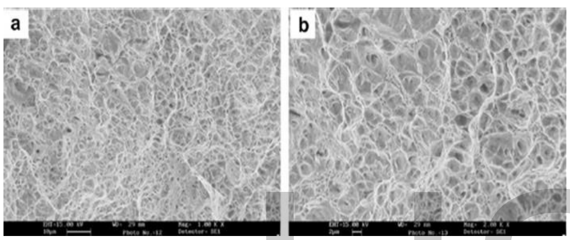

Fig. 3. SEM fractography of the tensile specimen welded at medium heat input (a) at 1000X (b) at 2000X

Vemanaboina1 et al. [16] investigated the effect of heat input on tensile strength of Multi-pass SS316L Using GTAW Process, the multi-pass butt joints were prepared with direct current using GTAW process. They found that, with the rise in heat input, the tensile strength in the weld decreased. While Moi et al. [17] have studied the effect of heat input on the mechanical and metallurgical characteristics of TIG welded joints. It was concluded that the value of micro- hardness value as well as tensile strength increases with increased heat input to a certain limit and subsequently begins to decrease, whereas the joint produced using medium heat input explains the significant increase in tensile strength, elongation percentage and hardness because of its finer grain structure. Sathish et al.[18] have a different perspective in their practice to investigate the weldability of carbon and austenitic stainless steel dissimilar pipe joints, findings show that lower heat input resulted in lower tensile strength and too high heat input also resulted in lower tensile strength. Balaji et al. [19] explained a different result by evaluate the mechanical properties of austenitic stainless steel joints welded by tungsten inert gas welding, micro-hardness revealed that, the lowest tensile sample had the highest micro-hardness.

2.2 Welding Voltage

Voltage is the force which causes flow of a current. In an electrical circuit, the voltage between two points is called the difference in potential. Using letter V to denote voltage as mentioned by Helzer and Cary [9]. Arc volt controls welding arc length and subsequent arc cone width and volume fig 4. Welding joints characteristics might be improved by rationally selecting welding parameters which including welding voltage in a GTA welding machine, increasing or decreasing welding voltage can lead to undesired results such as welding bead profile being wider or narrower because the arc cone becomes wider or narrower with voltage changes. Additionally, Arc voltage influences the arc length. As voltage increases, the arc length gets longer and the voltage decreases at the same wire feed speed as reported by Egerland [20].

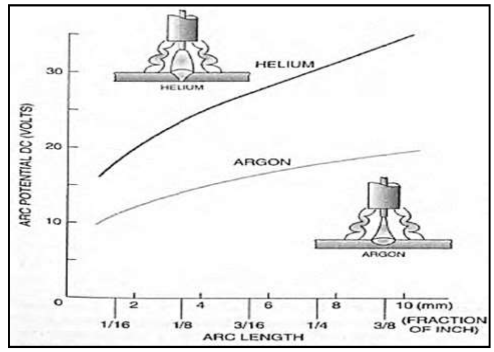

Fig. 4. Arc Voltage versus Arc length

Prabaharan et al. [21] found based on their research on parametric optimisation of GTAW processes, that welding voltage has an inverse effect on the deposit region of the weld. Accordingly increase in the welding voltage reduces the rate of deposition.
Ikpe et al. [22] studied the effects of arc voltage and welding current on the arc length of tungsten inert gas welding and concluded that, the higher the welding current and arc voltage resulted in a longer arc length creating unstable welding arc, decreased penetration, increased spatter, flatter and wider welds, and prevented shielding gas from protecting the atmospheric contamination of the molten puddle. Choubey and Jatti [23] studied the effect of heat input and their conclusion was the tensile strength of austenitic stainless steel decreases with an increase in welding parameters (current, voltage, and welding travel speed). Devakumar and Jabaraj [24] states that lower heat input was preferred when welding austenitic stainless steel using GTAW process because it gave good tensile strength, ductility and produce higher impact strength values about 10% compared to SMAW joints and 20% compared to GMAW joints. Furthermore, the size of the HAZ and coarsening of grain acquired at the welded joints was minimal.

2.3 Welding Polarity

The GTAW process typically uses an arc of direct current (DC), where the tungsten electrode has a negative polarity. The tungsten electrode thus becomes the cathode, and the work-piece becomes the anode. The polarity is called straight polarity, or Direct Current Electrode Negative (DCEN). Reverse polarity, or direct current electrode positive (DCEP), is literally DCEN's reverse where the tungsten electrode has a positive polarity. Since most of the heat is produced at the anode in the GTA welding process, DCEP is commonly applied to weld some thinner metals, low melting temperature materials whereas DCEN is used to give excessive penetration. Alternating current or ACEP is often used for take away an oxide film from the weld pool or work-piece surface.

Using a straight polarity (DC-), generates a deep penetrating weld is so practical as found by Kotecki and Armao [5]. A filler metal can be used directly into the melted metal zone either in the form of rods or in the form of the wire using a mechanised reel, allowing pre-heating of the filler metal to increase the deposit rate, where appropriate as found by Blondeau [25]. In almost all cases, the negative electrode (cathode) direct current is selected. In fig 5, the welding characteristics of DCEN, DCEP, and balanced alternating current are shown. When DCEN is used with a thermionic electrode such as tungsten, around 70% of the heat is produced at the anode (work-piece) and at the cathode (electrode) around 30% as reported by Brien [8].

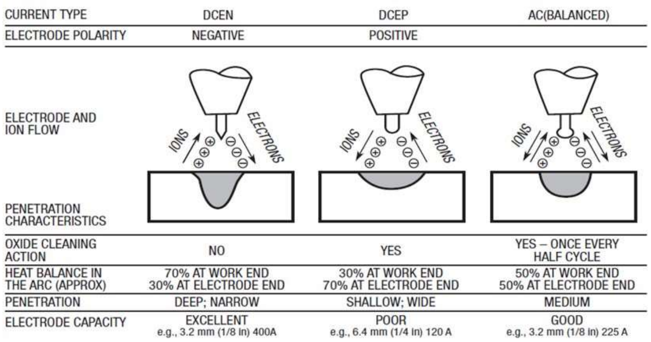

Fig. 5 Characteristics of Current types for Gas Tungsten Arc Welding

Thakur and Chapgaon [26] stated that, welding polarity affects the depth of penetration. DCEN polarity provides deep penetration, while DCEP provides shallow penetration. Kutelu et al. [27] discussed the impact of welding polarity by reviewing GTAW welding parameters on welding travel speed. Most GTAW welds using direct current on the negative electrode (DCEN) (straight polarity), as it generates higher weld penetration depth and higher travel speed than on the positive electrode (DCEP) (reverse polarity). Jeyaprakash et al. [28] studied the effect of polarity in a review paper on the parameters and equipment used in TIG welding to minimise the tungsten electrode temperature. DCSP - Direct Current Straight Polarity, tungsten connected to the negative terminal, only 30% of the welding energy (heat) will be provide. It means that, tungsten will run much cooler than DCRP.

Stenbacka et al. [29] examined the arc efficiency values influenced by gas tungsten arc welding process. It is necessary to know how much of the energy is really transferred to the work-piece being welded. Arc efficiency is also known as the process efficiency or the thermal efficiency or the heat transfer efficiency. This efficiency plays significant role in many areas of welding technology. Arc efficiency GTAW (DCEN) values, calculated from modelling program and simulation studies have increased over the years, and approaches values determined in calorimetric studies.

2.4 Welding (Travel)Speed

Welding speed is the rate of the electrode travels along the seam or the rate at which the work under the electrode travels along the seam. When the welding travel speed is very fast, the bead is too small and the penetration is minimal. A lower speed is needed when the work-piece is cold; as the work-piece absorbs heat and increases in temperature, the travel speed should be increased as found by Helzer and Cary [9]. Welding speed is an important parameter when welding by GTAW process. Increasing the welding speed for the same current and voltage decreases the heat input and effects on metallurgical and mechanical behaviour of metals. The following heat input formula (2) describes the numerical relationship between the basic parameters of welding such as (welding current, welding voltage and travel speed) as stated by Kutelu et al. [27]

$$H = \eta \; (IxV) \; / \; s \qquad (2)$$

Where, H = heat input in KJ/mm,
η = efficiency = 0.60 for GTAW,
V = voltage in volts,
I = current in amperes,
S= welding speed in mm/sec.

Abioye [30] clarified that heat input has an effect on the welding geometry size of AISI 304 electric arc weldments. fig 6 reveals the influence of the travel speed of welding and welding current on the weld bead width. The bead width was measured and it was discovered that, the bead width decreases as well as the energy per unit length at high welding travel speed.

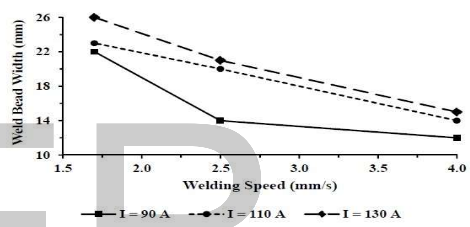

Fig. 6. The variation of the weld bead width with the speed and current

Thakur and Chapgaon [26] studied the effects of GTAW process parameters on weld through their review paper. They added a new finding that the increase in welding travel speed decreases the penetration depth and width of the bead. Javed et al. [31] have researched the influence of welding speed on tensile strength of welded joint in TIG welding process. In this research, Tensile strength is higher with lower weld speed. Additionally, weld metal hardness may be effected by changing of welding speed range as Chuaiphan and Srijaroenpramong [32] stated in their experimental paper studying the impact of welding speed on micro-structures, mechanical properties and corrosion behaviour of GTA welded austenitic stainless steel metals. They reported that, by all joints, weld metal's hardness is lower than that of base metal and it is also noticed that, the weld metal's hardness values increase with increasing welding travel speed.

2.5 Shielding Gas

The GTAW process typically uses an inert gas to shield the molten metal pool, filler rod, HAZ from atmospheric contamination. In all cases, the arc and electrodes are protected by gas, typically an inert gas or a gas mixture. Mixtures of argon and argon-helium are most commonly used, while argon-hydrogen mixtures are used for specified applications. A composition of the shielding gas has a very strong effect on the distribution of arc temperature and weld pool shape. Pure argon is used for welding of ultra-thin steel. Argon typically provides an arc that works smoothly and softly. Arc Penetration is less when using argon than the arc gained by using helium as mentioned by Bhavsar and Patel [33].

Only argon and helium are used because the other inert gases are much expensive besides that, the selection of gas type is depend on the metal to be welded. Argon is easily available and heavier than helium and a bit heavier than air, which allows for arc shielding at lower flow rate to be more an efficient.
In GTA welding of austenitic stainless steel in the hydrogen-argon mixture it is possible to achieve stable process and reliable welded joints with very clean surface. The argon shielding gas can be applied up to 20 % of hydrogen as achieved by Tusek and Suban [34].
Javed et al. [31] listed the perfect effects of shielding gases blend on welding of stainless steel. Pure argon is ideal for all metals, a mixture of argon-helium-hydrogen that provides lower ozone emissions, reduces amount of surface oxidation, improves weld performance, welding speed and welding penetration. Otherwise, Kumar and Bharathi [35] explained some features to use a new shielding gas technique of active shielding gas (A-GTA) welding which could increase the joint penetration and weld depth-to-width ratio. Lu et al. [36] demonstrated that, when the argon content in the He-Ar mixed shielding is less than 30%, the shielding gas to protect the weld metal from the atmosphere is poor, and the surface of weld bead is dirty and oxidised. The He gas shielded GTA welding arc ignitability and stability can be greatly improved when Ar gas is mixed into the He shielding. Kah and Martikainen [37] studied the influence of shielding gases in the welding of metals. In austenitic stainless steel, increasing the amount of nitrogen in the shielding gas increases ductility and improves the tensile strength, hardness and pitting corrosion resistance of the weld. The gas flow rate had considerable impact on the quality of austenitic stainless steel welds. Anawa et al. [38] studied the weldability of austenitic stainless Steel, they proved that, the gas flow rate was demonstrated to be directly proportional to impact and tensile strength.

3 Research trends

In this paper, many researchers have used welding current as the essential welding parameters which have a major impact on the micro structure and mechanical properties of welds. Whereas welding speed has almost the same importance.

4 Conclusion

The percent review paper studied the effect of gas tungsten arc welding parameters on the microstructure and mechanical behaviour of austenitic stainless-steel pressure vessel material. Based on the review, the following important conclusions are achieved.

- Increasing the arc welding current would increase the deposition rate, depth and width of fusion weld metal and decrease the ultimate tensile strength (UTS), yield strength (YS) whereas micro-hardness and grain coarsening would increase sequentially.
- Increase of the welding voltage will lead to increase the arc length and reduce the rate of deposition and penetration depth, then prevented shielding gas from protecting the atmospheric contamination of the molten area.
- DCEN polarity provides deep penetration and higher travel speed. While DCEP provides shallow penetration, slow travel speed and low arc efficiency.
- At high welding travel speed the bead width decreases and the energy per unit length and penetration depth as well. Furthermore, the hardness value of weld metal will increase and ultimate tensile strength will reduce.
- The gas flow rate is directly proportional to impact and tensile strength. Moreover, Increasing the amount of nitrogen in the shielding gas thus increases ductility and enhances the tensile strength, hardness and pitting corrosion resistance of the welded joints.

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