

Innovative Tandem GTAW with Alternating Side-by-Side Spot-Like Welds to Minimize
Centerline Solidification Cracking

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in
the Graduate School of the Ohio State University

By

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2017

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Abstract

Fusion welding is one of the processes industries prefer to use in order to produce high quality and safe joints for a desired manufactured product to meet customer needs. Unfortunately, sometimes fusion welding process is not applicable for some of the high strength materials and applying this type of joining processes can lead to a solidification cracking due to material wide solidification temperature range. This issue pushes the designers to use different types of join processes instead of fusion welding such as riveting or screws, which can be alternative solution for fusion welding. Using these processes instead of fusion welding can bring up even more problems for the joint such as material loss, increasing weight, corrosion, and high stress concentration. Therefore, improving the fusion welding process on one of the high strength and solidification crack susceptibility materials, like aluminum alloy 2024, will be the main goal of this study. Al alloy 2024 will be fusion welded autogenously, and material's solidification crack behavior and microstructure will be investigated in this work by four different GTAW processes and they will be compared with a new weld technique never used before this study called; tandem GTAW side by side process with alternating working electrodes.

Dedication

To my parents' souls

Ismaeel Albannai & Khatoon Qumbar

Acknowledgement

First, I am grateful to Professor Avraham Benatar, my advisor. He was patient with me and his guidance, recommendations, and encouragement pushed this work to reach this point.

Second, I thank Professor David Phillips for his support and serving as committee member to this work by providing helpful and positive suggestions.

Third, I acknowledge all the Professors John Lippold, Dave Farson, Wei Zhang, and Boian Alexandrov for their assessment and beneficial discussion towards this project.

Fourth, I would like to extend my thanks to the fellow graduate students in the department of welding engineering of Ohio State University. Specially, I would like to thank, Sebastian Romo, and Gaofeng Sha for sharing their rich knowledge on all metallurgy and characterization related. A sincere thank you goes to Guilherme Abreu Faria for all of his support, hard work, and helpfulness with the electric connections. Also, I send a special thank you to Ed Pfeifer, Tyler Borchers, Dan Tung, Emeric Suma, Andrea Peer, Tate Patterson, & Alex Alvarez for all of their help and kindness.

Fifth, I am thankful to both companies Lincoln Electric and Miller for their help and support to this project. I would specially thank Michael Flagg and Mike Barrett from Lincoln Electric, and Craig Eppley from Miller for their helpful technical supports.

Finally, I send great thank to all of Kuwait government, my family members, and friends for their constant love and support.

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Chapter 1

Introduction

1.1 Background & Research Issues:

Fusion welding is a process used to join materials with each other by melting and solidifying them under a heat source with high temperature applied on the desired location of the joint for a specific time. This process works locally (on the joint location) as casting process, which melts the material to allow the various elements mixing with each other forming an alloy after solidifying. One of the most important issues that fusion welding processes face is a crack type called; solidification cracking and known as part of hot cracking. This type of cracking always forces the designers to avoid using fusion welding process to join the susceptible materials to this cracking type. Therefore, having general knowledge on the solidification phenomena is always significant to reach better understanding of material behavior after welding, which helps to avoid solidification cracking or even to reduce the undesired resulted properties of the solidified material.

Fusion welding process depends on three main stages in general. First, applying the required heat input from a heat source on the desired location of the material surface (joint location). Second, staying for some time allowing that material to melt and form the right liquid spot (weld pool) on the desired location. Third, removing the heat source (heat input) to let the material cools down due to conduction through solid parts of the material away from the liquid spot, which cause the liquid to transform to solid forming the required weld joint.

During solidification process of an alloy, the composition of the solid and liquid in contact at the solidification front changes continuously as the temperature drops down within the solidification range (liquid to solid transformation), so if the solid does not have enough time to reach its equilibrium composition, the resulted solidified structure will form local variation in composition.

The equilibrium solidification behavior of two different components alloy can be simplify in the next following figure (1.1) as John Lippold did in his book [1]. The solidification process of type 1 alloy, starts from the liquidus line when the temperature of that alloy drops continuously and reaches the full solidification of solid (A) just below the temperature of the solidus line, where the solidification process ends with 100% solid A for alloy type 1. But, we should be aware of the nature of the cooling rate during the solidification process, which means during the rapid cooling rate or naturally what is happening after fusion weld process, the solidus line of an alloy will be shifted to the left as one can see in figure (1.1) where the blue dash line is located. This shift will lead to form different alloy composition as one can see the red dash line and that may cause a

series segregation due to non-equilibrium solidification behavior. Also, it is clear in the same figure (1.1) that the end of the solidification for alloy type 1 will be delay to reach (T_e) temperature and that will cause a formation of some eutectic structure at the end of solidification not only A phase, because the solidifying material is no longer following the theoretical solidus line which is mostly happening in fusion welding process due to rapid cooling rate and this consider to be the real reason behind segregation in the material during solidification process, which may lead to solidification cracking. For alloy type 2, the solidification starts with solid (A) when the temperature drops to a temperature below the liquidus line and ends after passing the eutectic temperature (T_e) , but with this alloy the remaining liquid which does not transformed to (A) before (T_e) line, will form (A+B) eutectic reaction after the (T_e) line. Therefore the final result of this solidification structure will be a mixture of (A) and eutectic reaction of (A+B).

Alloy type 3 solidification process will start and end on one single point at (T_e) line causing the liquid to form a complete eutectic solid structure of (A+B). The (A) and (B) phases can be determined by maximum solid solubility where the solidus and solvus lines interact with the (T_e) line at (C_{smax}) .

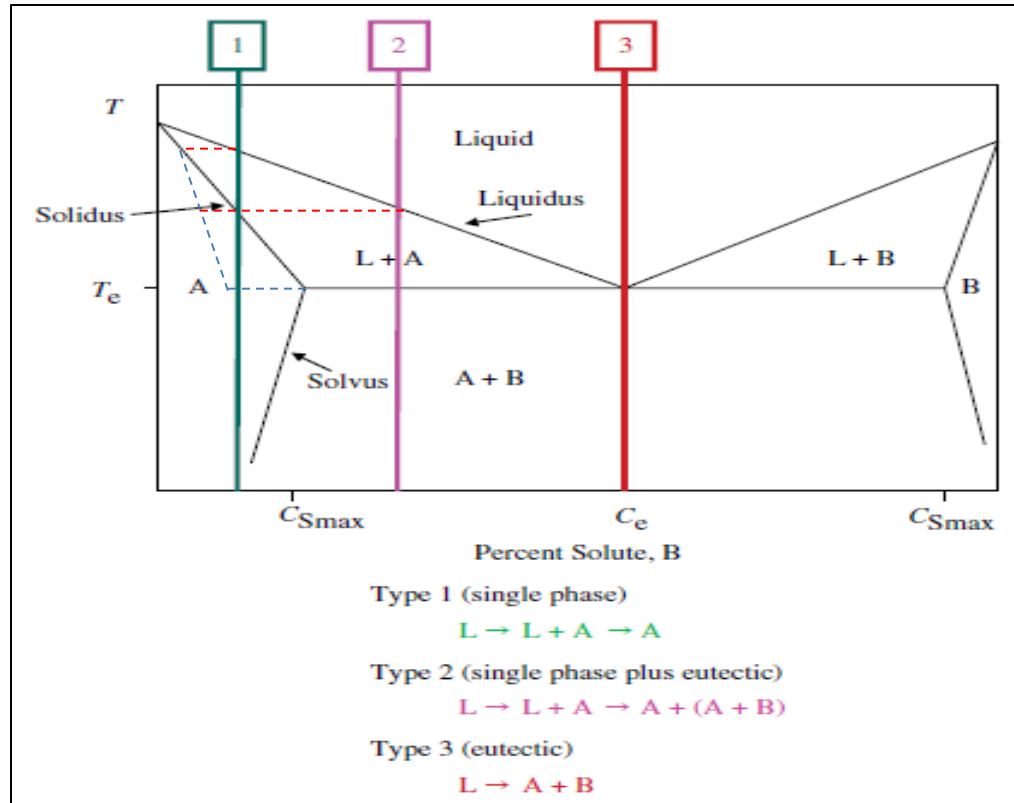


Figure (1.1): Basic phase diagram showing three different alloys solidifying differently [1].

So, from the previous figure (1.1), the solidification process of the material depends on the material composition to form the final solidification phase, which can result in specific material properties. Also, there are some other solidification parameters can control the resulted solidification structure or behavior, such as; cooling rate, temperature gradient (G), and solidification growth rate (R). Those parameters are very important for fusion welding process, because they can change the resulted solidified grain type, size, or even orientation. The mentioned parameters play huge rule in forming a non-equilibrium solidification, which may lead to unstable liquid-solid interface. The

non-equilibrium phenomena influence the solidification process and increase the possibility of crack occurrence. Therefore, to understand the effect of those solidification parameters, we will go through the solidification morphology and mode to get clear view of how the solidification process works in a fusion weld process especially as it is the mandatory work of this current study.

1.1.1 Solidification Modes:

There are five main solidification growth modes for a welded material and those modes are very important to build up the final properties of the solidified material, which can either improve the cracking resistivity, or increase the cracking susceptibility and for sure change some important mechanical properties, such as, hardness and strength. The five solidification growth modes are as they showing in the next figure (1.2) a) planer, b) cellular, c) cellular dendritic, d) columnar dendrite, and e) equiaxed dendrite. Some of the sources they just consider four growth modes by combining cellular with cellular dendritic as one single mode as Sindo Kou did in his book “welding Metallurgy” [2].

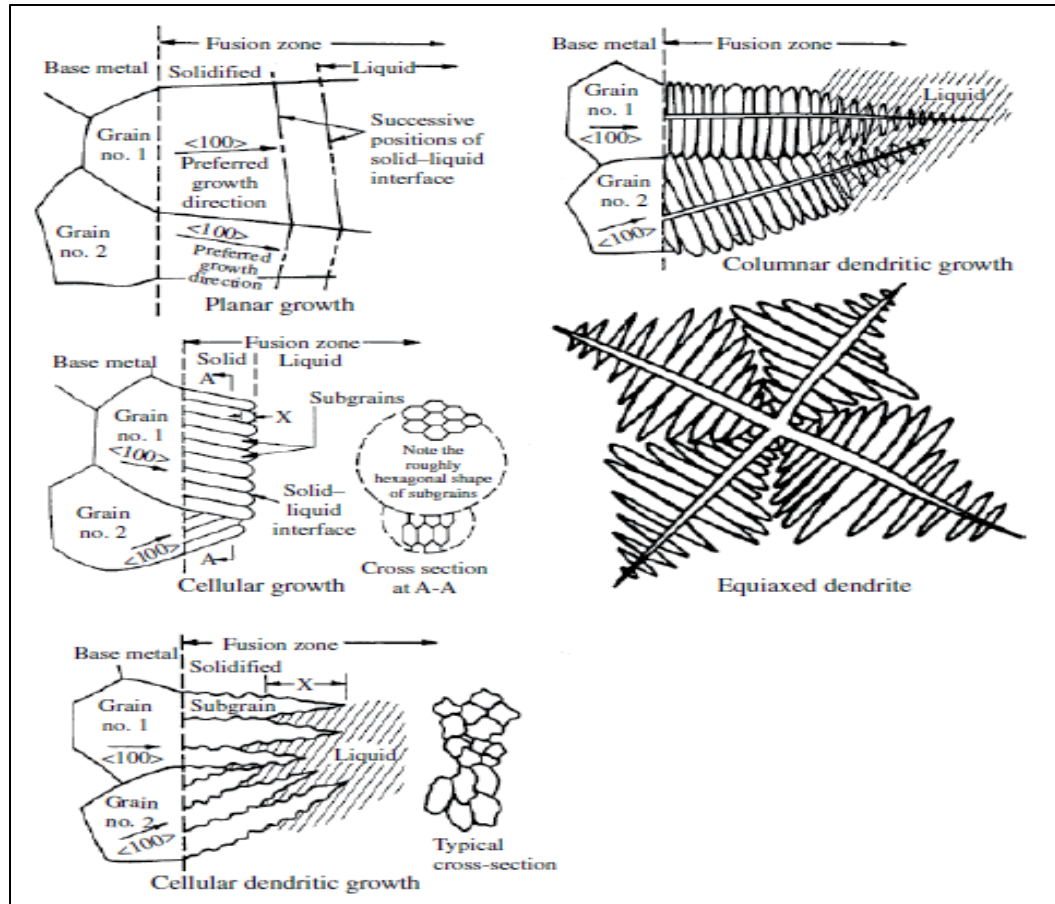


Figure (1.2): Showing the main five solidification growth modes in the fusion zone, where the material was melted and solidified, a) planer, b) cellular, c) cellular dendritic, d) columnar dendrite, & e) equiaxed dendrite [1].

The formation of these five modes depending on two main factors during the solidification process, the temperature gradient in the liquid (G) and the solidification growth rate of the grains (R). Changing the ratio between temperature gradient and the solidification growth rate (G/R) can transform the solidification mode from one to

another during the solidification process for the same material. Therefore, finding two or even more solidification modes in one solidified material gives the impression that the thermal history was changed from one spot to another in the weld pool causing the solidification mode to change and forming different grain mode type.

In general, increasing the temperature gradient in the liquid will lead to have more planar growth mode, while increasing the solidification growth rate helps to form more equiaxed grain growth mode as it shown in the next figure (1.3).

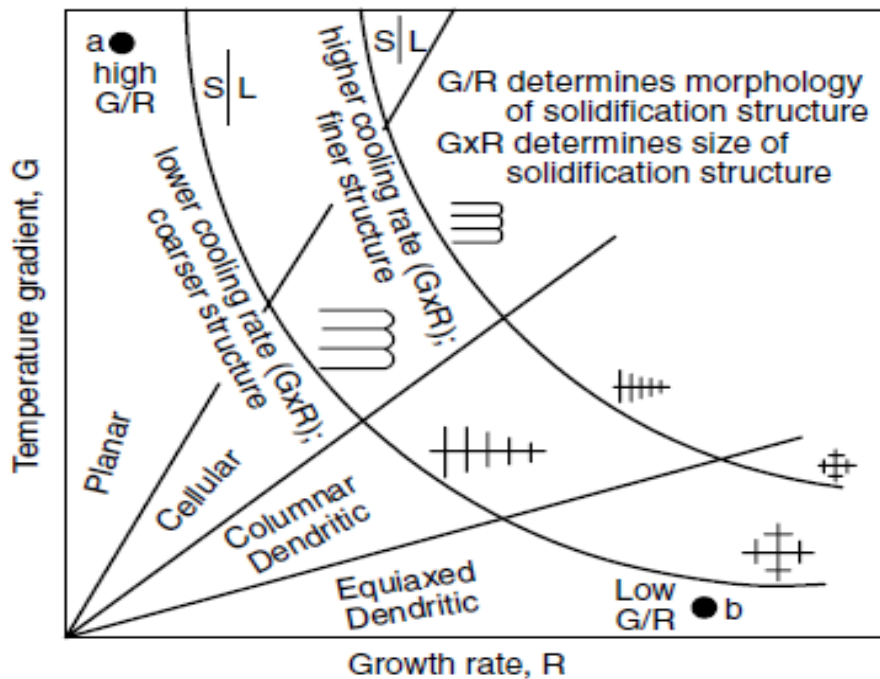


Figure (1.3): Showing the influence of both the temperature gradient and the solidification growth rate on the solidification mode transformation [2].

The previous figure (1.3) showing that the higher ratio of (G/R) the closer to planar structure will form, while the lower ratio will lead to form equiaxed dendritic. In other word, higher (G) leads to planar structure and higher (R) shifts the resulted mode to equiaxed dendritic more likely. Also, another important point in the same figure to be made is that mostly increasing (R) will lead to form finer structure mode for any of the four main solidification modes. Moreover, cooling rate, which showing in the following equation and depends on both (G) and (R), playing a huge rule in forming those solidification modes, the higher the cooling rate the finer the solidification grain mode structure and more likely equiaxed dendritic grain mode structure will form, while lower cooling rate will shift the solidification mode to cellular with larger grain structure or even to planar solidification mode.

$$\text{Cooling Rate} = (G) \times (R)$$

Eq. (1.1): Cooling rate

Equation (1.1) used widely to calculate the cooling rate of a heated material and the resulted unites should be in (°C/seconds) [3] & [4], where (G) is the temperature gradient in (°C/mm), and (R) is the growth rate in (mm/seconds).

1.1.2 Weld Pool shape:

In fusion welding process, having a weld pool is an important stage of the whole process as mentioned earlier, and moving the heat source from one location to another gives a motion of that weld pool causing the previous location to solidify and melting the following one and so on to complete the total weld line and forming the required weld joint. Therefore, the motion of the weld pool is very important on the solidification process and can change the cooling rate significantly. The motion of the weld pool is known as welding travel speed, and the higher the welding travel speed is the longer the weld pool shape will be, while slower welding travel speed forms almost round weld pool shape. Figure (1.4) showing the difference between the two main weld pool shapes, one is called elliptical weld pool shape and the other known as tear drop weld pool shape.

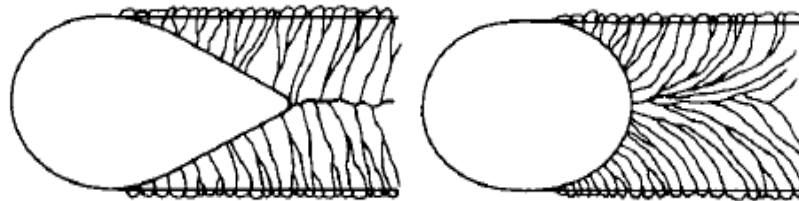


Figure (1.4): Showing the two different weld pool shapes, on the left Tear drop weld pool, and on the right Elliptical weld pool shape [3].

The previous figure (1.4) showing that by increasing welding travel speed, the growth of the solidify grains direction will change from angular growth toward the center line of the weld pool figure (1.4, right side) to almost straight and perpendicular growth figure (1.4, left side).

Therefore, it is important to understand how does the weld pool shape affect the solidification process and resulted grains, next figure (1.5) gives better understanding for a general weld pool shape resulted from a fusion welding process.

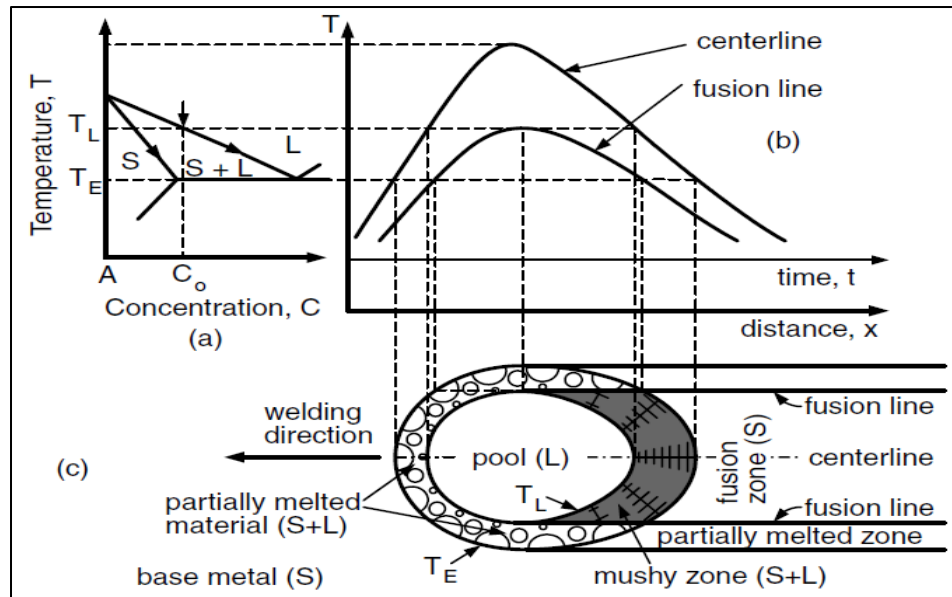


Figure (1.5): Showing a) the phase diagram of a welded material with a concentration of C_0 , b) a plot of different temperatures for different locations, and c) the weld pool shape [2].

From the previous figure (1.5), the relation among the location, weld pool shape and direction, and temperature are given in a good way to track the resulted solidifying material and its behavior after completing a weld line. Figure (1.5, c) showing the different zones during and after fusion welding process, and they are partially melted zone, fusion zone, and mushy zone. One of the most important zones that we need to focus on here is the mushy zone (where the liquid phase is coexist), because it is the most affecting zone on the solidification mode and it is the interface of both solidus and liquidus phases. Another important point to be mentioned from figure (1.5, b) is that the plot of temperature and distance can give the value of the temperature gradient (G) in that zone by calculating the resulted slope from the same plot. Therefore, with higher weld travel speed and tear drop weld pool shape, we can get shallower temperature gradient (G) and lower (G/R) ratio with high possibility of forming equiaxed grains, because the area where the liquid and solid co-exist (mushy zone) will be longer, while with elliptical weld pool shape and slower weld travel speed leads to a steeper temperature gradient (G) and higher (G/R) ratio will be resulted and the probability of forming equiaxed grains will be very hard, because of the shorter mushy zone. The next two figures (1.6 & 1.7) explain how the weld pool shapes control the temperature gradient (G) from one location to another in the weld pool.

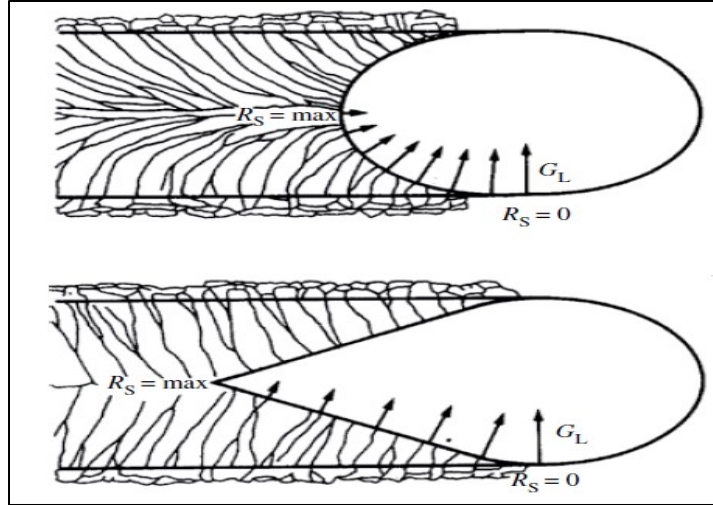


Figure (1.6): Showing both elliptical and tear drop weld pool shapes, where (R) reaches maximum value at the centerline of the weld pool edge and almost zero on the fusion boundary (side of the weld pools), while (G), which indicated by the arrows reaches maximum value on the fusion boundary of the weld pools [1].

It is clear from figure (1.6) that with elliptical weld pool shape (G) decreases slowly from the fusion boundary towards the centerline and it is not zero, while for tear drop weld pool shape (G) decreases in a sharp way and it reaches almost zero at the centerline of the weld pool. So, in general the temperature gradient (G) higher closer to the fusion boundaries of the weld pool, while it is low close to the centerline of the weld pool in the fusion zone, where the solidification growth rate is the opposite, higher at the centerline and lower at the fusion boundaries as one can see in the next figure (1.7).

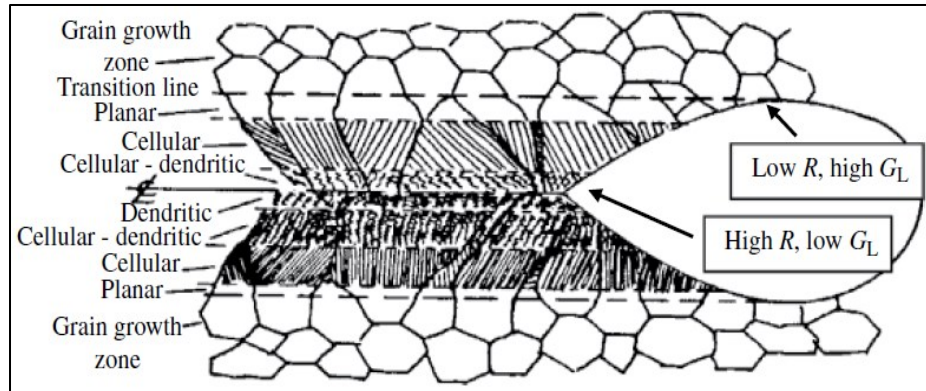


Figure (1.7): Showing multi solidification modes can be form with one weld line depending on the location and the ratio of (G/R) [1].

It is possible to have more than one or two solidification modes in one weld line and that due to the change in both temperature gradient and the solidification growth rate, so it is significant to know the desired weld pool shape and the size of the mushy zone before welding, which helps to control the resulted solidification modes and forming the required grain type in different locations in the fusion zone.

1.1.3 Weld Solidification Cracking:

Welding is the nerve of most material fabrications industries around the world. Industries using different weld processes for joining different materials in order to assemble the final product to meet customer needs and satisfaction. Therefore, the quality

of welding those materials are important and needed for both industries and customers to reach both satisfaction and to keep safety of products use at higher level. Even though, welding is a desirable process for industries to join metals, sometimes it can cause problems for some materials. These problems are correlated with material's behaviors and properties, and those behaviors or properties can be changed during and after welding. This change, may results in undesired material properties and behaviors during the service and causing the product to fail with shorter time than the designed and expected time. One of the worst metal behaviors is that called centerline solidification cracking susceptibility. During welding, melting a material by exposing it to an elevated temperature is one of the major steps of fusion welding processes as mentioned earlier. With this liquation process, most materials and especially high strength materials lose their designed properties trying to gain back their original and nature properties, which cause them to perform a hot center line solidification cracking during solidification process because of stress-strain concentration and material composition and properties. This is the main problem that fusion welding processes facing by welding high strength alloys. Solidification stage after welding can control the properties of the materials and build new ones as mentioned previously. Solidification cracking is a type of crack that initiates and propagates generally along solidified grain boundaries (SGB) or solidified sub grain boundaries (SSGB) upon two important factors, metallurgical and mechanical ones. Grain size and orientation, weld travel speed (weld pool shape), and differences in solidification temperature range among the elements of an alloy (mushy zone) are consider to be the metallurgical main factors, while thermal expansion, distortion, and

stress strain build up during the solidification process resulting from unbalanced thermal cycle around the fusion zone are the mechanical driving forces. These factors have been studied and many researches have been done on this area. Studies In the last 60 years confirmed that welding solidification cracking forming because of the relation between both material resistance to cracking and the mechanical driving forces appearing within the fusion zone. In other words, the material resistivity to solidification cracking should be high enough to handle the mechanical driving forces, otherwise the crack will form. In the next following figure (1.8) a better imagination will be given about the relation between the two main mentioned factors.

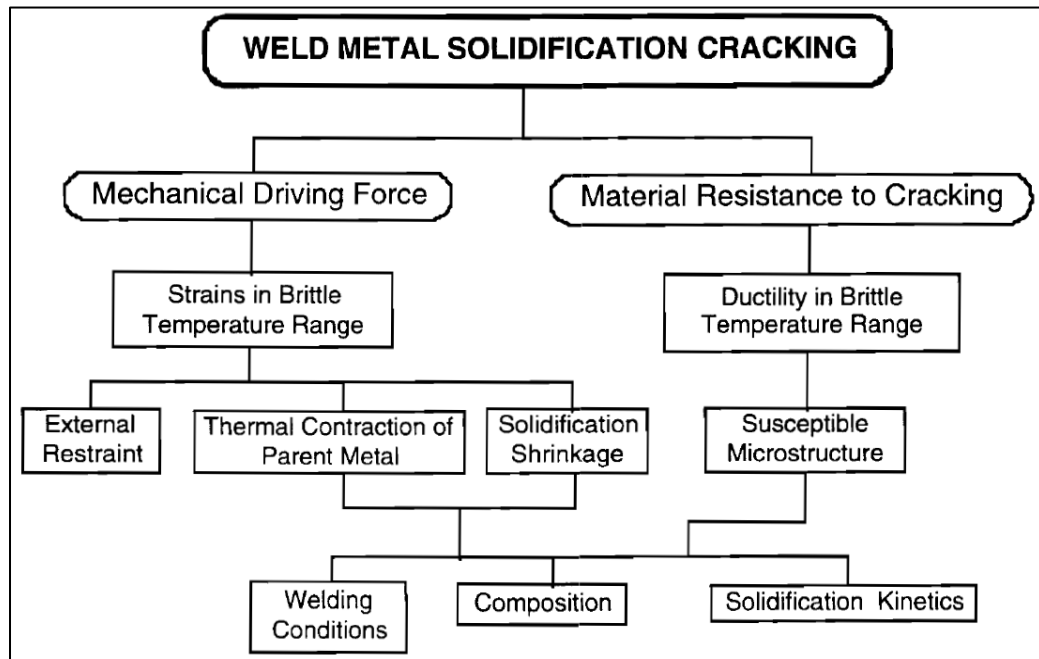


Figure (1.8): Showing the competition between the main two factors affecting the weld metal solidification cracking [5].

During a fusion welding process and in the last stage of the solidification process of the welded material a low melting point will exist causing the formation of some segregation between the resulted dendritic grains and that leads to have some liquid films in between the dendrite interface. This formation of liquid film with solid co-existence is known as the “Brittle Range Temperature” (BTR), where the mechanical strength of the material and ductility can be very low to handle the resulted buildup stress strain at the same time due to metal solidification shrinkage and thermal contraction. At this point the crack will appear if the mechanical forces exceed the mechanical strength and ductility of the welded material (material’s crack resistivity) as it showing in the following figure (1.9). In general, solidification cracking can be controlled by several important factors, such as; material composition (C_0), both solidification growth rate (R) and temperature gradient (G), and the solidification undercool temperature (ΔT) or what is known as mushy zone.

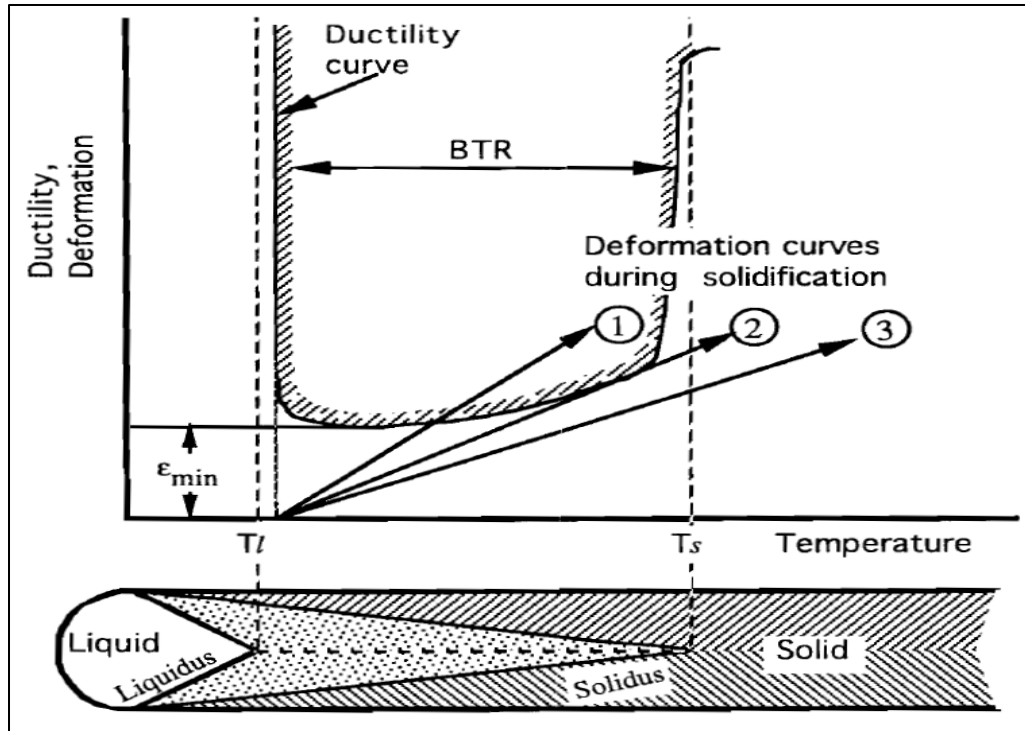


Figure (1.9): Showing the (BTR) region on the weld line and it is within the mushy zone of the weld pool, and if the strain occurs higher than the minimum strain (critical strain) the crack will exist in the weld line like arrow (1), while arrows (2, & 3) are out of the (BTR) region and the crack is not forming [5].

It is good at this point to mention the relation between the weld pool shape and the solidification crack resistivity by providing the next figure (1.10), which was a conclusion of Sindo Kou and his research team, who studied the effect of the weld pool motion on the centerline solidification crack susceptibility of an aluminum alloy [6].

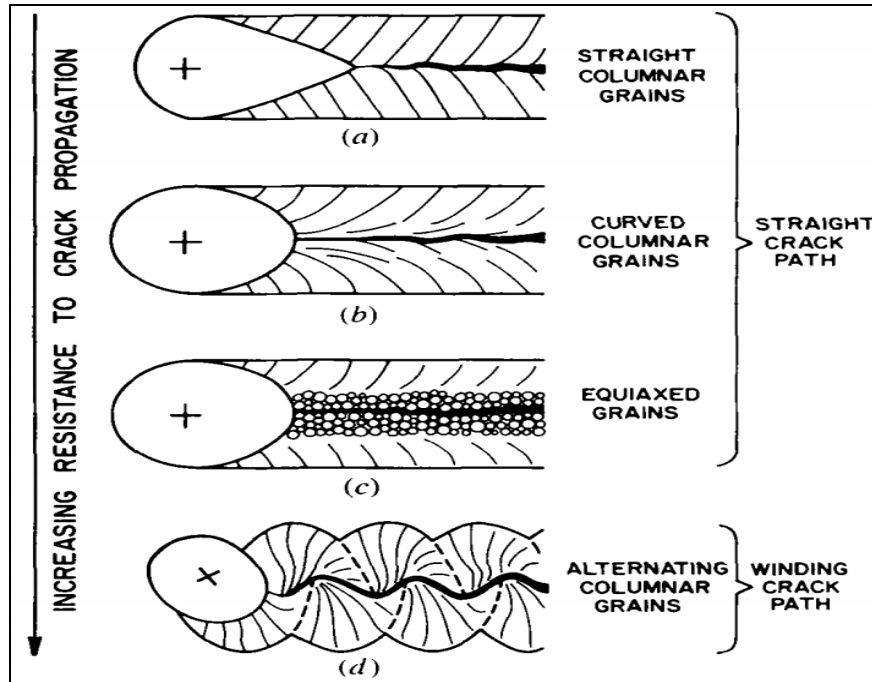


Figure (1.10): Kou showing that the weld pool motion can affect the propagation of solidification centerline cracking, (a) straight weld pool motion with fast weld travel speed has the highest crack propagation rate, (b) straight weld pool motion with medium or slow weld travel speed and elliptical weld pool shape, (c) straight weld pool motion with elliptical weld pool shape and equiaxed grain mode forming on the centerline of the weld pool, (d) weave weld pool motion has the best crack resistance [6].

The previous figure (1.10), showing that changing the weld solidification modes and the grain orientation will lead to huge change on the resulted centerline cracking. Therefore, the main conclusion can be gain from Kou study, is that having a weld pool with a weave motion and equiaxed grain formation in the centerline can reduce the centerline solidification crack sensitivity strongly.

1.1.4 Weldability Testing for Solidification Cracking Susceptibility:

1) The Varestraint Test:

The (variable restraint) test which depends on applying augmented strain on the test sample during a fusion weld process to bend it with specific radius, was developed by Savage and Lundin in 1960s [7]. The amount of the applied strain and the total crack length help to identify the solidification crack sensitivity of the tested sample. There are three different types of the mentioned test; the longitudinal test, transverse test, and spot test as they appear in the next figure (1.11).

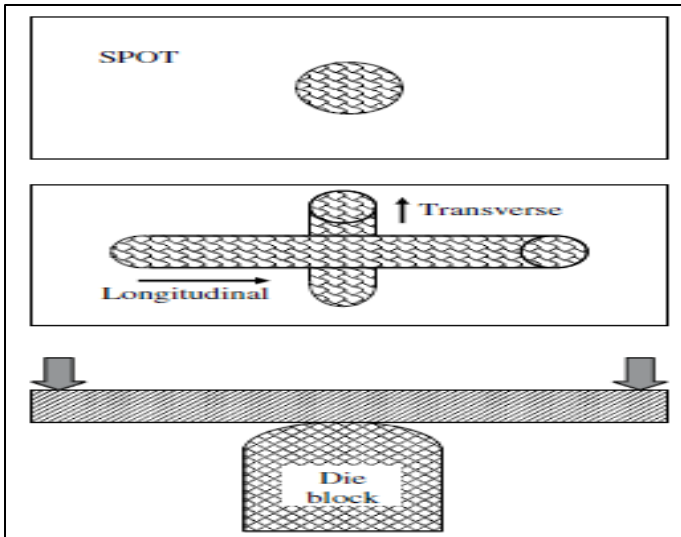


Figure (1.11): Showing the difference among the three different types of the restraint test [1].

A. The Longitudinal Test:

It is normally used to identify the cracking in both the fusion and the heat affected zone (HAZ), and it depends on applying bending forces along the length of the weld line. Since this type of test cannot separate the crack from the fusion zone and the HAZ, it is not accurate to be used for solidification cracking only.

B. The Transverse Test:

This type of test depends on applying bending forces across the weld line and the resulted cracking appear to be in the weld zone only, which is very good for identifying the solidification crack susceptibility of the material.

C. The Spot Test:

This test can be used to find cracking only in HAZ and not in fusion zone, which means it has nothing to do with solidification cracking and it is not applicable for identifying the sensitivity of the material to the solidification cracking.

Lin and Lippold in the 1990s have developed a technique to determine the crack susceptible region (CSR) using the transverse strain test, they have found that after reaching a specific amount of strain there will be a threshold strain where the crack starts to initiate and propagate with increasing the amount of the applied strain. Also, the crack will propagate by increasing the strain rate, and there will be a point where the crack won't propagate anymore even if the strain keeps increasing, and they call it the saturated strain level. Therefore, in between the threshold and the saturated strains, the maximum crack distance (MCD) will appear and it is related to the solidification cracking

temperature range (SCTR) and next following figures (1.12 & 1.13) will show both (MCD) and (SCTR).

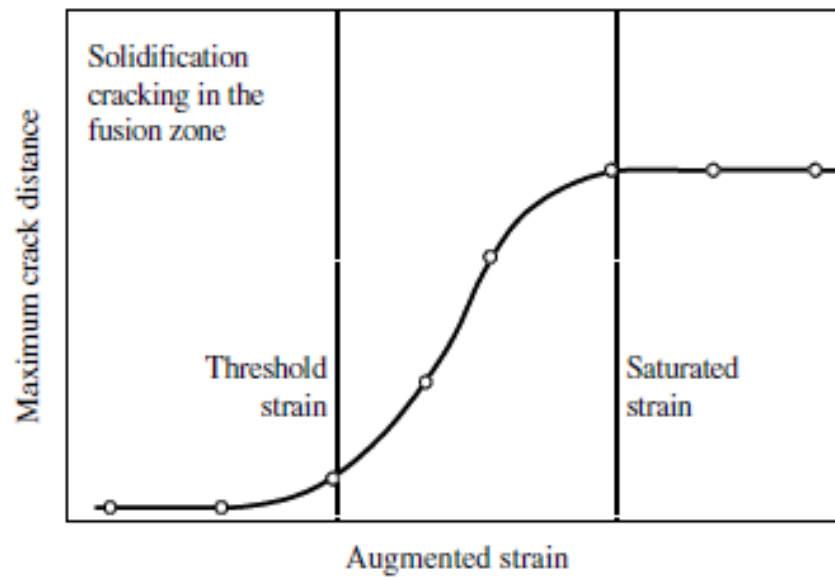


Figure (1.12): Showing the (MCD) falling between the threshold strain and the saturated one, and the crack won't increase after increasing the strain after the saturated strain line [1].

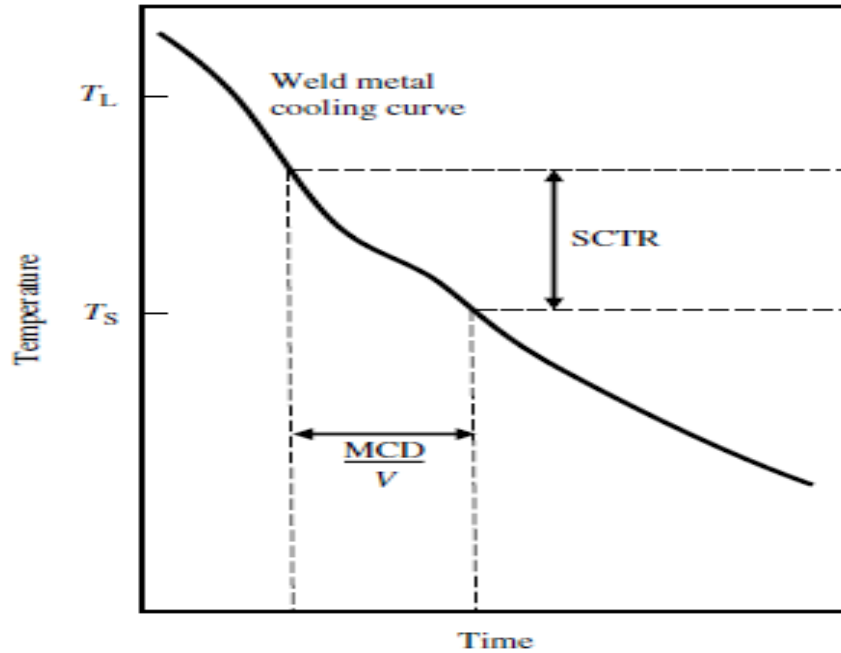


Figure (1.13): Showing the relation between (MCD) and (SCTR), and for sure the cooling rate and the weld traveling speed playing an important rule here [1].

2) *The Cast Pin Tear Test:*

In the late 1950s Hull introduced the cast pin tear test [8]. He used induction method to melt a small amount of material and cast it into copper mold with different pin geometries to have different strain level in each solidification case under argon shielding gas. The main idea in this test is changing the length and the width of the solidified mold, will form different strain level in the resulted solidified pin. The solidified pin will form a start point of a crack, and the relation between the initiation point of the crack and the

length of the solidified pin will lead to determine material susceptibility of the solidification cracking. Later on in 2011, this test was developed at OSU by Alexandrov and Lippold [9]. A water cooled copper hearth used with an arc as a heat source to melt and solidify a small amount of material under argon shielding gas. Thus, the magnitude of cracking as a function of the pin length is used to identify the material solidification cracking susceptibility. This test is usually consider to be one of best used tests because of several points, of these points are; self-strain test, good for testing the material cracking susceptibility by studying material composition, and one of the most preferred reason of using this test that it needs a small amount of grams of the material required to be used in order to be tested (less than 500 grams).

3) The Fishbone Test:

It is called also Houldcroft test, and usually used to identify the centerline solidification crack susceptibility. This test is a simple test depends on designing the sample to be self-strain and usually used for autogenous weld with no additional filler to produce a crack in the fusion line. The total length of the resulted centerline solidification cracking indicates material solidification cracking susceptibility. This test modified by KOU and LE [6], by adding an opening a slot at the start end of the sample to assist centerline solidification crack initiation. The design of a modified fishbone test is showing in the next following figure (1.14).

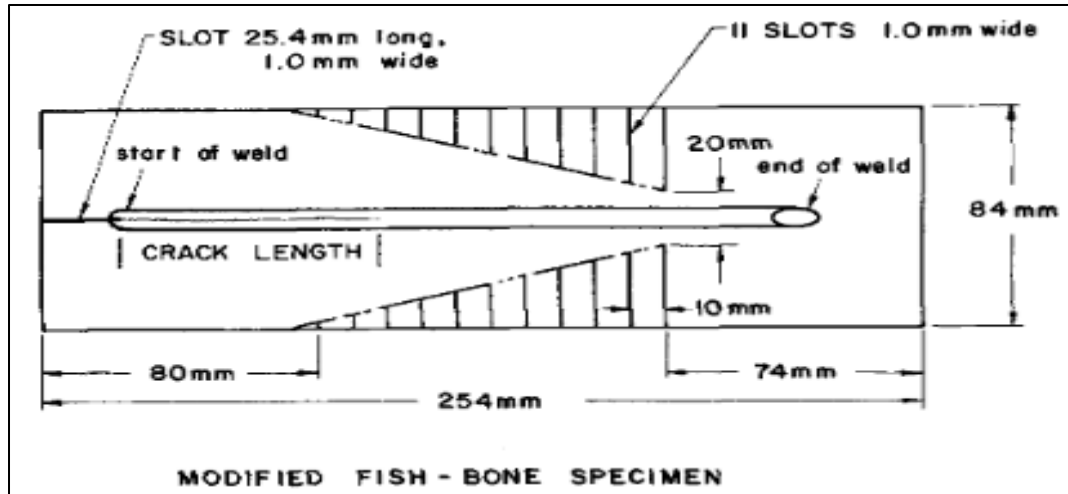


Figure (1.14): Showing the design of the modified fishbone test (Houldcroft test), and the weld will start from end of the horizontal slot to help initiation of the centerline solidification cracking [6] & [10].

The purpose of forming slots on the designed test; the horizontal slot is used to promote crack initiation, while the vertical slots are mainly there to reduce the strain gradually when the weld pass through the area between them and that will help reducing the total crack length.

The modified fishbone is really good for studying the solidification crack susceptibility of thin materials. Also, this test is good to study the effect of different weld parameters on the solidification cracking, and it is easy to analyze just by measuring the total length of the resulted crack, where the longer crack length showing that a sample has higher centerline solidification crack susceptibility. It is not recommended to be used for welding with filler, and it is only good for autogenous weld. Moreover, preparing the

sample may take time and needs to be machined with high accuracy in order to have balanced self-strain and good results.

1.1.5 Weld Process:

Similar to the weld pool shape and weld travel speed the weld process has high impact on the resulted grain structure and centerline solidification crack resistivity. It is important to have better understanding for the process effect on the solidification process. One of the important impacts that the weld process may have on the solidified material is the heat input, which is related to both temperature gradient (G) and solidification growth rate (R). Also, different heat input can result in different weld pool shape. Moreover, the dynamic of the weld process can form different solidification grain orientation, just as Kou proved in the previous figure (1.10). Therefore, a weld process may result in different solidification mode depending on the process type and heat source motion. Thus, designers always trying to produce and apply the right process for the required weld material and joint and minimizing or eliminating the material unwanted solidification behaviors.

One of the new fusion processes called tandem GMAW process, which recently released to the welding market by Lincoln Electric Company, and it is about using double heat source (torches) following each other on the same weld pool of a weld line as it shown in figure (1.15). The main purpose of the tandem GMAW process as Lincoln

Electric Company presented it is to get deep penetration and lower heat input in the same time. That means playing with both (G) and (R) from region to another in the weld pool. The leading electrode forming a weld pool in straight line, while the following electrode applying more heat on the existence weld pool to insure the deeper penetration of molten metal. Mention this process is important existing process to this work, because it forced me to come up with an idea of using this tandem process idea and changing the orientation of the two heat sources (torches) during the welding process and apply it on GTAW process. My idea depends on the motion of the two heat sources in side by side way on a weld seam line instead of following each other. Applying this idea using GTAW process may help to reach best approach of Kou and his research team, buy using two different working times for each electrode, so they are moving side by side, but they work alternatingly, which will help to form one weld pool as one spot at each time the electrode is on. This will cause the formation of almost two static weld pools with short motion overlapping each other at some distance one precedes the other one because of alternating working time for both electrodes as it shown in the next following figure (1.16). This idea of a new process, may lead to resist the centerline solidification cracking as Kou and his team showed in their study by forming alternating columnar grains as it show previously in figure (1.10). The new idea of new weld process will be study in this work and compare to different studies around the solidification centerline crack susceptibility field and the results will be presented later on in the following chapters of this work.

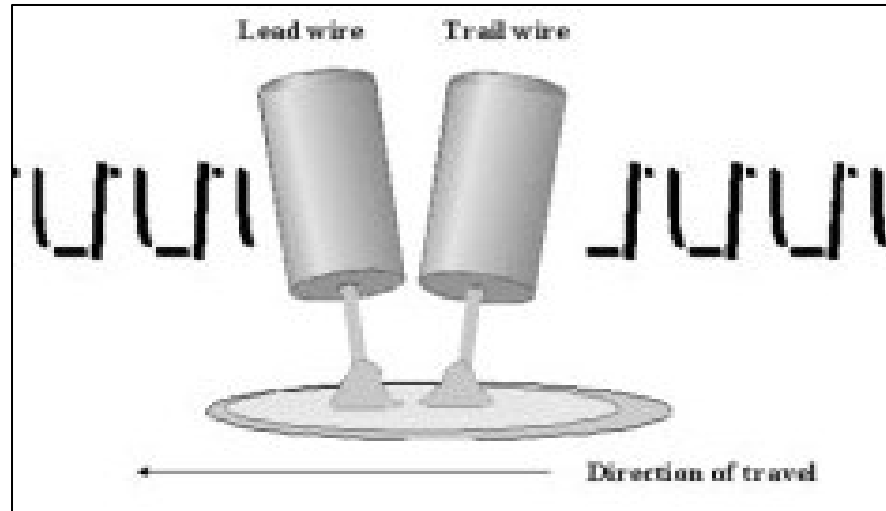


Figure (1.15): GMAW tandem process showing the motion and the orientation of the two electrodes during a welding process with two different pulsing systems.

(<http://www.lincolnelectric.com/en-au/support/process-and-theory/Pages/tandem-mig-detail.aspx>)

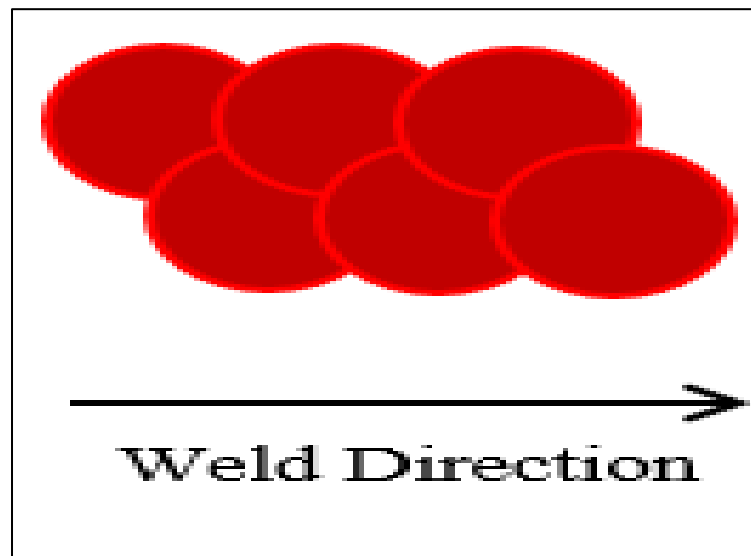


Figure (1.16): Schematic showing the expected weld line of a Tandem GTAW side by side welding process.

1.1.6 Theories of Weld Solidification Cracking:

Studying weld solidification cracking is very important for both welding and casting processes, and several theories have been proposed in the last 60 years, trying to have better imagination about the main cause of this type of cracking phenomena.

First, Pumphery, Bochvar, and Medovar [1], proposed the shrinkage-brittleness theory in late 1940s by studying the solidification cracking in welds and castings aluminum. This theory relays on an effective interval (BTR) that appears during the solidification process below the coherency temperature line within the solidification temperature as it showing in the following figure (1.17).

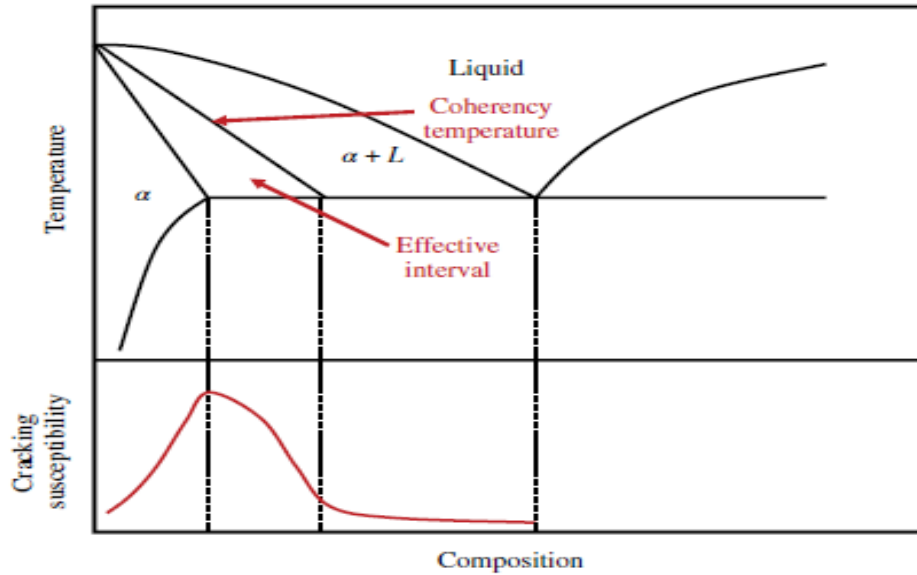


Figure (1.17): Showing the main two regions of the shrinkage-brittleness theory, where the material will be high crack susceptibility in the effective interval region [1].

At the coherency interaction line, the ratio of liquid to solid is high enough to surround the solidified dendritic grains by liquid films causing intensification of dendritic segregation, and a rigid network will form due to the solid transformation. The remaining solidification temperature range below this interaction temperature is called the effective interval (BTR), where always solidification cracking forms because of solid-solid separation and lack of liquid, while beyond this interval if a crack appears the surrounding liquid can work to heal this crack before reaching the effective interval region. Therefore, this theory stating that the solidification temperature range can be divided to two main regions, and the material with wider effective interval region will be higher susceptible to solidification cracking.

Second, Pellini has proposed a strain theory in early 1950s [11], and his theory depends on two different stages; the mushy stage and the liquid film stage following the mushy one. The mushy stage has higher temperature than the liquid film stage as it shown in the next figure (1.18). Based on Pellini and his theory, due to the uniform distribution of the strain in the solid-liquid mixture of the mushy stage the crack cannot appear, while in the liquid film stage the strain can be high enough to cause separation among the boundaries of the resulted dendritic grains with the existence of a liquid film, which means solid-liquid separation.

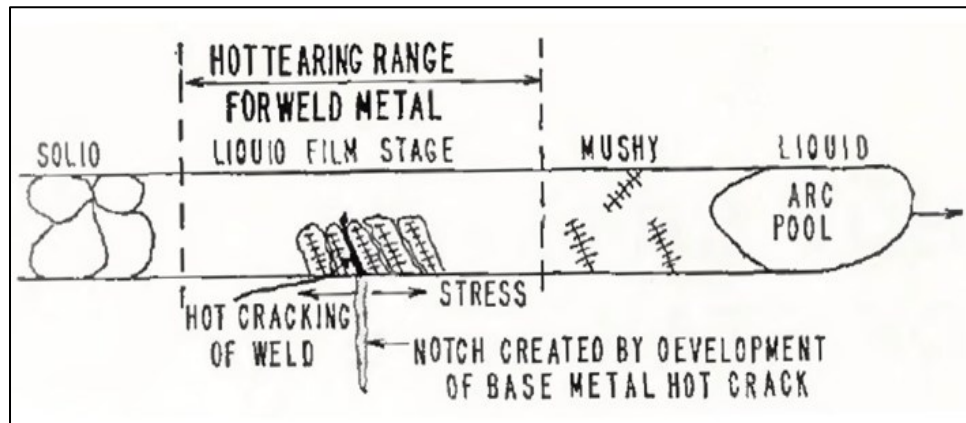


Figure (1.18): Showing the two main stages of strain theory as Pellini proposed it, and crack appears in the liquid film stage by segregation of dendritic grains with the existence of the liquid film [11].

Third, in 1960 Borland came up with the generalized theory, which divided the solidification process to four main stages [12]. Stage (1), where the dendritic grains dispersed and surrounded with massive liquid, so it is not possible for a crack to form yet during this stage. Stage (2) where it appears after a coherent temperature and agreed with shrinkage brittleness theory that below that temperature the interlock of the solidified dendritic grains occurs and a crack may exist at this stage, but Borland proposed that within this stage any crack has the possibility to be heal. Due to continues cooling process, stage (3) will be reached of the solidification process and a critical temperature range (CTR) will be reached too. In this region the interdendritic liquid networks will be isolated and if a crack forms, there will be no possibility of healing that crack. Stage (4) where there is no liquid left and before the complete solidification reached there will be no chance for a crack to form during this stage, because of the absence of liquid as Borland proposed in his theory, next figure (1.19) can give better explanation.

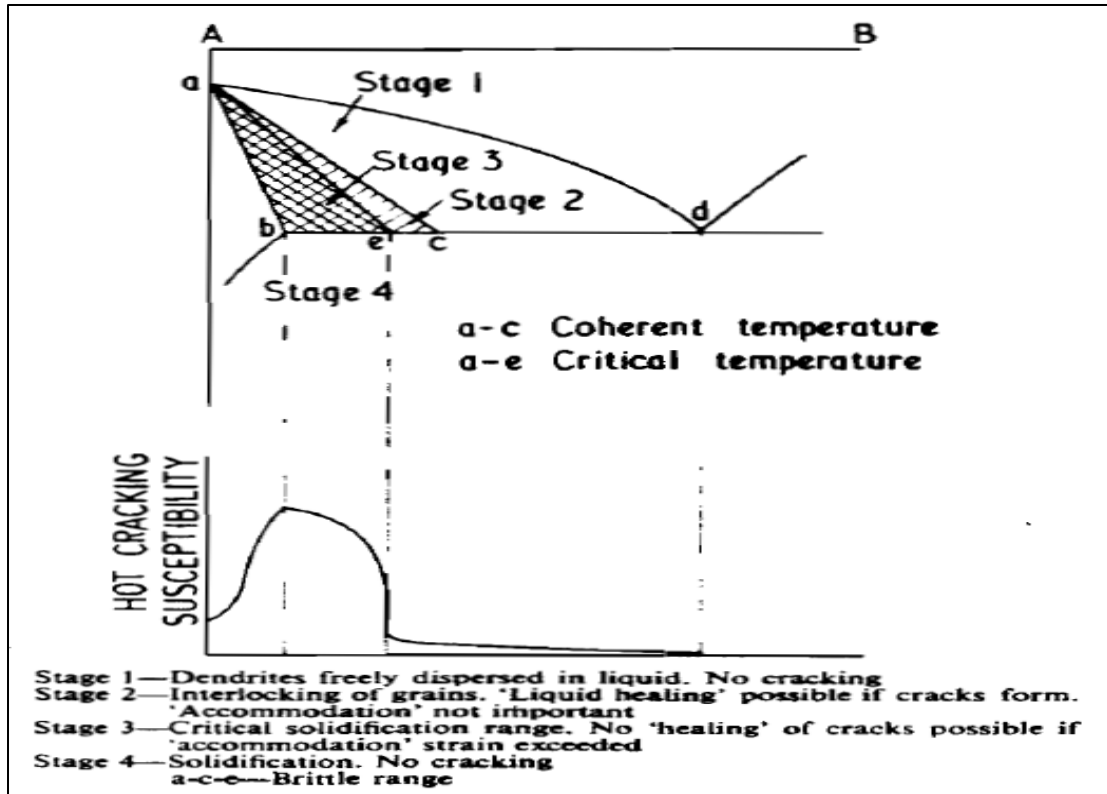


Figure (1.19): Showing the four different stages of generalized theory as Borland proposed, and it is clear that the crack can form within stage (2) below coherent temperature and can be heal, while in stage (3) there is no possibility of crack healing, and through final stage (4) no crack will be form if it was not formed already [12].

Fourth, Prokhorov presented a technological strength theory in 1962, and it was based on mechanical concepts [13]. He related the solidification cracking to the decreasing in the ductility in a weldment with in a specific temperature range, where the material goes under high strains resulted from thermal contraction and raising the brittleness within that temperature range, so Prokhorov named it brittle temperature range

(BTR). Therefore, if the strain reach a critical level within the brittle temperature range then the solidification crack will be exist for the welded material.

Fifth, Matsuda proposed a modified generalized theory in the early 1980s, and the main idea in his theory is about the size of stage (1) and stage (3) [14]. Matsuda stated that during the solidification process solid network will form rapidly just below the liquidus temperature, which cause the area for stage (1) to be narrower for most alloys he studied. Moreover, stage (3) found to be separated to two different sub stages, one called stage (3h) at higher temperature of stage (3), while the other one called stage (3L) at lower temperature of the same stage. Matsuda said that the crack initiation is possible within stage (3h) and call it as liquid film stage because of the appearance of the liquid film, but it is not possible for the crack to initiate in stage (3L) which known as droplet stage, but it is possible for the crack to propagate, because no more liquid left to heal. Next figure (1.20), showing the different stages as the proposed by Matsuda in his theory.

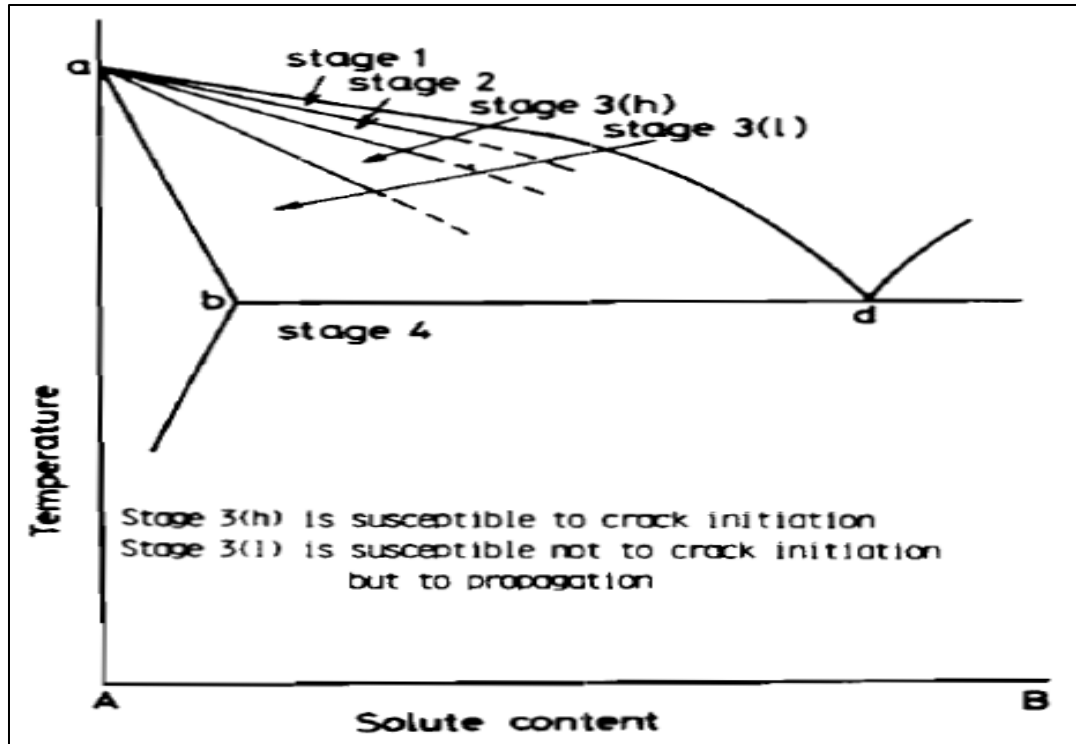


Figure (1.20): Showing the main stages of the modified generalized theory and first stage has been reduced from the generalized theory, while stage (3) divided in two sub stages and increased than what it was in generalized theory [14].

The previous figure (1.20), showing that the probability of forming a crack will be at earlier elevated temperature with narrower area within stage (3h) and after that region the crack has no chance to initiate but to propagate only in stage (3L).

Matsuda also proposed that there can be one of three different types of fracture behavior along the fracture surface of a solidification cracking as they appear in the following figure (1.21).

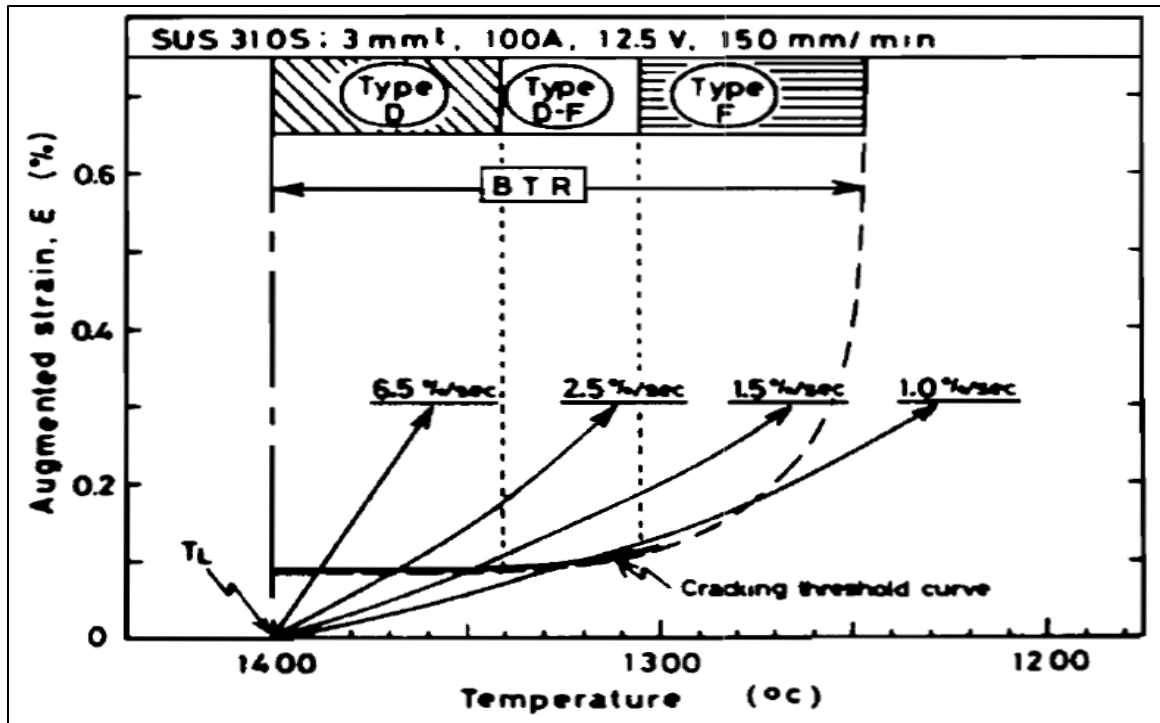


Figure (1.21): Showing the three types of the solidification cracking fracture surface [14].

From the previous figure (1.21), the three types of fracture surface based on metallographic and fractographic examination can be explained as John Lippold did in his book [1], and as they follow:

- **Type (D):** The crack will form an eggcrate fracture surface and known as dendritic fracture where it is resulted from separation the liquid film along the solidified grain boundaries (SGB), and it occur at highest level of strain as it shown in the figure 6.5% per seconds.
- **Type (F):** A flat fracture surface with no evidence of dendritic fracture, and it occurs at lower level of strain with 1.5% per seconds just above the threshold curve with.
- **Type (D-F):** A mixture of both flat and resulted from the transition region falls between both type (D) and type (F), and the fracture surface will show both flat and dendritic, and it occurs at medium level of strain with 2.5% per seconds.

1.2 Statement of Problem and Scope of Research:

High strength alloys are the most susceptible materials to a well-known hot cracking type called; solidification cracking, and it occurs during a fusion welding process in the fusion zone. This is due to some important factors, such as, grain size and orientation, weld travel speed, differences in solidification temperature range among the elements of an alloy, thermal expansion, and distortion. The addressed problem, limits welding applications for most of high strength materials, and forcing the designers to use different types of joining processes rather than fusion welding processes. Fortunately,

there are several significant studies made on this field to reduce the solidification cracking for high strength materials. Of these studies, one made by S. Kou and his team, which was about using weave motion for the weld pool to change the orientation of the resulted grains [6]. Another good study, made by A. F. Norman and his team, about studying the effect of welding parameters on the solidification microstructure of autogenous TIG welds in an AL-Cu-Mg-Mn alloy [4]. Therefore, in the current work, important results of these studies and other related to solidification cracking will be shown, and they will be compared by a new idea will be presented within following sections in this thesis using GTAW and it has been never used before, called tandem GTAW side by side process with alternating working electrodes. The aim of this study is to reduce the centerline solidification cracking in one of the most solidification crack susceptibility materials known as aluminum alloy 2024, and to study the material solidification behavior by using the new welding technique; the tandem GTAW side by side as autogenous weld.

Chapter 2

Material & Experimental Procedures

2.1 Material:

In this research the material used to investigate was a heat treatable aluminum alloy 2024, which is most widely used for aerospace and structural applications. Aluminum alloy 2024, known as Al-Cu because of the primary element of the alloy is copper. The mentioned material has high strength to weight ratio and good fatigue resistance, which makes it one of the preferred materials to be used widely. The investigated material has a commercial composition as it showing in the next following table (2.1), while table (2.2) showing the material most important properties. The 2024 Al alloy was chosen for three main reasons. First, it is one of the most Al alloys solidification crack susceptibility and it is known as a nonweldable material for fusion welding processes, and that forces the designers to use different processes to join this

material instead of using fusion welding processes. Second, 2024 Al alloy is one of the closest materials to 2014 Al alloy in crack susceptibility, as one can see in the next figure (2.3), in order to compare this study with S. Kou work [6]. Third, 2024 Al alloy was easy to find in the market, while 2014 Al alloy was not available in the material market.

The microstructure for the material as it received was investigated and compared with different research and found to be the same as what Huda and her research team proposed in their study about characterization of 2024-T3 [15]. The microstructure of Al alloy 2024 for this work is showing in the next following figure (2.1) and can be compared with figure (2.2) the one presented by Huda work.

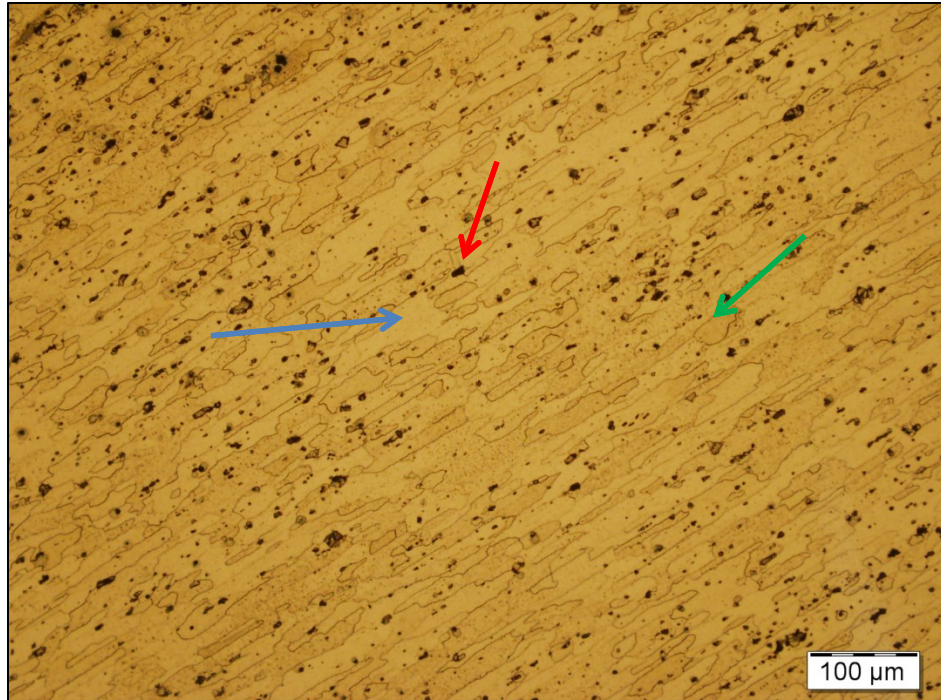


Figure (2.1): The optical microscope picture of the Al alloy 2024 microstructure as it received, showing the three different phases.

Figure (2.1), showing the three different phases of Al alloy 2024 as it received, and they are; the Alpha (α) phase distinct by blue arrow, the Theta (θ) phase pointed by green arrow, and precipitation particles (θ') pointed by red arrow. The average size of the grain was (20 μm).

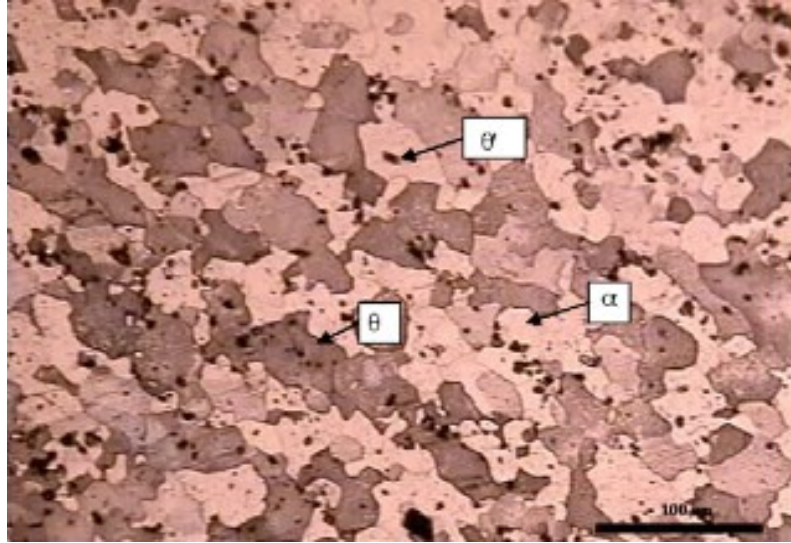


Figure (2.2): The optical microscope picture of the Al alloy 2024 microstructure as it presented in Huda's work [15], showing the three different phases, with average grain size (19.6 μm).

The last two figures (2.1 & 2.2) showing that this study has similar base material properties with different study. The important thing to be made here that the grain size measured of the base material as it received was almost the same as Huda showed in her study almost (20 μm). The size of the grains is very important to compare the grain refinement after welding in this work. Also, same figures showing the different phases appeared in the base material, which are Alpha (α), Theta (θ), and precipitation particles (θ'), where (α) is the formation of solid solution copper mixing with other elements in the lattice of aluminum with FCC (face center cubic), (θ) is the formation of the intermetallic compound of (Al₂Cu), and (θ') refers to the precipitation particles in the matrix or aging. The (θ') phase is good for the material to prevent the dislocation motion as Ambriz in his study of the mechanical behavior of precipitation hardened in Aluminum alloy [16].

Table (2.1): The commercial composition as it received of Al alloy 2024 used in this work.

Element	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	Other
Wt%	0.07	0.18	4.4	0.54	1.3	0.01	0.15	0.02	0.01	0.00	0.03

Table (2.2): Most of the material properties of Al alloy 2024 used in this work.

Material Properties	Metric	English
<i>Density</i>	2.78 (g/cc)	0.1 (lb/in ³)
<i>Hardness Vickers</i>	137	137
<i>Ultimate tensile strength</i>	469 (MPa)	68000 (psi)
<i>Tensile Yield Strength</i>	324 (MPa)	47000 (psi)
<i>Elongation at Break</i>	19%	19%
<i>Modulus of Elasticity</i>	73.1 (GPa)	10600 (ksi)
<i>Poisson's Ratio</i>	0.33	0.33
<i>Fatigue Strength</i>	138 (MPa)	20000 (psi)
<i>Specific Heat Capacity</i>	0.875 (J/g-°C)	0.209 (µin/in-°F)
<i>Thermal Conductivity</i>	121 (W/m-K)	840 (BTU-in/hr-ft ² - °F)
<i>Solidus Temperature</i>	505 (°C)	935 (°F)
<i>Liquidus Temperature</i>	638 (°C)	1180 (°F)
<i>Thermal Expansion</i>	23.2 (µm/m-°C)	12.9 (µin/in-°F)

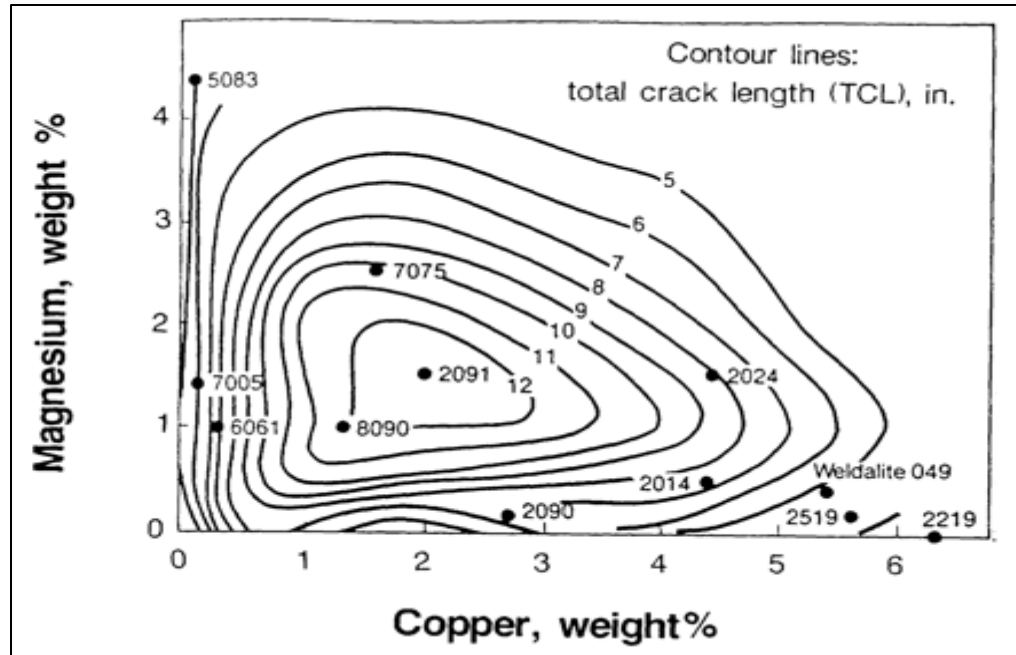


Figure (2.3): Showing the solidification crack length for different Al alloys versus the percentage weight of both MG and CU in each alloy [17].

The previous figure (2.3), showing most Al alloys solidification cracking susceptibility due to total crack length, and crack correlated to the weight content of both elements copper and magnesium in material composition. Al alloy 2024 has total crack length of (200 mm), while Al alloy 2014 has total crack length of (175 mm), which means Al alloy 2024 has almost (12.5%) more crack susceptibility compared with Al alloy 2014 as Liu presented this in his study with Kou on susceptibility of most aluminum alloys to cracking during solidification [17].

2.2 Material preparation:

The centerline solidification cracking test specimens used in this study is called the fish bone test, which is the same test used in Kou study [6], and it helps to initiate the centerline solidification cracking as mentioned previously. This test method has been chosen because it is easy to evaluate visually just by measuring the total length of the crack after welding, and it is significant for comparing this study with Kou's work. There were two prepared samples of Al alloy 2024 for each weld case study, and they were machined by electric discharge machining (EDM) process to reach accurate dimensions with only (± 0.1 mm) tolerances and earlier figure (1.14) showed the fish bone specimen dimensions and all the samples were with a thickness of (1.6 mm). The weld carried out as autogenous weld on bead on the center of the prepared test sample. The weld starts at the end of the horizontal slot and finished when the weld length reach a length of (190 mm) after the start point. During the weld process the 2024 Al alloy test sample was cleaned well with acetone and fixed on a mild steel fixture to prevent any change in weld parameters as possible. After the weld process, the resulted centerline solidification crack was measured longitudinally and recorded. The welded samples later on cut and polished well by multi stages; starting with sandpaper from 200 grains until 1200 grains, and finishing the polishing process with cloth sandpaper with (1 μ m) grain size to reach better and smoother polished surface.

To study the resulted solidified material, an optical microscope is used with different magnifications after etching the polished samples for (10-15 seconds) by Keller's reagent etchant, which consist of (2ml Hydrofluoric acid, 3ml Hydrochloric acid, 5ml Nitric acid, and 190ml Distilled water). The obtained figures from the microscope were studied and analyze to understand the material behavior during the different five used processes.

2.3 Welding Parameters:

In this study direct current with straight polarity (DCSP) was used in GTAW process through 2.4 mm (3/32 in), (2 pct) thoriated tungsten electrode of (50-degree) tip angle. The current was (60 Amp), and the voltage was (11 V) for all the weld cases studied. The shielding gas used in this study was Argon (99.9%) and considered as pure Argon. The motivation of using these parameters is to be consistent with what Kou used in his work [6], and to have fair comparison results. The welding travel speeds used in this study were three different speeds for five different cases. (3.6 mm/s) and (8.4 mm/s) for single electrode GTAW process, which is known as regular GTAW with constant current (R.C.C.). Also a single electrode GTAW process with pulsed current (R.P.C.) at a welding travel speed of (3.6 mm/s), (80) pulsed per second, (85%) peak temperature, and (33%) background amperage was included in this work. Moreover, a single mechanical arc transverse oscillation (Weave) was added to this study with a longitudinal weld travel

speed of (4.2 mm/s), (1.9 mm) amplitude, and a frequency of (1 Hz) to have four different cases to be studied and to compare them with the fifth and the main study case, which is the new idea of this study and called Tandem GTAW side by side with alternating working electrodes and has a weld travel speed of (3.6 mm/s). In the next following table (2.3) all the five study cases are presented with the welding parameters used in this work. One thing needed to be added here, is that the measured average current for both weld cases (3, & 5) showed (57, & 65A), respectively, and that due to the changing in the current during the process.

Table (2.3): Showing the five different processes and their weld parameters.

Case #	Weld Case Name	Weld Travel Speed	Power Input
1	<i>(R.C.C.) (Slow Process)</i>	3.6 (mm/s) 0.14 (in/s)	462 (J/s)
2	<i>(R.C.C.) (Fast Process)</i>	8.4 (mm/s) 0.33 (in/s)	462 (J/s)
3	<i>(R.P.C.) (Pulsed Process)</i>	3.6 (mm/s) 0.14 (in/s)	439 (J/s)
4	<i>Weave Process</i>	4.2 (mm/s) 0.16 (in/s)	462 (J/s)
5	<i>Tandem Process</i>	3.6 (mm/s) 0.14 (in/s)	508 (J/s)

The previous table (2.3) shows welding parameters used for all the five cases studied in this research and all the studied cases had full penetration. The differences in weld travel speed are used for some reasons as they follow:

- First, cases (1, 3, & 5) have the same travel weld speed and they can be studied and compare with each other to see the effect of the different process types.
- Second, cases (2 & 4) have different weld travel speeds and the reason of using different weld travel speeds for different weld processes to control the heat input and compare the different heat input on the examined material with different processes.
- Third, considering that the slow process will have the worst result in solidification cracking and that due to higher heat input, which leads to higher grain segregation and higher thermal stresses around the weld pool.
- Fourth, changing the processes with weld travel speeds will give for sure different results as mentioned earlier due to changing in (G) and (R), and that will lead to good comparison between the new idea used in this study with the other four different processes presented in the previous table (2.3).
- Fifth, choosing the weld travel speed for the weave weld process is to be like what Sindo Kou used in his study and to have fair comparison with the current work.

Another important point need to be clearly presented from the previous table (2.3), that the power differs among some processes, and that due to the actual current and voltage used in each process. One can see that both tandem and pulsed processes have different power amounts comparing them with other processes, and that was a result of

the measurements done for the current specifically for those two processes during the actual welding. The change in power predicted because of the unstable of the current during actual welding and that force me to measure the current and know exactly the average current during the process to have fair and accurate comparison. After measuring the current using data acquisition connected to a computer, the average current for both tandem and pulsed processes found to be (66, & 57A), respectively as they appear in the next figures (2.4 & 2.5). Therefore, the power is calculated for each process by using the following equation (2.1), which was used by A. F. Norman in his study on the same field for the same material Al alloy 2024 [4].

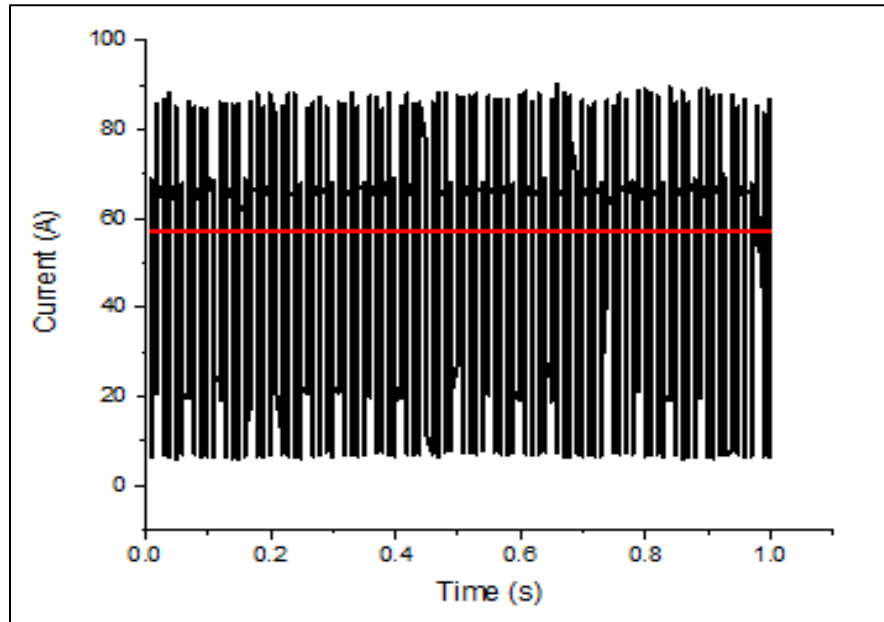


Figure (2.4): Showing the measured average amperage of the pulsing process, which appears by the red horizontal line on the plot at (57 A).

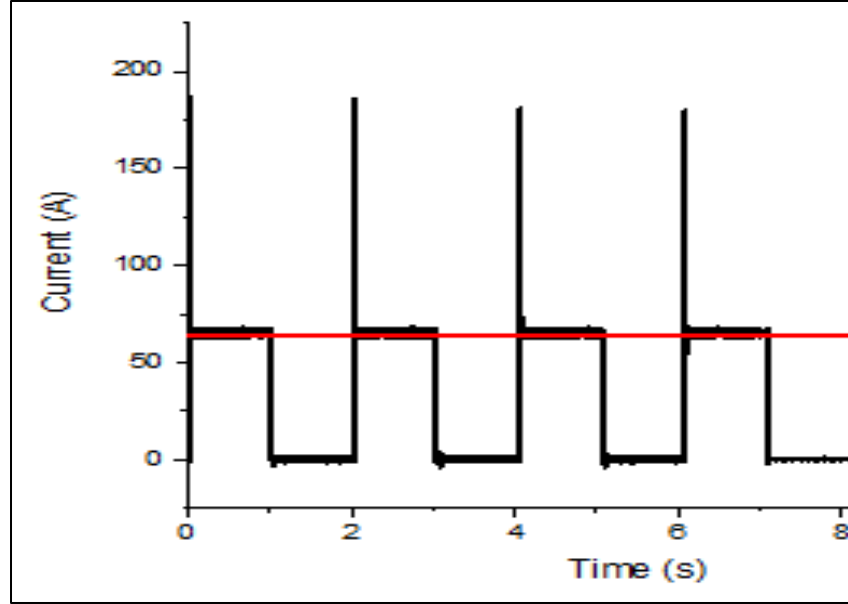


Figure (2.5): Showing the measured average amperage of the tandem process for one working electrode, which appears by the red horizontal line on the plot at (65 A).

$$P = (A) \times (V)$$

Eq. (2.1): Power

The above equation (2.1), used in most studies to find the power produced by the heat source, where (p) is the power in joules pre seconds, (A) is the current produced from the weld machine with the unites amperage, (V) is the voltage and it depend on the height of the electrode toward the surface of the material, and (η) is the arc efficiency and generally for GTAW process the efficiency is consider to be (70%) as it been used with both Kou and Norman in their studies [3] & [4].

2.4 Tandem GTAW Side by Side Process Setup:

The new technique used in this study depends on two tungsten electrodes setup side by side with an angle of (30-degree) toward each other and they are in one box with one ceramic cup as it shown in next figure (2.6), to have same shielding gas source to prevent arc disturbing during the weld process. The distance between the electrodes tips is (3.8 mm), which means the amplitude is (1.9 mm) matching with the one used for weave weld process in this study. Both electrodes are (2 pct) thoriated tungsten electrodes, with 2.4 mm (3/32 in) diameter and a tip angle of (50-degree).

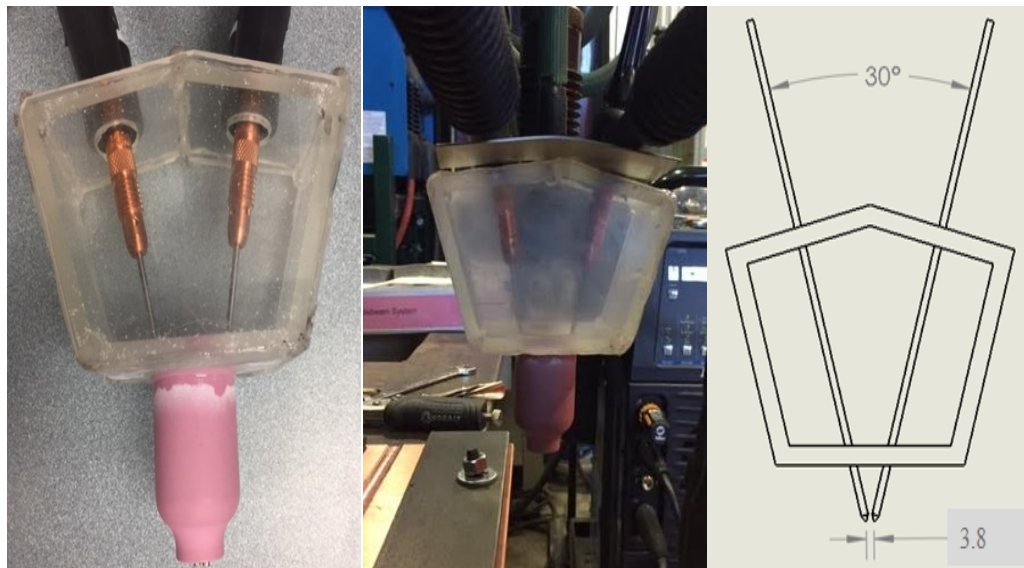


Figure (2.6): The custom made of the torches fixture box to combine two tungsten electrodes.

Figure (2.6), showing the fixture box used to fix the two electrodes accurately and set them in one chamber with one gas flow cup and the distance between the electrodes is (3.8 mm), while the angle is (30^0). This custom torches fixture box has been made in Ohio State University welding laboratory.

In this new technique, each electrode connected to a different welding machine power source of GTAW, so each electrode can work independently. Therefore, a microcontroller needed in order to control the two machines accurately, and the main work of the microcontroller is to run one electrode for one second and to shut it off and run the other one for another one second, which means the whole cycle for running and shutting off one electrode is two seconds as the cycle for each electrode appears in next following figure (2.7). During the process the torches' box is moving with a weld travel speed of (3.6 mm/s), and repeating this cycle several times continuously to reach the required welding length. The microcontroller device used in this study called Arduino, it is accurate and helpful by connecting each machine wire trigger to it and setup a program code on a computer to transfer the information to the Arduino to control the two welding power sources, and next figure (2.8) showing the program used in this study.

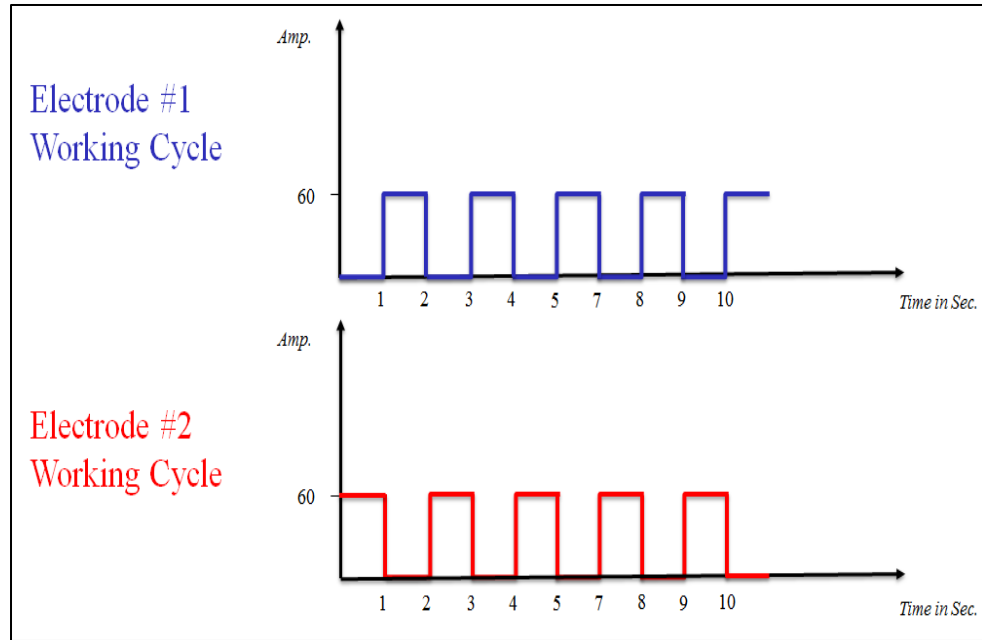
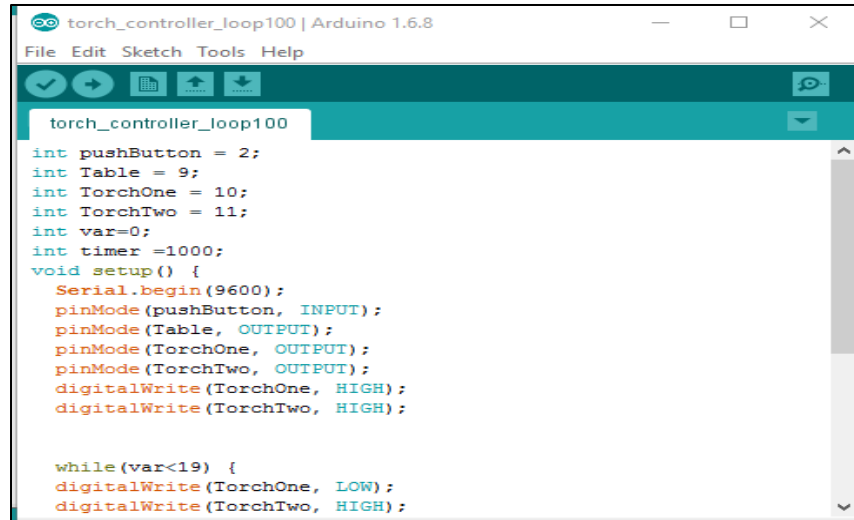


Figure (2.7): Showing the working cycle for each electrode one second at a peak current of 60 Amp. in tandem weld process, and when one electrode works the other one is completely turned off, and the whole process controlled by the Arduino.



```
torch_controller_loop100 | Arduino 1.6.8
File Edit Sketch Tools Help

torch_controller_loop100
int pushButton = 2;
int Table = 9;
int TorchOne = 10;
int TorchTwo = 11;
int var=0;
int timer =1000;
void setup() {
  Serial.begin(9600);
  pinMode(pushButton, INPUT);
  pinMode(Table, OUTPUT);
  pinMode(TorchOne, OUTPUT);
  pinMode(TorchTwo, OUTPUT);
  digitalWrite(TorchOne, HIGH);
  digitalWrite(TorchTwo, HIGH);

  while(var<19) {
    digitalWrite(TorchOne, LOW);
    digitalWrite(TorchTwo, HIGH);
```

Figure (2.8): A sample of the program code that connected to the Arduino, which used in this study to control the two power sources and the motion of the table during welding process.

2.5 Measurements Methods Used:

In this work some measurements have been used to reach better and accurate results, of these measurements as they follow:

1) Centerline Solidification crack length measurement:

After welding a ruler with an accuracy of (0.5 mm) was used to measure the total crack length, and the slot is not included in the total crack length.

2) Average grain size measurement:

Another type of measurements used in this work to define the average grain size of the resulted solidified grains. This part of the work carried out by a software named ImageJ and specified for microstructure measurements. The shape of the required grains part measurement set to be elliptical and the measured average major diameter is recorded as the average grain size of the uploaded figure.

3) Data Acquisition for Voltage Measurement:

Data acquisition connected to a computer were used to measure the power for both cases the pulsed process and the tandem side by side to have accurate power input during those process, since the two mentioned processes have unstable power input due to the pulsing mode. Therefore, the data acquisition were used to analyze the actual current by measuring the voltage in the weld area and a conversion program used in the computer to covert the voltage measurement to identify the actual current during the process. Also, the data acquisition used to identify the thermal cycle in the weld area by connecting thermocouple to the data acquisition, and the same thing here a voltage was measured to give the variation values of the temperature in the weld area due to time.

4) Thermocouple Type (C) used to measure the temperature & cooling rate:

One of the important things used to measure the thermal cycle in the fusion zone is the thermocouple type (C). The purpose of using type (C) thermocouple is that it can stand high temperature without melting, and maximum temperature it can hold before melting (2300°C). The two wires used in this thermocouple are the positive wire material has a composition of Tungsten-3%Rhenium, while the negative wire material has a composition of Tungsten-26%Rhenium. The accuracy of the used thermocouple is good enough for this work and it was about (± 2 °C) and the thickness of the wires were about (0.5 mm).

5) Micro Hardness Vickers:

Part of the current work to study the effect of each process from the five processes presented previously in table (2.3) on the resulted grains in the fusion zone and HAZ. One of the most significant mechanical properties that can be measured is the micro hardness Vickers, which can give reasonable explanation of thermal cycle and the resulted solidification grain mode. Therefore, in this study I have used the micro hardness machine in Ohio State University lab with load of (50 g), which is recommended for

aluminum alloys, and the distance between any two close measured points (indentation) used is (150 μm) to prevent overlap deformation and error in measurements.

Chapter 3

Result & Discussion

3.1 Temperature Gradient (G) & Growth Rate of Solidification (R):

As mentioned earlier in the first chapter of this thesis, two of the important solidification parameters need to be measured for a welded or casted material during the solidification process to have better understanding for material solidification behavior and resulted grain structure, or even some of the mechanical properties are (G) and (R). Therefore, in the current study a thermocouple type (C) was used and attached to the welded material from the back side and welded in the center of the weld line after drilling a hole of (0.5 mm), as showing in next following figure (3.1), to measure the cooling rate from the liqudus temperature to the solidus temperature (the mushy zone) at the centerline of the weld pool. The following table (3.1) shows the actual measured cooling rate for all the five processes used in this work.

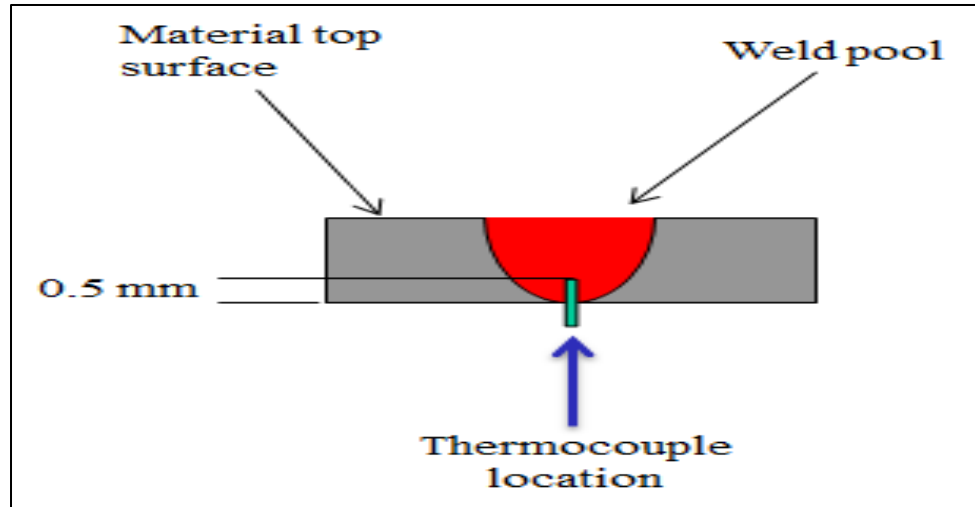


Figure (3.1): Schematic of the location of the thermocouple type (c) placed in center of the weld pool, showing by blue arrow, where it submerged in the material from back side (the root) by (0.5 mm).

Table (3.1): Showing the five different processes and their measured cooling rates.

Case #	Weld Case Name	(G)	(R)	Cooling Rate (G)/(R)	(G)/(R)
1	<i>Slow Process</i>	23 (°C/mm)	3.63 (mm/s)	83.5 (°C/s)	6.33
2	<i>Fast Process</i>	30 (°C/mm)	8.3 (mm/s)	249 (°C/s)	3.6
3	<i>Pulsed Process</i>	22.85 (°C/mm)	3.83 (mm/s)	87.5 (°C/s)	5.87
4	<i>Weave Process</i>	31 (°C/mm)	4.1 (mm/s)	127 (°C/s)	7.56
5	<i>Tandem Process</i>	21.9 (°C/mm)	8 (mm/s)	175 (°C/s)	2.74

The previous table (3.1) show good results for both (G) and (R), and the first thing one can catch from that table is the cooling rate for each process. The highest cooling rate of (249 °C/s) obtained by the fast weld process, while the lowest cooling rate of (83.5°C/s) recorded by the slow weld process, and this is expected due to the differences in the weld travel speed and the resulted heat input. Therefore, at this point it is good to present the heat input equation to prevent confuse between heat input and the previous power equation (3.1).

$$\text{Heat Input} = \frac{(A) \times (V) \times (\eta)}{(S)}$$

Eq. (3.1): Heat input

Equation (3.1) is used in most papers for calculating the heat input like Shen in his study about the effect of heat input on the microstructure and mechanical properties of TIG [18], where (A) is the current, (V) is the voltage, (η) the arc efficiency, and (S) is the weld travel speed, and the resulted unites for the heat input should be joules per distance. Mentioning the heat input is very important for welding processes, because it has an impact on the cooling rate, which means can control both (R) and (G). For example, comparing the slow process with the fast process one can see that the power amounts for both processes are the same, but the cooling rate showing a huge difference because of the weld travel speed differences. It is clear by dividing the power on the weld travel speed for both processes will give better explanation about the reason behind the appeared differences in the cooling rate. Higher heat input value leads to lower cooling

rate and results to larger grain forming. Thus, by comparing the cooling rate for each process in the previous table (3.1) it is easy to arrange and classify the heat input from the highest to the lowest. The most interesting cooling rate one can find in the same table (3.1) is the one carried out by tandem process and comparing it with the process weld power and the weld travel speed should show the lower cooling rate but it is not. The explanation for the strange process behavior is that due to shut off the arc and running the other arc on different location at some distance, it is like the arc jumps from one point to another, this leads to have larger area the weld covers and that gives lower power density, which means lower heat distribution process. Moreover, shutting the arc off in one location causes the thermal gradient to be reduced, and the amazing thing happens is that the solidification growth rate went very high almost two times of the actual weld travel speed of the process, and the weld process kindly act like stationary weld. To show the effect of the heat input on the formed weld structure, transverse view showing in next following figures of the resulted welds made by all the five different processes.

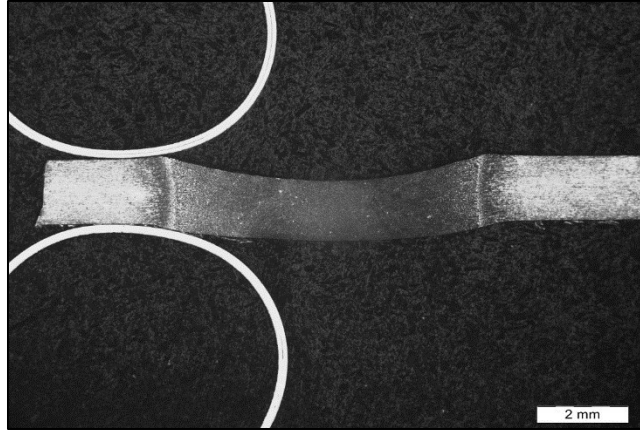


Figure (3.2): Optical microscope picture of a transverse view of the resulted weld from slow weld process and the weld structure has a concave surface width concavity of about (0.63mm).

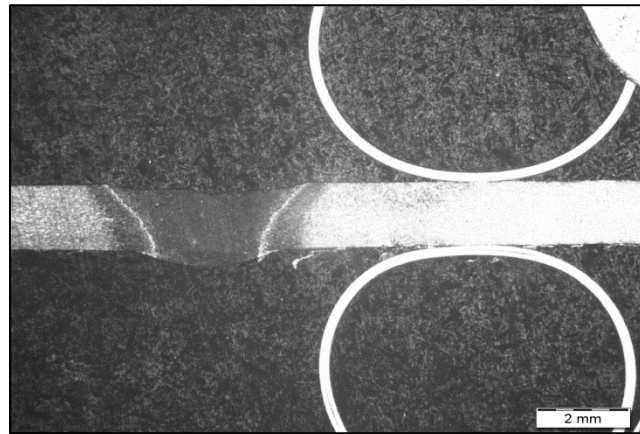


Figure (3.3): Optical microscope picture of a transverse view of the resulted weld from fast weld process, and the weld structure has no concave surface shape, and the width of the weld is about (3.5mm). But the weld showed a strange V-notch shape on the surface of the center of the weld.

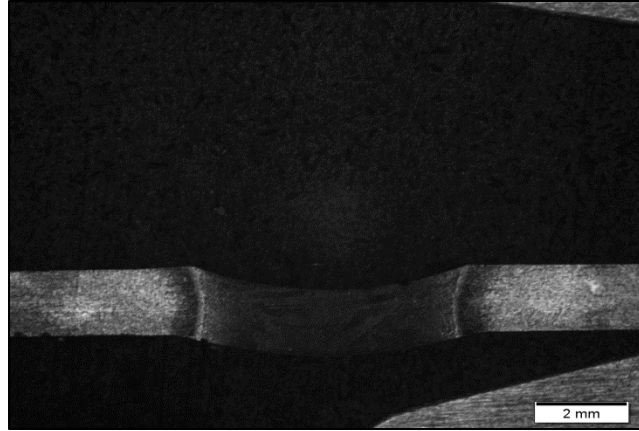


Figure (3.4): Optical microscope picture of a transverse view of the resulted weld from pulsed weld process, and the weld structure has concave surface shape with concavity of about (0.58mm).

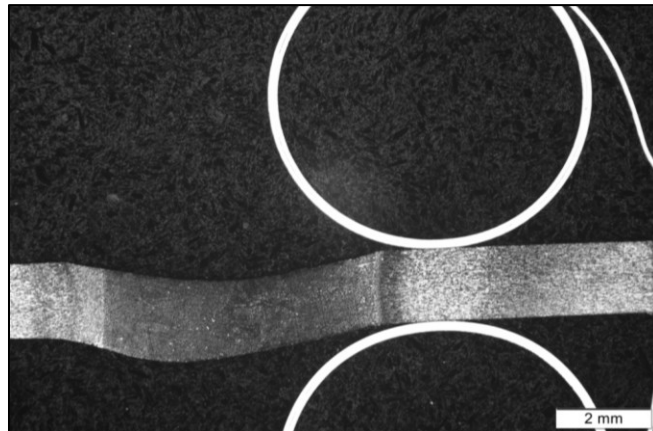


Figure (3.5): Optical microscope picture of a transverse view of the resulted weld from weave weld process, and the weld structure has concave surface shape with concavity of about (0.56mm).

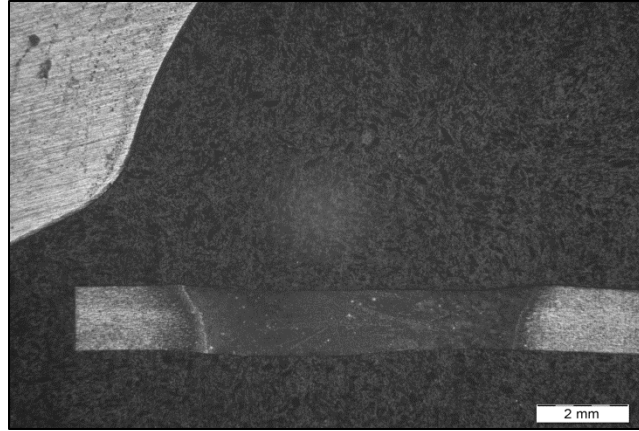


Figure (3.6): Optical microscope picture of a transverse view of the resulted weld from tandem weld process and the weld structure has almost no concave surface shape.

The previous figures (3.2, 3.3, 3.4, 3.5, & 3.6), showing that slow, pulsed, and weave have concave weld structure, and that due to higher heat input compared with the other two processes tandem and fast. Also, comparing the width for slow, pulsed, and fast processes can show that the fast process has the lowest heat input and the slow process has the highest heat input due to the weld travel speed, while pulsed weld process has lower heat input than the slow process, because of the lower average power used for that process. Comparing weave process with tandem process, the concavity in the weld showing that weave process has higher heat input than tandem weld process, and that due to the advantage that the tandem process has of semi stationary weld action.

3.2 Total Centerline Solidification Crack Length:

After using five different welding cases on fish bone specimens of Al alloy 2024 as it is showing in the next table (3.2), first thing one can pay attention to it, is the total centerline crack length for each case, and it is clear from both table (3.2) and next figure (3.7), the longest total crack length is (155 mm) and obtained by using a regular GTAW at a weld speed of (8.4 mm/s), which specified in table (3.1) as (Fast Process and case 2). While the shortest total crack length is (56 mm) and obtained by using the new technique, tandem GTAW side by side, which is specified in the same table (3.1) as (case 5) and it reduced the crack length of slow process by (60%). On the other hand, the weave weld process showed good reduction in the total crack length by (50%) of the total crack length obtained by slow weld process, but the improvement of the crack length is higher with the tandem GTAW side by side and a comparison in crack length is showing in the following figure (3.7) for slow, weave, and tandem processes. The use of tandem GTAW side by side made a significant reduction in the total crack length, the reduction was about 60% of what the slow process had, from (137 mm) to only (56 mm). Even though, the regular pulsed GTAW (case 3) reduced the total crack length from (137 mm) to (124 mm), it doesn't show huge difference in total crack length reduction, it was reduced by only 10% of the slow process and that is due to lower power for pulsed process, which reduced the local restraint in the centerline. The strange thing can be notice from the same table, is that the fast process showed the longer crack length, while it has lower heat input due to the weld speed, but there will be some explanation later on in this chapter.

Moreover, in next table (3.2) all the first three cases or processes showing crack paths of straight line, while both processes weave and tandem GTAW side by side showing tortuous centerline cracking path as it showing in the next figure (3.8), which means the new technique made a huge change in the material solidification behavior and that due to two main reasons. First, the overlapping weld pools change the grain orientation on the weld seam line causing the crack to follow specific type of grain types cause it to form a tortuous crack path and leads to reduce the total centerline solidification line. Second, generally the local strain appears in the middle of any weld pool during solidification process causing high concentrated tensile forces on the centerline of a weld pool, but by using the new weld process technique, the overlap weld pool reduced the local strain of the last weld pool made by the other electrode and change the tensile forces to compression ones as it appears in next figure (3.9), agreed with what Ploshikhin and his research team concluded in their study [19]. His point is that having a heat source moving parallel with the original weld heat source reduce the centerline solidification crack, and that due to the compression forces exist from both heat sources towards each other. Therefore, in the current work the crack not only forced to shift from side to side (first weld pool to the second one), but also to be reduced and harder to connect with the second weld pool following.

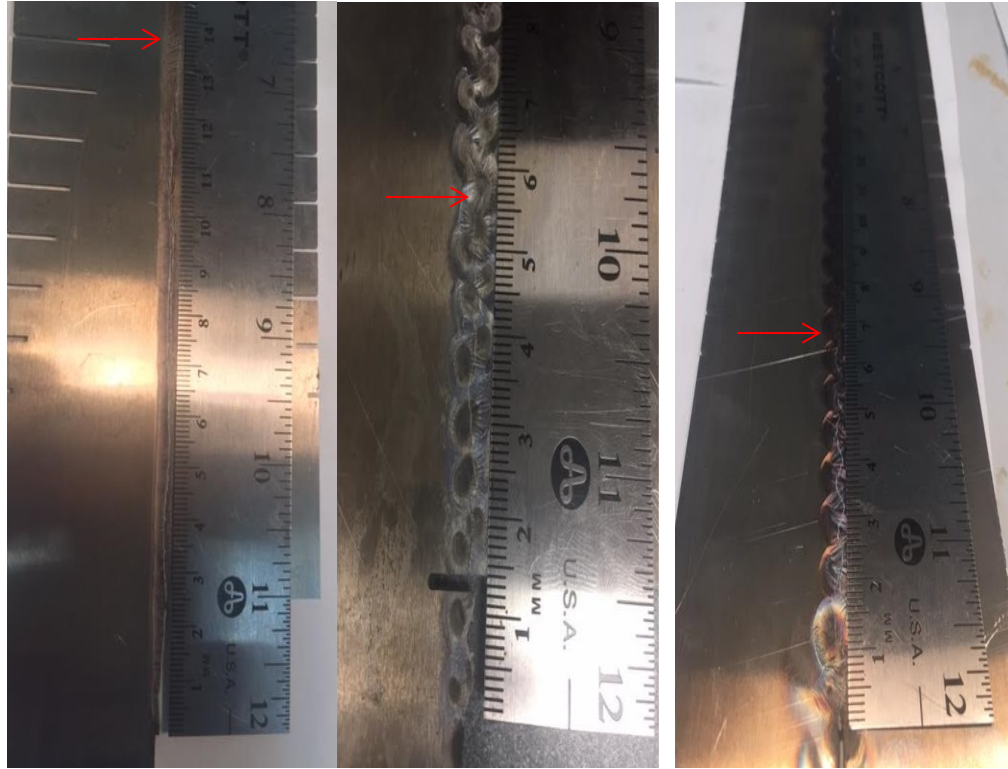


Figure (3.7): A picture of comparison the three centerlines cracking resulted in current study from slow, tandem, and weave processes, respectively from left to right. The red arrows show the end of the resulted crack and the measured length on the ruler.

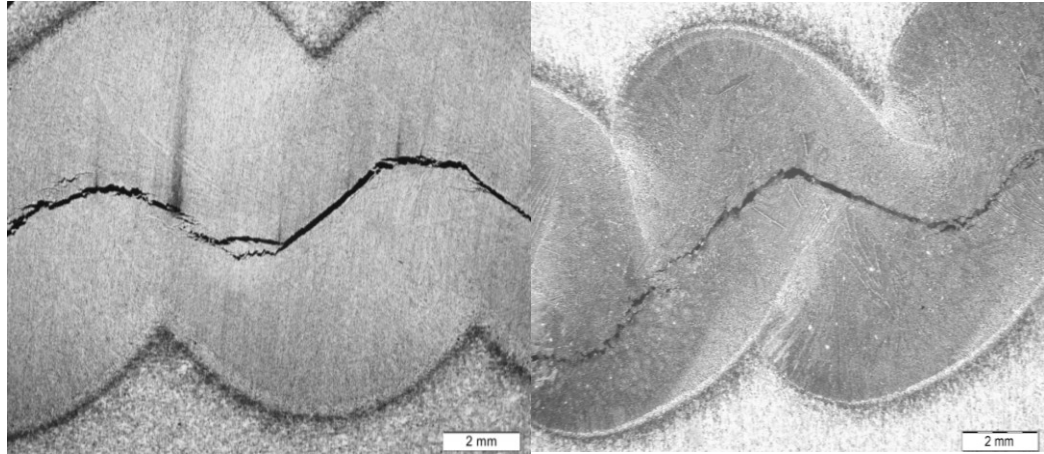


Figure (3.8): Optical microscope pictures showing top view of resulted tortuous centerline crack formed in current work, on the left the crack obtained by weave weld process and on the right crack obtained by the new weld process (tandem GTAW side by side).

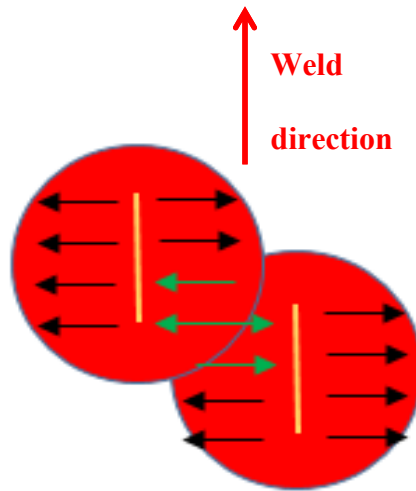


Figure (3.9): Schematic of two weld pools overlapping each other resulted from tandem GTAW side by side process. The yellow lines refer to the local stress location, the black arrows showing the tension forces applied on the centerline of each weld pool resulted from material thermal expansion and restraint, the green arrows showing the compression forces obtained on the centerline of each weld pool where the two weld pools overlapping each other, and the red arrow showing the weld direction.

Table (3.2): The results of centerline cracking and path for each weld process used.

Case #	Weld Case Name	Weld Travel Speed	Power Input	Crack Length	Crack Path
1	(R.C.C.) (Slow Process)	3.6 (mm/s) 0.14 (in/s)	462 (J/s)	137 mm	Straight
2	(R.C.C.) (Fast Process)	8.4 (mm/s) 0.33 (in/s)	462 (J/s)	155 mm	Straight
3	(R.P.C.) (Pulsed Process)	3.6 (mm/s) 0.14 (in/s)	439 (J/s)	124 mm	Straight
4	Weave	4.2 (mm/s) 0.16 (in/s)	462 (J/s)	68 mm	Tortuous
5	Tandem Process	3.6 (mm/s) 0.14 (in/s)	508 (J/s)	56 mm	Tortuous

The predicted total solidification centerline crack length in tandem process showed that the process has higher improvement than other used processes in this work. Also, comparing the new process with weave weld process showed that tandem process reduced the crack length by (17%) of the crack that appears with weave process. Moreover, it is important to put in mind that weave process has higher longitudinal weld travel speed in this study, which gives the advantage to weave weld process to reduce the crack, but still the tandem process is leading in this study. Even though, the tandem process showed shorter crack length among all of the five processes, comparing this study to Sindo Kou study [6], he showed better result almost (86%) reduction in total crack length of the slow process by using the weave weld process. I believe that the

difference between this study and Sindo Kou, is due to some important points, such as; Al alloy 2014 has lower crack susceptibility than alloy 2024 as mentioned earlier, different and unknown actual weld travel speed used (from one point to another side to side) even if the longitudinal speed used is the same, and the fixture used during the process may change the mechanical driving forces and the thermal cycle around the weld area.

Another point to be made here, the tandem showed tortuous crack path just like the weave weld process, which means the tandem process does changed the solidification behavior of the investigated material in this work.

3.3 Microstructures & Crack Path through the thickness:

After welding Al alloy 2024 samples, they were etched with Keller's reagent for (10-15 seconds) after polishing and evaluated under optical microscope. The grain orientation, size, structure, and type were investigated for all five cases to have better understanding of this Al alloy solidification behavior and to have reasonable explanation of the differences in the resulted centerline solidification crack among all five processes. Four main significant approaches were stated in this study about the different solidification processes for Al alloy 2024.

First, changing the welding speeds and welding processes causes a clear change in the grain structures as we can see in next figures (3.11, 3.12, 3.13, 3.14, & 3.15), and this was consistent with Norman result, which was shown in his study and through the following figure (3.10). But, in this study, I have found that each type of welding processes (cases) has showed its own grain structure with some amount of dendritic grains arranged in an axial mode formed mostly on the centerline of the weld line. Moreover, the centerline cracking always appear on this axial region, and the wider it is the higher susceptibility the weld is for centerline solidification crack. As next figures (3.11 & 3.13) showing that for both weld process slow and pulsed the grain structures were axial modes and the axial region width were about (600 μm) and (550 μm) in average, respectively, while for fast weld process the grain structure was stray with a very sharp centerline with v-notch shape formed. On the other hand, for weave process, there was no clear structure, but usually it has both axial and stray structures, and that due to the motion of the weld pool and the heat input, the distinct point in this process that the dendritic formed in the middle of the fusion zone with the same axial mode formed in both slow and pulsed processes, but with weave process the dendrites formed following the (G) direction with curved shape and made them to have shorter arms, and that due to higher (G) and weave motion of the weld pool, and that is agreed with S. Henry and his research team work, who studied the dendrite growth morphologies in aluminum alloys [20], they found that the reason of the curvy dendrite growth resulted from changing in surface tension associated with solute content variation, which means if the dendrites grow perpendicularly to (G) new dendrite trunks will grow trying to follow the direction

of (G), which cause the production of this amazing structure as it can be seen in the next following figure (3.14).

For tandem process, multi grain structures were formed around the centerline of the fusion zone as one can see in the following figure (3.15). The centerline of the weld line showed both axial dendrite forming with and some equiaxed grains. The strange thing here is that the axial structure had a tortuous formation, which forces the crack to follow their direction as one can see in figure (3.15). Still one can see clearly there was a very thin region of axial mode forming in the middle of the weld line, and it was only (150 μm) wide in average figure (3.15). The statement here, is the wider the axial region forming at the centerline of the surface of the weld metal zone, the higher centerline crack susceptibility resulted, and that due to the fact of backfilling liquid amount needed in the axial region is not enough in the wider area and the local strain is higher, which makes it poor in crack resistivity during solidification process under high local strain. Also, an important point to be mentioned here, the tandem process showed formation of some equiaxed grains in centerline and around it, which means a new approach in this work comparing with Norman [4], and Kou [3]. The tandem process has very low power compared with those two studies, and it showed formation of equiaxed grains, where Kou and Norman proved that in order to have equiaxed solidification mode the power should be more than (1000 J/s) and the weld travel speed has to be more than (12 mm/s), and as we know here in this study tandem process has much lower power and weld travel speed. Therefore, the explanation of having equiaxed grains is due to lower power density, which gained by shutting off the arc for each electrode and made this process to act

somehow like stationary weld and motion weld, where (G) can be shallower and (R) is very high. To have better understanding of this phenomena three different stationary welds made and studied in current work using the same weld parameters with three different weld timing of (1, 1.5, & 2 seconds) to compare with and to see what is the resulted grain modes around the center of the fusion zoon next figures (3.16, 3.17, & 3.18) will show the results.

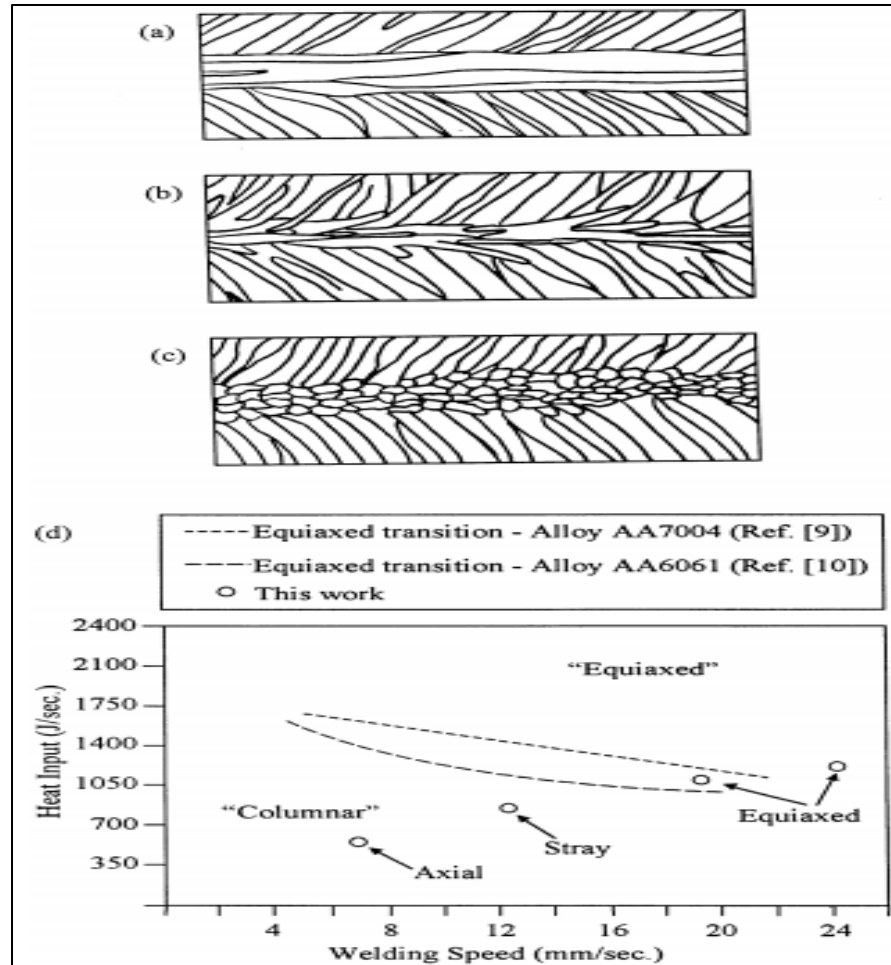


Figure (3.10): Schematic diagram from A. F. Norman showing the different types of grain structures formed in Al alloys in weld metal region by changing the welding speeds and heat input. (a) Axial grain structure. (b) Stray grain structure. (c) Equiaxed grain structure. (d) A plot of welding speed versus power for different grain structures formed by Norman's study [4].

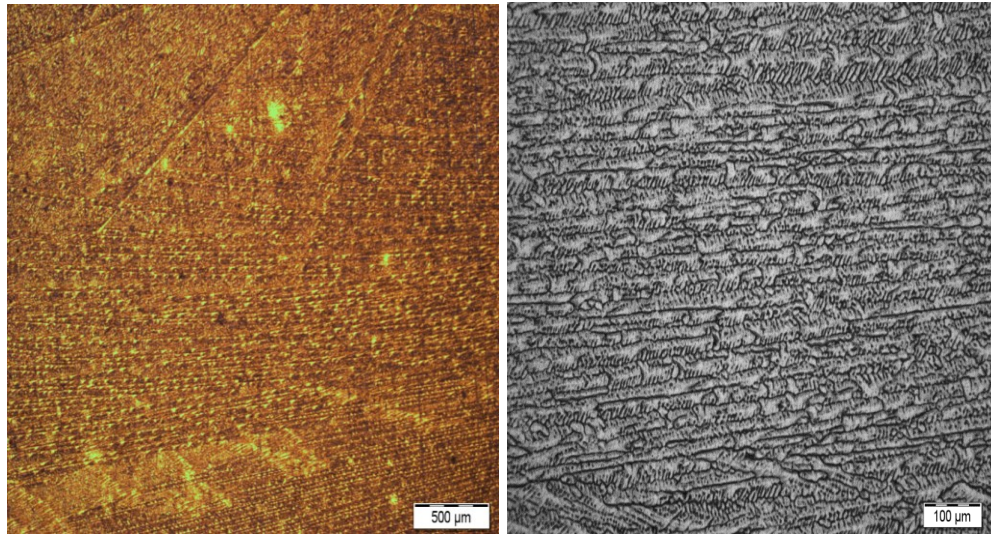


Figure (3.11): Optical microscope pictures showing top view of slow weld process, showing the resulted weld structure on the centerline of fusion zone, on the left lower magnification of axial dendrite grains with an average width of (600 μm) and on the right higher magnification of those axial dendrites and clear segregation lines found in between.

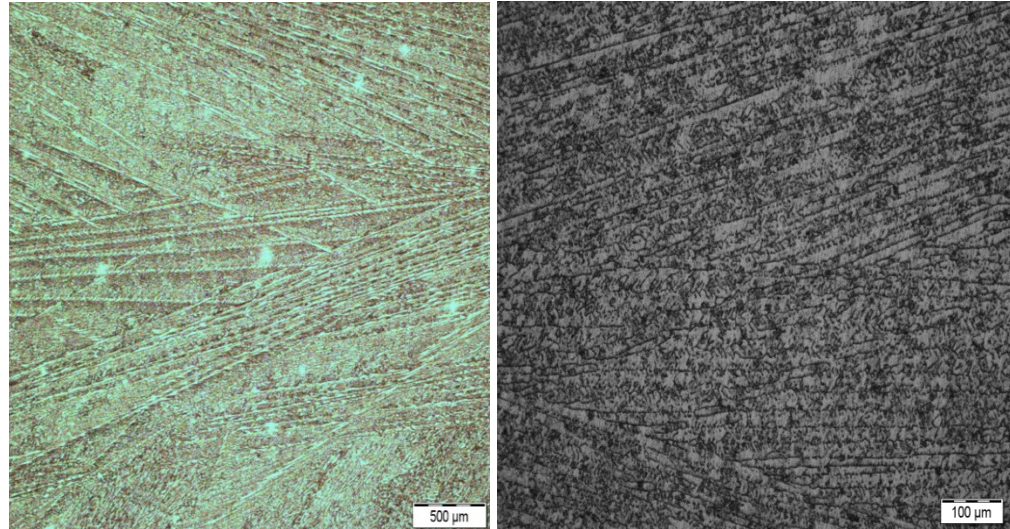


Figure (3.12): Optical microscope pictures showing top view of fast weld process, and the resulted weld structure on the centerline of fusion zone, on the left lower magnification of stray dendrite grains and on the right higher magnification of those stray dendrites (are the same as axial but they have opposing angles towards the centerline) and it is clear a straight Sharpe centerline formed in between, and the dendrites have very thin width.

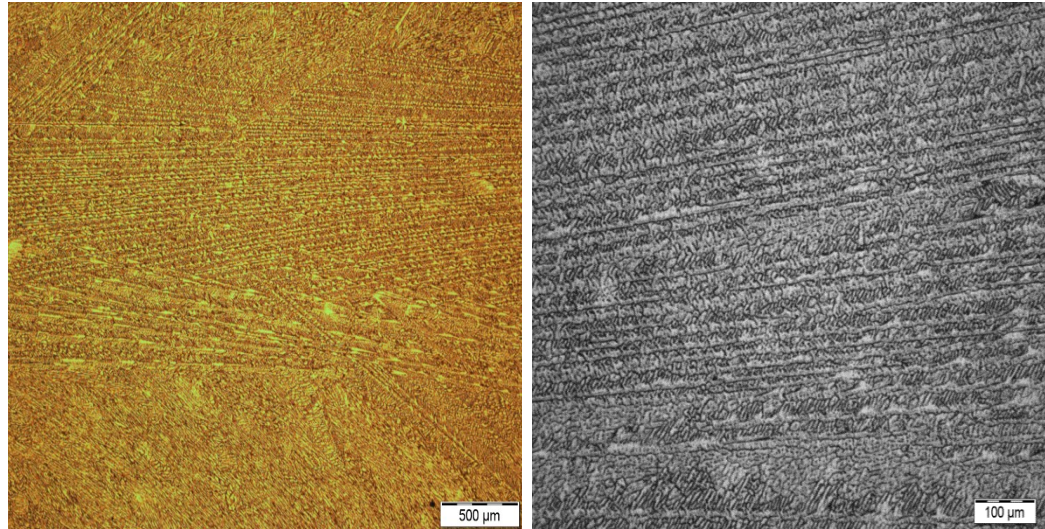


Figure (3.13): Optical microscope pictures showing top view of pulsed weld process, showing the resulted weld structure on the centerline of fusion zone, on the left lower magnification of mostly axial dendrite grains with an average width of (550 μm) and on the right higher magnification of those axial dendrites (are the same as axial but they appear with some angle) and it is clear narrower width of both the axial and the dendrites formed than slow process.

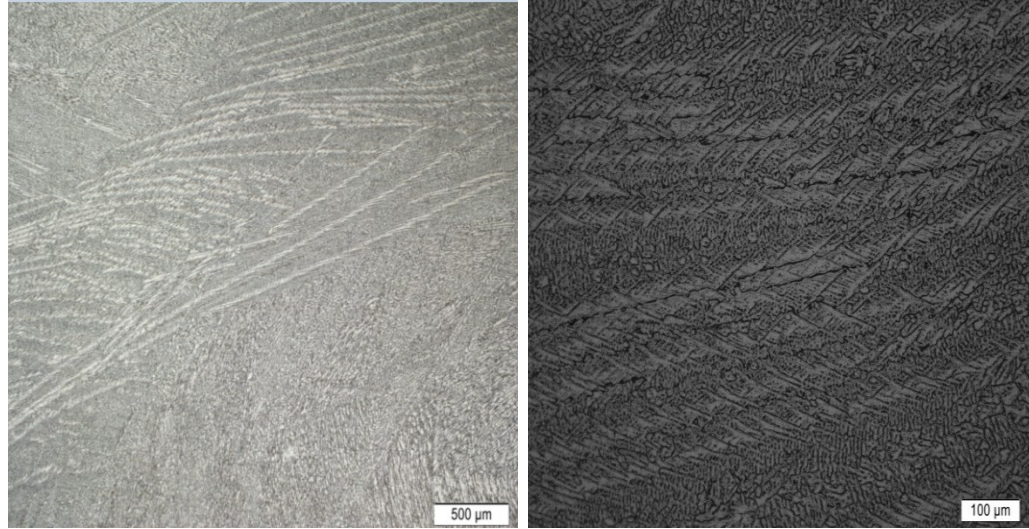


Figure (3.14): Optical microscope pictures showing top view of weave weld process, and the resulted weld structure on the centerline of fusion zone, on the left lower magnification of mostly stray dendrite grains and on the right higher magnification of some strange axial dendrites with different angles with average width of (260 μm) axial structure.

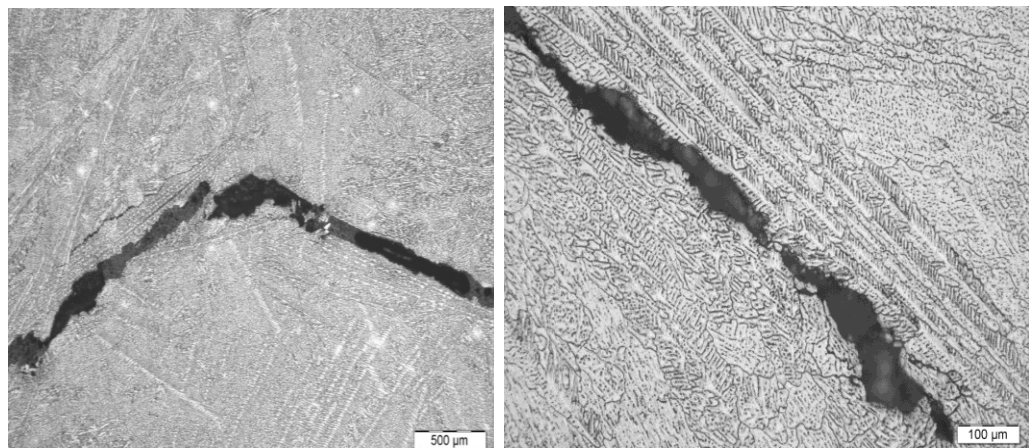


Figure (3.15): Optical microscope pictures showing top view of tandem weld process, and the resulted weld structure on the centerline of fusion zone, on the left lower magnification of mixed axial dendrite and some equiaxed grains and the width of the axial structure (150 μm). On the right higher magnification of both axial dendrites and equiaxed, and it is clear the crack forms along the path of the axial dendrites.

Most of the processes showed an axial structure of dendritic grains formed along the centerline of the weld. This axial structure, found to be the attraction for the centerline cracking, and the wider the axial structure is the longer the crack is. Only the fast process does not show this axial structure is straight way, but instead a sharp centerline formed, which was even worst for crack resistivity. The thinner axial structure formed by tandem process, which means the new process has also improved the grain structure. Moreover, with tandem process the axial structure was at some locations disturbed by formation some equiaxed grains as one can see in the next figure (3.36) and that helped in crack resistivity.

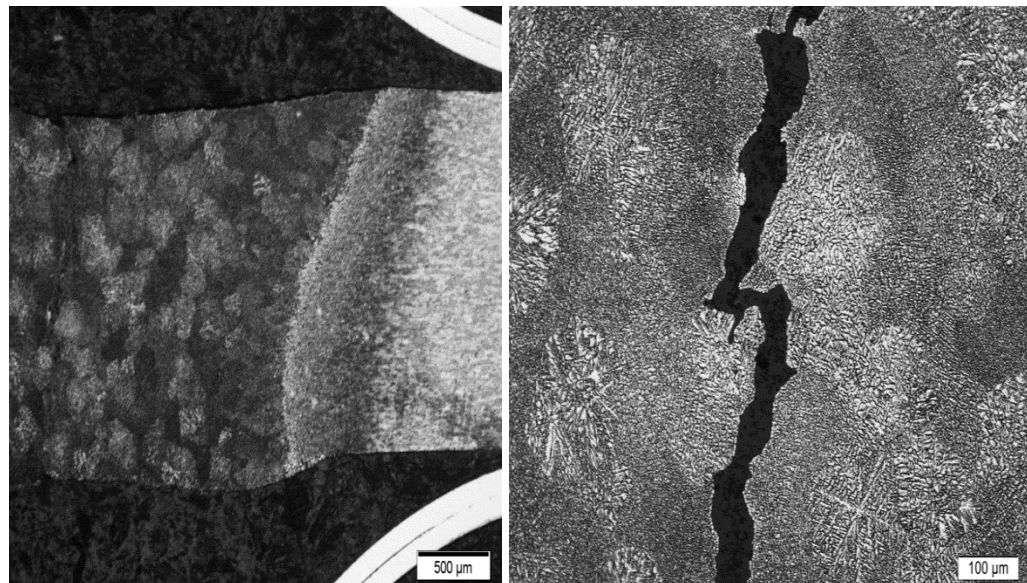


Figure (3.16): Two different magnification pictures optical microscope showing transverse view of a stationary weld, which made by (60A, & 11V) for only (1 second), the equiaxed grains are very clear almost everywhere in the fusion zone, and a solidification crack formed in the center of the fusion zone as it shown in right side picture.

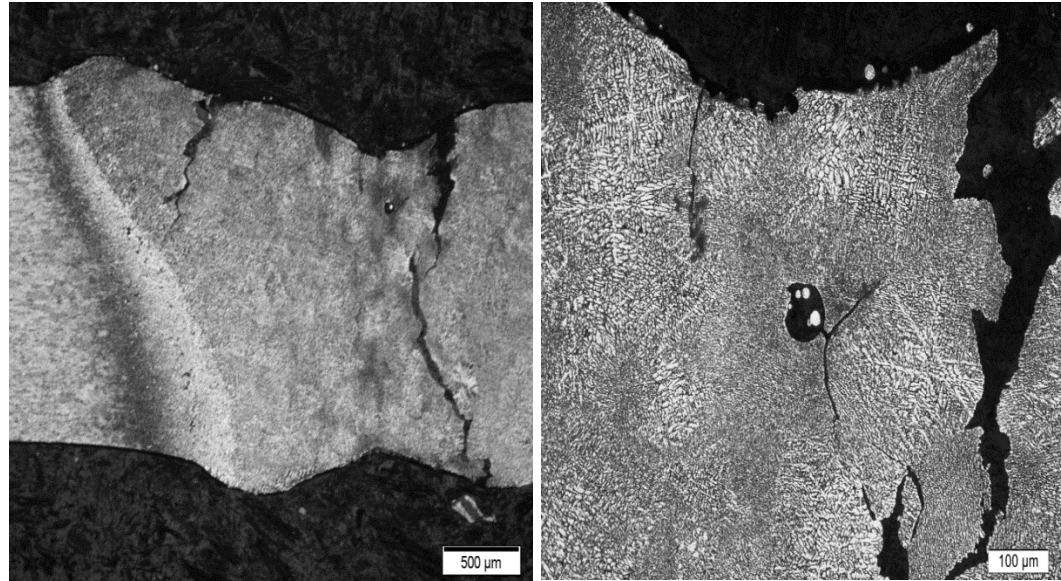


Figure (3.17): Two different magnification pictures optical microscope showing transverse view of a stationary weld and made by (60A, & 11V) for (1.5 second), the equiaxed grains are very clear formed only in the center of fusion zone, and a solidification crack formed in the center and on side, while few and short liquation cracking formed on the partially melted zone (out of fusion zone) showing on the left side picture.

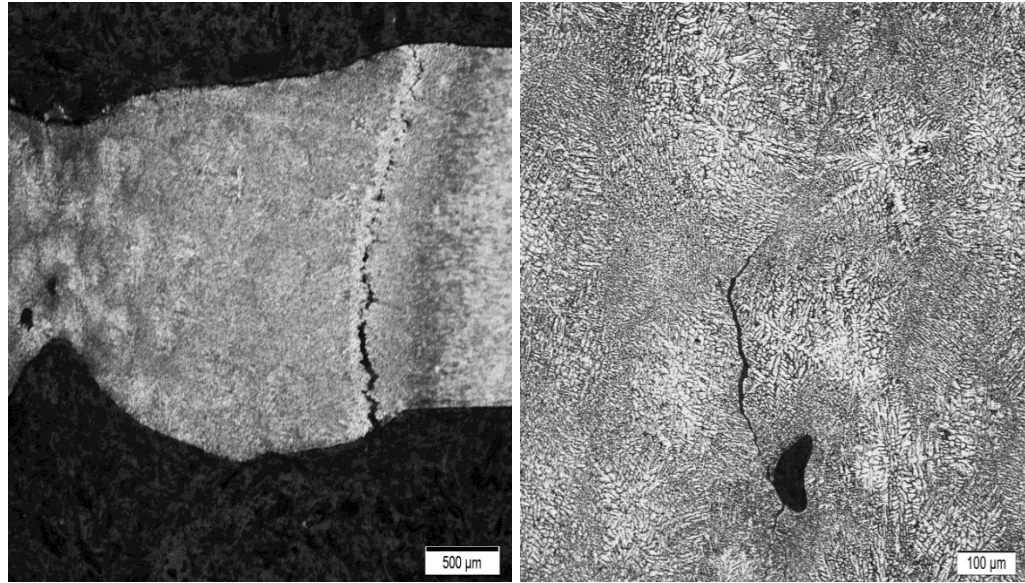


Figure (3.18): Two different magnification optical microscope pictures showing transverse view of a stationary weld and made by (60A, & 11V) for (2 second), the equiaxed grains are very clear just few formed in the center of fusion zone, and a short solidification crack formed in the center, while long liquation crack formed on the partially melted zone (out of fusion zone) showing on the left side picture.

In the previous figures (3.16, 3.17, & 3.18), a conclusion can be made of the three studied stationary welds, that a stationary weld with shorter weld time can form more equiaxed than longer time ones and almost everywhere in the weld zone not only in the center, and that due to very small value of (G) and high value of (R). It is also clear that the longer time the fewer equiaxed grains formed with larger size, which means (R) is being reduced by time and (G) increased just like what have been explained in the first chapter in this thesis in figure (1.3). Moreover, longer time leads high deformation in the weld pool after solidification and higher liquation cracking along the partially melted

zone (PMZ) on the border of the fusion zone, which means the shorter the time the better resulted weld area.

Second, the centerline of the fusion zone showed different grain solidification paths and arrangement from the top surface to the bottom of the fusion zone, and one can see that clearly in the following figures (3.19, 3.20, 3.21, 3.22, & 3.23) of transverse view of the material microstructure for each process. The clear points to be made of these figures, that when the dendritic grains arranged in a multi rows horizontally in the middle of the fusion zone, the solidify material can be more susceptible to centerline solidification cracking, because the perpendicular local strain on the grain boundaries of the weld centerline can reach higher amount with less backfilling liquid than if they arranged in angle. Another point to be made here, at higher weld speed, a very sharp centerline formed as one can see in next figure (3.20), and that helps the local strain on the centerline to reach even higher amount than normal situation and promotes crack susceptibility. Applying the mentioned points here on both Kou and his team research studies [6] and their previous figure (1.10) found to be consistent and supporting their approaches toward the centerline solidification cracking.

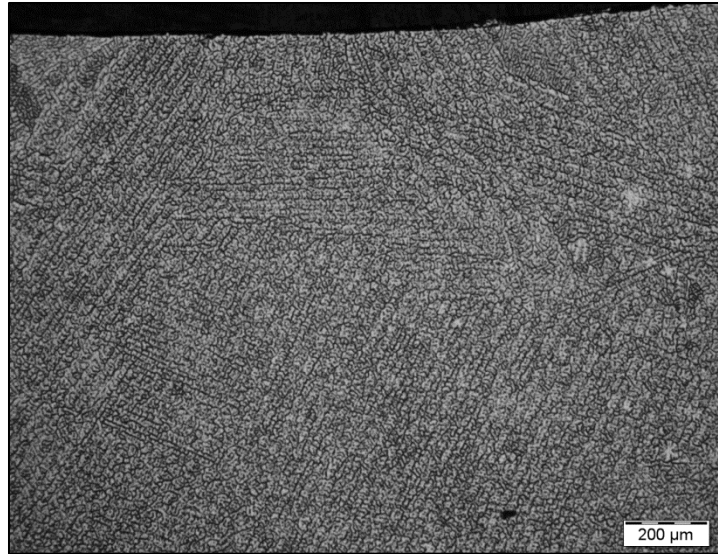


Figure (3.19): Optical microscope picture showing a transverse view of the center fusion zone of the resulted weld from slow weld process.

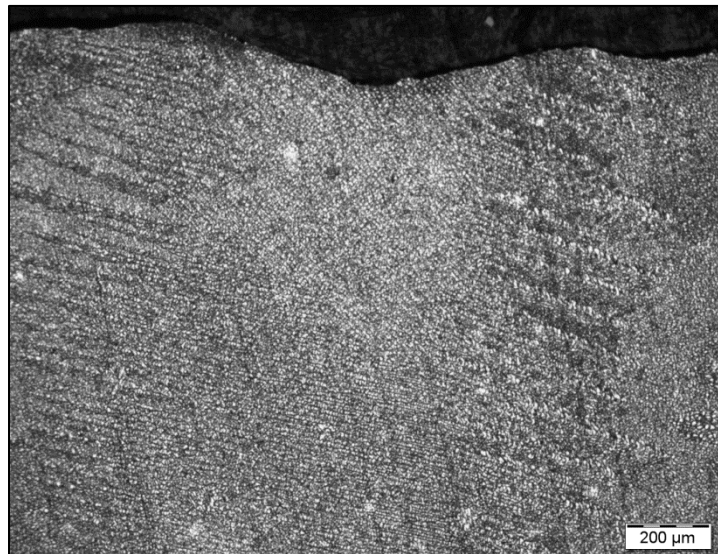


Figure (3.20): Optical microscope picture showing a transverse view of the center fusion zone of the resulted weld from fast weld process.

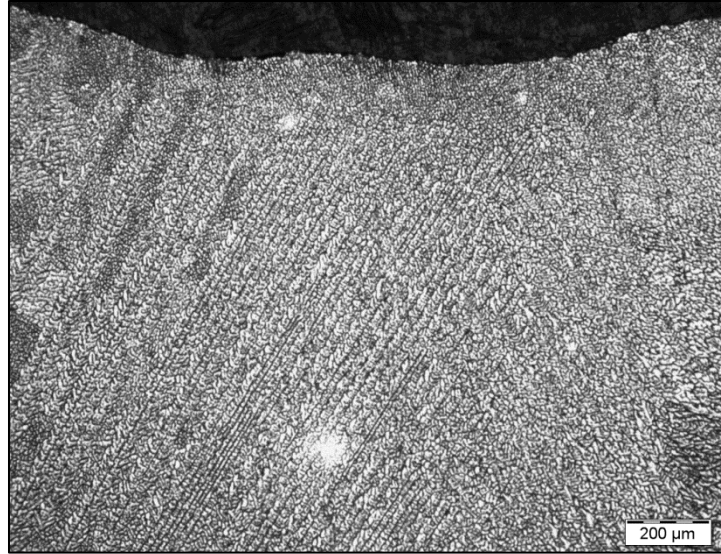


Figure (3.21): Optical microscope picture showing a transverse view of the center fusion zone of the resulted weld from pulsed weld process.

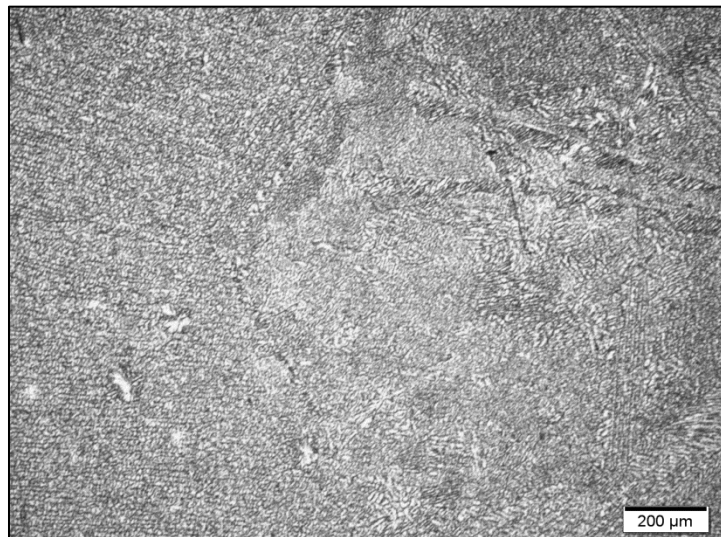


Figure (3.22): Optical microscope picture showing a transverse view of a weld resulted of the center fusion zone of the resulted weld from weave weld process.

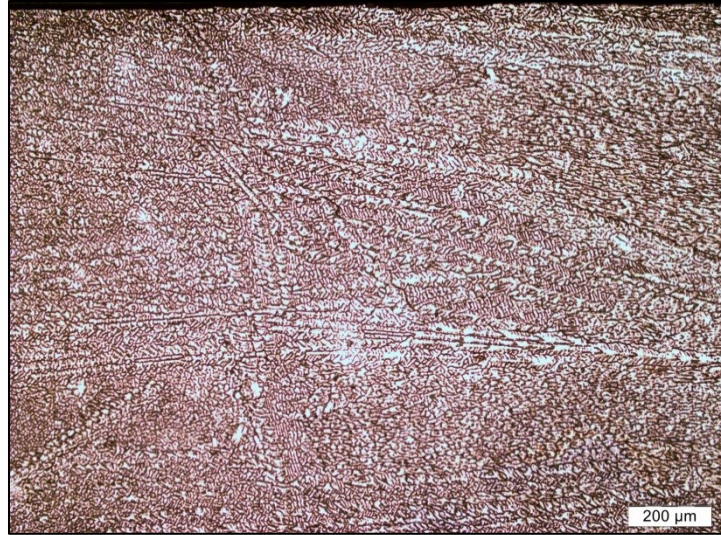


Figure (3.23): Optical microscope picture showing a transverse view of the center fusion zone of the resulted weld from tandem weld process.

The figures (3.19, 3.20, 3.21, 3.22, & 3.23) showing that each process has its own resulted grain growth path from sides (fusion boundaries) towards the center of the fusion zone. The order of the grains from the surface to the bottom of the weld at the center of the fusion zone is important and it changes from process to another due to the amount of heat input, heat flow, and weld pool motion that each process has. In different words, disturbing the heat flow during any weld process may change the growth path of the solidified grains towards the centerline of the fusion zone. For example, in the slow weld process the high heat input made the growth to take two different paths, one horizontally close to the surface around (300 μm), and another growth found with an angle from the bottom and that due to the convection of heat flow where the material connected to the base fixture. For the fast process, the growth path showed almost horizontal in the center

of the fusion zone, and formed very sharp V-notch shape on the surface of the centerline of the fusion zone. Both the arrangement of the grains and the V-notch shape found there because of the high travel speed used in the fast process, which consider a bad thing for centerline solidification crack resistivity. In pulsed process the order of the grains at the center of the fusion zone was with an angle and that due to the pulsing mode which disturb the solidification growth process and it consider a good thing for centerline crack resistivity. In the case of weave process, the resulted weld showed disorder grain growth path, and that due to both weld pool motion and heat flow which created by the weave motion of the arc. The disorganized solidified grain path resulted from weave weld process considered to resist centerline solidification cracking. The most significant grain growth path was obtained by the tandem weld process which showed a messy solidification path in the center of the fusion zone with different solidification modes leads to have higher solidification centerline crack resistivity.

Third, the crack path through the thickness of the material showed important facts. The arrangement of the grains solidification path along weld centerline of the fusion zone is very important to form the crack path through the depth of the material (from surface to the root of the weld at the center of the fusion zone). The horizontal grain solidification path mode will form a very sharp and straight crack line vertically along the grain boundaries of the centerline of fusion zone as it shown in next figure (3.25) for fast weld process, which means the crack growth during solidification process very easily with less resistance compared with other processes. On the other hand, for the grains arranged in an angle along the centerline of the fusion zone, one

can see clearly that the crack forced to change its path to follow the grains order, which cause the crack to face more resistance to deflect and that in my opinion helped to reduce the total crack length longitudinally. Next figures (3.24, 3.25, 3.26, 3.27, & 3.28) showing that the best crack deflection obtained by using Tandem process, and that because of the disorder grain solidification paths with different angles along the centerline of the fusion zone.

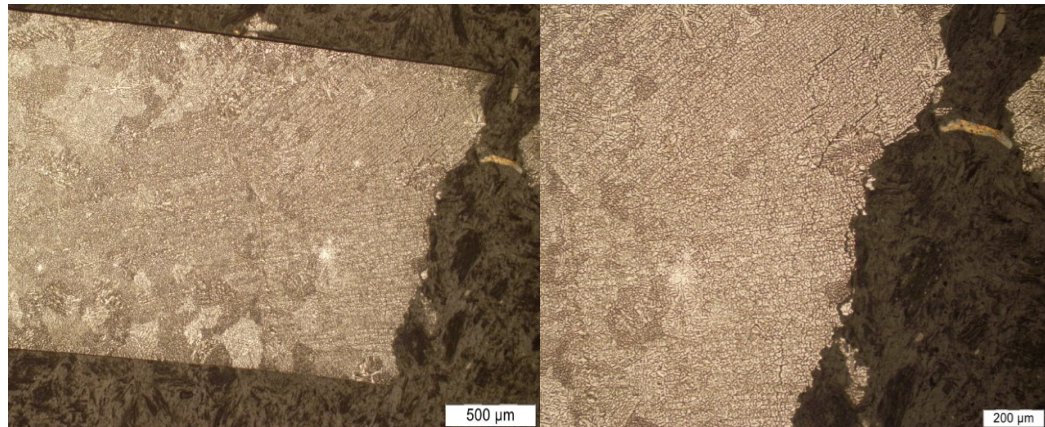


Figure (3.24): Optical microscope pictures with transverse view showing the result of slow weld process with centerline crack path. On the left, the centerline crack path changed with the grains order (solidification path), and on the right, higher magnification of centerline crack.

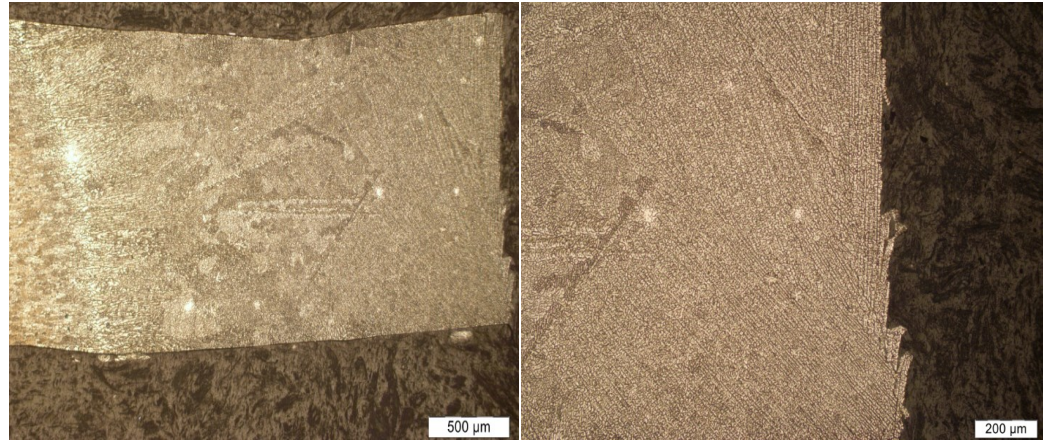


Figure (3.25): Optical microscope pictures with transverse view showing the result of fast weld process with centerline crack path. On the left picture, a vertical and straight centerline crack path, and on the right higher magnification of that centerline crack.

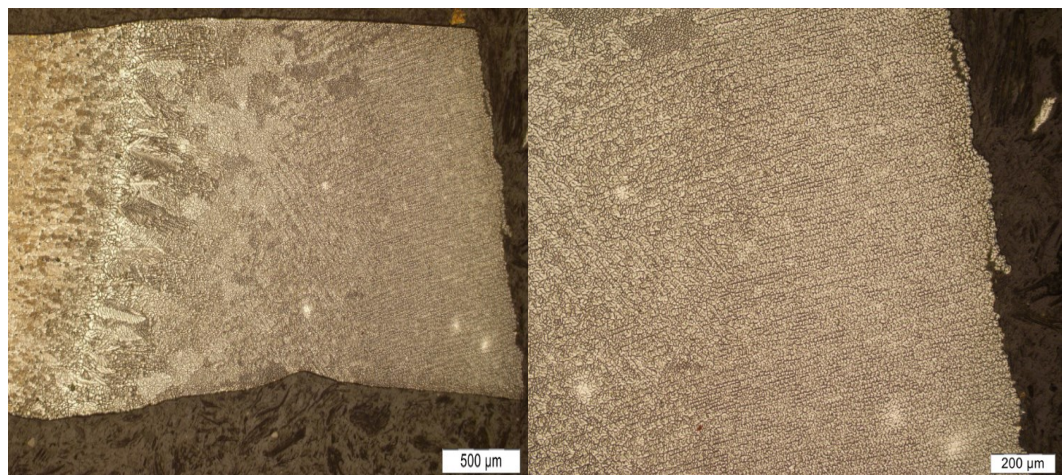


Figure (3.26): Optical microscope pictures with transverse view showing the result of pulsed weld process with centerline crack path. On the left, the centerline crack path formed with angle, and on the right, higher magnification of centerline crack.

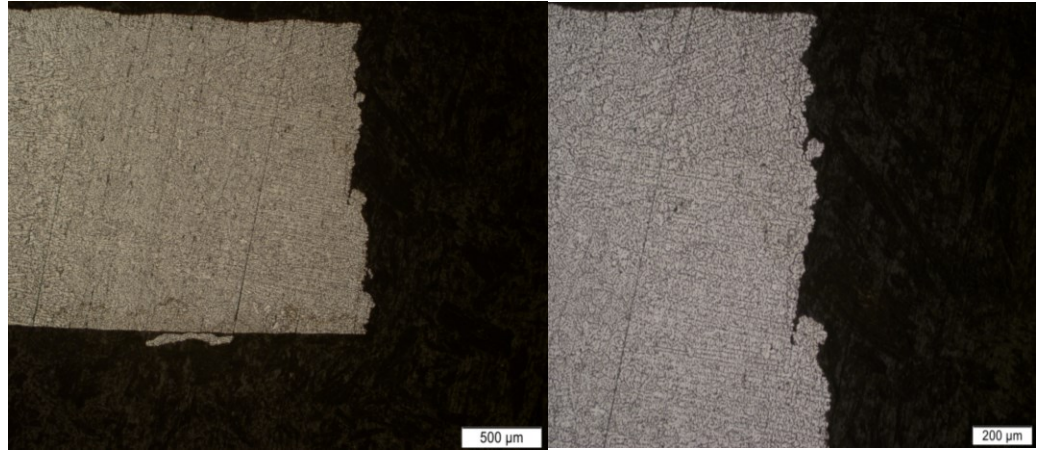


Figure (3.27): Optical microscope pictures with transverse view showing the result of weave weld process with centerline crack path. On the left, the centerline crack path formed with several angles, and on the right, higher magnification of centerline crack.

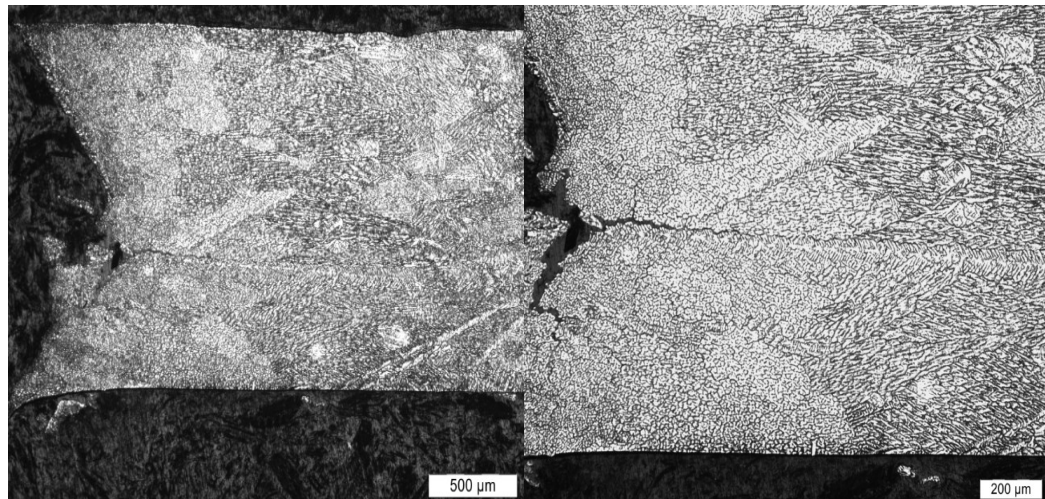


Figure (3.28): Optical microscope pictures with transverse view showing the result of tandem weld process with the most deflected centerline crack path. On the left, the centerline crack path formed with huge deflection, and on the right, higher magnification of centerline crack.

The tandem weld process showed it has the most resistivity for the centerline cracking, the crack not only deflected, but also it went horizontally as one can see in the previous figure (3.28). This leads to a new approach, which is the order of the solidification grain paths in the center of the fusion zone can either increase the resistivity or the susceptibility of the centerline cracking during the solidification process of a weld process. The mentioned approach in this part of the current study reached because of the unstable arc process resulted from the tandem process which leads not only producing a disturbing grain growth path, but also forming different solidification grain mode in the centerline of the weld line.

Fourth, the study of grain size and types for each process (case) has shown significant differences on both centerlines of fusion zone and fusion boundaries. In the following five figures (3.29, 3.30, 3.31, 3.32, & 3.33) of fusion boundaries showing the grain sizes of each process and the larger grain size obtained by using the slow weld process, because of higher heat input, while the finer grain size noticed by using tandem process. The grain sizes lead to an important approach, which is the tandem process uses the same welding parameters of slow process, but it produced lower heat input, and that because of the two electrodes working interchangeably one at a time alternately, which means the arc jumps from one spot to another when the first arc shuts off and the second starts. Another important point to be stated here is that by using tandem process the grains on the right side of the fusion zone differ from those on the left side, and one can see some of equiaxed grains formed on both sides in both figures (3.34 & 3.35). The difference in grain size and shape on both

sides, is due to the two different weld pool overlapping each other with one precedes the other, so it is very hard to find a region where the left side is symmetric with the right side of the fusion zone area by using tandem process. Moreover, using tandem process proved that each weld pool will have a fast cooling rate because of the time of turning on and off each electrode during the process, and that helps forming the equiaxed grains in the fusion zone because of lower (G) and higher (R) as mentioned earlier, that due to semi stationary action of tandem weld process. The following figures (3.29, 3.30, 3.31, 3.32, & 3.33) showing the differences in the grain sizes and types on the grain boundaries for each process.



Figure (3.29): Optical microscope picture with transverse view showing the result of slow weld process of the fusion boundary with average grain size of (21 μm).



Figure (3.30): Optical microscope picture with transverse view showing the result of fast weld process of the fusion boundary with average grain size of (12.5 μm).

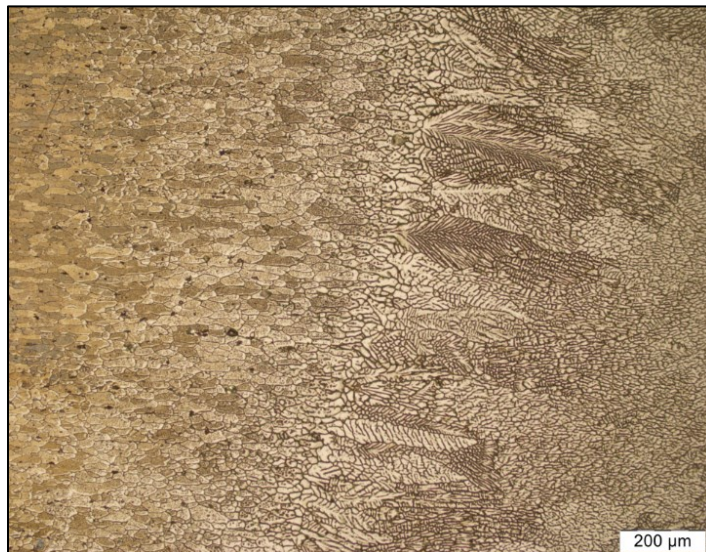


Figure (3.31): Optical microscope picture with transverse view showing the result of pulsed weld process of the fusion boundary with average grain size of (18 μm).

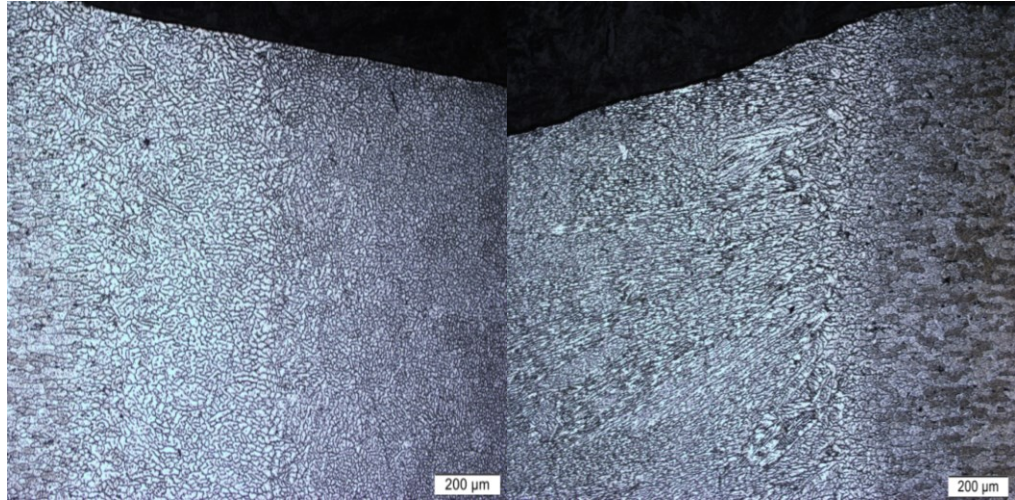


Figure (3.32): Optical microscope picture with transverse view showing the result of weave weld process of the fusion boundaries. On the left the average grain size of (15 μm) of the left side of the weld fusion boundary, while on the right the average grain size of (14 μm) of the right side of the weld fusion boundary.

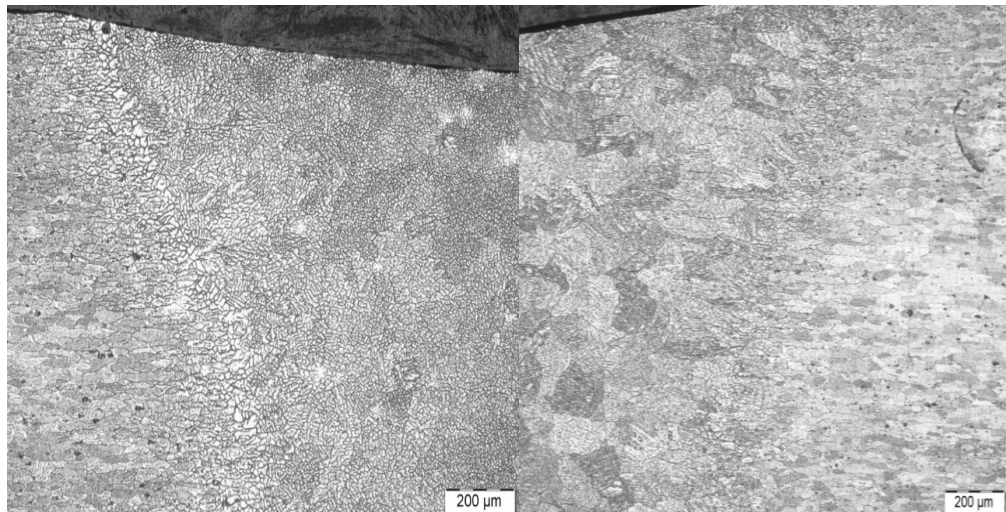


Figure (3.33): Optical microscope picture with transverse view showing the result of tandem weld process of the fusion boundaries. On the left the average grain size of (10 μm) of the left side of the weld fusion boundary, while on the right the average grain size of (8 μm) of the right side of the weld fusion boundary.

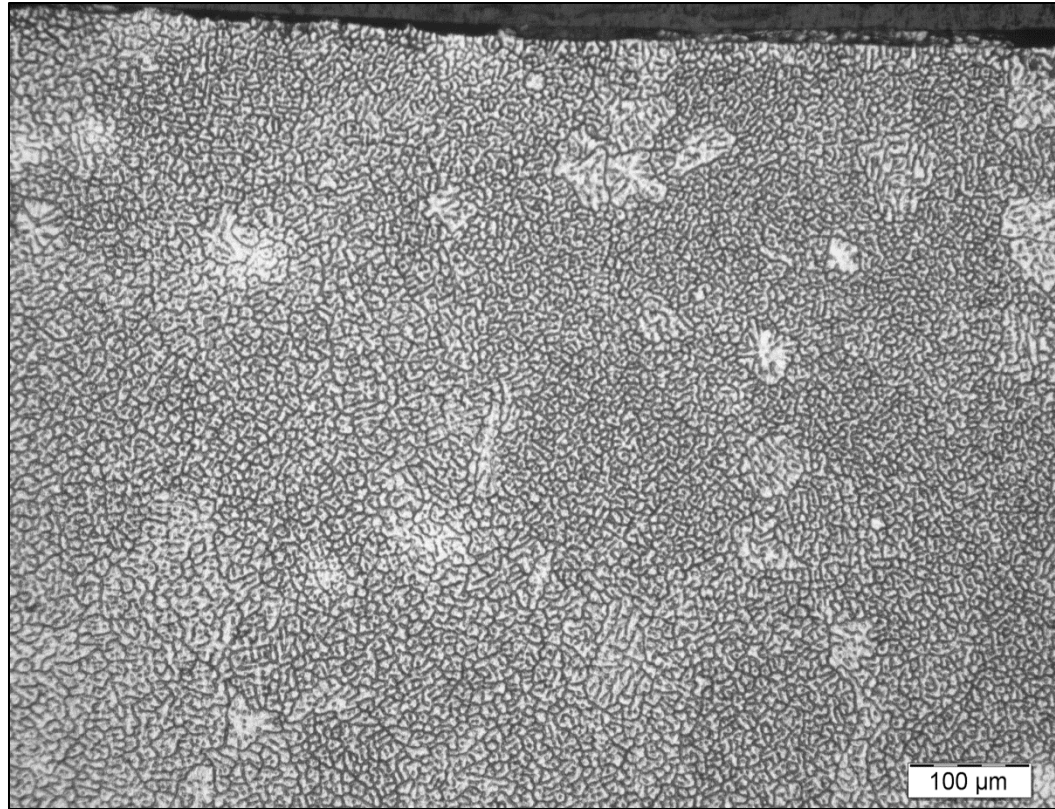


Figure (3.34): Optical microscope picture with transverse view showing the result of tandem weld process of the left side of the weld fusion zone close to the weld centerline.

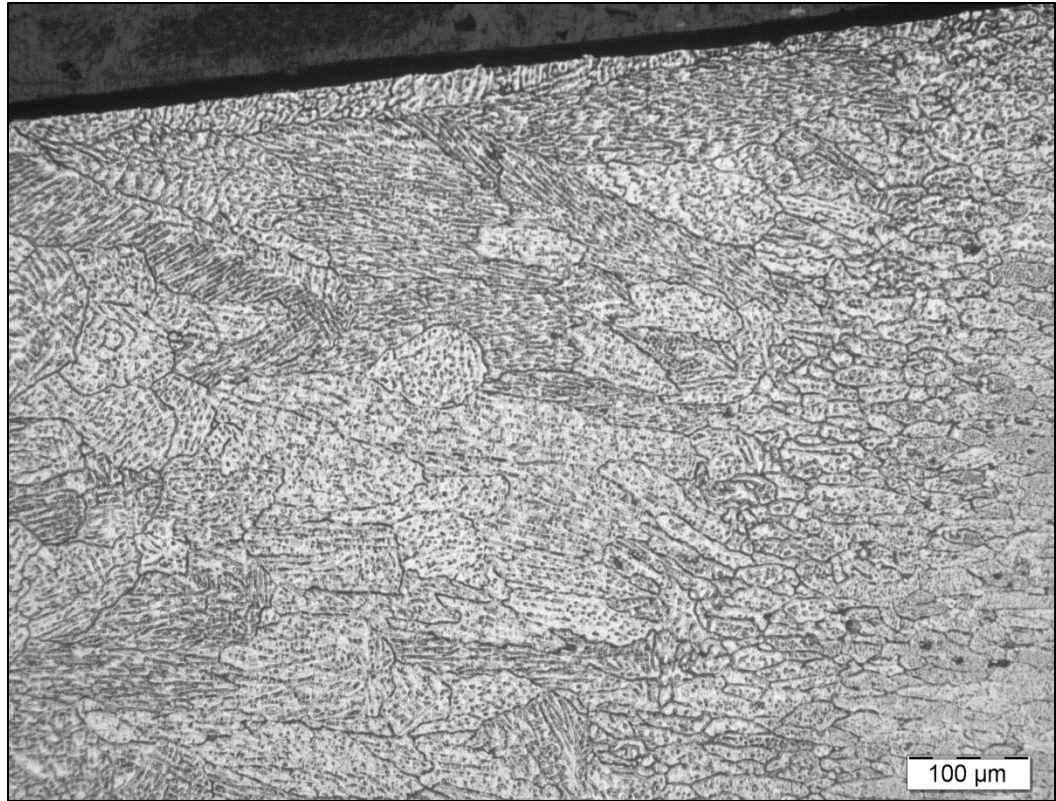


Figure (3.35): Optical microscope picture with transverse view showing the result of tandem weld process of the right side of the weld fusion.

Last figures (3.34 & 3.35), showing that some equiaxed grains formed on the two sides of the centerline of the fusion zone almost (15%) equiaxed formation.

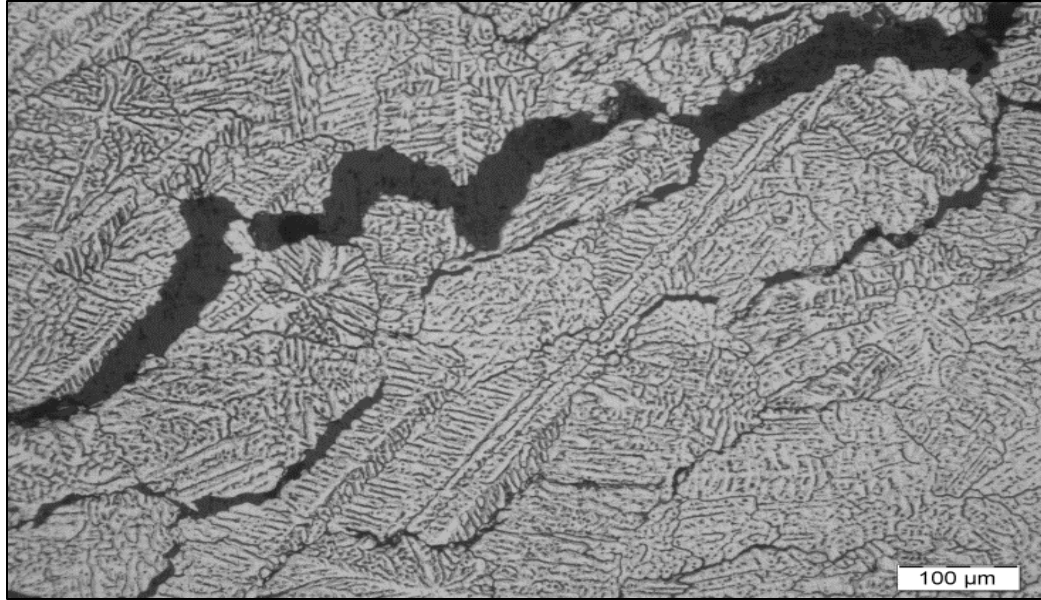


Figure (3.36): Optical microscope picture with top view of the centerline solidification cracking obtained by the tandem weld process, and some equiaxed grains formed and deflected the crack.

Last figure (3.36), proves the benefits of the equiaxed grains formed in the centerline of the resulted weld by tandem process. The equiaxed grains forced the crack to deflect multi times, which means forming equiaxed grains in any process will assist to resist the centerline solidification cracking.

3.4 Micro-Hardness:

The micro hardness Vickers test and measurements for welding processes used in this study was taken for different locations from the transverse surface by eight indentations

vertically for each region and the final value of the hardness was taken from the average of those eight points, and the indentations at different locations are shown in the next figure (3.37).

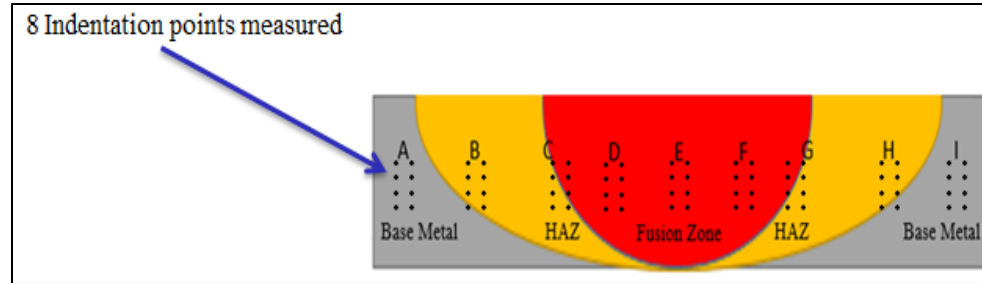


Figure (3.37): A schematic of a transverse weld, showing the eight indentations made on each location of the nine locations of the resulted weld for each process to measure the average micro hardness at each location.

The micro hardness Vickers test in this study showed that the highest hardness at the centerline of the weld pool obtained by fast weld process, while the lowest hardness reported by slow weld process as showing in the following figure (3.38). The tandem weld process showed significant mechanical properties, by providing gradually change in hardness from base metal to centerline of fusion zone, while other processes showed a sharp drop between HAZ to the fusion boundary as one can see in figure (3.38). Moreover, tandem process showed the highest values of hardness Vickers on almost all the location from the HAZ up to the fusion zone, but the centerline location of the fusion zone the fast process showing the highest value of (110) in there, while tandem process

showed the second highest value of (106) and weave process following by (102). Elsewhere, tandem process leading in hardness values by higher values and that due to the high cooling rate everywhere, but the centerline, which was the last point to solidify and that is a result of the overlapping area of the two weld pools made by both electrodes, which made that area to have lower cooling rate and to be softer. Another point to be made here, the weave weld process showed lower values compared by tandem and fast processes, and that due to the lower cooling rate resulted from the motion of the arc that passes from one side to another causing overlap area heated twice, one time when the arc passes from left to right then when the arc passes from right to left. Moreover, the resulted hardness gained in the current work has good agreement with H. Kaya and his team, who presented on his study of the effect of the growth rate on the micro hardness in directionally solidify Al-Si alloy [21]. He concluded that increasing the solidification growth rate (R) for a process will lead to higher hardness by providing the following equation (3.2).

$$HV = (k) X (R^b)$$

Eq. (3.2): Hardness Vickers

Where (HV) is the micro hardness Vickers, (k) is material's constant, (R) is the solidification growth rate, and (b) is another constant.

Applying Kaya equation on the resulted (R) from the previous table (3.1), match with current micro hardness results of all processes.

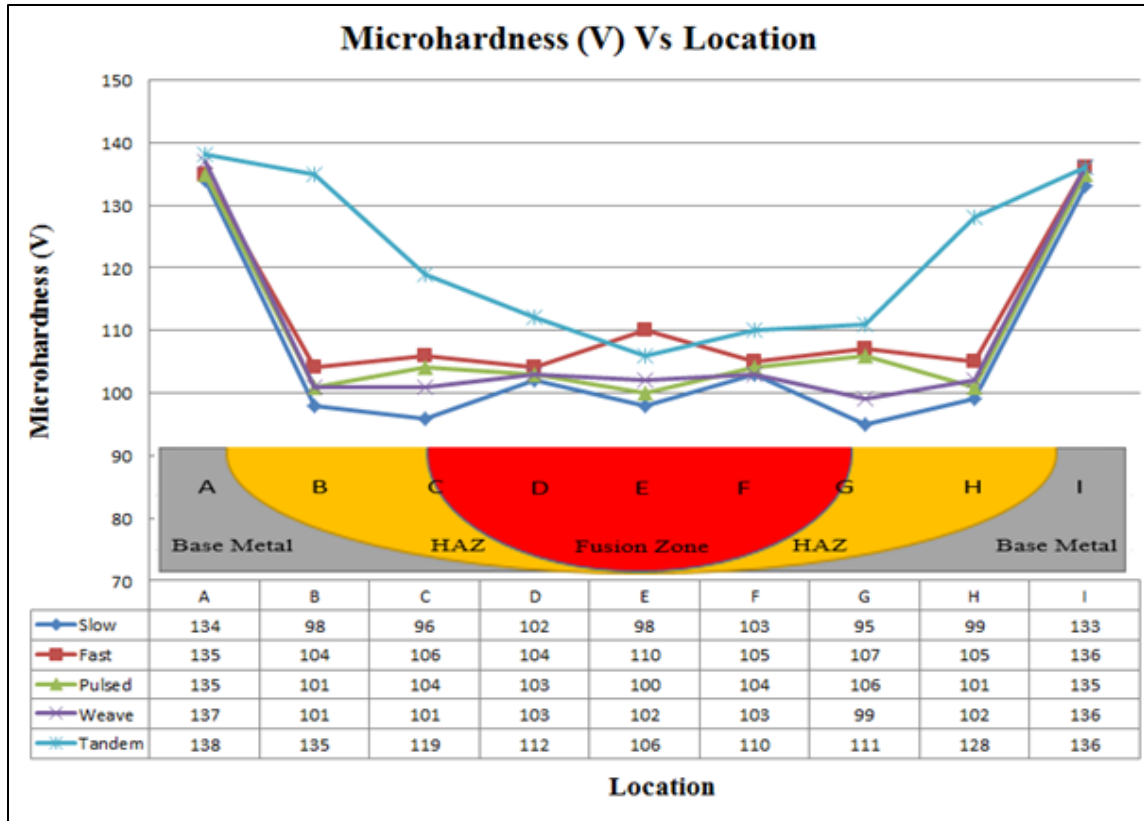


Figure (3.38): Showing the micro hardness Vickers test results on different locations of the welded samples for the five different weld processes used in this study.

The hardness results provided in the last figure (3.38), showing that the average grain size of each process was identical with the values of the micro hardness Vickers.

Chapter 4

Project Challenges

In any project or study there are some challenges or difficulties facing the researchers, and those challenges sometimes can be very hard to get through them and forcing the researchers to use different ways or even to change the whole idea of the project. On the other hand, challenges most of the time brings good and new ideas additional to the main project. Therefore, in this section I will share with the readers some of the challenges that this project faced before it come to this point.

4.1 Material:

As I mentioned earlier in this thesis, the material used in this study was aluminum alloy 2024 because it was close to the material used by Sindo Kou study [6] for fairly comparison, and it is one of the highest materials which has high solidification crack susceptibility. Therefore, one of the challenges faced me as a student is that the material

is really costly, for each sample with the dimensions of (12" X 12" X 0.063") costs almost (\$18) per sample. Another challenge due to cost was that the accuracy of machining the samples to produce the fish bone test was an important point to have good comparison among the samples. As we know, that the material was very thin (0.063"), which means cannot be machined with any of the unexpensive machining processes. The EDM was one of the best options to prepare the material and produce the fish bone without bending them or putting high stresses in the material after machining them. This was one of the hardest choices that I made in this project, preparing each sample cost (\$50) and I had to prepare thirty samples, which means the price of preparing the samples only is (\$1500), these are the most material draw back of the initiation of this study. But on the other hand those challenges pushed me to be more careful dealing with any test I made on those samples, which helped to plan for any step very well before applying it on the actual material even if this was time consuming but somehow it is a good thing and money saving. Thinking in positive way this build more responsibility and patient dealing with experimental procedures.

4.2 Setting up The Process:

The new process is depending on two working GTAW electrodes at different times, and for that I needed to have two different GTAW power sources. The good thing that OSU offering good GTAW welding machines, but unfortunately I needed two

welding machines have the same model and brand to connect them on the Arduino without differences in arc efficiency. Therefore, the challenge here is that the welding department of OSU has only two GTAW welding machines meet my requirements, and the problem that many student using those machines and I cannot reserve the two machines for long time, due to other project going on and using those two welding machines. Thus, mostly my welding experimental work was mostly during the weekends, which made my time of work very short and that buildup lot of stresses on my working time. On the other hand, the weekends were very good for working because it is quiet and that made my time more productive, which also gave me some kind of comfort because if I setup the process I don't have to reconstruct it before Sundays midnight.

4.3 Experimental:

In this part actually most of the challenges fit for current study. One of the most challenging factors I have faced is setting the parameters of the working electrodes. In order to compare my study with Kou work, I needed to have same power used, which means I need the same voltage and amperage. Therefore, I had only two parameters to change through the process in order to get the best process performance. First, I had tried many trails to get the right working time for each electrode and next figure (4.1) showing the differences in the resulted weld by changing working time for each electrode.



Figure (4.1): Showing three different resulted tandem weld trails for three different working times for each electrode, on the left (0.5 second), in the middle (0.75 second), and on the right (1 second). All the trails made by (3.6 mm/s) weld travel speed.

By changing the time, I have reached that the best weld pool shape can be obtained by the one second working time for each electrode. Also, I have noticed another thing, the weld pool size would be unstable and it differs from the start point to the end point, as one can see in the same previous figure (4.1). Therefore, I needed a start hold time at the beginning of the process which helps to give the material some time to have stable weld pool size and there where I added some changes to the process by having

some start holding times to see the result, and next following figure (4.2) showing some of those trails.



Figure (4.2): Showing three different resulted tandem weld trails for three different start hold times and two different weld travel speeds, on the right a start holding time of (4 seconds) and weld travel speed of (4.2 mm/s), in the middle a start holding time of (6 seconds) and weld travel speed of (3.6 mm/s), and on the left a start holding time of (4 seconds) and weld travel speed of (3.6 mm/s).

From last figure (4.2) it was clear the best weld line appears by using a (4 seconds) start holding time, weld travel speed of (3.6 mm/s), and for sure the timing of each working electrode is one second. Therefore, the best result obtained can be presented by next figure (4.3).



Figure (4.3): The best weld obtained by tandem weld process with a start hold time of (4 second), working time for each electrode of (1 second), and weld travel speed of (3.6 mm/s).

Another significant challenge I have faced during my work, is that measuring the temperature gradient (G) and the solidification growth rate (R) in the mushy zone (part of weld pool). For this part, I had to use a thermocouple, to get the thermal cycle in the weld pool, unfortunately this was very hard to do because the weld pools were very small and the arc cover it in all the processes used in this study. So, each time I tried to submerge the thermocouple in the weld pool, the arc touched it and melted it and that due to the arc plasma high temperature. Therefore, I tried to find a way to solve this problem, because both (G) and (R) are very important for current study. The solution I provided is that to have a thermocouple attached inside the material thickness from the backside (the opposing surface of the arc). A hole made in both the material fixture and the material, so the thermocouple can be submerged inside the thickness of the material for (0.5 mm) from the back side. The problem were solved without melting the thermocouple, but

another came up with using tandem process only, that the measuring voltage gave unreasonable values, which showed me there is some voltage loss during running the process. I figured that the ground of both welding machines needed to be connected to each other and directly to the sample and not to the table.

As a conclusion for this section, challenging is in my opinion is a main part for any study or project, which means the main idea that human can face to produce results for any situation is challenge. Challenges make the work worth the effort and time, and it gives test after passing them. Generally, having difficulties or challenges can be good things or bad things, it is a researcher's decision, who can form a positive thinking and build up pushing motivation, or think negatively and give up.

Chapter 5

Additional Work to Prove Tandem GTAW Side by Side Idea

We have seen in previous chapter how tandem GTAW side by side improved not only the crack resistivity in Al alloy 2024, but also improved the grain refinement and some mechanical properties. Therefore, I decided to do more work on the same field to prove that I can get even better results by changing some of the dimensional process parameters and weld travel speed. So, I wanted to apply the tandem idea on a weave weld process and to make it act like tandem process as much as I can. In this section I will explain the methods and procedures of the additional work that I have made on this study and for sure I will show the results for this additional work in the same section.

5.1 Methods & Experimental Procedures

To apply the tandem idea on the weave weld process, we need to understand that the main idea in tandem weld process is about applying semi-stationary weld on one side of the center weld line and to be followed with another semi-stationary weld overlapping it on opposite side of the center weld line with some longitudinal distance as explained in the beginning of this work in the first chapter figure (1.16).

Therefore, the method is to use a mechanical arc oscillation with one electrode, which uses the same power parameters (60A & 11V) used in Kou study [6] and next table (5.1) will show the weld parameters used in this additional work. Now in this process we need to have semi-stationary weld, which means I need to have the arc to stay at each side of the two sides of the center of weld line. This gave me an idea of using robotics arm to move the torch as weave weld, but by having different weld travel speed compared with last five processes, and with holding time at each side of the two sides (to have semi-stationary weld pool) very close to tandem weld process. Also, one of the important points needs to be covered is that increasing the distance between the two weld spots (amplitude) causing smaller area of overlapping in the centerline of the weld line, which will also lead to lower heat input at the centerline.

Table (5.1): Showing welds parameters used by applying tandem idea on robotic weave weld process.

Process	Power	Weld travel speed (longitudinally)	Weld travel speed (from point to point)	amplitude	frequency	Hold time at each side point
Tandem Idea by robotic Weave	462 (J/s)	4.2 (mm/s)	45.5 (mm/s)	3 (mm)	5 (Hz)	0.3 (s)

So, to have better understanding of this process next figure (5.1) will give clear view of the main idea behind using the robotic by weave weld pool motion to be close to the tandem GTAW side by side with alternating working electrodes. The red arrow showing the longitudinal weld direction and speed of (4.2 mm/s), points A and B referring to two different weld spots having hold time at each point of (0.3 seconds) with transverse distance (horizontal distance) of (6mm), the longitudinal distance (vertical distance) of (2mm), and the actual distance of (6.5mm) with travel weld speed of (45.5 mm/s).

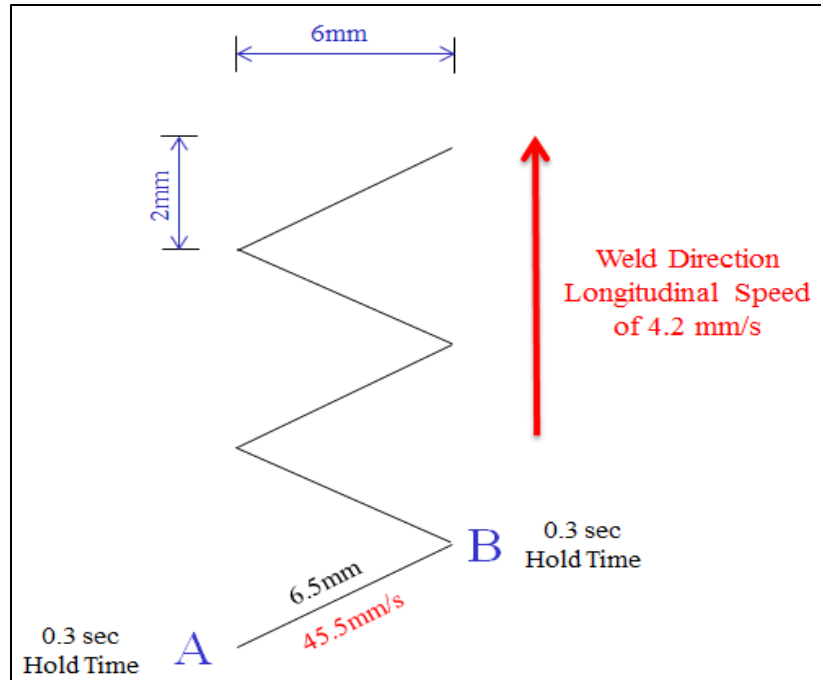


Figure (5.1): Schematic of the motion of applying the tandem idea process on a robotic weave weld process.

So, the tandem idea here is that the arc will stay at point (A) for only (0.3 s) as it shown in the previous figure (5.1), then the arc will travel for a distance of (6.5mm) in angle at very high travel weld speed of (45.5 mm/s) to stay after that at point (B) for (0.3 s). The point of this systematic motion here is that we want to have two different semi-stationary weld pools overlapping each other and we want to reduce the effect of the arc in between the two points (A & B) and reducing the heat input as much as we can. This has been made because here in this case we don't have two electrodes, we have only one and we are trying to make it works like two electrodes as tandem process. That means in tandem process, we had two side by side electrodes and we got the benefit of their

distance and shutting of the arc for some time and running the other one at different location, which cause the heat input to be reduced significantly. Therefore, in this case here we are trying to have one electrode works like two, and that's the reason of having very high speed between the two points, to reach the following point needs to be welded before solidifying the first completely. Moreover, here we do not have shutting the arc stage between point to point so we needed to have high travel speed to act like shutting the arc off. Also, to have the points (A & B) with the shortest distance vertically I have used frequency of (5 Hz) the highest the robot can reach, which made the vertical distance between two points to be only (2mm).

In this case, the weld was made autogenous and the same solidification testing method was used, fish bone test method and both material microstructure and total crack length were investigated as additional to the previous work, and to be sure of the idea behind the tandem process if it is accurate enough to be as what we analyzed. Therefore, I expected after this case I will improve the percentage of the equiaxed grains and higher possibility of increasing the resistance of the centerline solidification cracking.

5.2 Results & Discussion

A. Total Centerline Solidification Crack Length:

The total crack length showed very high reduction compared with all the previous five case studied earlier in the current thesis. The reduction in total crack length was almost (92%) of the slow process with a crack length of (11 mm). Moreover the crack was very thin less than (0.5 mm) thick and barely can be seen by naked eyes as one can see in the next following figure (5.2).

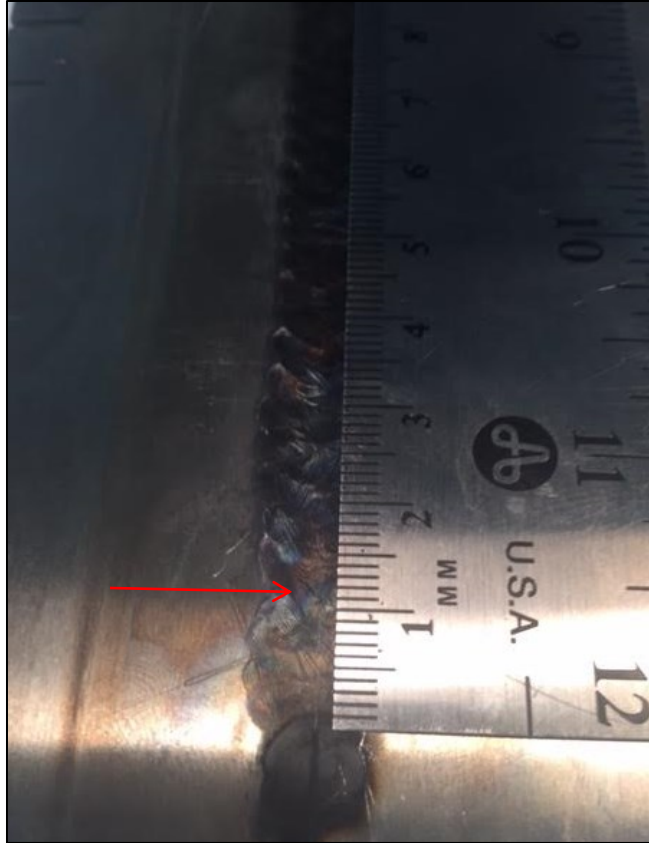


Figure (5.2): Test sample of resulted tandem idea weld process, showing a crack length of (11 mm) only and the red arrow pointing the end of the crack tip.

The crack length was amazingly reduced and reached very high percentage in reduction compared with slow weld process studied earlier. Also, the crack shows very thin, which means the resistance to the crack was really high, and as I expected that is due to low heat input, which means low power density, and the compression forces resulted from each welded point following the past one.

B. Microstructures & Crack Path through the thickness:

Investigating the microstructure of the resulted weld line showed some significant points; first, the resulted grain structure formed almost equiaxed and appears with higher density in the center of each hold location (weld spot), where in the centerline of the weld was few equiaxed grains and mostly columnar dendritic grains, next figure (5.3) showing the top view of the resulted weld and equiaxed grain structure of (70%).

Second, the orientation of the grains and the crack path were also studied through the thickness of the weld from top surface to the bottom of the weld. The next following figures (5.4 & 5.5) will show also good results.

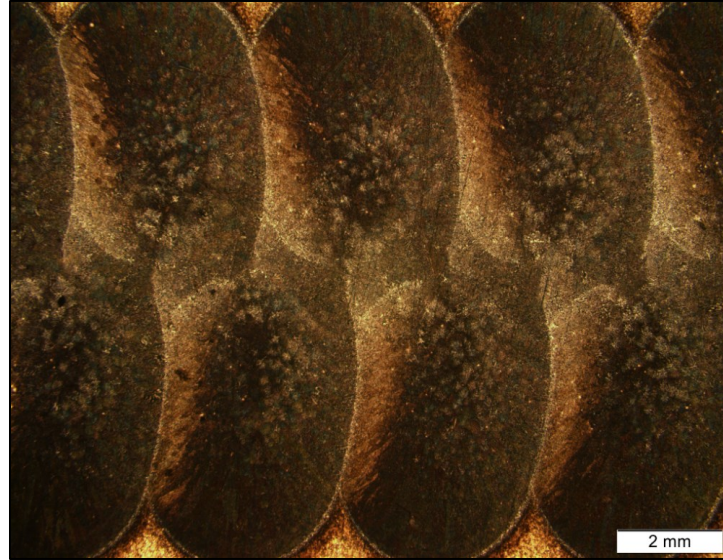


Figure (5.3): Top view of optical microscope of the resulted weld of tandem idea robotic weave process, showing high amount of equiaxed grains around the centerline of the weld line.

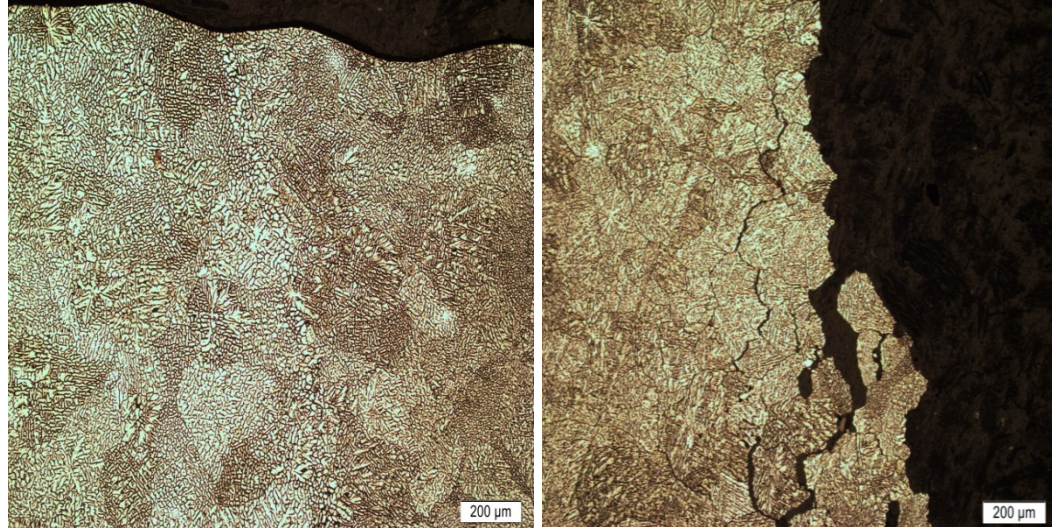


Figure (5.4): Transverse view of optical microscope of the resulted welds of tandem idea robotic weave process, on the left showing high amount of equiaxed grains around the centerline of the weld line, while on the right showing the centerline crack path with high deflection.

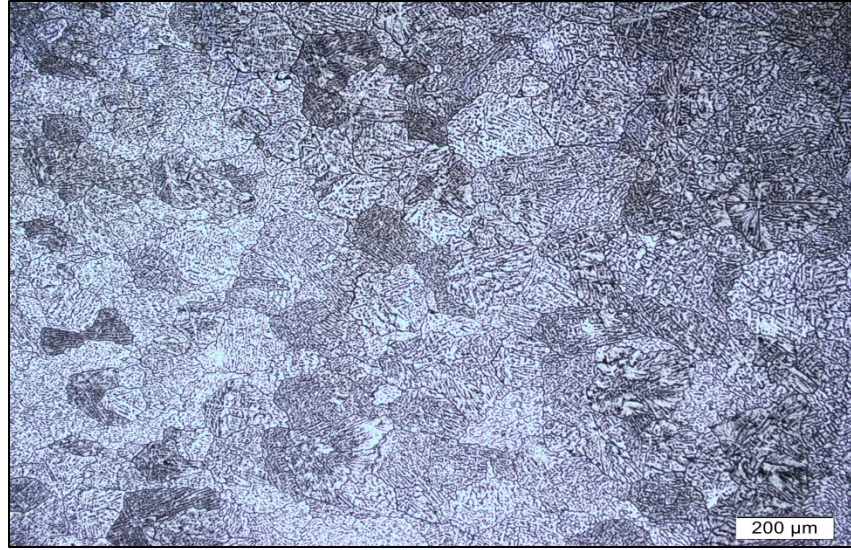


Figure (5.5): Transverse view of optical microscope of the resulted weld of tandem idea robotic weave process, showing high amount of equiaxed grains in the fusion zone.

Third, in this case the crack path was also tortuous but with very small angle as one can see in the next following figure (5.6). The crack was following a thin axial dendritic form with average thickness of (20 μm) on the centerline. That means this process also improved the reduction of the axial dendritic structure on the centerline of the resulted weld.

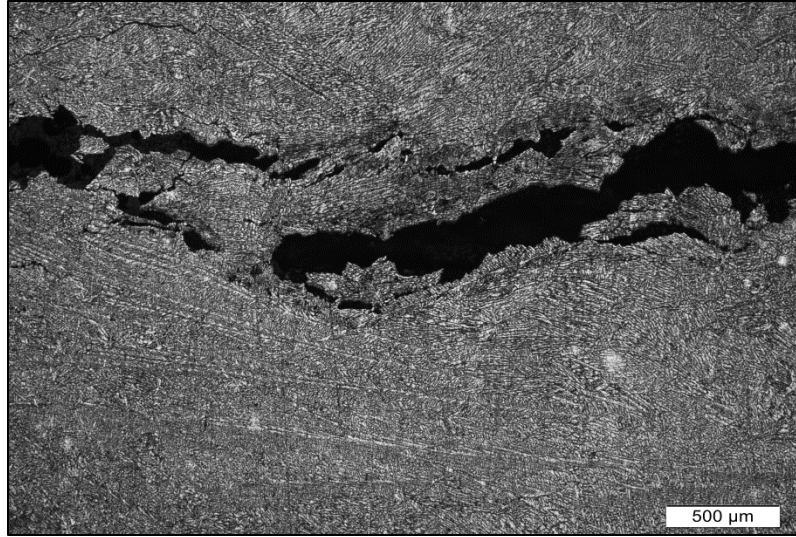


Figure (5.6): Top view of optical microscope of the resulted centerline solidification cracking of tandem idea robotic weave weld process with a tortuous crack following the very thin axial dendritic grains direction.

Fourth, the concave shape (concavity) of a transverse view for a weld mostly proving high heat input was applying on that weld, but for this case it is symmetric to the tandem weld process studied earlier and showed in this work as one can see in the following figure (5.7).

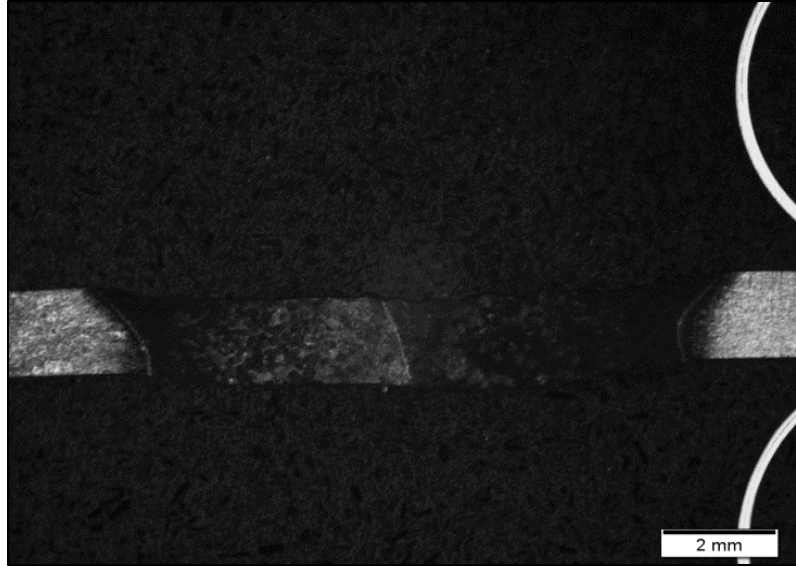


Figure (5.7): Transverse view of optical microscope for the resulted welds of tandem idea robotic weave process.

Fifth, the average fusion boundaries grain size was studied of this case and found that the grain refinement was good and comparable to the other five cases as the following figure (5.8) showing. The average grain size measured on the fusion boundaries is ($6\text{ }\mu\text{m}$), which means in general the tandem idea works very well and that proves that the lower the power density, the higher solidification crack resistivity will obtained.

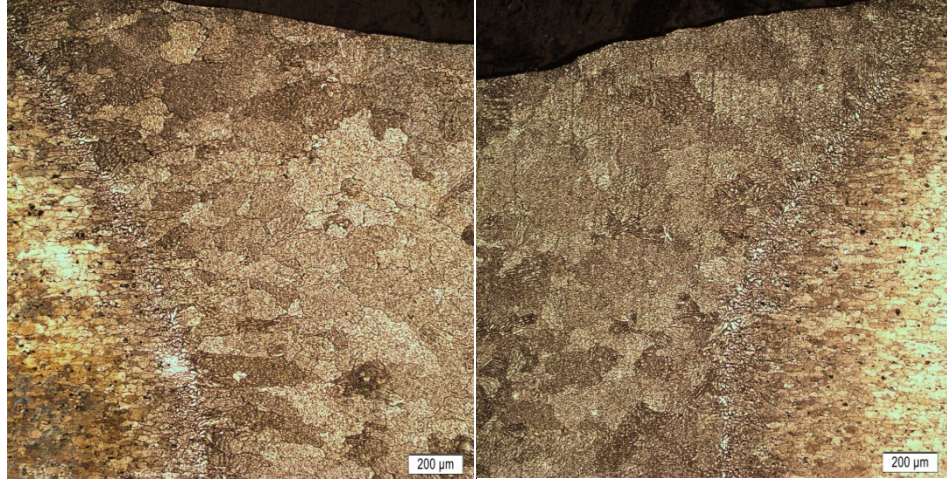


Figure (5.8): Transverse view of optical microscope of the resulted weld of tandem idea robotic weave weld process, the left side of the fusion boundary and the right side of the fusion boundary, with average grain size of (6 μm).

The additional work of this section was made to prove that the tandem process works well and can be improved more if we use two electrodes and to get the advantage of the shutting off and on the arc during the process, which will cause the arc to jump from one point to another as mentioned and discussed earlier. Therefore, in this section we have changed the amplitude and the semi-stationary weld and got almost perfect results, I expect using same parameter and apply them on the tandem process will show even better result and the crack may be eliminated with those parameters on tandem GTAW side by side weld process.

Chapter 6

Conclusions & Future Work

4.1 Summary & Conclusions:

A new weld process technique has been found to reduce and resist centerline solidification cracking and called Tandem GTAW side by side with alternating working electrodes. This new weld technique used in this study on one of high solidification crack susceptible materials, Al alloy 2024, lead to some good and significant conclusions as they follow:

- (i) Tandem GTAW side by side process reduced the total centerline solidification cracking by (60%) of the crack length obtained by slow weld process.
- (ii) The new process proved in current study that it changes the solidification behavior and the grain orientation of the material by forming a tortuous centerline crack path and improve the crack resistivity more than weave weld process.

- (iii) Existence of axial dendritic grains structure along the centerline of the weld zone helped the centerline solidification crack to appear among those grains along the boundaries, and the wider axial grain structure formed the longer centerline solidification cracking length and poorer centerline solidification cracking resistivity reported. The Tandem GTAW side by side process showed the thinner axial grain structure among all processes used in this study.
- (iv) The solidification grains path angle during solidification process along the centerline of the weld pool played a huge role in centerline solidification crack resistivity and deflection, and the horizontal path with no angle showed poor crack resistivity with straight crack path from surface to bottom of a weld line and obtained by fast weld process, while the best disorder grains path and high crack resistivity with huge deflection was reported by Tandem GTAW side by side process.
- (v) Tandem GTAW side by side resulted finer grains and some equiaxed grains in the weld zone, and the resulted reduction in average grain size was (40-60%) in comparison with the other four processes studied in this study.
- (vi) Comparing with different studies made on aluminum solidification grain mode, this is the first study showed that equiaxed grains can be obtained by low heat input and slow weld process.

- (vii) Tandem GTAW side by side process showed lower heat input resulted from running one electrode and shutting off the other one acting like semi stationary welds, which cause the heat to jump from one spot to another resulting in some heat loss and that cannot be obtained by other four processes, because they use a continues running arc. That gave the advantage to tandem process to show shorter crack length than other four processes and almost no concavity weld shape.
- (viii) The two working electrodes side by side, believed that they provide some compression forces on the weld centerline which leads to reduce the restraint and tensile forces occurred on the centerline from the thermal cycle around the weld pool. As a result, the centerline crack reduced and that due to heat flow from one weld pool to the other one beside it.
- (ix) Although Vickers hardness test in this study showed that fast weld process has the highest hardness along the centerline of the fusion zone, the tandem GTAW side by side showed better and gradually variation in hardness from base metal toward the centerline of the weld zone with no sharp drop in hardness.
- (x) Applying the tandem idea on a robotic weave weld process showed even better results, such as higher solidification crack resistivity, finer grain size, very thin axial dendritic grains, and high equiaxed grains formed

4.2 Future Work & Recommendations:

Tandem GTAW side by side showed significant improvement in reduction of centerline solidification cracking with a very high susceptible material to this type of cracking. The process can be optimize and improve more by changing some important setup parameters, which has been shown by applying the tandem idea on the robotic weave weld process earlier in this work. Some of those parameters are changing the electrodes angles or the distance between each other may even lead to better results in the future. Also, producing a mechanical electrodes' fixture, will help changing the angles and test different angles in one study in a flexible way with saving time. Moreover, studying the new process in homogenous or heterogeneous weld (with filler) may lead to new different approaches than this study, because this study focused only on autogenous welds.

I strongly recommend that providing or creating a numerical simulation program for the current work would help in better understanding to the thermal cycle around the weld pool during the new weld process and the subject of this current work.

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