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A Review of Porosity Formation and Recommendations on the Avoidance of Porosity in TIG Welding of Steels

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ABSTRACT

Welding defects can adversely affect the mechanical properties and performance of products in service. Therefore, a thorough understanding of these defects, how they occur, their severity, and remedies can guarantee high quality products and enhanced performance. The purpose of this review report is to investigate the root causes of welding porosity defect, and suggest measures to minimise or eliminate the defects. To determine the root cause of porosity in a welding process without a grasp of the fundamental principles of the problem can be time consuming, and even a frustrating task. It is therefore necessary to deal with porosity problems through organized problem-solving approach, by identifying the different causes, before we find and eliminate the root cause. The literature survey is concerned with published data and general comments are made on the cause of porosity, mechanisms of porosity formation, and porosity in TIG welding, surface cleaning methods, welding parameter effects on porosity, and issues relating to the welding of ferritic stainless steels and austenitic stainless steels. In discussing the causes of porosity, recommendations have been made on the avoidance of porosity.

Keywords-*TIG or GTAW, TIG torch, Weld pool, Solubility, Gas entrapment, Contamination, Solidification, Porosity, Gas shielding.*

1. LITERATURE SURVEY

1.1   Causes of porosity

The causes of porosity are many and varied; however, they have been associated with the absorption of oxygen, nitrogen and hydrogen in the molten weld pool. Porosity caused by nitrogen or oxygen is usually related to poor gas shielding when air is entrained in the arc atmosphere, Harris [1]. Hydrogen on the other hand can be produced from different sources, such as the dissociation of moisture in the shielding gas, on the surface of the components or on the filler wire. Grease or oil on the metal or the filler surfaces are other sources of hydrogen which can be absorbed by the molten weld pool. Desorption of hydrogen on cooling and solidification of the weld pool will result in porosity, Harris [1].

According to Harris [1], the fundamental cause of porosity is the difference between the solubility of the gas in the liquid and solid states. The solubility is much lower in the solid state. The remaining gas, which is rejected upon solidification, either escapes from the weld pool or is trapped in the form of pores. This however, depends primarily on the size and cooling/solidification rate of the weld pool. Protection of the back of a weld is an important area which is often neglected but can cause porosity. For example, in welding the root of the joint, it is common practice to use back shielding especially when adding a filler metal which does not contain de-oxidants, Harris [1].
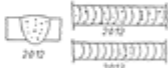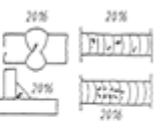
In general, Porosity is caused by factors which include:

- Low or high gas flow rate.
- Impure shielding gas.
- Too high an arc voltage
- Inadequate weld area cleaning
- Too long a time between cleaning and welding
- Air flow that can cause gas entrainment or cause turbulence
- Faulty equipments.
- Decomposition of water which may be present as moisture on the parent metal or filler wire.
- Decomposition of ferrous oxides formed on the metals surface, TWI [4].
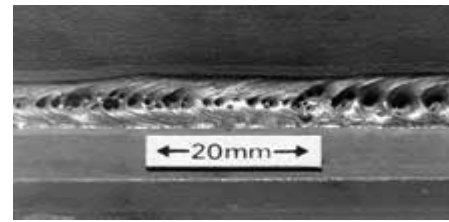
1.2 Classification and appearance of pores

Cavities in the weld metal or at the fusion boundary are usually referred to as pores or porosity. However, porosity is a group of pores. Harris [1] defined the most common types of pores as spherical, elongated and interdendritic (irregularly shaped). IIW [2] and BS 499 [3] classified porosity defects as shown in table 1 and table 2 respectively.

Table 1: Defect classifications 1[2]

Reference number	Reference radiographs	Designation	Explanations
1	2	3	5
201	A	Group no.2 Gas cavity	A cavity formed by entrapped gas.
2011	Aa	Gas pore	A gas cavity of essentially spherical form.
2012		Uniformly distributed porosity.	A number of gas pores distributed in a substantially uniform manner throughout the weld metal; not to be confused with linear porosity (2014).
2013		Localised (clustered) porosity	Group of cavities.
2014		Linear porosity	A line of gas pores situated parallel to the axis of the weld.
2015	Ab	Elongated cavity	A large non-spherical cavity with its major dimension parallel to the axis of the weld.
2016	Ab	Wormhole	A tubular cavity in weld metal caused by release of gas. The shape and position of wormholes is determined by the mode of solidification and the sources of the gas and they may be distributed in a herringbone formation.
2017		Surface pore	A small gas pore which breaks the surface of a weld.

**Table 2: Defect classifications 2, BS 499: Part 1, 1983 [3]**

Number	Term	Definition
BS 499:Part1:1983		
60 029	Gas pore	A cavity, generally under 1.5mm in diameter, formed by entrapped gas during the solidification of molten metal.
60 030	Blowhole	A cavity, generally over 1.5mm in diameter, formed by entrapped gas during the solidification of molten metal.
60 031	Porosity	A group of gas pores.
60 032	Uniform porosity	Porosity distributed in a substantially uniform manner throughout a weld.

Note: Uniform porosity may be classified according to the number of pores per unit volume and the size of pores as follows:

Extent of uniform porosity	Number of pores per 10cm² of radiograph (weld only) where t is the metal thickness in cm
Extensive	> 100t
Scattered	⩽ 100t to > 25t
Sparse	⩽ 25t to > 3t
Very sparse	⩽ 3t

Grade of uniform porosity	Approximate average diameter of pores, mm
A	0.4
B	0.8
C	1.6
D	3.2 or greater

TWI [4] identified the several forms of porosity as follows:

- Distributed
- Surface breaking pores
- Worm hole

1.2.1 Distributed porosity and surface pores

Figure 1 shows a uniformly distributed porosity while figure 2 is surface porosity. The former are usually found as dispersed fine pores all through the weld bead, and the latter are large amount of surface pores, TWI [4].

Fig. 1: Evenly distributed porosity [4]

Fig. 2: Surface porosity [4]

1.2.2. Wormholes

Wormholes are characteristically elongated pores that reveal a herring bone appearance on the radiograph, TWI [5] as shown in fig. 3.
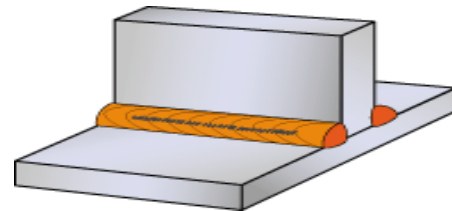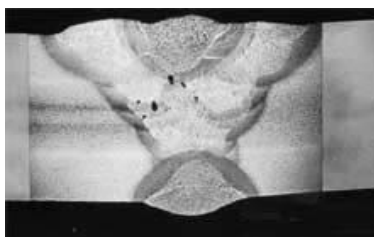

Fig. 3: Elongated pores or wormholes [4]

1.3   Formation of porosity in stainless steels

The tendency to form hydrogen porosity in stainless steel will be dependent on whether the steel is ferritic, austenitic or a combination of the two. Castro and Cadenet [6] showed that generally, for stainless steel, the solubility of hydrogen and oxygen is considerably higher in the liquid state than in the solid state. As a consequence, the evolution of gas is rapid during solidification resulting in porosity when the weld metal solidifies before the gaseous bubbles can escape. They further revealed that the drive to form pores due to hydrogen and oxygen tends to increase with increasing nickel content of the steel, and is quite manifest in nickel-based alloys.

Hydrogen has a higher solubility in iron in the γ-austenite phase than in α- or δ- ferrite phase. It is

therefore assumed that the tendency to form porosity is reduced if the stainless steel solidifies with a greater proportion of austenite than ferrite. It was found that austenitic steels can be welded with the above composition of shielding gas without porosity, Castro and Cadenet [6].

1.3.1 Remedies

To obtain sound welds devoid of porosity, the following processes should be adopted, TWI [4]:

- The use of welding process that generate low amount of hydrogen
- Using a streamlined and adequate gas flow rate
- The preheating of the parent metal to lower the rate of solidification
- The joint edges should be cleaned and welded immediately
- Change of the welding parameter (arc length, welding current, speed etc)
- Modifying the base metals composition example by reducing the sulphur content
- Use filler wire with de-oxidants in the correct proportion
- Avoid a joint design that creates a cavity and is not easily accessible for cleaning
- Add filler wire for TIG welding in other to compensate for weld pool shrinkage
- Use run-off plate in butt weld
- The stop should be ground out before using another electrode or depositing the next weld run.

In general, the causes and remedial actions for porosity are well documented, but it can be a persistent problem for some aluminium alloys. Nevertheless, porosity may occur in all materials when proper attention is not given to maintenance of welding plant and cleanliness of the components.

1.4 Porosity in TIG welding

Tungsten Inert Gas (TIG) or Gas Tungsten Arc Welding (GTAW) is a common welding process. The process is generally chosen for its ability to achieve high joint integrity in different materials. It is therefore a well-established welding process and with proper attention to maintenance of the equipment including the gas supply system, to proper joint cleaning, and to welding techniques, sound welds with negligible porosity can be achieved. On the other hand, due to the large number of variables involved, porosity may occur intermittently for reasons not very clear. Consequently, this may present problems in recommending appropriate solutions, Harris [1].

Due to the importance of the protection of the arc and weld pool, the effectiveness of gas shielding should be one of the first things to be checked if porosity occurs. Adequate care should be taken to ensure that there is no leakage of the shielding gas through the delivery system. It is believed that this factor is as important as proper cleaning of the material to minimise porosity, Harris [1]. Harris [1] further observed that of the factors controlling shielding efficiency, the purity of the shielding gas flowing from the torch should be assured as opposed to that from the cylinder itself, and also the

correct selection of gas flow rate for a particular nozzle size. Assurance that the correct gas purity is being maintained can be obtained from periodically testing the cylinder, for example by measuring the moisture content by means of a moisture meter.

TIG process has an important feature which gives it an edge over other welding process in terms of shielding from gas entrainment. This is achieved by replacing the standard gas collet of TIG torch with a gas lens collet. The latter is an enhanced collet body that is engineered to improve shielding gas coverage. It creates a laminar flow of shielding gas, thereby providing effective coverage, and removing turbulence that can suck in contaminants from the atmosphere. It is particularly useful with stainless steel and other very reactive materials such as titanium and aluminium that are very sensitive to contamination by oxygen.

1.5   Surface cleaning Methods

The removal of sources of contamination from the work piece surface and proper surface preparation of the material can significantly lower the level of porosity thereby resulting in the production of porosity-free welds. Surface cleaning methods involves mechanical cleaning, solvent degreasing and pickling. Atlas Specialty Metal [9] listed some sources of contamination and recommended appropriate cleaning methods as shown in table 3.

1.5.1   Degreasing

Solvent or alkaline degreasing is recommended for cleaning oily or greasy surfaces AWS [7]. They can also clean joint edges of other contaminants such as dirt, etc. The cleaning solvents used included; Acetone, Trichloroethane, and Isopropanol.

1.5.2   Mechanical cleaning

Mechanical cleaning includes the following:

- Mechanical sanding or grinding
- Hand filing or sanding
- Cleaning with steel wool
- Wire brushing or scraping
- Grit or shot blasting, AWS [7].

Typical surface cleaning methods entail the combination of mechanical and solvent cleaning.

1.5.3   Pickling

Picking or acid cleaning is used to remove rust, scale and oxides or sulphides from the metal to provide a clean surface for welding. The inorganic acids such as hydrochloric, sulphuric, phosphoric, nitric, and hydrofluoric, singly or mixed will serve the purpose. However, hydrochloric and sulphuric are the most frequently used. It is necessary to wash the cleaned pieces thoroughly in hot water after pickling and dry as quickly as possible, AWS [7].

1.5.4   Laser cleaning

Laser systems provide novel laser cleaning technology for industrial surface treatment, cutting, paint removal and cleaning applications. This innovative ablation technology eliminates contaminants, residue and coatings without destroying the base material, Laser Ready [8]. The process offers an additional advantage of being a cost effective and environmentally friendly method of cleaning, surface preparation and paints removal, Laser Ready [8].

Table 3: Recommendations for cleaning specific products [9]

Problems	Cleaning agent	Comment
Routine cleaning All finishes	Soap or mild detergent and water. (preferably warm)	Sponge, rinse with clean water, wipe dry if necessary.
Fingerprints All finishes	Soap and warm water or organic solvent (acetone, alcohol, methylated spirits)	Rinse with clean water & wipe dry. Follow polish lines.
Stubborn stains and discolouration. All finishes.	Mild cleaning solutions. Phosphoric acid cleaners may also be effective.	Use rag, sponge or fibre brush Rinse well with clean water & wipe dry.
Oil or grease marks. All finishes.	Organic solvents (acetone, alcohol, methylated spirits). Baked-on grease can be softened beforehand with ammonia.	Clean after with soap and water, rinse with clean water and dry. Follow polish lines.
Rust and other corrosion products. Embedded or adhering "free iron".	Very light rust stains can be removed by 10% nitric acid. More significant rust or embedded iron will require pickling. Sand blasting is another option.	Wear PPE as appropriate. Afterwards rinse well with clean water. Mix in acid proof container, and be very careful with the acid.
Dark oxide from welding or heat treatment	"Pickling Paste" or pickling solutions given on previous pages.	Must be carefully rinsed, and use care in handling

1.6 Effect of welding parameters on porosity

The welding parameters selected for a specific welding process can influence the level of porosity in the weld. For example, TIG welding of aluminium using Direct Current Electrode Positive (DCEP) will give oxide cleaning of the metal surface and thus reduce the occurrence of porosity. Several welding parameters that can influence the formation of porosity are dealt with in this section.

1.6.1 Welding current and voltage

Welding current is one of the factors that influence the formation of porosity. Heat input during welding is directly proportional to welding current, voltage and indirectly proportional to the travel speed. High welding current implies high heat input which may reduce the formation of porosity. The effect of heat input can be explained from the fact that at high heat input, the size of the weld pool will increase leading to a longer life time of the pool before

solidification. Consequently, there will be enough time for the formation, growth and escape of gas bubbles before solidification, thereby minimising porosity. On the other hand, at low heat input, the size of the weld pool will be small, which result in faster solidification. As a result, some bubbles which could not escape before solidification will be trapped thereby causing porosity.

Wikipedia [10] established the fact that too low or too high a voltage leads to an unstable arc which can cause turbulence in the shield gas flow pattern and this again can lead to porosity caused by gas inclusion.

1.6.2 Travel speed

Travel speed is other important welding parameters that can influence porosity formation. According to Harris [1], high welding speed tends to give sound weld, while slow welding speeds allow time for porosity to escape. High welding speed usually gives fine porosity which is uniformly dispersed and unnoticed on radiographs. Such porosity has negligible effect on weld strength.

Welding with low travel speed results in excessive heat build up. This according to weld craft [11] can lead to instability and turbulence in the molten weld metal that favours the formation of porosity amongst other defects. On the other hand, excess speed can also cause porosity or cavities as Zhao and Beroy [12] explained that nucleation and growth of gas bubbles occur during welding, but because of the fast solidification rate, there is not enough time for coalescence and escape of the bubbles. A balance between the two extremities

should be established to eliminate the formation of porosity.

At the optimum travel speed Zhao and Beroy [12] and Karimzadeh et al [5] established that there is sufficient time for the formation, growth and escape of the gas bubbles. Table 4 shows the effect of welding speed and heat input on porosity, while figure 4 depicts the influence of welding speed on the volume of porosity in TIG welds deposited on AL-6%Mg. Hence there is need to avoid the intermediate speed where porosity formation is high.

Table 4: The effect of welding speed and heat input on porosity [5]

Welding speed Cm/min	Heat input J/ min	Porosity density = (area of pore/ area examined) x 100
15	88.4	0.4
20	66.3	1.8
25	53	0.21
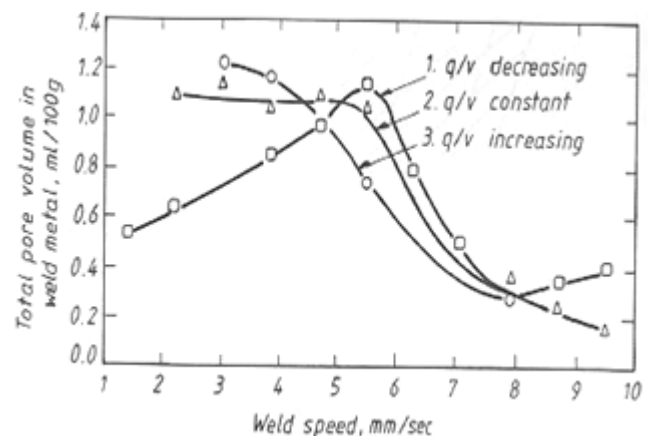
Fig. 4: Influence of welding speed on the volume of porosity in TIG welds deposited on AL-6%Mg, [1]

q = welding power, W;

v = welding speed

h = q/v = total arc energy

1.6.3   Shielding Gas

This is perhaps the most critical factor since it provides shielding for the weld pool and the weld area generally. Without shielding gas, atmospheric gases can be entrapped inside the weld pool and subsequently cause porosity. Welding processes need shielding to avoid these contaminations. The shielding gases where mixed, must be in the correct proportion. Another problem caused by lack of complete shielding gas coverage is arc stability which can also cause gas entrainment,

resulting in porosity back shielding is also critical in achieving welds without porosity. Insufficient or absence of back shielding gas can cause the entrapment of porosity causing gases in the joint area, which subsequently cause porosity. Fig. 5 below show some arrangements for back shielding that may be used on different structures to be welded, depending on their shapes.
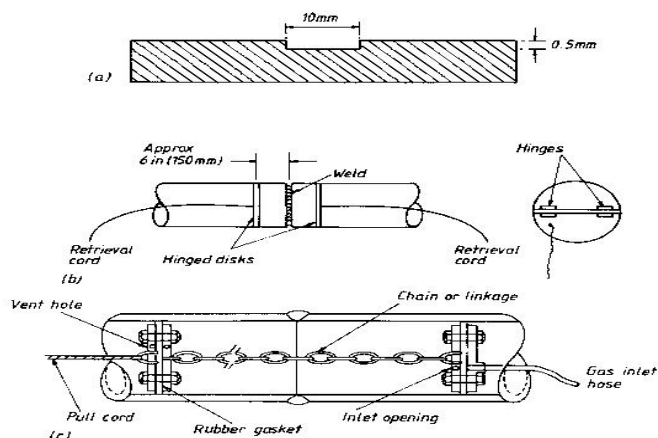
**Fig. 5:** A typical gas backing systems employed in TIG welding, [1]

    a.   Temporary backing bar for sheet material;

    b.   Hinged collapsible purging disks for tubes and pipes;

    c.   Gas dams with sealed gaskets for tubes and pipes.1.6.4   Contact tip

The distance from the contact tip to the work piece is another welding parameter that can cause porosity in the welded work piece. If the distance is too large, it could lead to improper coverage by the shielding gas, and consequently lead to gas entrapment. The electrode tip is another area that can introduce contamination in to the weld pool. If the electrode tip picks up contamination, which could come from different sources, such as dirt, oil, grease, and even from touching it with dirty hands, this contamination may be introduced in to the weld metal during welding and may cause porosity.

Improper preparation of the electrode tip either by incorrect grinding of the tip or wrong electrode angle may increase the chances of contaminants getting in to the weld pool. The former may cause the arc to become unstable and consequently affect the flow of the shielding gas, which could lead to turbulence and possible entrainment of atmospheric gases. According to Weld craft [11], wrong arc shape and also incorrect formation of arc is the first result of bad electrode preparation.

As shown in Figure 6, grinding direction should be along the length of electrode because the arc which is formed by this kind of electrode tip is more stable than the other kind of arcs, Weld Craft [11].
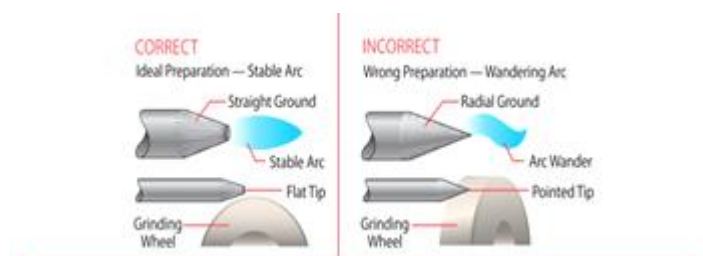
Fig.6: Correct Tungsten preparation, [11]

1.6.5   Joint Geometry and porosity

Kunjanpaa [13] observed that good accessibility for cleaning and welding is one of the most significant reasons for good joint geometry. The design of a joint geometry is an important factor that should be taken into consideration before welding any component. If the joint line is not readily accessible for cleaning prior to welding, the chances are that some dirt and other contaminants could still be left at the joint after cleaning. These may ultimately get in to the weld pool and cause porosity.

Joint geometries that will minimise the occurrence of porosity are those that have edges with curved geometry as against those that have sharp edges. The former will be accessible to cleaning solvents and mechanical cleaning, while the latter may not be easy to clean.

1.7 Problems with welding of ferritic steels

These are the basic type of steels and have body centred cubic structure at room temperature. According to Regis [14], ferritic steels contain a minimum of 11.5% Cr to form an oxide layer on the surface which gives its corrosion resistance and a maximum of 0.1% carbon. Moreover ferritic steels contain 11.5 to 29% Cr, generally low carbon content and other alloying elements such as Mo for corrosion resistance, Al for temperature behaviour and Ti/Nb for stabilization etc. They have less ductility and weldability as compared to austenitic stainless steels. Not strong as martensitic steels but easier to weld. Moreover corrosion resistance is better than plain carbon steel and good scaling resistance at high temperature.

Regis [14] showed that the properties of these steels are based primarily on the Cr content, resulting with a corrosion resistance. Ferritic steels are weldable but a care must be taken to compensate for critical properties as illustrated in table 5 below.

Table 5: Precautions and critical properties related with welding of ferritic steels, [14]

Critical properties	Precautions
C (insoluble)=>carbides=>corrosion	stabilization
N_2(insoluble)=>nitrides=>corrosion	stabilization
Risk of grain growth	N_2 and H_2 to be forbidden
H_2(insoluble)=>embrittlement	N_2 and H_2 to be forbidden

Kou [15] mentioned poor HAZ toughness as a typical problem due to HAZ grain growth and formation of grain boundary martensite when welding ferritic steels. He explained that during welding of these steels, the material is heated to a temperature at which austenite is formed, and on cooling martensite can be formed very easily especially in the HAZ. Due to this martensitic formation, grain growth occurs at high temperature and hence results in HAZ with poor properties.

Ray and Shankar [16] also showed that ferritic steels are less weldable as compared to the austenitic steels because the welded parts experiences poor toughness due to grain coarsening. They further explained that low heat input during welding addition of carbide and nitride formers to suppress grain growth and addition of Nb, Ti, can be used as the suitable control measures to reduce martensite.

According to Bailey [17] the other problems that may occur during welding of ferritic steels are

cavities or porosity and hydrogen cracking. Regis [14] suggested that the ferritic steels can be welded without preheating or post heating according to table 6 below.

Table 6: Recommendations for welding ferritic steels, [14]

Advice	To combat
Stabilized grades of steel	Corrosion, grain growth, high temperature embrittlement
Low welding energy	Grain growth and embrittlement
Stability of ferrite	Percentage of martensite in semi ferritic
H_2 and N_2 are prohibited	Corrosion or cracking
CO_2 is not advisable	Carbides

1.8 Porosity in ferritic stainless steel

It is reported in literature that a lot of gases cause porosity, but among them, hydrogen, oxygen and nitrogen are mostly involved due to their appreciable solubility in molten metal. Their solubilities decrease with decreasing temperature, Lancaster [18]. The mechanisms of formation of porosity by these gases are discussed below:
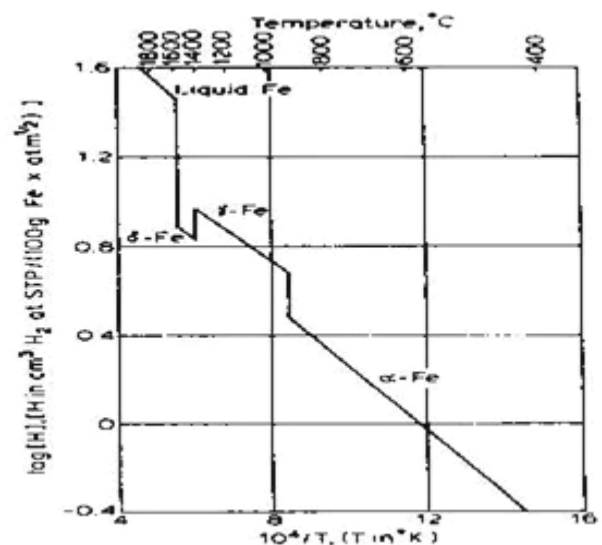
1.8.1 Hydrogen induced porosity

Hydrogen porosity is formed due to excessively dissolved hydrogen gas in metals. The solubility of hydrogen in molten iron based alloy is about four times that in solid delta iron at the melting point (see fig. 7 below). Thus, during solidification, the molten metal at the boundary with solid metal becomes supersaturated with hydrogen as the solubility limit has been exceeded and tiny bubbles of hydrogen gas nucleates and if sufficient hydrogen is dissolved, spherical voids will form. Sulphur

present in the base metal may also combine with hydrogen to form gases such as hydrogen sulphide that also forms porosity.

The hydrogen liberated from any of the sources is converted to atomic hydrogen and absorbed into the weld pool. Lancaster [18] and Devletian and wood [20], established that the absorption of the hydrogen into the weld pool is guided by the Sievert's law, which states that the solubility of hydrogen is directly proportional to the square root of the partial pressure of hydrogen above the melt.

$$(H) = K\sqrt{PH_2} \quad \text{(eqn. 2)}$$

Where (H) is solubility of hydrogen, K is the equilibrium constant and PH_2 is the partial pressure of hydrogen.

**Fig. 7:** The solubility of hydrogen in Iron as a function of temperature, [18]

1.8.2 Oxygen induced porosity

Oxygen is introduced into the weld metal from oxides in the base metal, the arc atmosphere and also from the dissociation of moisture on the base

metal. The gas can become entrapped in the solidifying weld pool to form porosity. Oxygen in the weld pool also reacts with carbon in the steel causing carbon monoxide and carbon dioxide porosity.

Lancaster [18] shows that oxygen in the weld metal also leads to the precipitation of non metallic inclusions, loss of alloying elements by oxidation or precipitation.
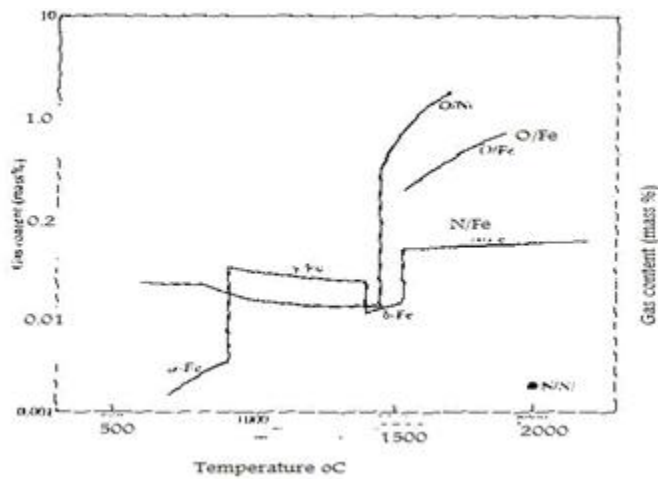

Fig. 8: The equilibrium solubility of nitrogen and oxygen in iron at 1 atm. pressure, [18]

1.8.3   Nitrogen induced porosity

This type of porosity is caused when nitrogen gas is entrapped in the weld pool. The gas could come from the atmosphere, improper shielding gas composition or from dissolved nitrogen in the base metal.

Blake and Morgan [21], Lancaster [18] established that Nitrogen absorption by steel weld pool under a TIG arc is proportional to the partial pressure of nitrogen in the arc and with the quantity of oxygen also, hydrogen reduces nitrogen absorption.

Lancaster [18] explains that porosity forms when the amount of nitrogen in the weld is higher than 0.045% by mass, but Blake [22] gave the nitrogen limit at 0.03%.
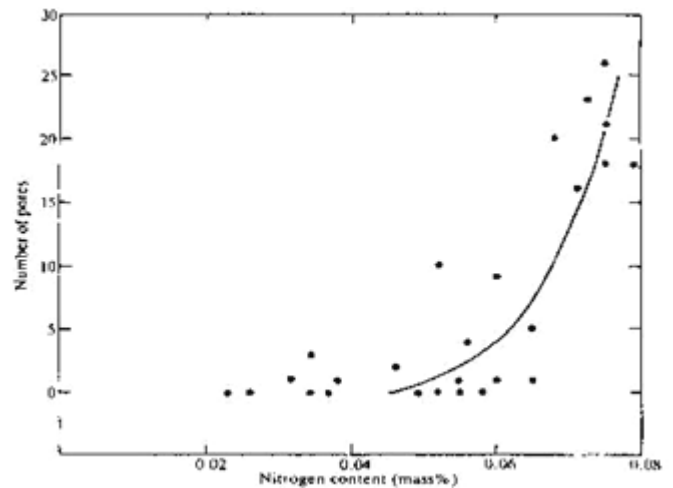
Fig. 9: The number of pores in a fractured surface of a tensile test piece as a function of nitrogen content, [18].

1.9   Effects of porosity on the strength of ferritic steels welds

Porosity is regarded as a sort of weld discontinuity. In studies conducted on the effect of porosity on the strength of the material, it was found that in amounts less than 3% by volume, porosity has a negligible effect on the static tensile or yield strength of the material, Leonard [19].

Harris [1] explained that porosity becomes a concern when it occur in thin sheets that is under fluctuating loading, when it occur in welds that must be leak proof (e.g. in pressure vessels), when porosity mask other defects (e.g. lack of sidewall fusion and lack of penetration) and when the porosity breaks into the surface.

The weld metals properties may also be affected by the porosity forming gas that dissolves in it for example, nitrogen in the form of iron nitride FeN has a severely embrittling effect on the weld metal. In Carbon manganese steel, nitrogen is responsible for strain age embrittlement Lancaster [18] and the pore acts as a source of stress concentration leading to brittle failure, thereby making cyclic loading of the affected part dangerous as it could easily fail by rupture. It compromises the mechanical integrity of the weld.

2. RECOMMENDATIONS

General recommendations on the avoidance of porosity in TIG welding can be summarised as follows, Harris [1]:

- Particular attention must be given to the torch connections and gas hoses to ensure that they are free from leaks. Metal lines should be used when practicable, particularly stainless steel as water can be absorbed through the walls of rubber or polythene hoses.

- Proper cleaning of the joint and filler wire if used is very important in order to avoid contamination by moisture, grease, etc. Care should be taken to avoid contamination from handling after cleaning especially during industrial production.

- The joint area should be cleaned mechanically by grinding or wire brushing in combination with solvent degreasing as suitable for a particular material. Rotary wire brush seems appropriate for this material.

- Adequate shielding gas coverage of the weld pool must be provided. Attention should be given to gas flow rate and nozzle size, especially back shielding. The use of a gas lens is highly recommended to ensure laminar gas flow.

- Moisture content of the shielding gas should not exceed 4ppm for welding grade argon, and 2ppm for high purity argon, helium-argon, and argon-hydrogen, the shielding gas should also be of sufficient purity.

- Adequate gas flow rates should be maintained.

- Gas backing system (hinged collapsible purging disks, or Gas dams) should be used to ensure effective gas shielding for the back of the component. This system is used to provide back shielding during the welding of tubular components. See fig. 5.

- The selection of welding parameters particularly welding speed, welding current and arc voltage should be made to minimise the formation and entrapment of porosity. Fig. 4 provides a useful guide in this regard.

- Preheating may be adopted to drive away condensed moisture on the surface of the metal.

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