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Dissimilar metal welding using Shielded metal arc welding: A Review

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Abstract— One of the fabrication technique is welding. Based on Material, welding can be divided into welding the same Material (similar welding) and welding with different materials (dissimilar welding). Based on the joining process, welding can be divided into arc welding with wrapped electrodes (SMAW), submerged arc welding (SAW), gas arc welding (GMAW), tungsten arc welding (GTAW) and others. This study presents a review of dissimilar welding with the Shielded Metal Arc Welding (SMAW) process. Dissimilar welding has been applied in various industries such as automotive, power plant, construction, etc. SMAW Method is one of the methods for dissimilar welding is used for this paper. SMAW is a procedure that uses an arc to accomplish the weld between a covered electrode and a weld pool. This paper aims to contribute and improve the basic theory of dissimilar welding, especially the SMAW method. This paper also explains the SMAW welding process, the equipment used, and the Material and electrodes used. As a result, this review showed the SMAW process capable of welding dissimilar Material due to easy and simple equipment. It can be used for all metal combinations on dissimilar welding likely low carbon steel and stainless steel, or stainless steel and stainless steel, etc. Weld quality can be performed with a destructive test (hardness, bending, and tension test), Microstructure (SEM and EDS), and non-destructive test (Magnetic particle, radiography, ultrasonic test). Furthermore, the effect of dissimilar welding with the SMAW process on microstructure and mechanical properties will be investigated.

Keywords— Fabrication; Dissimilar Welding; SMAW; Non Destructive Test (NDT); Destructive Test (DT)

1. Introduction

Metal fabrication is a process of metal production, which includes engineering, design, cutting, forming, joining, assembling, or finishing. In technical terms, this activity refers to metal building structures with stages of cutting, bending, and assembly. Metal fabrication techniques are usually preceded by refining, alloying, and often heat treatment processes, which produce alloys with desirable characteristics. Classification of fabrication techniques includes various methods of metal forming, casting, powder metallurgy, welding, and machining. Often two or more of these methods must be used before certain parts are finished. The method chosen depends on several factors; the most important are metal properties, size and shape, and cost [1]. One of the fabrication technique is welding. Welding according to the welding handbook [2], is a process that causes between two different metals to become one unit involving atoms that are on edge adjacent to the edge atoms that are on the other parts so that bonds occur between atoms. According to Harsono [3], welding is the local joining process of two or more metals that involve heat. In general, the welding process can be used for the construction industry, including railroads, bridges, shipping, steel frames, and so forth. Based on the joining process, welding can be divided into arc welding with wrapped electrodes (SMAW), submerged arc welding (SAW), gas arc welding (GMAW), tungsten arc welding (GTAW) and others. Welding based on welding material can be divided into welding the same material (similar welding) and welding with different materials (dissimilar welding) [4].

Dissimilar welding is widely used in the construction industry, such as making boilers, making rig towers, making automotive components, and so on [5]. In principle, dissimilar welding uses a base metal with different content in it, for example, welding between stainless steel and carbon steel or between duplex and carbon steel [6]. The purpose of dissimilar welding is to unite several metal properties to reduce material costs and increase equipment reliability [7]. Researchers have researched dissimilar welding. According to Dewin Purnama et al. [8], that welding of different metals involves different types of metals. They have different chemical composition, mechanical and thermal properties. They researched the effect of metal filler and protective gas on the microstructure of SS304 and SS400 with GMAW and FCAW welding systems. The properties of the three metals must be considered in dissimilar welding (Dissimilar welding), namely two connected metals and filler metal, to combine the two [9]. Welding processes for different welding metals include fusion welds, low dilution, and nonfusion joining. Of the three methods, only fusion welds are often used in the industry, which provides for fusion welds, including SMAW, GTAW, SAW, and FCAW. There is Research on the composition of welding metals, the influence of usage conditions, mechanical properties, physical properties, resistance to corrosion, or oxidation [10]–[12]. Materials that are often used for this research include martensite stainless steel to austenitic stainless steel, duplex stainless steel with carbon steel, austenite steel with Inconel, and austenite steel with titanium. This paper aimed to to contribute and improve the basic theory of dissimilar welding, especially the SMAW method. The results of detailed research progress were reviewed in the follow-up sections.

2. SMAW PROCESS AND EQUIPMENT

2.1 SMAW (Shielded Metal Arc Welding) Proces

SMAW (Shielded Metal Arc Welding) is one of the most widely used welding methods in the industrial world. Welding, in this way, uses metal electrode wires wrapped in flux. In Fig 1, we can see a welding method with a covered electrode where an electric arc occurs between the parent metal and the electrode tip. SMAW is a procedure that uses an arc to accomplish the weld between a covered electrode and a weld pool. As the welder continuously feeds the coated electrode into the welding pool, the decomposition of the coating creates gasses that protect the pool. The process is used no pressure application and with the metal filler from the electrode. The SMAW process created welding metal deposits used for joining metal and applying the metal surface of the product. In welding booths and shops, a linear metal rod with a coating is called a stick, and the shielded metal arc welding process is called stick electrode welding.

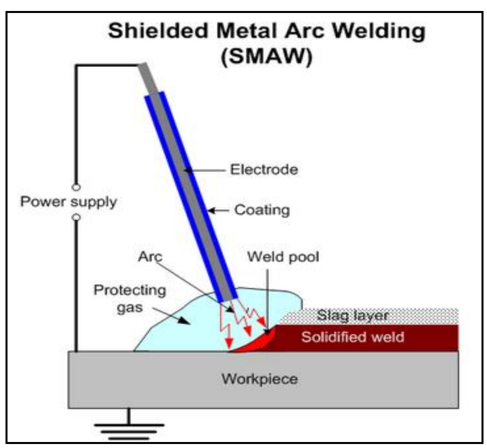

Fig. 1 SMAW Process [13]

The shielded method of welding the metal arc uses an electrical connection that supports a welding arc to transform an electrical line or fuel into heat. The heat from the welding arc is intense and highly concentrated, and a portion of the workpiece and the electrode end instantly melts. The welder preserves the duration of the arc by maintaining a “clear” space or "distance" between the electrode and the weld pool forming on the piece of work. The liquid fuses and the melt solidifies into continuous metal as the arc is removed. The process schematics in Figure 2, showed the power source is connected to the electrode and the workpiece in series into a circuit. Many essential elements of the circuit are the welding cable used in the circuit, the electrode holder, and the connection between the wire and the workpiece. The power source has two distinct output terminals. A connection to the workpiece is made from one terminal, and the other is a connection to the electrode. The proper terminal for the electrode connection when using direct current (dc) is determined by the polarity needed for that form electrode. The electrode may be connected to either terminal by applying alternating current (ac). The circuit is open between the electrode and the workpiece. For this open-circuit (pre-welding) state, the circuit stays open as long as the SMAW electrode is kept away from the workpiece, and a voltmeter can be used to calculate the voltage drop between the electrode holder and the workpiece. The welder grasps the electrode holder's handle and, after lowering its welding mask, initiates the arc by punching the electrode's tip onto the workpiece and gradually retracting it. This quick retraction and touch provide a direction for current flow. The voltage drops across the narrow gap due to the electrode tip stay close to the workpiece causes current to flow through the air, resulting in an arc.

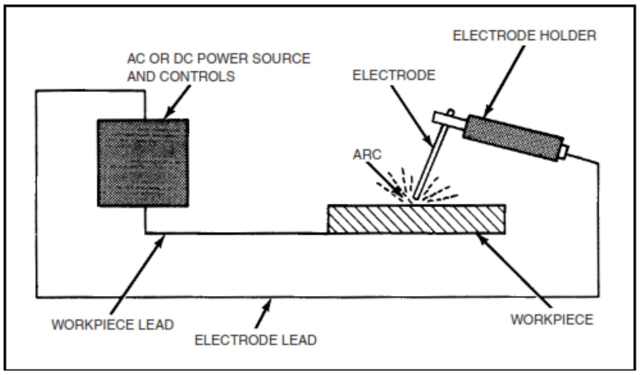

Fig.2 Element of SMAW Process [13]

A plasma holds the current in the arc and is the ionized state of a gas. The arc's extreme heat immediately melts the neighboring core wire and burns the concentrated coating off. Any of the covering materials vaporize and decompose, yielding a massive quantity of gases. Some ingredients that persist and begin to shape a protective cone inward towards the core wire; other parts melt and combine with the core wire in the form of drops propelled across the arc. At the same time, at the workpiece surface near the arc, a pool of molten metal starts to form. Instantly a quasi-stable state is formed, in which a distinct weld pool becomes visible, and the welder is ready to manipulate the electrode. When the arc is created, and the weld pool is identified, the welder starts feeding the electrode into the arc and managing it within the weld joint while maintaining a constant arc length between the tip of the electrode and the weld pool. The welder continuously tests the flow of the solidifying slag, the wetting of the weld bead, the stability of the arc, the silence of the metal transfer.

2.2 SMAW Equipment

Shielded metal arc welding equipment falls into four categories as sown on fig 3 [14].

1. The equipment is necessary to establish the electrical circuit that supports a welding arc — the power source, the welding cable, the workpiece connector, and the electrode holder.
2. The equipment is necessary to ensure the safety and well-being of the welding and others in the welding area.
3. The tools used to complete the welding in compliance with a specified welding procedure.
4. The convenience items such as those needed to insulate the welding booth in the working environment or the fastener to position the welding component properly.

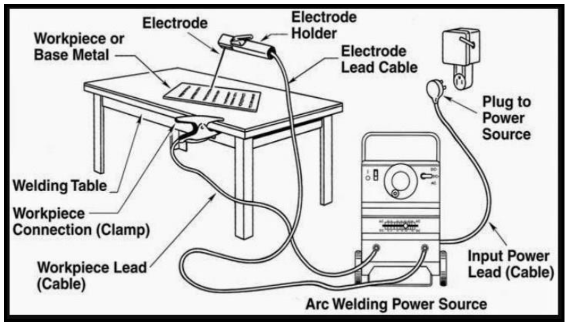

Fig 3 Equipment SMAW Process [15]

3. DISSIMILAR WELDING WITH SMAW METHODE

3.1 Overview of Dissimilar welding

Dissimilar welding is welding carried out on different materials in terms of physical, mechanical, thermal, metallurgical properties, etc [16], [17]. This welding process creates a permanent and robust discharge between two metals. Several factors should be considered for dissimilar welding, including:

1. Solubility: the ability of metals to melt in liquid. In this case, both metals must be able to melt together. Weld metal has two or three phases of single or combination, and is therefore stronger than the weakest Base Metal. Weld Metal has sufficiently tensile strength and ductility that can withstand failure. In multipass welding the composition of the welded bead varies. Ductile matrix phase with good toughness [18]
2. Intermetallic component: this is formed in the transition region during the welding process and fused metallic bonds. It is easy to attach dissimilar metals to produce brittle IMCs which will increase welded joints' embrittlement. The brittle IMCs can become weak area in weld metal by the action of external stress, and cracks are easily created in this area [19], [20]

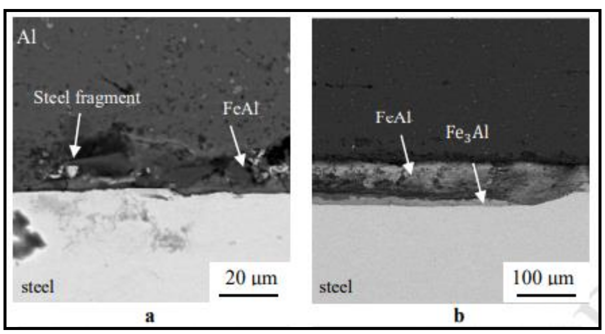

Fig 4. Sample SEM Intermetallic compound [21]

3. Weldability: the ability of a metal to be welded into a single unit. Selected filler metal must have strong weldability consistent with dilution, melting temperature and other characteristics of physical properties [22]– [24]
4. Thermal expansion: is how much the shape of the metal will change while working temperature. Variations in thermal expansion coefficients, which may result in interface crack formation, hard zone formation near the weld interface, relatively soft areas adjacent to the hard zone; large differences in hard and soft zones and expected differences in microstructure may result in service failures [25].
5. Melting rates is the point where both metals will melt. More metals are melted in the case of too strong welding conditions. The more heat generated, under the condition of broad current, mostly led to the metals melting. Welding time and force of the electrodes have a detrimental effect on the fusion rate [26].
6. Corrosion: if the two metals have very striking differences on the electrochemical scale, corrosion will occur. The greater resistance to corrosion, particularly against stress corrosion cracking, makes them ideally applied in some environments. In general, the finer the grain is, the easier it forms the compact passive film. As a result, the corrosive ions cannot easily diffuse through the passive film, and the metal has better resistance to corrosion [27].

7. Operating conditions: when will the conditions of the two metals work together. It used for determine optimum operating conditions such as temperature, operating load, environment conditons, etc. [28], [29].

The welding process is not the same as almost the same welding process. For dissimilar welding, there are several ways of welding, including fusion welding, low melting welding, and non-fusion welding. SMAW process included in fusion welding. Several researchers carry out research based on SMAW welding. Verma et al. carried out dissimilar welding research on DSS 2205 duplex SS and ASS 316L material in terms of microstructure, mechanical properties, and grain boundary corrosion (fig 5) [30]. Also, Verma et al. also conducted a study on corrosion resistance and behavior of 22% Cr SS and 316L materials (fig 6) in an aggressively modified environment [31]. In the same year, Verma et al. also researched the effect of the welding electrode on microstructure and mechanical properties. They focus on 2205 austeno-ferritic materials and 316L austenitic stainless steel [32]. Wherein their research using E2209 welding wire (ferrite mode) and E309 (ferrite-austenite mode).

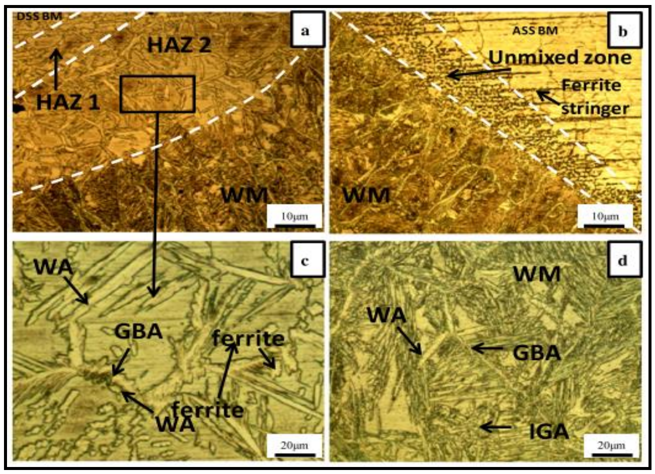

Fig. 5 Microstructure DSS 2205 and ASS 316L [30]

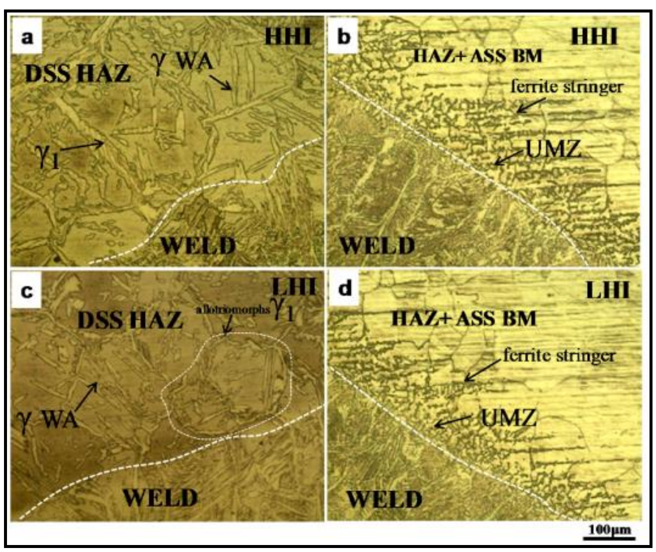

Fig. 6 Microstructure 22% Cr SS and 316 SS [31]

Research on the tensile properties of nuclear ferritic grade metal materials and austenite stainless steel was carried out by Karthick et al., Where the results obtained that the toughness of the weld area decreases compared to base metal [33]. For Incoloy 800 and SS316L material research conducted by Manikandan et.al. They research mechanical and metallurgical properties. They compared the results of SMAW and

GTAW welding as shown fig.7, where the strength and toughness of the GTAW welding results are better than SMAW welding [34]. Research on the effect of PWHT temperature (Post-weld heat treatment) in microstructure and mechanical properties on A517 Gr B material found that PWHT affects the metal roughness and agility of the metal [35]. Research on the electrochemical and mechanical properties of metal AISI304 and austenitic steel was carried out by Allou et.al. They concluded that vermicular ferrite and equiaxed cellular dendrite formed in the weld region. The hardness of the weld area is better than base metal [36].

TABLE I. COMPARISON STRENGTH AND TOUGNES FOR GMAW AND SMAW METHODE [34]

Welding	Average UTS (MPa)	Yield strength (MPa)	%Ductility	Toughness
GTAW	649.5	352.45	47	55
SMAW	567.5	329.32	37	44
Inconel 800	764	353	55	
AISI 316L	558	290	50	

3.2 Material and Electrode On SMAW

1) Material

Nickel and nickel-containing alloys are readily welded to most of the commercially used metals. There are a few combinations for dissimilar welding material likely:

1. Steel to stainless steel welds below 800oF.

These are possibly the most commonly used in industry, with the possible exception of boiler tube welds, dissimilar welding. When designing a DMW process, it is necessary to remember the welding parameters that are usually used for each of the joining metals so that they are appropriate for welding. When service temperature-exceeding 700oF, carbon migration from austenitic stainless steel filler. Base metal thermal coefficient must be considered. Significant difference results in high thermal pressures at high temperatures. Weld ferrite number should be predicted when use austenitic filler metal.

2. Carbon and low alloy side consideration.

An essential guide for making DMW's is to use the same parameters as preheating, inter-passing temperature, heat input, post-welding treatment, etc. used in welding the alloys. Austenitic filler without preheat can normally weld for carbon steel less than 0.2% carbon and for greater than 0.3% carbon should be considered preheat temperature control. Consideration of low moisture content of electrode or flux cored wire to prevent hydrogen-associated defect in the low alooy HAZ.

High restraint joints are susceptible to cracking unless preheat is used. The degree of restraint varies with joint design and material thickness. Temperature 300oF is generally sufficient with 400oF used in severe conditions when preheat is needed.

3. Stainless steel side consideration

As for self-welding stainless steel, good technique covers things such as proper pre-welding washing, correct fitting, and proper shielding gasses, PWHT such as 1100-1300oF, and faulty stainless steel heating. For improving HAZ in ferritic stell, PWHT treatment such as 1100oF-1300oF can be done. Heat treatment in unstablized SS (contain 0.03% or higher carbon) should be reduced intergranular corrosion resistance. Used columbium- or titanium stabilized types or low carbon contain less than 0.03% for heat treatment.

4. Stainless steel and low carbon steel

The effect of dilution can be calculated on an austenitic stainless steel weld. Inoxidable steel framework welds completely austenitic or contains varying amounts of delta ferrite. The amount of ferrite can be determined by weld cooling rates and composition. Fig 7 showed forming martensite when nickel and chromium equivalent is reduced.

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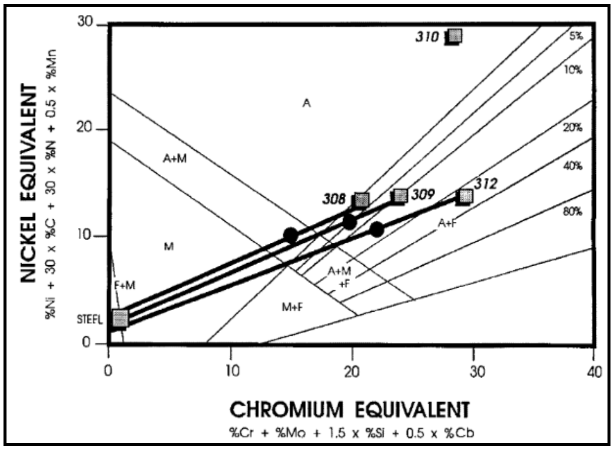

Fig. 7 Effect mild steel dilution and forming martensite [9]

5. Steel to stainless steel welds over 800oF

A nickel-chrome or nickel-chromium-iron metal such as AWS A5.14 class ERNiCr-3 or AWS 5.11 class ENiCrFe-2 or class ENiCrFe-3 electrodes is the perfect filler when service temperature is above 800oF. Heat treatment should be assed carefully due to high delta ferrite contains in weld metals. It can lose room temperature ductile and corrotion resistance.

2) Electrodes

Electrodes are also available for surface application to these same base metals to make them wear-resistant, impact-resistant, or corrosive. The surfacing can also be added to enhance the product's appearance.

In the United States, the American Welding Society (AWS) and the US Department of Defense categorize the electrodes. The documents which are classified are referred to as AWS specifications and Mil / Military specifications. The content of the specification, as shown in Table 1, defines classifications (or types) of SMAW-covered electrodes for use on groups or categories of the base material. The spec specifies the ratings based on one or more of the attributes that follow: type of welding current, a model of electrode cover, the orientation of welding, the chemical composition of undiluted welding metal, and mechanical properties of undiluted welding metal.

TABLE II. ELECTRODE SPECIFICATION BASED ON AWS STANDARD [13]

Type electrode	AWS specification
Carbon steel	Specification for carbon steel electrodes for shielded metal arc welding, AWS A5.1
Low-alloy steel	Specification for low-alloy steel electrodes for shielded metal arc welding, AWS A5.5
Corrotion resistent steel	Specification for stainless steel electrodes for shielded metal arc welding, AWS A5.4
Cast Iron	Specification for welding electrodes and the rod for cast iron, AWS A5.15
Alumunium and alumunium alloys	Specification for aluminum and aluminum alloys electrodes for shielded metal arc welding, AWS A5.3/ A5.3M
Copper alloys	Specification for covered copper and copper alloys welding electrodes, AWS A5.6
Nickel alloys	Specification for Nickel and nickel alloys welding rods for shielded metal arc welding, AWS A5.11/ A5.11M
Surfacing	Specification for solid surfacing welding rods and electrodes, AWS A5.13 Specification for composite surface welding rods and electrodes, AWS A5.21

3.3 Advantages and Disadvantages SMAW Process

As for the advantages of SMAW include:

1. Equipment used is relatively simple, inexpensive and can be moved (portable)
2. Electrodes for this type of welding are both protective and fill metal
3. The welding process is not influenced by the wind factor, different from the welding process of the gas protector.
4. Additional gas shielding or granular flux is not needed.
5. The dimensions of the electrode are ideal for welding with narrow areas (the electrodes can be bent, using glass can be used in areas that are not visible).
6. This welding process can be used for various types of metals and alloys that are commonly used.
7. The welding process is flexible and can be used for various types of joints and welding positions.
8. Welding results can be obtained easily and reliably.

For the disadvantages or limitations of this welding process include:

1. This welding cannot be done for metals with low melting temperatures such as lead, tin, and zinc or their alloys.
2. This welding also cannot be used for reactive metal types such as titanium, zirconium, tantalum, and niobium.
3. This welding deposit rate is lower than gas shield welding (GMAW or FCAW). It is due to the limited use of welding machine currents.
4. The occurrence of stub loss results in a low deposit efficiency where the disposal of the remaining electrodes at the end of the grip holder cannot be used.

The operator factor is very influential in this welding process, where the electrode replacement process occurs when long welding is needed (a large volume of filler metal).

3.4 Non-destructive test for SMAW process

Testing for weld areas needs to be done to determine its suitability for use. There are few types of tests for the NDT test on SMAW process likely Magnetic particle testing, radiographic, and ultrasonic.

1) Magnetic Particle Testing

If one or more parts of the joint are non-magnetic, magnetic particle testing is not possible. Also, if all material is magnetic, the degree of ferromagnetism may vary due to the difference in composition, and the magnetic difference may offer false indications on the line of fusion. For this reason, the most frequent use of liquid penetrating inspection is for surface inspection.

2) Radiographic testing

The same method and inspection pattern used in similar-metal joints may be used to test DMW's. The material visibility and thickness of most significant interest should be selected. Based on the difference in radiographic density, radiographic analysis can be very different from that of similar metal welds

3) Ultrasonic testing

When the welded metal is coarse-grained (such as austenitic stainless steel, nickel-chromium, or nickel-copper weld joining a ferritic alloy), the interpretation of the fusion line is a significant concern. For this reason, DMW's ultrasonic testing is seldom feasible

3.5 Destructive Test SMAW Process

In the specification of the welding process, DMW is typically tested by tensile and bend test like metal-like welds. Usually used hardness measures like Brinell, Rockwell, or Vickers for surface hardness at weld metal.

1) Hardness testing

Hardness testing is the resistance of the material to the compressive force of the harder material [37]. Nonetheless, the results of hardness testing are often used as a fast method to estimate the maximum tensile strength in the area under test. Hardness measurements can also provide information about metallurgical changes caused by welding as shown fig.8. In alloy steel, high hardness can indicate the presence of martensite in the heat-affected welding zone, while low hardness can indicate over tempered conditions. Welding can cause significantly lower hardness in the heat-affected zone of cold-worked metal due to recovery and recrystallization. Based on the emphasis method, the hardness test method can be divided into three namely the scratch method, the reflected / elastic method, the indentation method.

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The indentation method is usually used for hardness testing. These three types of hardness testing for the indentation method are the Brinel method based on the ASTM E10 standard [38], Rockwell method based on ASTM E18 standard [39], and Vickers method based on ASTM E92 [40].

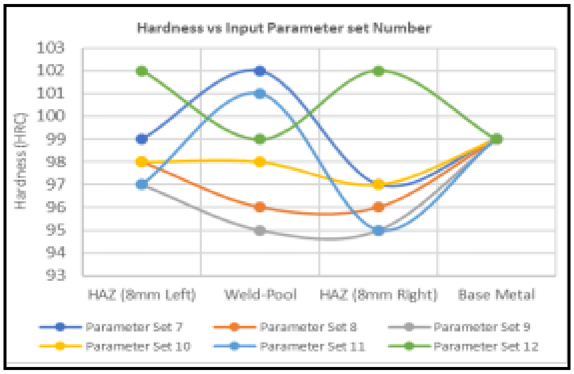

Fig. 8 Sample Hardness testing [41]

2) Tensile Testing

Tensile testing is used to determine the strength and tenacity of base metals, welding metals, and welding metals. This test provides qualitative data for the analysis and design of structures to be welded as shown fig.9. Tensile testing is often carried out to verify the strength of the welds meets the specified minimum value. The data obtained in the form of changes in length and load changes are then displayed in the stress-strain curve. From the results of this test, it is expected to obtain the mechanical behavior and characteristics of the fracture [37].

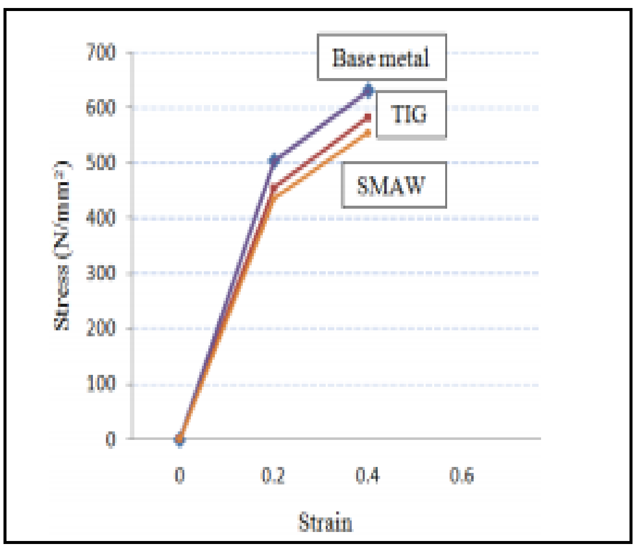

Fig.9 Sample tensile test result [42]

The testing procedure is based on the ASTM E8 standard [43]. Fig. 10 showed configuration for specimen tensile test. The holder on the tensile test equipment holds both ends of the specimen. Then the anchor has moved away with a uniaxial load on the specimen. The device records the movement of the load. Only the maximum load required to define the maximum tensile load (Ultimate Tension strength)

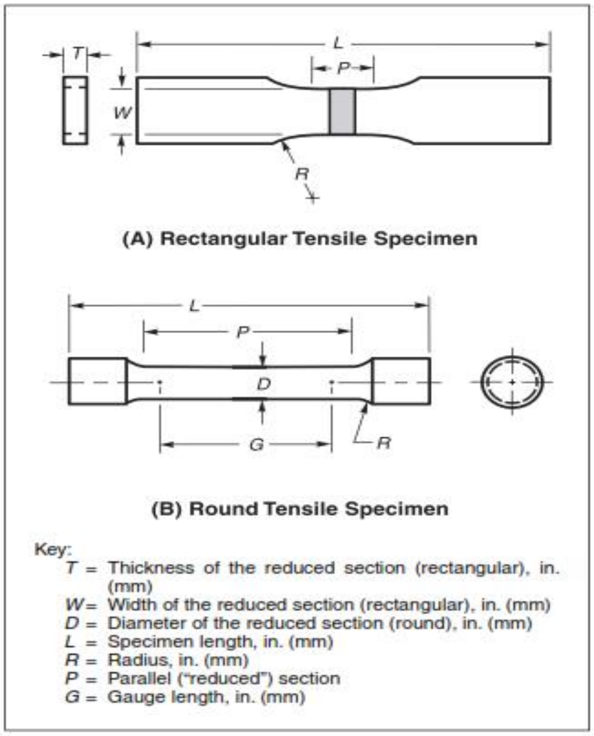

Fig 10. Configuration specimen on tensile test [37]

3) Bending testing

Bending test (bending test) is one of the testing methods to determine the tenacity and strength of the material [37] due to loading from the welding results both for the HAZ region, weld metal, and weld area. Result from this test is graphical as shown on fig.11.

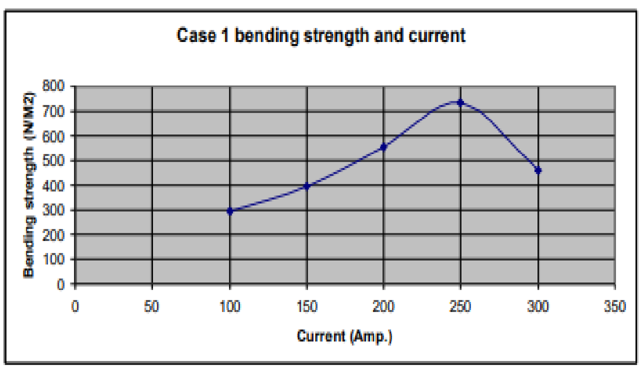

Fig 11 Result bending test [44]

Based on specimen collection, bending tests can be divided into transversal bending and longitudinal bending. Bending transversal is taking a bending test specimen perpendicular to the direction of the weld. Whereas longitudinal is taking test specimens that are parallel to the direction of the weld. The two types of testing can be divided into three parts, namely face bend, root bend, side bend (fig. 12). In face bend testing, the weld surface experiences tensile stress, and the root part experiences compressive stress. In the root bend test, the reverse occurs where the weld surface experiences compressive stress while the bottom surface experiences tensile stress. In the side bend test, only the welds where the tensile stress occurs on both sides are tested.

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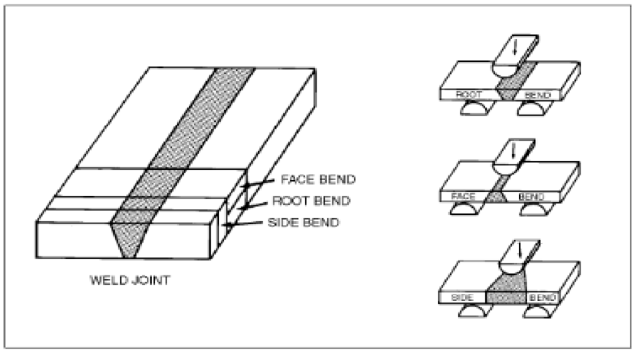

Fig. 12 Specimen and test orientation on bending test [37]

4) Metalografi testing

Tests for specimens carried out are SEM (Scanning Electron Microscopy) and EDS (Energy Dispersed Spectrocospy). For SEM and EDS testing, samples will be taken for the regions of the weld, the HAZ area, and the parent metal region as shown on Fig 13. For SEM testing, it will be done twice, namely macro photo observation with optical magnification of 10X and micro photo observation with optical magnification of 500X as shown fig.14. For EDS observations will be made in the area of the weld.

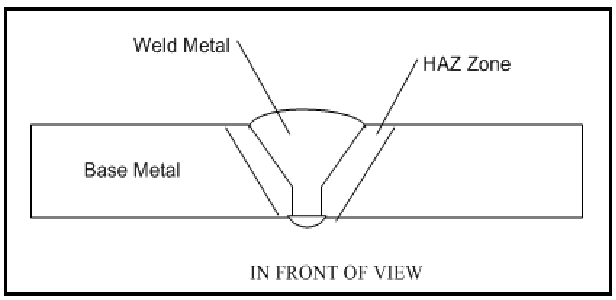

Fig 13. Specimen testing area

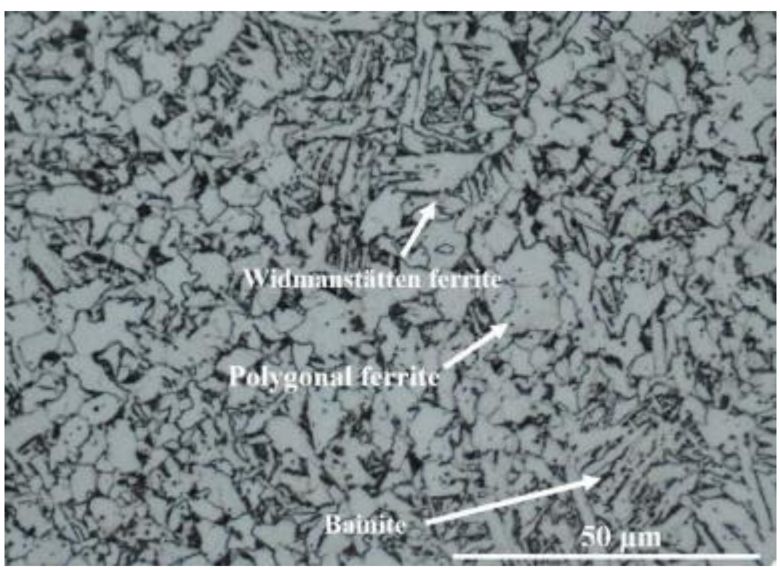

Fig 14 Microstructure HAZ sample [45]

4. CONCLUSION

Shielded Metal Arc Welding (SMAWI is a welding process procedure that uses an arc to accomplish the weld between a covered electrode and a weld pool. SMAW is usually used in industry due to easy and simple equipment. It can be used for all metal combinations on dissimilar welding likely low carbon steel and stainless steel, or stainless steel and duplex stainless steel, etc. Weld quality performs with several testing in the weld metal, HAZ area, and base metal. Nondestructive tests like Magnetic particle, radiographic, and ultrasonic testing is one of these testing. For the destructive test, we perform the hardness test, bending test, and tension test. SEM and EDS test perform for examination microstructure at weld metal, HAZ, and Base metal. Furthermore, the effect of dissimilar welding process with SMAW process on the microstructure and mechanical properties will be investigated in the future.

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