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Review Paper

Characterization of Fusion Welded Joint: A Review

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ABSTRACT

Welding process is most widely used in joining components or structures in industry. Although welding is part of a larger category called metals joining, the weld itself still gives significant problems to engineers, researchers and manufacturers until today. Several widely used welding processes, such as the Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), and Manual Metal Arc (MMA), were studied. In the present paper, the characterization of the macrostructure, microstructure, hardness and residual stress distribution are highlighted and discussed to achieve a better understanding of the welded quality which is crucial in determining the welded products.

Keywords: **Fusion welding, macrostructure, microstructure, hardness and residual stress**

ABBREVIATIONS

MIG	Metal Inert Gas
TIG	Tungsten Inert Gas
MMA	Manual Metal Arc
BM	base metal
HAZ	heat-affected zone
WM	weld metal
FZ	fusion zone
RS	residual stress

INTRODUCTION

Development in welding has been greatly investigated since 1800. During the late 1800s, gas welding and arc welding were developed and became a practical joining process. The variation and implementation of knowledge give a high value in the development of welding industry and therefore, provide new findings of welding applications, i.e. from conventional to the newest process such as friction and laser welding (Stephens *et al*., 2001; Suresh, 1998).

Significantly, versatility of welding provides maximum application process in joining metals such as stainless steel, low alloy steel and high strength steel. Appropriate welding control techniques, with a maximum penetration, commonly produced good weld qualities. Some examples of these applications include welding of industrial piping in petrochemical refineries, constructions and repair of nuclear power facilities, ship building, aerospace and ground vehicles.

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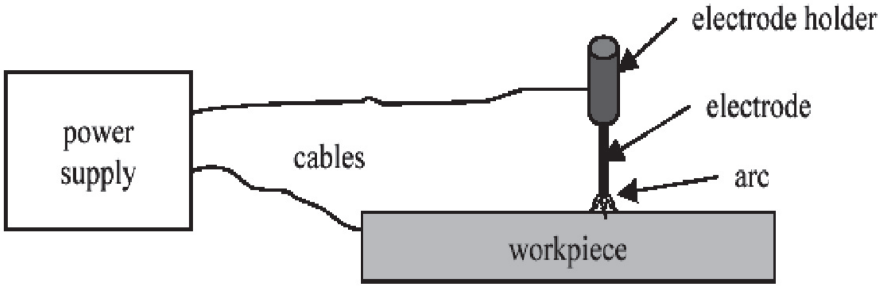

Fig. 1: Illustration of a simplified welding circuit (David et al., 2003)

Qualification of the welder and the structural code of welding procedures have been well covered by the standard welding specification to provide standardized specific information of welding procedure for the last 200 years. Engineers come out with a common code used in the welding industry, such as the American Welding Society Standard for Welding Procedure and Performance Qualification (AWS B2.1) which covers the qualification of the welder and welding procedure. In contrast, the AWS Structural Welding Code for steel provides a structural code for the use of steel welding procedure specification (Burgess, 1989).

OVERVIEW OF FUSION WELDING

Without any doubt, fusion welding is the oldest welding technique. It plays an important role in machine tools nowadays, particularly in the fabrication of joining engineering structures especially steels. Due to the advancement of technology, there are many ways in which the process can be carried out, but it is interesting to note that most of them involve the same parameters. For many years, engineers have been aware that most common type of fusion welding include manual metal arc (MMA), metal inert gas (MIG), and tungsten inert gas (TIG) welding (Weber, 2001).

Of course it is known now that the entire arc welding processes utilise variation of electrical circuits, but are still controlled by the same parameters. Power source cables are connected to the work piece and electrode. The power source creates a current through the welding circuit and an arc is created between the electrode and the work piece. *Fig. 1* shows a simple illustration of a simplified welding circuit (David *et al*., 2003).

CHARACTERISTIC OF FUSION WELDED JOINTS

In general, fusion welding consists of three distinct zones, namely the base metal (BM), heat-affected zone (HAZ) and weld metal (WM) or fusion zone (FZ), as depicted in *Fig. 2* (David, 2003).

WM is a part of a weldment which melts during welding process. It comprises a metal from the original work piece and may contain filler metal which is melted during the process. Near the weld area but outside the fusion weld is the HAZ. Volume of metal in this regime does not melt, but it is still being recognized as a part of the FZ. The HAZ area was affected mainly by the heat produced during the welding process. The third region is known as the BM or the parent plate region which is unaffected by any heating operation during the welding processes.

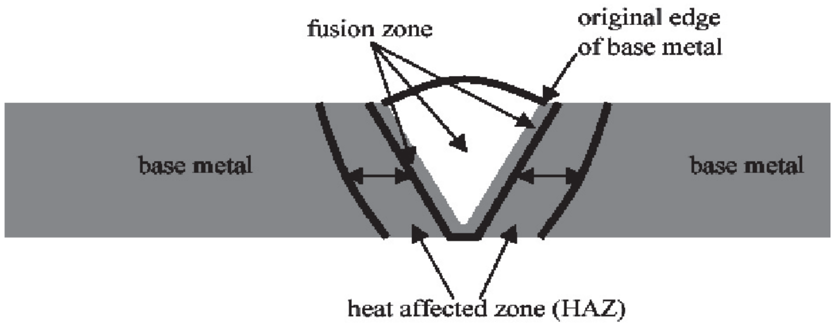

Fig. 2: Three zones of fusion welded joint (David et al., 2003)

MACROSTRUCTURE AND MICROSTRUCTURE OF FUSION WELDED JOINTS

In welding, there have been many attempts on observations of fusion welded joint microstructures by engineers, scientist and manufacturers. Yet again, it is well established that during welding process, the microstructure properties vary from region to region when the heat input interacts with the metal. For example, the macrostructure of the above mentioned three main regions for the low carbon steel fusion welded joint is as shown in *Fig. 3* (John *et al*., 2006).

As it progressed, instead of the three main recognized regions in fusion weld, the researchers again segregated the fusion weld region into six zones which could be discerned in the welded area and the BM adjacent to it, as illustrated in *Fig. 4*. These zones were created because they had been subjected to a kind of different degrees of heat treatment in the welding process. However, to simplify, one can group them into six basic zones, as follows:

1. Deposited Metal Zone 2. Fusion Zone	} Weld Metal Zone
3. Grain Growth Zone 4. Grain Refinement Zone 5. Transition Zone	} The Heat Affected Zone
6. Unaffected Zone	} Base Metal

The question remains is, how can an engineer differentiate them? Indeed, up to the best of authors' knowledge, the FZ was observed to normally consist of a fine dendritic network, as shown and labelled in *Fig. 5*. The edge of the FZ exhibits a more columnar structure growing in from the FZ boundary (Lefebvre *et al*., 2005).

The structure closed to WM in Mg/Al TIG welded joints is columnar crystal, which grows into the WM. There is an obvious boundary between the Mg substrate and WM, as shown in *Fig. 6a*. Moreover, *Fig. 6b* shows the columnar crystals which are closed to the WM, and the length of the crystals is almost half of the FZ width. The microstructure of the WM and the region were observed to mainly compose of the dendrite crystals, as illustrated in *Fig. 5* (Liu *et al*., 2007), and is also in agreement with the finding by Lefebvre *et al*. (2005).

In the previous research, the microstructure of the cross-sectional structures of the MIG welded joints was investigated. In that attempt, two kinds of specimens were used, namely the low carbon steel of 0.1C, and ferritic stainless steels of 18Cr-1Mo-Ti. The samples were welded with three types of welding material; the ferritic welding wire of 16Cr (W1), austenitic welding wire of 23Cr-12Ni (W2) and flux cored wire of 23Cr-12Ni (W3). It is interesting to discover that in each

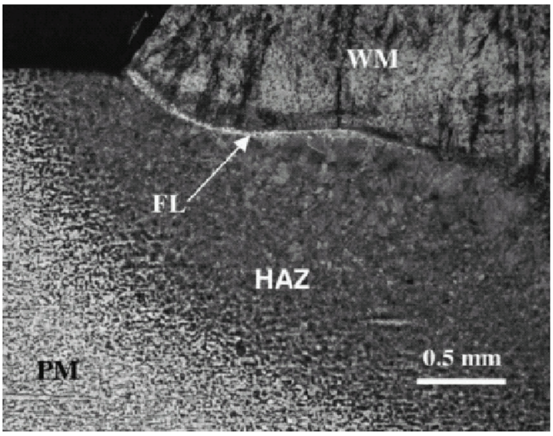

Fig. 3: Typical optical micrograph through welded section showing fusion line, FL, base metal or parent metal, PM, weld metal, WM, and heat affected zone, HAZ (John et al., 2006)

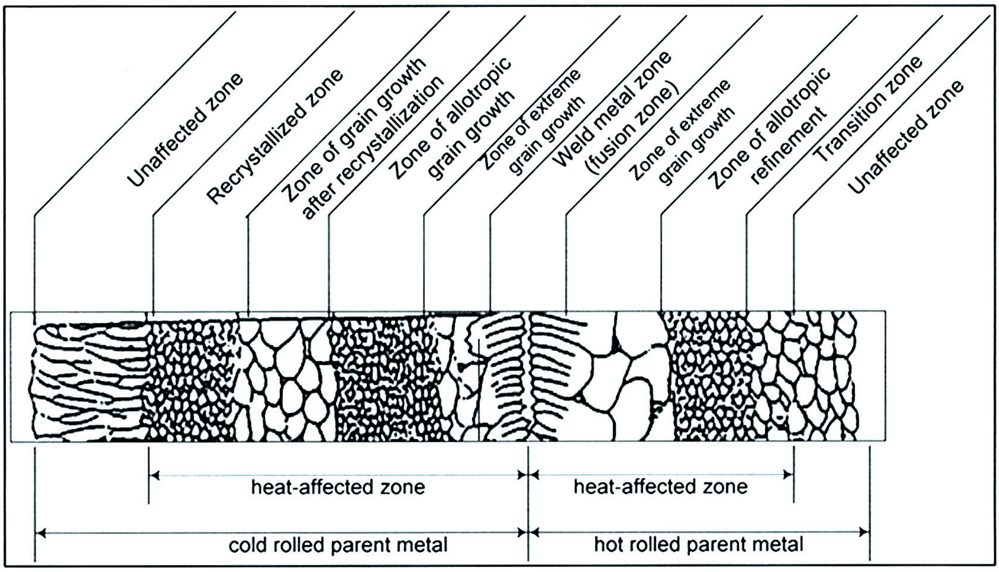

Fig. 4: Schematic diagram showing six micro-structural zones in the welded steel (Metallography, 2002)

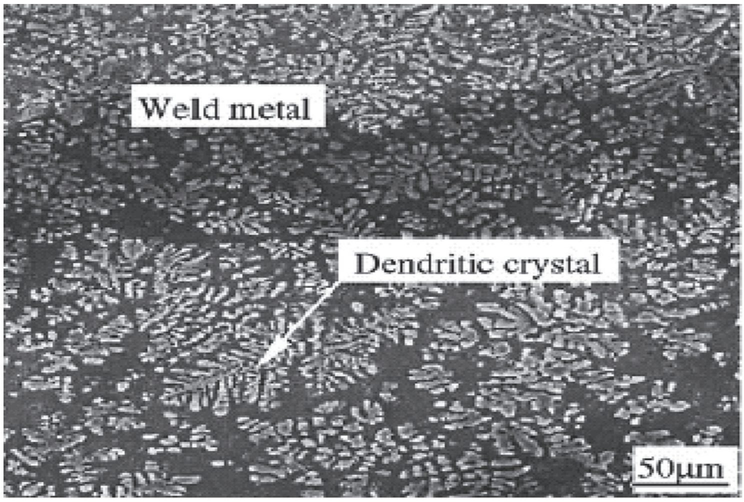

Fig. 5: The microstructure of weld metal for Mg/Al TIG welded joints (Peng Liu et al., 2007)

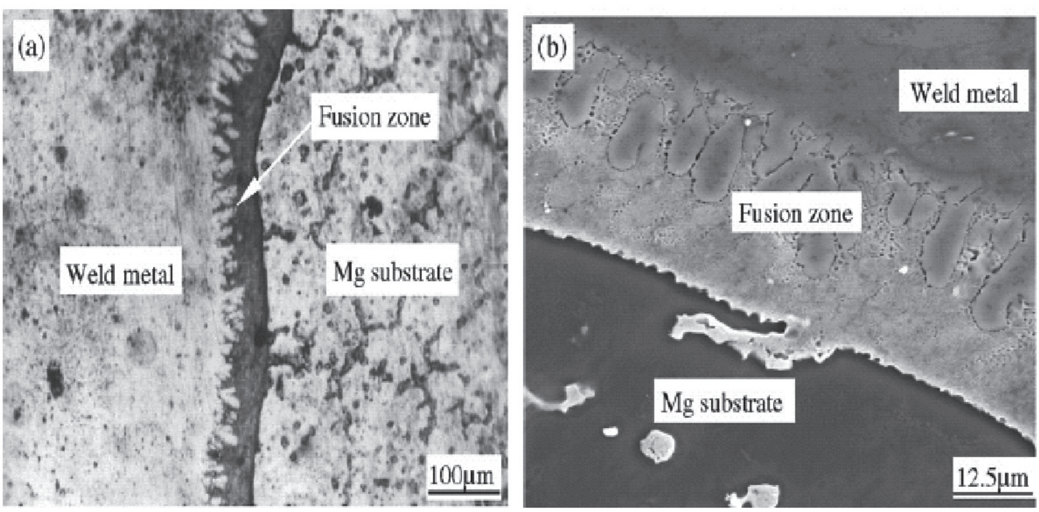

Fig. 6: The microstructure near the fusion zone of Mg side for Mg/Al TIG welded joint, (a) Metallography structure, (b) SEM structure (Peng Liu et al., 2007)

deposited zone, the columnar structure was developed from the HAZ of the BM. Nevertheless, the cell dendrite structure or oxidation inclusion admixed from the flux was also observed (Xiaoguang *et al*., 2003).

HARDNESS CHARACTERISATION

There have been numerous works in hardness characterisation. It is evident that the hardness distribution has strong influences on the strength and toughness of the welded joints (Liu and Bhole, 2002).

As can be noticed in *Fig. 7a*, the micro-hardness near the FZ of Mg side is higher than the Mg substrate region. In addition, *Fig. 7b* also shows the increase in the hardness of FZ between the WM and Al substrates. Their work indicated that the Mg and Al substrates, which are close to the FZ, are affected by the welding thermal cycle, and consequently the hardness increases gradually. Moreover, the brittleness phase with high hardness may be formed near the FZ (Liu *et al*., 2007).

The hardness value in the pressure vessel steel weld zones is indicated in *Fig. 8*. The hardness value in the HAZ region is higher than that in both BM and WM, which was also agreed by Liu *et al*. (2007), John *et al*. (2006) as well as Liu and Bhole (2002). According to John *et al*. (2006), a high hardness value indicates quite severe cooling conditions in the heat affected area in the low carbon steel weldment. These observations are different when compared to the experiment done by Itoh *et al*. (1989) who found that the Vickers hardness distributions were high in the WM, followed by the HAZ region and BM, respectively.

In previous work done by Itoh *et al*. (1989), the FZ region was clearly shown to present a minimum hardness value based on the hardness value obtained in the MIG weld, and it yielded a similar result. The hardness peak was noticed in the HAZ region, whereby the hardness level was greater than the BM (Lefebvre *et al.*, 2005).

Particularly, the HAZ is a transition zone on the welded joints and it is rationale to suggest that there is a risk of cracking along this zone. The HAZ readings were consistently higher than both the BM and WM readings, depending on the welding type (Yayla *et al*., 2006).

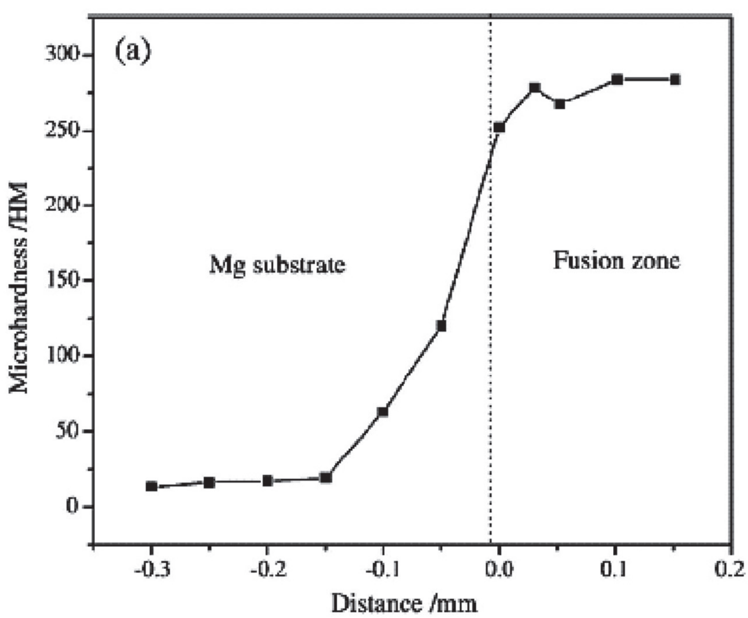

Fig. 7a: Micro-hardness for Mg fusion zone of Mg/Al TIG welded joint (Peng Liu et al., 2007)

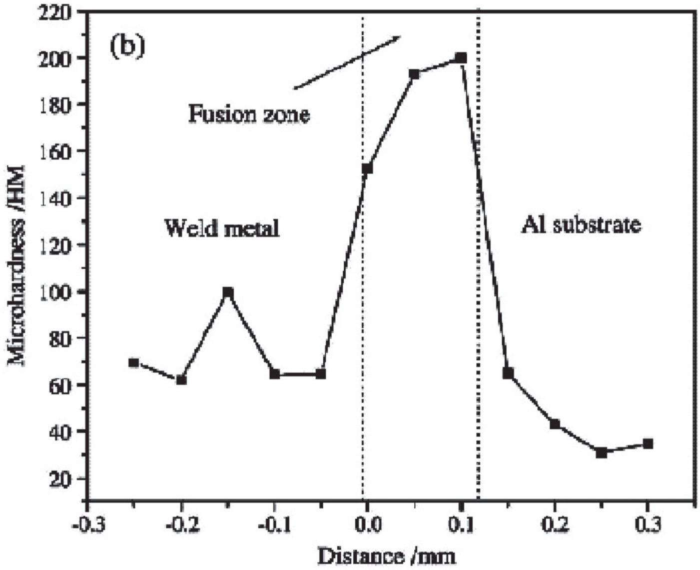

Fig. 7b: Micro-hardness for Al fusion zone of Mg/Al TIG welded joint (Peng Liu et al., 2007)

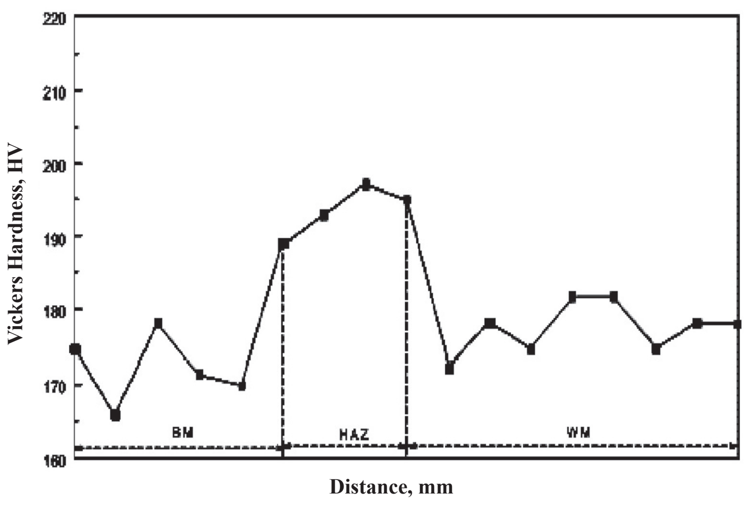

Fig. 8: Hardness distributions in pressure vessel steel weld (Liu and Bhole, 2002)

RESIDUAL STRESSES CHARACTERISATION

In welding, residual stresses (RS) are the stresses which remain after the welded members have cooled down to the normal temperature. The RS have also been called "self-equilibrating stresses" because they are in equilibrium within a part, without any external load. The tensile residual stresses have to be relieved to prevent cracking or fracture in the weld, which majority believed to have caused the crack to open. Several processes were used to relieve this stress; these include pre-heating, post-heating, as well as full annealing and peening (Stephens *et al*., 2001).

The RS which are formed in a weld pad are dependent on (i) thermal conditions like peak temperatures, rate of cooling and the temperature of the base material; (ii) material properties like coefficient of thermal expansion and modulus of elasticity; and (iii) restraint conditions, whether the material is restrained or left free to allow them to deform.

The RS distribution increases with the increase in the thickness of the weld pad for both low carbon steel and stainless steel weld pad. The increment is more pronounced in a low carbon steel weld pad due to the higher heat input during the welding process. This experiment shows that there is a correlation between two welding parameters, heat input and geometry of material which characterize the RS (Murugan *et al*., 2001).

In this study, the RS were measured using the Neutron Diffraction Technique for the low carbon steel and it was found that the maximum tensile residual stress was near the middle of the weld, as shown in *Fig. 9*. High RS may lead to the loss of performance in corrosion, fatigue and fracture (John *et al*., 2006).

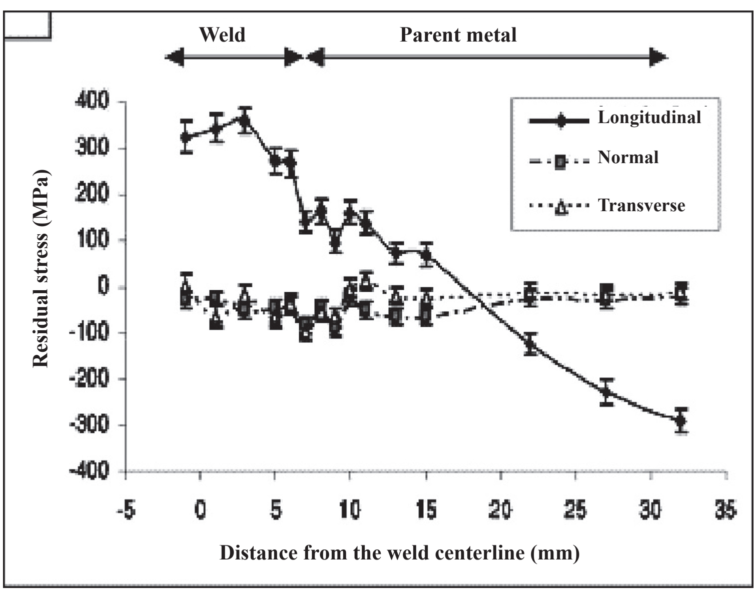

Fig. 9: The longitudinal, transverse and normal components of strains measured by Neutron Diffraction against distance from the weld centerline (John et al., 2006)

The RS distribution was also investigated in welded butt joints in carbon-manganese-silicon steel (SS41) and austenitic stainless steel (SUS304). The result revealed that the RS distribution was rather inhomogeneous in the longitudinal and transverse direction of the weld, as well as across the thickness of the weld, particularly for the transverse direction (Itoh *et al*., 1989).

It is clearly proven that the tensile residual stresses are located in the HAZ, in the area of WM. From these maximum values, the tensile residual stresses decrease in the BM adjacent to the HAZ area, which contains compressive residual stresses. As the distance from the weld area increases, the RS is then gradually changed into the initial stress state of the BM.

CONCLUSIONS

In this paper, the macrostructure, microstructure distribution, hardness and residual stresses of fusion welded joints were investigated and discussed to better understand and clarify the characterization of fusion welded joints. In the weld failure assessment, a profound knowledge in the weld characterization is required to determine the mechanisms of the weld failure and what can be done to prevent them. Without any doubt, a study and a deeper analysis should be performed through experimental and analytical methods as suggested from the past investigations. Undoubtedly, the inspections and proper precautions still need to be taken seriously to prevent such weld damages.

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