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# The Physics of Weldpool Formation: Phase Transition Process In Gas Metal Arc Welding Of Mild Steel Electrodes

***Joseph I. Achebo***

**Department of Production Engineering**
**University of Benin, Benin City, Nigeria.**

## *Abstract*

***The phase transition process which takes place during weldpool formation is examined. The phase transition processes occur in three zone determined stages. The fusion zone, the mushy zone, and the heat affected zone (HAZ) are greatly affected by the amount of heat input. The phase change model was used to determine the state of the transition process. From the application of this model, it was found that at the obtained phase change of 0.5, the liquid metal has already cooled, and transited into the mushy zone at a temperature of 1489$^{o}$C. A Biot number of 0.0073, which is much less than 1.0 was obtained. This indicates that the heat flow in the weld pool is convective and further shows that the formation of molten weldmetal droplets that form the weldpool are under the influence of the arc heat and this makes the flow turbulent. From the findings and the microstructural analysis, it can be found that during the melting process, phase transition took place but did not significantly alter the microstructure of the weldment. This study also supports the claims made by different investigators about the different heat treatments given to metals to determine a particular hardenability level. This heat treatment process is an indicator of phase change.***

## 1.0 Introduction

Phase transition process that lead to the formation of weld pool is of great importance in modern day welding technology. In a controlled welding environment, a phase transition process leads to a desirable weld metal quality free from the contamination of elements like Nitrogen and hydrogen, which are majorly responsible for weld porosity.

In the formation of the weld pool, when arc heat is applied to the electrode, during the melting process, the electrode transits from its solid state to the mushy zone unto the heat affected zone (HAZ). During this transition process, the electrode is susceptible to high absorption of moisture from environmental inclusions like water, grease, paints etc. Because metals are known to readily absorb moisture under high temperature, the environment is well controlled to avoid inclusion that could adversely affect its load bearing capacity, that is its quality features. At its transition stage, the welding process becomes sensitive and requires an appreciable level of technical welding skill. The electrode transition from the solid state to the mushy zone, requires that the localized heat applied to the electrode, would have agitated the potential energy of the molecules that make up the solid electrode and make them mobile. What actually occurs is that as the heat is sustained over a long welding period of time, the molecular mobility of the grains becomes apparent, as the solid electrode transits into the mushy zone.

The flow in the mushy zone is plastic and usually droplet formation is mostly influenced by surface tension force (retaining force), but as the arc heat or temperature is prolonged, the flow transition advances from the lower part of the mushy zone to the upper part. In the upper part, the surface tension force would inevitably be overcome by the detaching forces induced by the shielding gas, the temperature, and the mass of the droplets. Flow takes place due to the sliding action, where molten metals are forced to slide over one another, as the droplets detach into the weld pool. The droplets transit from the mushy zone to the HAZ, at this point, the mobility of the molecules is quite high, causing the continuous collision of these molecules, which leads to further molecular disintegration. This molecular disintegration transits the plastic weld metal into liquid weld metal. It is at this liquid state that a weld pool is formed.

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[1] Corresponding author: ***Joseph I. Achebo,*** E-mail: dracigboanugo@yahoo.com, Tel.: +2348033830934

From the period spanning the heating of the solid electrode, to when the electrode actually melts and forms a weld pool, there are heat losses that would have occurred. This theory was adequately explained by Kim et al. [1] that heat losses occur by conduction in the solid electrode, radiation by exchange with the environment, convection to the shielding gas, and evaporation at the weld pool surface. However, the combination of these heat losses does not significantly affect the arc heat input, as has been observed by Norris et al. [2].

Some investigators have considered in their research, the impact of the mushy zone in the transition process that occurs during the formation of weld pool. Amongst them are Wang and Tsai [3], who studied the impingement of droplets onto the weld pool, considering the phase changes that occur during molten metal solidification process, by employing the volume of fluid technique and the continuum formulation. Das and Cleary [4] considered the effect of phase changes on weld pool formation when modeling the plastic deformation and thermal response in a weld pool using smoothed particle hydrodynamics. Betram [5] studied the role of heat and liquid flows on the final weldment solidification microstructure, considering the mushy zone behavior. Zhang et al. [6] in understanding the phase transformation kinetics during the heating and cooling process of weld metal, the behavior of the mushy zone was investigated. Wang et al. [7] showed in their research work that heat transfer and phase change effects exert a significant impact on metal transfer modes. In this study, the phase transition behavior that occurs during the weld pool formation process is investigated by applying the model proposed by Xiangqian [8].

## 2.0 Materials and Methods

In this study, the gas metal arc welding (GMAW) machine is used to melt 3.2 mm mild steel electrodes, whose melt (or liquid metal) formed the weld pool. Thermocouples were utilized to measure the solidus and liquidus temperatures. The following equations were employed to study the phase change phenomena.
The net heat input in any arc welding process used for this study is written as

$$Q_{net} = h \; x \; Q_{arc} \tag{1}$$

where, $Q_{net}$ is the net heat input, $Q_{arc}$ is the arc energy, kJ/m, h is the heat transfer coefficient, $W/m^2.^oC$

$$Q_{arc} = \frac{q}{v} = \frac{EI\eta}{v} \tag{2}$$

where E is the arc voltage = 9V, I is the welding current = 170A, v is the welding speed = 0,0052 m/s, η is the heat transfer efficiency = 0.8. Nissley [9] and Atkins et al. [10] gave the values of the heat transfer efficiencies for different welding processes as follows:
Submerged Arc Welding (SAW) η = 0.9 – 0.95, Gas Metal Arc Welding (GMAW) η = 0.7 – 0.85 and Submerged Metal Arc Welding (SMAW) η = 0.7 – 0.8
Poorhaydari et al. [11] proposed an equation for determining the temperature, T at time, t as

$$T - T_0 = \frac{q/v}{2\pi t} \exp\left(\frac{-r^2}{4\alpha t}\right) \tag{3}$$

where $T_0$ is the preheat temperature = $240^0C$, heat input, q/v (J/m.s), welding time, t = 30 s, thermal diffusivity,$\alpha = 6.82 \times 10^{-6}$ $m^2/s$ and radial distance from the weld, r = $3.46 \times 10^{-3}$m.
Xiangqian [8] proposed an equation for determining the phase change ratio, $f_s$ as

$$f_s = \frac{T_l - T}{T_l - T_s} \tag{4}$$

where T is the workpiece temperature, $T_l$ and $T_s$ are the liquidus and solidus temperatures respectively. $f_s$ values ranges from 0 to 1.0.
Holman [12] reported that the criterion for the appearance of approximately isothermal conditions is given by the Biot number, $B_i$. For the temperature distribution radially across a cylindrical section, $B_i$ becomes

$$B_i = \frac{h.d}{4k_{solid}} \tag{5}$$

where $k_{solid}$ is the thermal conductivity of solid = 29.4 J/m.s. $^0$C or W/m.$^0$C, d is the diameter of the material or workpiece, for plate, d = ½ thickness and the plate thickness is 8 mm. h is the heat loss coefficient given by De et al. [13] as

$$h = 2.4\,x\,10^{-3}\varepsilon T^{1.61} \tag{6}$$

where $\varepsilon$ is the emissivity = 0.7 and temperature, T = 1489 $^0$C.
Jones et al. [14] proposed an equation for determining the minimum molten metal film thickness, δ □ obtained from the deepest part of the weldpool. This equation is given as

$$\delta^* = \left(-\frac{4abu}{Q_{\max}}.\frac{\mu k_i}{C_\gamma}\right)^{\frac{1}{3}} \tag{7}$$

where a is the standard deviation of the heat source, given as $10^{-3}$ m, $k_i$ is the heat conductivity of the liquid = 65.4 W/m$^o$C, b is the liquid layer thickness obtained from the heat source, was given as 1.5 x $10^{-3}$ m. $C\gamma$ is the surface tension coefficient given as -3.6 x $10^{-4}$ Nm$^{-1}$K$^{-1}$. u is the travel velocity = 5.2 x $10^{-3}$ m/s

## Discussion of Results

In this study, the physics of weldpool formation was investigated with focus on the phase transformation process during droplets to weldpool formation. From the measurements obtained by embedding thermocouples into the arc heated melting electrodes and weldpool, the solidus and liquidus temperatures obtained are 1469$^o$C and 1509$^o$C respectively. From the equation proposed by Poorhaydari et al. [11], the workpiece temperature (T) at time (t) was determined to be 1489$^o$C. The temperature lies between the solidus and liquidus temperatures. Applying Eq. (4) for determining the phase transition status, it was found that, $f_s$, which is the solid phase change ratio is 0.5, which lies between the range of values 0 to 1.0. This value indicates that the weld geometry is in the mushy zone. Yang and Debroy [15] classified the weld geometry to be in the fusion zone, mushy zone and HAZ and also reported that the mushy zone is the region between liquidus and solidus temperatures. This claim was also supported by De et al. [13]. Xiangqian [8] wrote that when $f_s$, is equal to zero, the metal is in the liquid condition. When $f_s$ is equal to one, metal is in the solid condition, and when $f_s$ is greater than zero and less than one, metal is said to be in the mushy phase change zone.

The mushy phase change zone constitutes the condition where the molten metal is in the visco-plastic form. At this stage the droplet detachment process takes place when molten metal droplets slide over one another as the flow advances into turbulence. Malinowski-Brodnicka et al. [16], Choo and Szekely [17], Hong et al. [18] and Yang and Debroy [15] were of the same opinion that, in many cases in gas tungsten arc (GTA) welding, fluid flow in the weld pool is turbulent in nature. Yang and Debroy [15] reported that in GMAW, the high level of agitation in the weld pool is aided not only by large mean velocities in a relatively small weld pool, but also by the impact of metal droplets.

Turbulent weld pool flow occurs at the convective part of the HAZ where the arc heat is most felt. This is determined by obtaining the Biot number (Bi). The Biot number was determined to be 0.0073 which is much less than 1.0 (Bi □□ 1.0). This indicates that surface convection is dominant and the temperature distribution at the center of the weld pool is uniform. This also confirms that flow in the weld pool is turbulent. The minimum molten metal film thickness obtained from the deepest part of the weld pool is calculated to be 1.03 x $10^{-8}$ m with a droplet radius of 0.58mm constituting a volume in a single droplet of 1.418 mm/s. At the molten metal droplet stage the molten metal would have left the influence of the intense arc heat and moved to the influence of the lower part of the arc heat column, making the molten metal visco-plastic texturally. This visco-plastic molten metal texture further confirms that the molten metal has entered the mushy zone.

As the electrode temperature transits from the preheat temperature, to the solidus temperature, to the mushy zone temperature, and then to the HAZ temperature, the molten metal forms a globule of molten metal which is held to the electrode by the surface tension force (retaining force), as the detaching forces (electromagnetic force, gravitational force and drag force) overcome the retaining force, the molten weld metals drop to form weld pool at the joint of the pieces of metals to be welded.

The transition processes that occur as the molten metal drops to form a weld pool is studied. It is discovered that the mushy zone of the weld pool formation was achieved in the transition process. This shows that flow is still in its visco-plastic stage. The visco-plastic stage can be used to predict two stages, first, the transformation of the electrode materials from the solid state to the liquid state, and the solidification process of the liquid state (weldpool) when the weldpool temperature drops. In either of the two stages, the microstructure of the weld metal is affected, which has a profound effect on the quality of the weldment.

Temperatures and heat input have a significant effect on weldment microstructure as well. Increase in these parameters (temperature and heat input) would vaporize volatile alloying elements in the weldpool. This in turn would alter the chemical composition of the resulting weld metal [19]. From the microstructural analysis of the weldment, shown in Fig. (1). It is shown that there are a few large microstructural grains. These large grains are responsible for spore formation in the weld. The large grains can not flow continuously in the weldment when heat is applied. The blockages caused by these large sized grains allow gaseous evolution to be retained in those openings. The microstructural view has been able to show that these large sized grains are minute and the fine sized grains are dominant. This shows that the weldment underwent a transition process, either where the large grains have diffused into small grains or small grains are building up into large grains. From literature, it has been reported that large grains are as a result of oxidized metallic grains. This means that the arc column has not been able to completely prevent the HAZ from interacting with the atmosphere. It may occur at the edge of the HAZ away from the heat source.

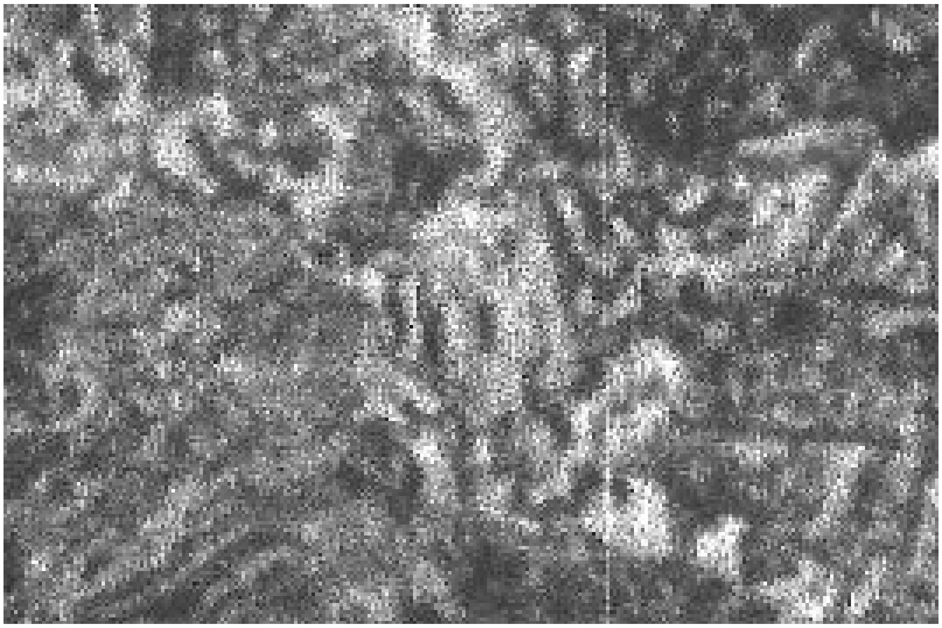

**Fig. 1** Weld Microstructure

## Conclusion

The transition process characteristics encountered during the formation of the weldpool is studied. It was found that the weld pool state (HAZ) transited to the mushy zone, which was found to be visco-plastic texturally and as a result of this, the molten metal would have lost some of the heat retained at the center of the arc column, to the atmosphere. This heat loss is fundamentally responsible for the molten metal transiting from its initial liquid state to the mushy state.

This study has also disputed the claim made by Shackleton and Lucas (1974) that metal transfer expected to occur at 200A is subthreshold. In this study, at 170A, a spray transfer mode was achieved. The claim is supported by the value obtained for the diameter of the droplet, which is twice its radius ($2R_d$). For globular droplets, the droplet diameter is assumed to be equal to the diameter of the electrode. Droplet diameters much less than that attributed to globular droplets are regarded as spray droplets. However, it is interesting to know that spray transfer modes can be obtained by setting your welding machine to 170A which is less than 200A. Although, the electrode material was not tested to reveal its mechanical properties in order to determine its quality level. The preheating temperature may be rather too high for the electrode, if its mechanical properties are inferior. For this reason, the microstructure of the electrode may contain volatile alloying elements that could reduce the weld's hardenability. These factors could be responsible for the reason why a current less than 200A can agitate a spray transfer mode.

In this study, the phase transition process that occur from the liquid state, HAZ to the mushy zone has been investigated and the associated characteristics have also been determined.

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