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Brazing Cast Iron Using Ag20 and BAg-8 Filler Alloys

A Thesis

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وزارة التعليم العالي والبحث العلمي
جامعـــــة بـــابـــــــــل
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برصمة حديد الزهرباستخدام سبائك الملئ Ag20 وBAg-8

رسالة

مقدمة الى قسم هندسة المعادن في كلية هندسة المواد /جامعة بابل

كجزء من متطلبات نيل درجة الماجستير في هندسة المواد /المعادن

من قبل

ياسر لؤي عزيز صالح

بإشراف

أ.د. احمد عوده الربيعي

2022م **1444هـ**

اللَّهُ وَلِيُّ الَّذِينَ آمَنُوا يُخْرِجُهُمْ مِنَ الظُّلُمَاتِ إِلَى النُّورِ

سورة البقرة جزء من الايه257

Dedication

الى إشراقة الشمس ... ...

الى ضوء القمر ... ...

الى التي لولاها لما كان للكون وجود ... ...

فاطمة الزهراء (عليها السلام)

الى ... ...

أبي وامي

الى ... ...

زوجتي وأطفالي

أهدي رسالتي والله الموفق ...

ياسر

Acknowledgment

I would like to express my gratitude and thanks

To God the Lord of the Worlds

To my Supervisor **Prof. Dr. Ahmed Ouda Al-Roubaiy**

To my College, Materials Engineering / University of Babylon and the department of Metallurgical Engineering

To my **family**, special thanks are given to **my mother** and **my father** for standing beside me. Without my family this study could not have been accomplished.

Yasser

2022

Supervisor Certificate

I certify that this thesis entitled ***"Brazing Cast Iron Using Ag20 and BAg-8 Filler Alloys."*** is prepared by (***Yasir Luay Azeez)*** under my supervision at the Department of Metallurgical Engineering/ College of Materials Engineering / University of Babylon in partial fulfillment of the requirements for the degree of Master of Science in Materials Engineering

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Name: Professor

Dr. Ahmed Ouda Al-Roubaiy

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Date: / / 2022

Abstract

In the present work, cast irons were joined by a furnace brazing. Cast iron-to-cast iron lap joints were studied: of 10 mm rod of ductile cast iron, brazed inside a ductile cast iron and grey cast iron tube, 10 mm rod of grey cast iron, brazed inside a grey cast iron using Ag20 and BAg-8 brazing alloy. Joint clearance between the metals (0.1mm) has been set to obtain the optimum strength of the joints. Electrical furnace and microwave furnace were used to brazing cast irons.

Electrical furnace was used with argon atmosphere used as shielding gas. The medium used to cool the furnace samples was slow cooling by furnace. Brazing temperature of 820 ˚C and 780˚C were held for 15 min.

The brazed joints were examined by optical microscopy, scanning electron microscope with energy dispersive spectrometer (EDS). X-ray diffraction was used to identify the phases. For evaluation the mechanical properties, the shear strength of the brazed joints was obtained by loading the samples in compression, and the microhardness was tested.

The results indicated that the maximum shear strength (286.624MPa) obtained from the samples brazed with Ag20 filler metal was higher than that brazed with BAg-8. The highest shear strength value was for ductile to ductile cast irons joint that furnace brazed and slow cooled in the furnace, then ductile to grey cast irons joint brazed byAg20.

Microstructural analysis showed the presence of a copper based solid solution, and a lamellar eutectic of brazing alloy between the base metals, when the metals brazed with Ag20 filler metal. On the other hand, the sample brazed with BAg- 8 had eutectic structure of copper and silver. Microstructural analysis revealed that

the nodular shape of ductile cast iron has changed to compact shape during brazing process.

Also the graphite has migrated the original site towards the interface between the brazing alloy and ductile cast iron.

The XRD patterns did not identify the formation of the intermetallic phases or oxidation. From X-ray diffraction analysis, presence of α (Cu) solid solution between ductile cast iron and grey cast iron was when brazing done by Ag20 filler metals, and Ag base solid solution and copper was when cast iron brazed by BAg-8.

The joining of cast irons using microwave energy was unsuccessful perhaps because microwave used was domestic.

The applications of cast irons were pipes, machines, automotive, industry parts, cylinder, and gears boxes.

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List of Abbreviations and Symbols

Abbreviations	Description
ASTM	American Society of Test Materials
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
XRD	X-Ray Diffraction
HV	Vickers hardness
OM	Optical Microscope
AWS	American Welding Society
symbols	**Description**
$\mathcal{W}$**adh**	Adhesion energy between liquid in contact with be solid surface
G	The joint gap dimension
Tm	Melting Temperature
γ**sv**	Surface Free Energy
γ**sl**	Surface Free Energy
γ**lv**	Surface Free Energy

List of Abbreviations and Symbols

γl/v	Free energy of a liquid in balance with the liquid vapor (J/m2).
η	η is the molten alloy viscosity (N/m^2. s).
θ	The contact angle.
ρ	The density of filler metals (kg/m3)
H	The molten alloy viscosity (N/m2.s).
D.C.I	Ductile Cast Iron
G.C.I	Grey Cast Iron

CHAPTER ONE

INTRODUCTION

1.1 General Review

Welding is the process of joining two pieces of metal by creating a strong metallurgical bond between them by heating or pressure or both. It is distinguished from other forms of mechanical connections, such as riveting or bolting, which are formed by friction or mechanical interlocking. It is one of the oldest and reliable methods of joining [1]. Welding involves more sciences and variables than any other industrial process. The principal processes involved in welding are physics, chemistry and metallurgy [2]. Welding process is different from the brazing process through which only the used filler metal melts [3].

While joining by the brazing process is binding metals together by using a nonferrous filler metal with a melt (liquids) at a temperature higher than 450℃ (840°F). As the filler material is liquid at less than 450°C, this joining process tends to be regarded as a soldering instead of brazing [3]. Soldering is not suitable for high temperature applications [4]. Prior to choose a proper welding technique, many factors must be considered, like the base metals composition, filler metals (if utilized), thickness, welding position, and the conditions of service [4].

The distinctive joining processes without fusion of base metals are diffusion bonding, soldering, brazing and friction welding [5]. During the process of the joining, all these methods show fewer difficulties than the fusion welding due to the fact that the base material stays in the solid condition and controls the

intermetallic compound layer thickness at the interface at lower temperatures and in a short time [4, 6].

Brazing is defined by the American Welding Society (AWS) as a group of joining processes that produce the coalescence of materials by heating them to the brazing temperature in the presence of a brazing filler metal that has a liquidus temperature above 840ºF (450ºC) and below the solidus temperature of the base materials. The brazing filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action. The term brazing temperature refers to the temperature, to which a material is heated to enable the brazing filler metal to spread and adhere to, or wet, the base metal and form a brazed joint [7]. If the following three essential requirements have met, the filler metals can adequately wet the surfaces of base materials [8, 9]:

1. The filler can be alloyed by base material.

2. Uncontaminated base material surfaces and oxide free by cleaning.

3. Both the base material and the filler reach working temperature.

It is easy to join assemblies that combine ferrous to nonferrous metals [10], as well as ceramic-metal joining can be obtained by either direct or indirect brazing depending on the ceramic surfaces and the type of the filler [11].

Brazing induces less thermal distortion than fusion welding because the whole component can bring up the same temperature of brazing, thus avoiding the type of the localized heating that can result in a distortion in the welding process. However, brazing does not involve any melting of the base metals and has several advantages over other welding processes [10].

1.2 Joining of Cast Iron

Cast iron is one of the extensively used materials in many structural applications including machines and automobile sector, due to its excellent properties of wear resistance [12, 13]. The effective utilization of materials can be enhanced by its abilities of being processed easily by available manufacturing processes. The joining of cast iron by conventional welding processes is very complex, difficult and problematic; due to the presence of high carbon content. The crack formation due to rapid cooling and change in phases owing to the formation of hard carbides is commonly reported in conventional welding of cast iron. It requires extensive precautions like pre and post heat treatment processing, optimal welding speeds, proper gaps in welding, etc. To reduce the size of heat affected zone (HAZ), a lot of methods are used which mainly involves reduction of heat input at the weld zone, use of lower diameter electrodes, use of low melting point welding rods and use of lower preheat temperatures [14].

1.3 Applications of Cast Iron Joints

The assemblies shown in Figure (1.1) [15]:

(a) Two pieces of cast iron cut from an automotive engine block and one piece of 1010 carbon steel that was to be brazed between the two castings any free carbon on the surface of the cast iron.
(b) Show a tripod section made of steel tubing brazed to a cast iron base.
(c) Show a steel sprocket brazed to a cast iron hub.
(d) Show several diesel engine subassemblies made of cast iron fittings brazed to steel tubing.
(e) Show an assembly of steel tubes brazed to a malleable iron header.

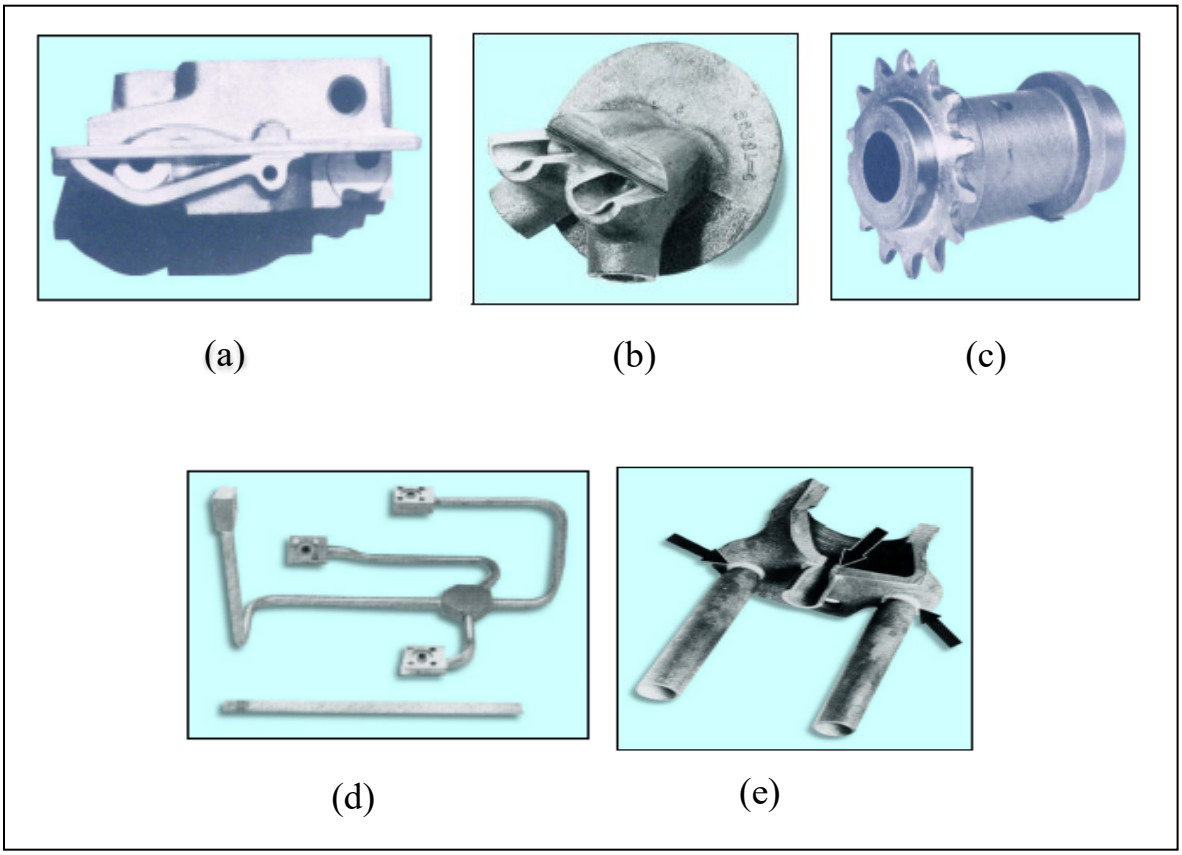


Figure (1.1): Applications of cast iron joints [15]

1.4 The Aim of this Study

1. The main goal of this study is to solve the problem of cast iron welding, in industrial facilities where the bodies of machines are damaged due to mechanical stress or cracks. The bodies of these machines are often made of cast iron, and the process of repairing them is difficult and expensive with traditional welding methods or mechanical method. As a result, the brazing method may be used to solve this problem.

2. Assess the optimum brazing conditions of two metals produce an excellent brazing joint. The following subjects will be applied:

- Study the interfacial joining between ductile cast iron, grey cast iron and two types of filler metals Ag20 and BAg-8 developing microstructures by EDS, SEM, and OM between the cast irons and brazing alloy.
- Comparing the failure value of joints resulted from different fillers.
- Investigating the characterization of the brazing alloy for two types of filler.

Chapter Two

Theoretical Part and Literature Review

2.1 Brazing

When stronger joints are required than are obtainable by soft soldering, brazing is used by which, with suitable joint design, is usually possible to form joints which are as a strong or stronger than the basis materials. Brazed joints are neat, and the comparative uniformity of heating and cooling involved in their formation results in a minimum of residual stress and distortion [13, 16]. Brazing involves a limited dissolution or plastic deformation of the base metal [17].

2.2 Brazing Principals

Brazing of metal or non-metal parts are brazed using filler metal, which is fused and distributed via the capillary action between the intimated surfaces of the metal parts to be joined. Only the filler metal melts, while the base metal doesn't. The filler metal melting temperature (T_m) must exceed 450℃. At the same time, the (T_m) of filler should be below the (T_m) of base metal [18, 19].

2.2.1 Mechanism of Brazing

Brazing proceeds through four distinct steps [10]:

1. The assembly or the region of the parts to be joined is heated to a temperature of at least 450 °C (840 °F).

2. The assembled parts and brazing filler metal reach a temperature high enough to melt the filler metal but not the parts.

3. The molten filler metal, held in the joint by surface tension, spreads into the joint and wets the base metal surfaces.

4. The parts are cooled to solidify, or “freeze,” the filler metal, which is held in the joint by capillary attraction and anchors the parts together by metallurgical reaction and atomic bonding.

2.2.1.1 Wetting

It can be defined as the filler metal distribution above the joining work-piece surface. A liquid that has the ability to wet the solid surface, if it is a film, rejects to flow away and if it is a force like gravity makes the liquid bulk flowing off the solid surface, and then lower brazing temperatures. Another factor to be regarded is the filler metal ability to moisten the base material [8, 20].

It is realized that this case accrue only when a mutual attraction exists among the solid and liquid molecules. Such attraction is not significantly owing to the chemical bonds, but certain chemical affinity must present. For instant, clean water does not moisten the paraffin wax, but it can cling to it by the wetting agent interposition such as soap. That is due to the molecules of soap possesses an attraction for water and, simultaneously, an affinity for hydrocarbons. However, recent wetting detergents or agents work in the similar way [21].

The factors that are important when determining the extent of wetting can be illustrated by the familiar problem of a liquid droplet in contact with a flat solid surface. In the ideal case in which no chemical reactions occur between the solid, liquid, and vapor phases and gravitational forces can be ignored (e.g., for relatively small droplets), the liquid droplet assumes an equilibrium configuration dictated by surface free energy considerations. The shape of the liquid droplet is uniquely

characterized by θ and its contact angle with the solid is shown in Figure (2.1) [15].

The relationship between the contact angle and the surface free energies at the liquid-vapor, solid-vapor, and the solid-liquid interfaces is expressed as follows [16]:

$\cos\theta = (\gamma_{SV} - \gamma_{SL})/\gamma_{LV}$ ………………………………….. (2.1)

Where

θ = Contact angle degrees, γ_{SV} = Solid-vapor interface, γ_{SL} = Solid-liquid interface, and γ_{LV} = Liquid-vapor interface.

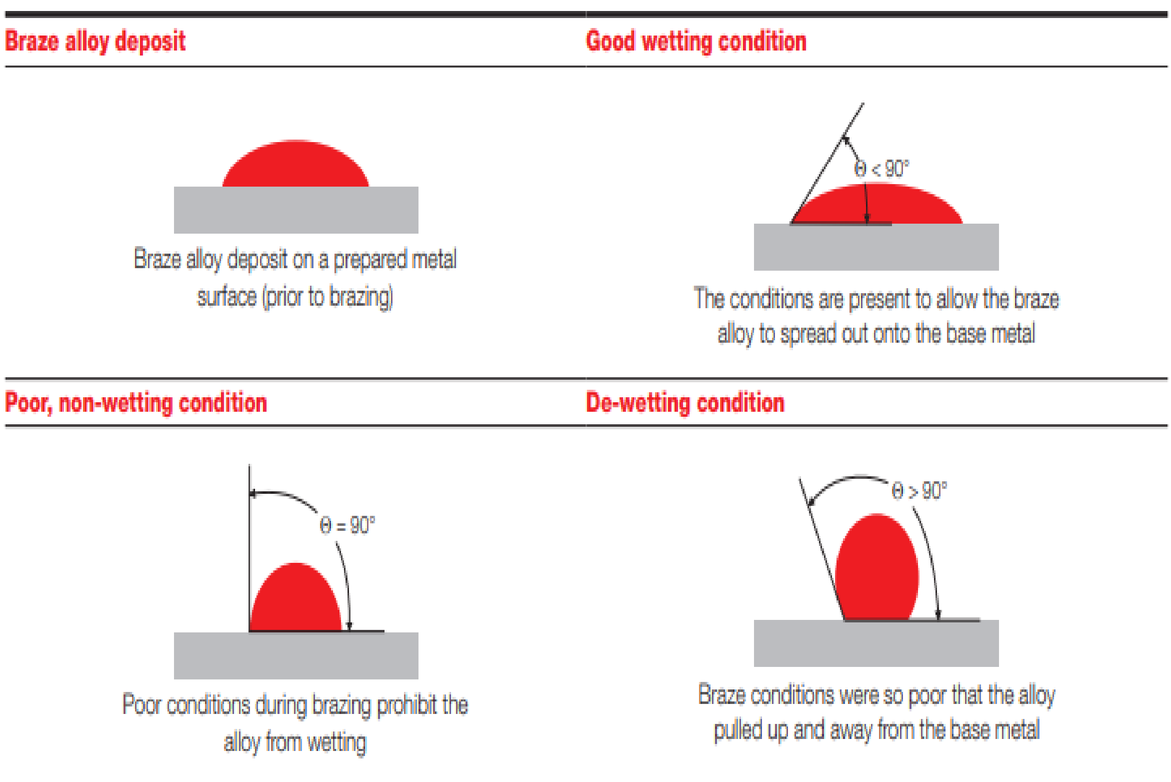


Figure (2.1): The drops distribution of various liquids with different wetting characteristics [22].

The boundary between wetting and nonwetting conditions is generally taken to be $\theta = 90^{o}$. For $\theta < 90^{o}$, wetting occurs, while $\theta > 90^{o}$ represents a condition of nonwetting [15].

The term spreading is defined as the condition in which the liquid completely covers the solid surfaces. This condition occurs when θ approaches the value of 0^{o}. For most brazing systems, the optimum value of θ is in the range of 10^{o} to 45^{o}. This is determined by joint clearance or thickness—a small contact area for very thin joints [15].

2.2.1.2 Capillary action (Capillary flow)

As illustrated in Figures (2.2) and (2.3), the capillary flow of a molten brazing alloy depends on its capacity to moisten the base materials. It was also acquired through studying the interaction between the liquid and solid phases [23].

It is obvious that the best soaking degree and molten filler metal distribution result from an angle of contact with a smaller magnitude. However, it should be emphasized that if the angle of contact is less than 90°, capillary flow is still feasible [4, 20]. The wetting angle measurement permits first to obtain the ability of materials for brazing and then to predict the brazed joints characteristics [10, 24].

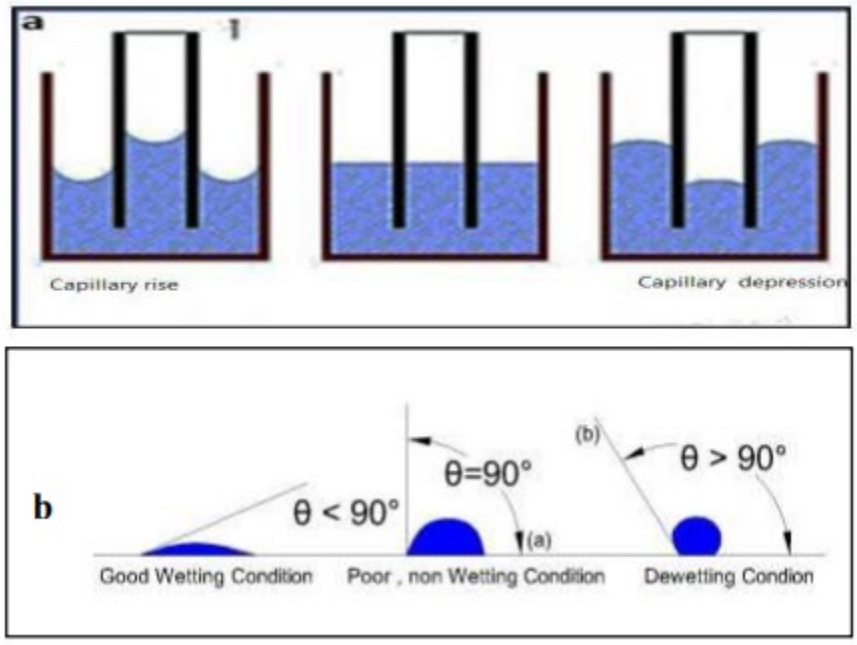


Figure (2.2): (a) the corresponding behavior of liquids in vertical capillaries: (b) the drops distribution of three various liquids with different wetting characteristics [10, 24].

The difference in velocity (V) between the horizontal and parallel surfaces is the flow average velocity and is represented mathematically as follows [25]:

$V = (d\Upsilon\ l/v)/(6\eta\ s)\cos\theta$…..…. (2.2)

ΥL/V stands for the liquid surface's free energy in balance with the liquid vapor.

θ is the angle of contact is a radian or degree.

η is the viscosity of the molten alloy is given as N/m^2. S

S represents how far the filler metal has migrated (m).

The filler metal's time (t) requirement for covering the distances is indicated as [16]:

$t = (3s)/(dg\cos\theta)$ ……..……..…. (2.3)

The same relations can be applied to the capillary paths that are either at right angles or inclined to the horizontal level. For these states, a peak height, H, will exist, and the melted filler shall rise to it. That is provided by using the following expression [16, 26]:

$H = 2\gamma \cos\theta / d\rho g$ ……. (2.4)

Where,

d = The dimension of joint gap (m).

g = The acceleration due to gravity (m/s^2)

ρ = density of filler metal (kg/m^3)

It is proposed that the composition and surface energies of liquids and solids are constant. However, the interactions take place if [27, 28]:

1. The alloy is sandwiched between the liquid and the base metal.

2. The filler is where the base substance diffuses.

3- Within the grains of the base metal, the filler metal diffuses.

4-The filler is penetrated along the grain's edge.

5- The components of the intermetallic are created.

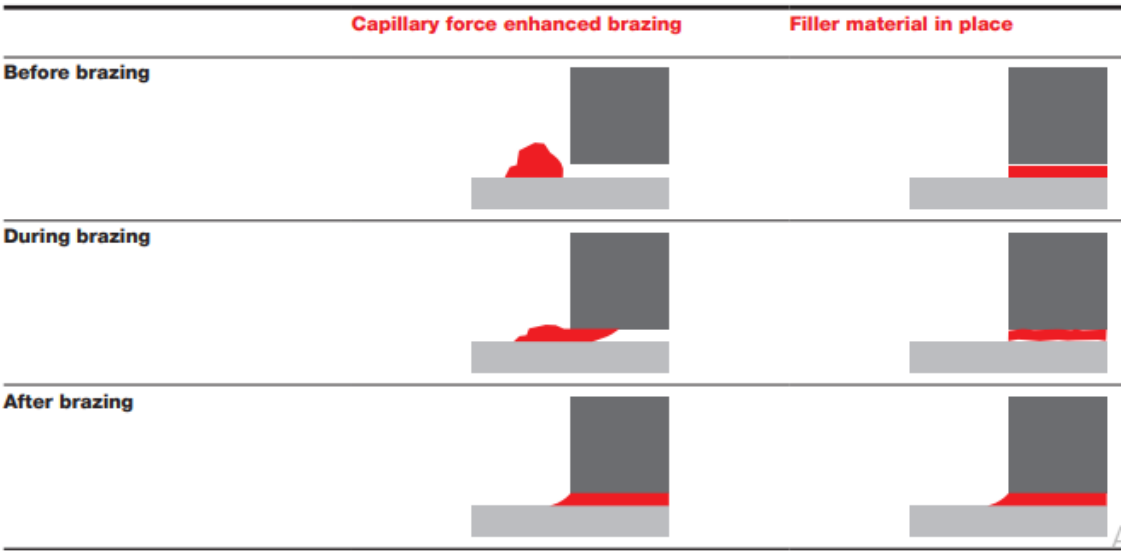


Figure (2.3): The capillary flow of a molten brazing alloy [22].

2.2.1.3 The Diffusion Process

The coalescence of materials by heating the components to the right temperatures and using liquid metallic filler, this technique coalesces the materials. Through the capillary attraction, this filler can disperse. Additionally, this filler diffuses into the base material to the point where the joint characteristics converge on the qualities of the base material. Additionally, the pressure may or may not be applied [3].

In a proper brazing procedure, the thin layer surface of the base material is partially alloyed by brazing the filler metal. Diffusion is the name given to the metal atoms' migration, which is important for such activities. As shown in Figure (2.4), the diffusion regions are also known as the development of the transformation regions. The constituents of the filler metal are obtained in the base materials that are called diffusion zone in parent material (DP); the base material components can be found in the layer of the filler metal that are called diffusion zone in filler metal (DF) [29].

The creation of the diffusion zone affects the consistency of the brazed joint. In order to form such regions, the metal atoms of the base material's metal structure must be altered to accommodate the brazing alloy atoms. Obviously, not all metal atoms have the same capacities for meeting these demands for solid solution growth. Atoms of the smallest size should be introduced, with the option of slowing down their movement capacity for larger variations in atomic fields. The filler metal must reach the liquid phase within 5 to 10 seconds to guarantee the development of a sufficient depth of the diffusion area and the fulfillment of the ideal consistency [30].

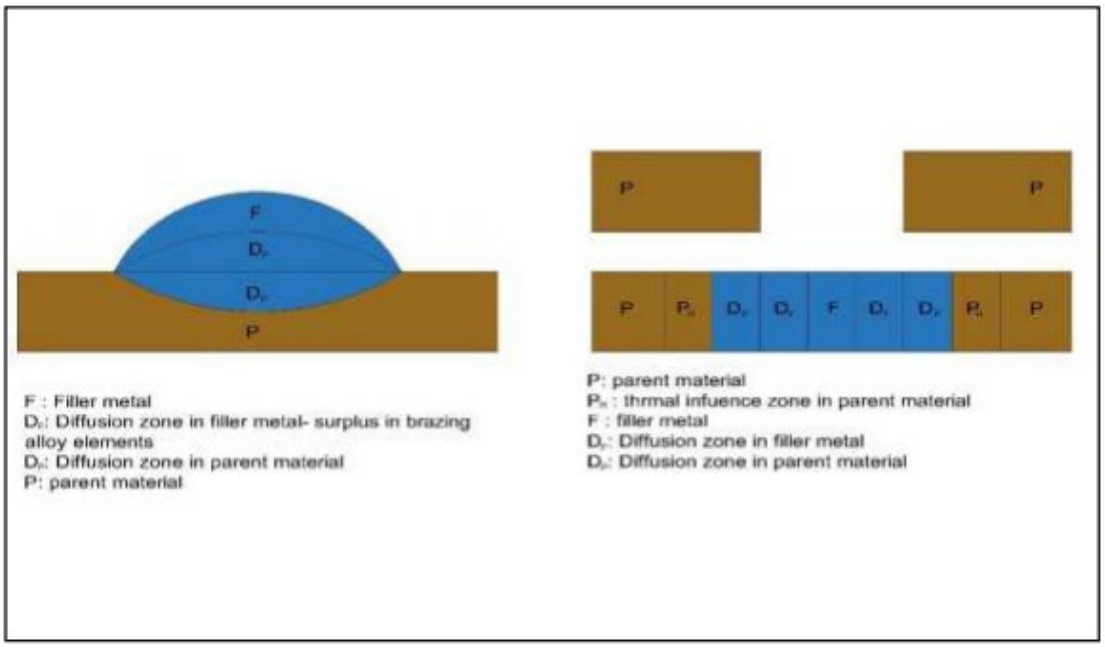


Figure (2.4): The diffusion zone [31].

2.2.2 Advantages of Brazing

Brazing can be applied which is desirable for several advantages over other joining processes [10, 16]:

• Little operator skill is required.

• Many joints can be produced in one operation with automatic techniques.

•Where a flux-free brazing technique has been used surface treatment can subsequently be applied to components without prior cleaning.

•A combined brazing and heat treatment can be carried out.

•Most metals and combination of metals can be brazed.

• Ability to join cast materials to wrought metals.

• Ability to join nonmetals to metals.

• Ability to join metal thicknesses that vary widely in size.

• Ability to join dissimilar metals.

• Ability to join porous metal components.

• Ability to join fiber- and dispersion-strengthened composites.

• Capability for precision production tolerance.

• Reproducible and reliable quality-control.

For these reasons, brazing is often preferred to welding for joining components where large areas of joint are not involved—large joint areas are difficult to fill with braze metal [16].

2.2.3 Limitations of Brazing

The main disadvantages of brazing are that joint designs must be used which provide for capillary attraction, and the combination of different materials gives potential susceptibility to corrosion, but with careful choice of materials these are not major problems [16].

The brazed joint is not a homogenous material, but it is heterogenous, consists of various phases having various chemical and physical characteristics. composition can vary, therefore, the chemical and physical properties of the boundary region that formed at the filler-base metal interface and frequently of the whole joint. In the two different materials, a complicated transition, or even a completely different zone, must be considered [10].

2.3. Elements of the Brazing Process

The following factors must be carefully and intelligently evaluated in order to generate satisfactory brazed joints [10, 32, and 33]:

- Filler-metal flow
- Base-metal characteristics
- Filler-metal characteristics
- Surface preparation
- Joint design and clearance
- Temperature and time
- Rate and source of heating

2.3.1 Filler-Metal Flow

Wetting is only one important facet of the brazing process. If the molten filler metal does not flow into the joint, the effectiveness of the filler metal is greatly restricted. Flow is facilitated by capillary attraction, which in turn results from surface-energy affects [34, 35]. Flow is the property of a filler metal that

determines the distance it will travel away from its original position due to the action of capillary forces [10].

2.3.2 Base-Metal Characteristics

The base metal has a prime effect on the joint strength. A high-strength base metal produces joints of greater strength than those made with softer base metals (other factors being equal). When hardenable metals are brazed, joint strength becomes less predictable. This is because there are more complex metallurgical reactions involved between hardenable base metals and the filler metals. These reactions can cause changes in the base-metal hardenability and can create residual stresses [36]. There are several metallurgical phenomena that influence the behavior of brazed joints and, in some instances, necessitate special procedures. Included among these base-metal effects are (a) alloying, (b) carbide precipitation,(c) stress cracking, (d) hydrogen, sulfur, and phosphorus embrittlement, and (e) oxide stability [10].

2.3.3 Filler-Metal Characteristics

Brazing can provide strong joints with almost any good commercial filler metal if brazing methods and joint design are selected and applied correctly, the main characteristics are: melting range, composition, fluidity and wettability [10].

2.3.4 Surface Preparation

A clean and nearly oxide-free surface is imperative to ensure uniform quality and sound brazed joints. A sound joint may be obtained more readily if all grease, oil, wax, dirt, and nearly all oxides have been carefully removed from the base and filler metals before brazing [10].

2.3.5 Joint Design and Clearance

There are many different types of brazed joints, and the process of selecting the type of joint depends on the amount of force required as well as other service requirements including appearance, pressure-tightness, and electrical conductivity. The gap or fit up between base metal faces that is required for joining is preferred to be as little as possible. The filler material is forced into the gap by the capillary effect in this way because the smaller clearance results in better capillary performance. The clearance with a close fit provides a stiff, sound, and sturdy joint [37].

2.3.6 Temperature and Time

The temperature of the filler metal naturally has an important effect on the wetting action, because the wetting and alloying action improves as the temperature increases. Of course, the temperature must be above the melting point of the filler metal and below the melting point of the base metal. Within this range, a temperature generally is selected that gives the best filler-metal wetting and flow. The brazing time has an impact on the wetting operation, in particular, with regard to the full distance of filler [10].

2.3.7 Heating Source and Rate

The size and value of individual assemblies, the quantity needed, the rate of production, the rate of heating, the differential thermal gradients, and the rate of cooling must all be taken into account before choosing the heating technology (furnace, microwave, flame, induction, etc.). Dimensional stability, distortion, and metallurgical structure are all impacted by these considerations [10].

2.4 The Brazing Technique

Brazing process can be divided by means of the technique employed to heat the assembly. Several heating techniques can be utilized for producing the brazed joint. Selecting the technique to be employed depends on the kind of the available brazing equipment, the operator skill, the labor and materials relative costs, and the brazed parts state. Brazing of the base materials and certain filler metals can only be achieved through one of the following heating techniques [2, 9].

2.4.1 Torch Brazing

The production of satisfactory joints by torch brazing needs skill on the part of the brazing operator. Generally, a slight reduction flame is favored. The adjustment of the oxyacetylene flame is relatively simple and may be maintained by observing the characteristics of the flame. The flame outer enveloped, but not the internal cone, must be subjected to the work [2].

2.4.2 Induction Brazing

In the induction brazing heating process, the components that require brazing are positioned in a magnetic field of a coil that is cooled by water and carries a current with a high frequency. The eddy currents are generated within any conducting body located in coil. The induced currents move in the body surface skin, and are focused on the field nearest to the coil. The selection of the induction brazing over the other methods is usually based on the assumption that it has a distinct advantage to heat only a local area of the part immediately adjacent to the joint [2].

2.4.3 Dip Brazing

The bath of this technique requires not only a suitable container, ceramic or metal, for flux, but also a procedure for heating the flux to keep it as fluid. Dip brazing in a molten metal is always restricted to braze small assemblies, like metal strips or wire connections. Normally, a graphite crucible is heated from outside to the desired temperature in order to keep the filler in fluid state [2, 9].

2.4.4 Microwave Brazing

Microwave heating is a new approach to produce brazed joints. Microwaves provide an effective method of raising the assembly temperature. They are efficient and use less power than processes such as furnaces. Microwave brazing is a versatile heat source whose joint properties are found to be comparable to more established methods. Metals reflect microwaves due to high dielectric loss factors. The process requires a susceptor that will absorb microwaves. Typically, the process uses a material such as silicon carbide. The microwave energy is converted into heat and transferred to the assembly by radiation [15].

2.4.5 Vacuum Furnace Brazing

In this process, the furnace has electrical heating elements surrounding the working load, and heats the filler to the liquidus case in order that the flow as well as the capillary action is conducted. For conducting the brazing process of materials susceptible to the oxide formation at the elevated temperature, a vacuum system has to be used to remove the oxygen. Ceramic, cobalt, nickel, titanium and copper based filler materials are adequately brazed in vacuum [2, 9].

2.4.6 Furnace Brazing

Furnace brazing was first commercialized in about 1930. The essential automotive nature of this process and its use by unskilled labor accounted for its popularity. This process is not restricted to any base metal, nor is to any brazing filler metal, but is governed by a combination of various factors, such as equipment design joint, filler metal and fluxes [2, 9].

2.4.6.1 Advantages of Furnace Brazing

1. The process has the ability to produce large quantities of assemblies at lower unit cost on either a batch or a continuous basis.

2. It can replace another brazing process to increase the production rate.

3. At all stages of the brazing cycle, it provides a close temperature control and uniformity, including cooling. Furnace brazing can provide atmospheric protection through both heating and cooling and provide different protective atmospheres in different chambers of the furnace.

4. In a single operation, multi joints can be brazed on the same assembly.

5. The brazed assemblies that leave the furnace chamber are clean, bright, and require no cleaning with atmospheric protection [2, 38].

2.5 Brazing Filler Metals

A very wide range of metals and alloys can be brazed with suitable filler metals. Although these filler metals cover a wide range of compositions, they have certain common characteristics. These are [7]:

(a) A melting range below that of the base components.

(b) A stable and homogeneous composition.

(c) Fluidity, to enable the filler to flow into the joint.

(d) Wettability, to form a strong metallurgical bond.

(e) Suitable mechanical and physical properties.

(f) A composition free from toxic or excessively volatile constituents.

2.5.1. Brazing Filler Metal– Base Metal Interaction

For the brazed joint to be sound, brazing should occur without undesirable diffusion into the base metal, dilution with the base metal, erosion of the base metal or the formation of brittle compounds. The factors influencing the extent of these interactions include the following [15]:

(a) Mutual solubility between the brazing filler metal and the base metal.

(b) Amount of brazing filler metal present.

(c) Temperature to which the brazement is exposed.

(d) Time of the brazing cycle.

(e) Joint geometry (e.g., thick components versus very thin components, long joints versus short joints).

2.5.2 Forms of Brazing Filler Metal

The form of brazing filler metal required for a particular application affects the selection of the filler metal. Some brazing filler metals are available in a limited number of forms, while others are available in all forms. One way to distinguish between forms is to classify them as those that are added after the joint which has

been heated and those that are preplaced before heating. Available forms include rod, wire, strip, preforms, powders, paste, tape, and flux coated forms [15].

2.6. Base Metal

2.6.1. Cast Iron

Cast irons are iron-carbon-silicon alloys, typically containing 2–4% C and 0.5–3% Si, that pass through the eutectic reaction during solidification shown in Figure (2.5). The microstructures of the five important types of cast irons are shown schematically in Figure (2.6) [39].

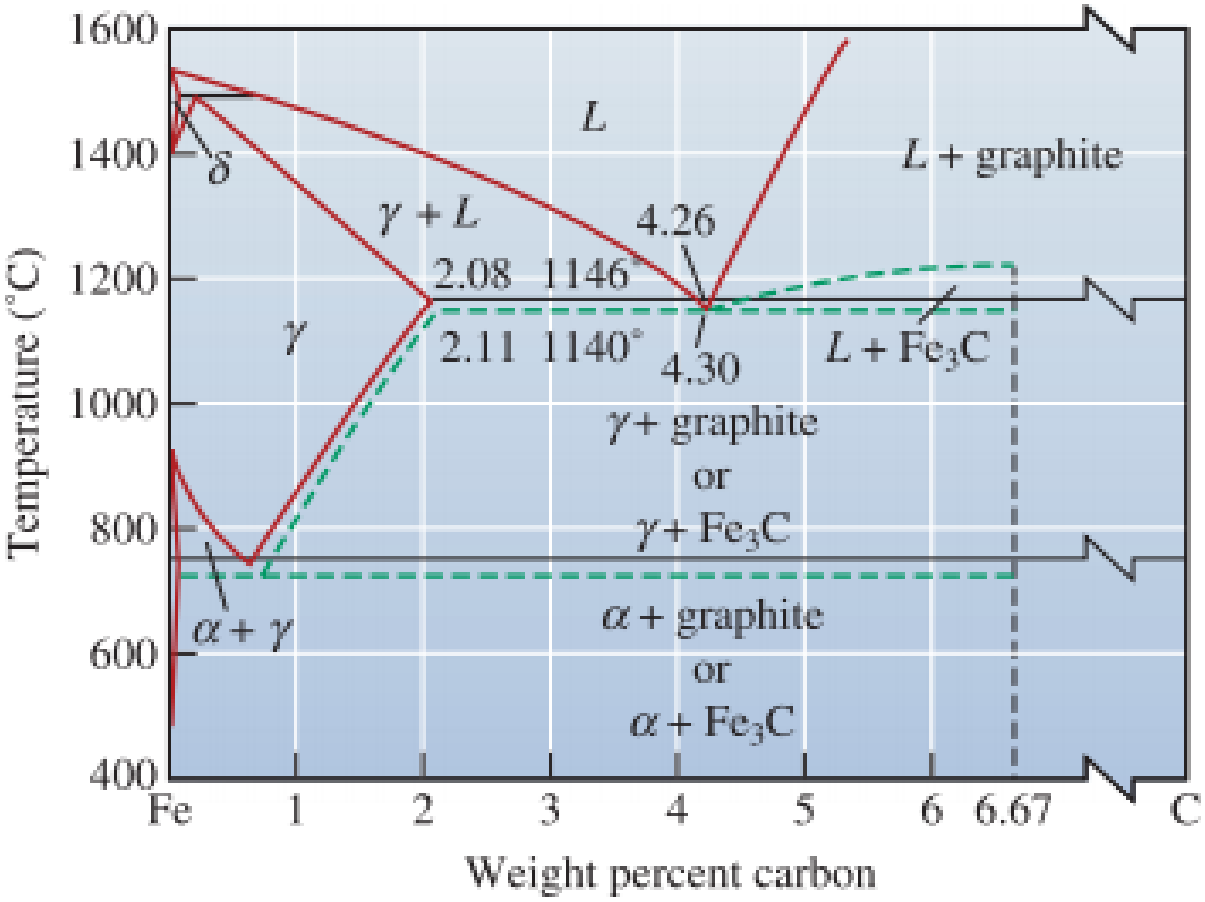


Figure (2.5): The Iron-Carbon phase diagram showing the relationship between the stable Iron-Graphite equilibria (solid lines) and the metastable Iron-Cementite reactions (dashed lines) [39].

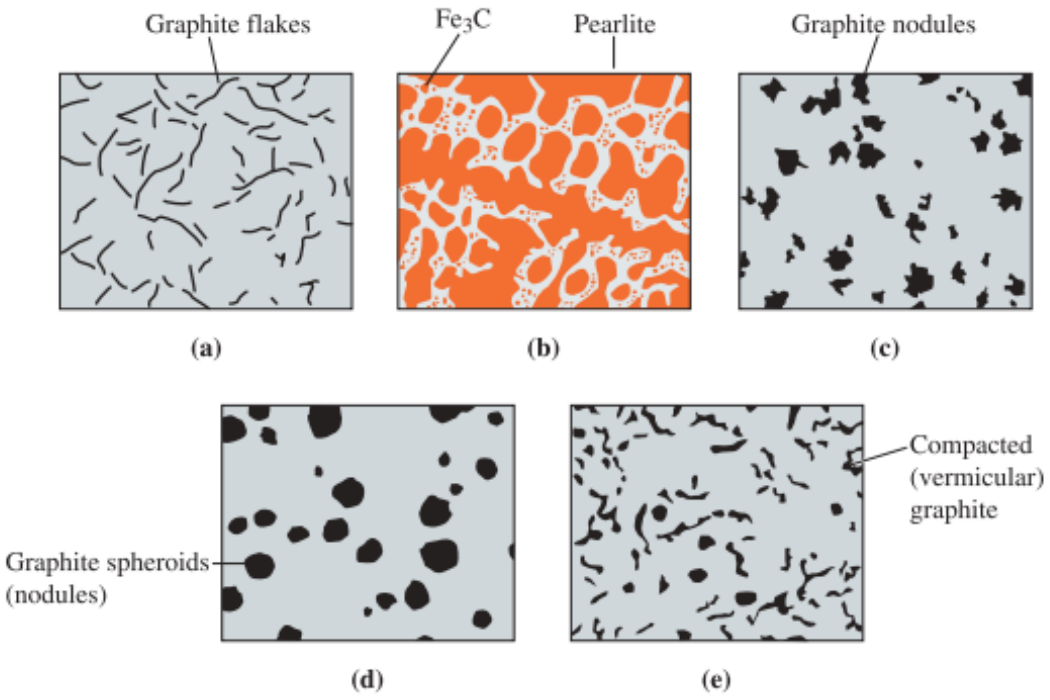


Figure (2.6): Schematic drawings of the microstructure of five types of cast iron: (a) gray iron, (b) white iron, (c) malleable iron, (d) ductile iron, and (e) compacted graphite iron [39].

2.6.1.1 Grey Cast Iron

Contains small, interconnected graphite flakes that cause low strength and ductility. This is the most widely used cast iron and is named for the dull gray color of the fractured surface. Grey cast iron contains many clusters, or eutectic cells of interconnected graphite flakes as shown in Figure (2.6). Grey iron has a number of attractive properties, including high compressive strength, good machinability, good resistance to sliding wear, good resistance to thermal fatigue, good thermal conductivity, and good vibration damping [39].

2.6.1.2 White Cast Iron

White cast iron is a hard, brittle alloy containing massive amounts of Fe_3C. A fractured surface of this material appears white, hence the name. A group of highly

alloyed white irons are used for their hardness and resistance to abrasive wear. Elements such as chromium, nickel, and molybdenum are added so that, in addition to the alloy carbides formed during solidification, martensite can be formed during subsequent heat treatment [39].

2.6.1.3 Malleable Grey Cast Irons — Graphitisation of White Cast Irons

White cast irons can be made ductile by prolonged annealing. The process is termed malleablising. Two phenomena can be concerned. One consists of surface decarburising to decrease the amount of cementite. The product is then termed white heart malleable cast iron because of the steely white appearance of the core fracture surface. The second involves the transformation of the cementite to nodular graphite and leads to blackheart malleable cast iron. This is achieved by treatment for several hours at about 1000^{o}C. The technique has been known for a very long time and the conditions were first described publicly by Reaumur at the end of the 18th century. The cementite decomposes and the carbon liberated forms rosette-shaped graphite nodules, sometimes called temper carbon. They have a ragged, non-compact morphology, unlike the nodules in spheroidal graphite (SG) irons. The matrix becomes ferritic, and the white cast iron is converted to a perfectly ductile grey cast iron [40].

2.6.1.4 Ductile Cast Iron

Ductile or nodular cast iron contains spheroidal graphite particles. Ductile iron is produced by treating liquid iron with a carbon equivalent of near 4.3% with magnesium, which causes spheroidal graphite (called nodules) to grow during solidification, rather than during a lengthy heat treatment. Several steps are required to produce this iron. These include desulfurization, nodulizing, and inoculation. In desulfurization, any sulfur and oxygen in the liquid metal is

removed by adding desulfurizing agents such as calcium oxide (CaO). In nodulizing, Mg is added, usually in a dilute form such as a MgFeSi alloy. If pure Mg is added, the nodulizing reaction is very violent, since the boiling point of Mg is much lower than the temperature of the liquid iron, and most of the Mg will be lost. A residual of about 0.03% Mg must be in the liquid iron after treatment in order for spheroidal graphite to grow. Finally, inoculation with FeSi compounds to cause heterogeneous nucleation of the graphite is essential; if inoculation is not effective, white iron will form instead of ductile iron. The nodulized and inoculated iron must then be poured into molds within a few minutes to avoid fading. Fading occurs by the gradual, nonviolent loss of Mg due to vaporization and>or reaction with oxygen, resulting in flake or compacted graphite instead of spheroidal graphite. In addition, the inoculant effect will also fade, resulting in white iron. Compared with gray iron, ductile cast iron has excellent strength and ductility. Due to the higher silicon content (typically around 2.4%) in ductile irons compared with 1.5% Si in malleable irons, the ductile irons are stronger but not as tough as malleable irons [39].

Ductile cast iron (DCI) possesses much of the strength and ductility of steel. In ductile iron, the graphite is converted into spheroids that minimize the notch effect and thereby produce a product combining the strength and ductility of cast steel with the low cost, wear resistance, and damping characteristics of cast iron [41].

2.6.1.5 Compacted Graphite Cast Iron

Compacted graphite cast iron contains rounded but interconnected graphite also produced during solidification. The graphite shape in compacted graphite cast iron is intermediate between flakes and spheres with numerous rounded rods of graphite that are interconnected to the nucleus of the eutectic cell. This compacted graphite,

sometimes called vermicular graphite, also forms when ductile iron fades. The compacted graphite permits strengths and ductilities that exceed those of gray cast iron, but allows the iron to retain good thermal conductivity and vibration damping properties. The treatment for the compacted graphite iron is similar to that for ductile iron; however, only about 0.015% Mg is introduced during nodulizing. A small amount of titanium (Ti) is added to ensure the formation of the compacted graphite [39].

2.6.2 Brazing of Cast Iron

The processes used for the brazing of cast irons are the same as those used for the brazing of steel: furnace, torch, induction, and dip brazing. Like for other metals, the selection of a brazing process for cast iron largely depends on the size and shape of the assembly, the quantity of assemblies to be brazed, and the equipment available. Many applications require that grey, malleable, and ductile cast irons be brazed either to themselves or to other metals. White cast irons are seldom brazed. The brazing of grey, ductile, and malleable cast irons differs from the brazing of steel in two principal respects. First, a special precleaning method is necessary to remove graphite from the surface of the iron. Second, the brazing temperature should be kept as low as feasible to avoid a reduction in the hardness and strength of the iron [15].

2.7. Joint Design (Types of Joints)

There are basically only two types of brazed joints: butt and lap. All other joints are really only modifications of these two basic types. Common types of brazed joints are shown in Figure (2.7).

Butt joint is used where the lap joint thicknesses are undesirable as well as where the brazed joint strength will adequately satisfy the service needs [10].

The lap joint bonding area can be made bigger than that of a butt joint. Indeed, the area of overlapping may vary so the joint becomes as vigorous as the feebler part, even if a less strength filler metal is utilized or when small defects are present in the final braze.

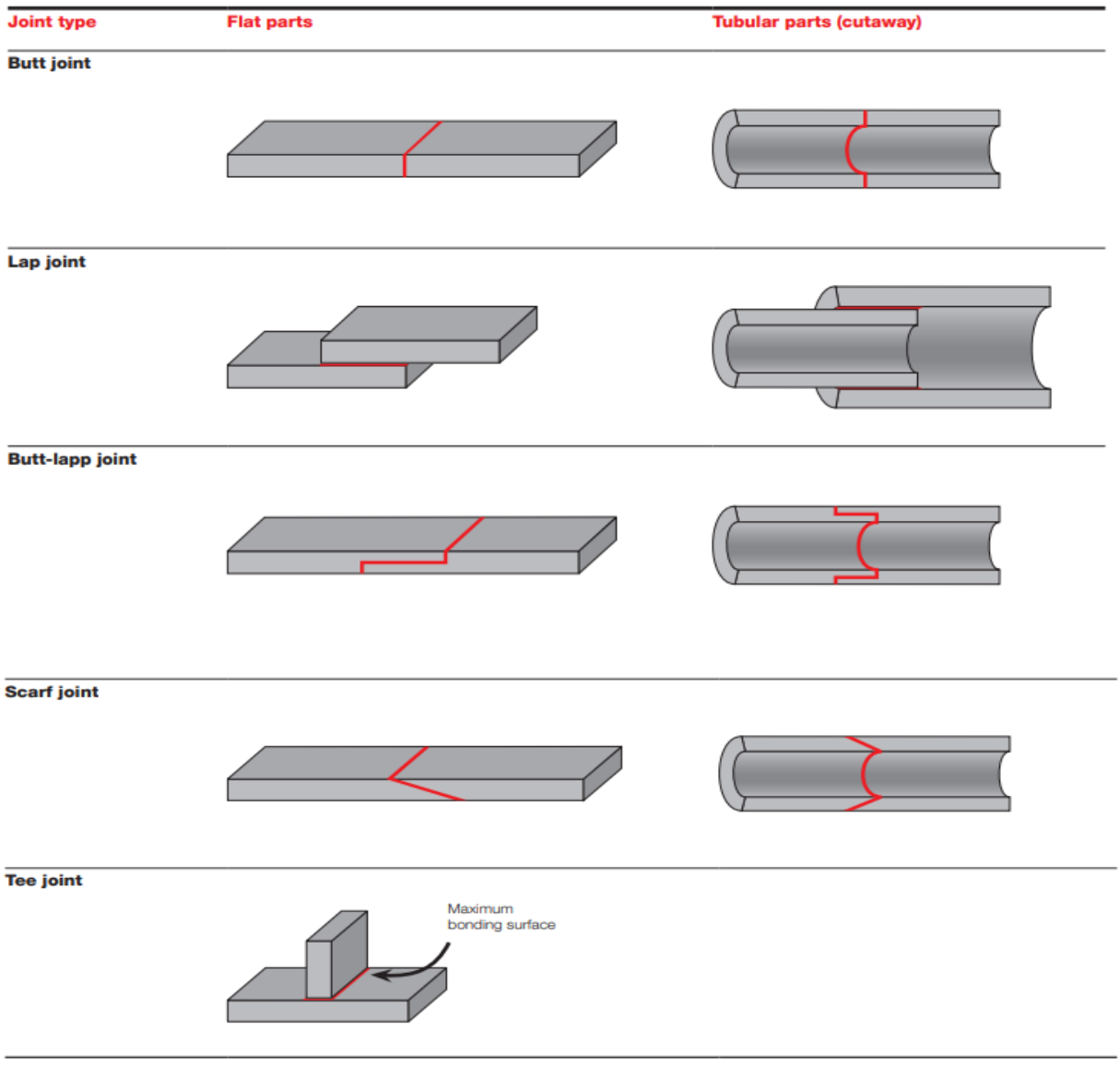


Figure (2.7): Design of joint [22].

For accurate finding of the lap length for maximum strength, one can use one of these formulas [2]:

See Figure (2.8)

Flat L = F (T * t / S)…… (2.5)

Tubular L = F [T * t (D-t) / S]……. (2.6)

Where, L is the lap length (mm).

Joint Flat Tubular Butt Lap ButtLap Scarf

F is the safety factor.

T is the tensile strength of thinner member (MPa).

t is the thinner member wall thickness (mm).

S is the filler shear strength (MPa).

D is the lap diameter (mm).

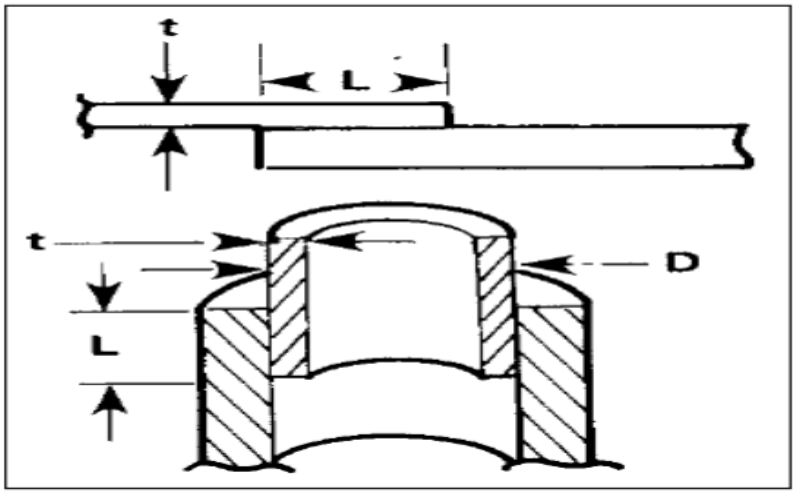


Figure (2.8): Flat and tubular lap joints [10].

2.8 Brazing Alloy

Brazing filler metal has been defined via (AWS) as an added metal in the brazing operation. The filler metals for brazing are nonferrous metals or alloys which possess higher melting points than 450℃ but lower than for brazed base metals. Formerly, these metals were referred to brazing alloys, but these terms are being replaced by more clearly defined terms for brazing filler metals [10]. For an adequate utilization as a filler metal for brazing, either the metal or the alloy should possess these properties [45]:

1. Capability for wetting the base metals on which it is used to make a strong and sound bound.

2. Proper temperature of melting and flow properties that allow the spread in the suitably made joints via the capillary attraction.

3. Composition having the enough uniformity and stability to reduce the separation via the liquidation at brazing states to be met and free of excessively volatile constituents.

4. Desirable mechanical and physical properties in the joint, such as strength, ductility, etc.

2.8.1 Siver-Copper

Figure (2.9) is the equilibrium diagram for the silver-copper binary system. The solidus temperature line, ADCEB, represents the start of melting for all alloy combinations of silver and copper in the system. The liquidus temperature line, ACB, represents the temperatures above which each of these alloys in the system is completely liquid. At point C the liquidus and solidus temperature lines meet, indicating that a particular alloy melts at a constant temperature instead of melting

over a range of temperatures. This temperature is known as the eutectic temperature and the alloy, in this case, 72% silver and 28% copper, is known as the eutectic composition. This alloy is essentially as fluid as a pure metal [43].

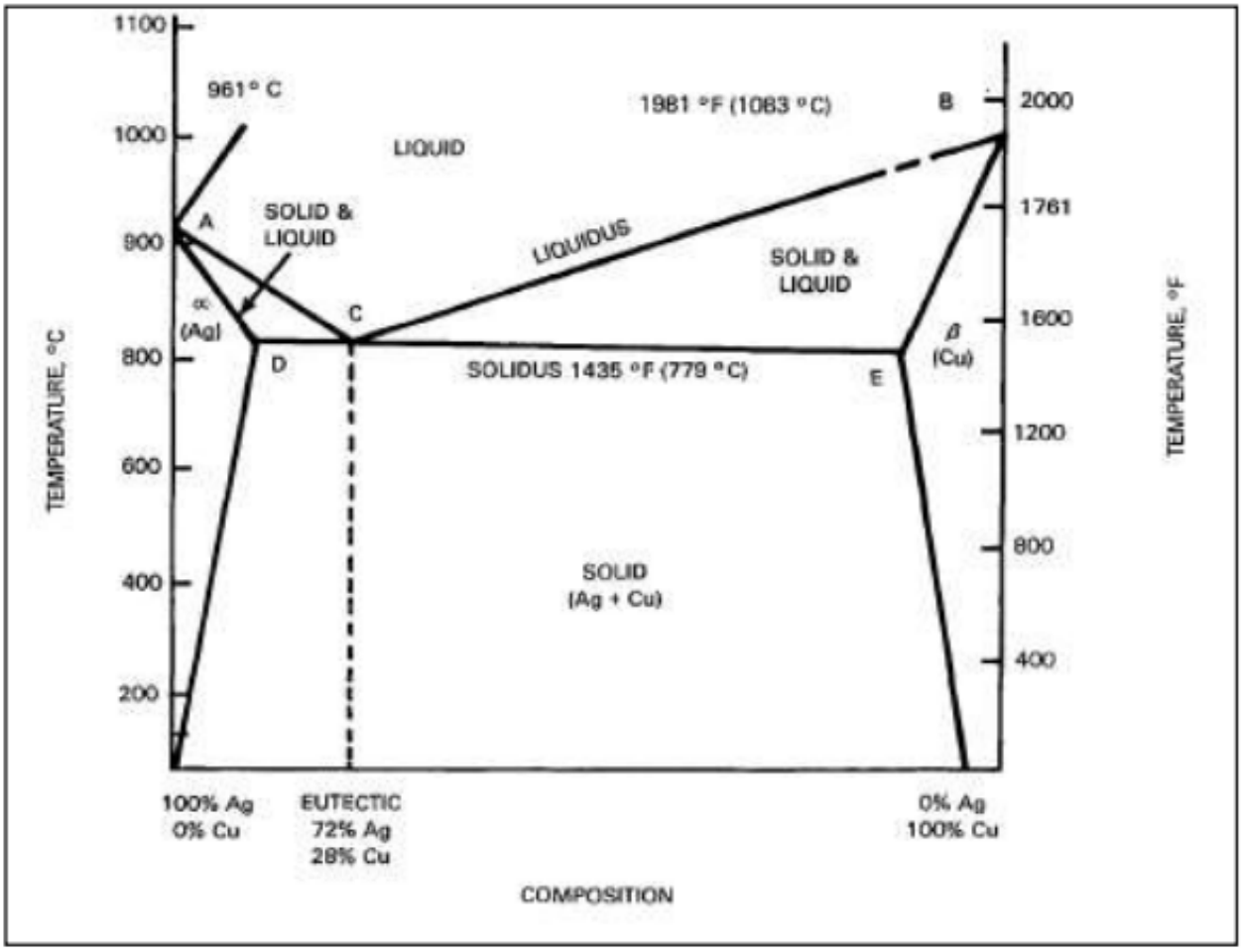


Figure (2.9): Equilibrium diagram for the silver-copper binary system [43].

2.8.2 Silver Base Filler Metals

The silver base brazing filler metals are used for joining most ferrous and nonferrous metals, with all methods of heating. They may be preplaced in the joint or fed into the joint area after heating, when mineral - type fluxes are used.

However, butt joints may be used if the service requirements are less stringent. Fluxes are generally required, but fluxes brazing with filler metals free of cadmium and zinc can be done on most metals in an inert or reducing atmosphere (such as dry hydrogen, dry argon, vacuum and combusted fuel gas) [47].

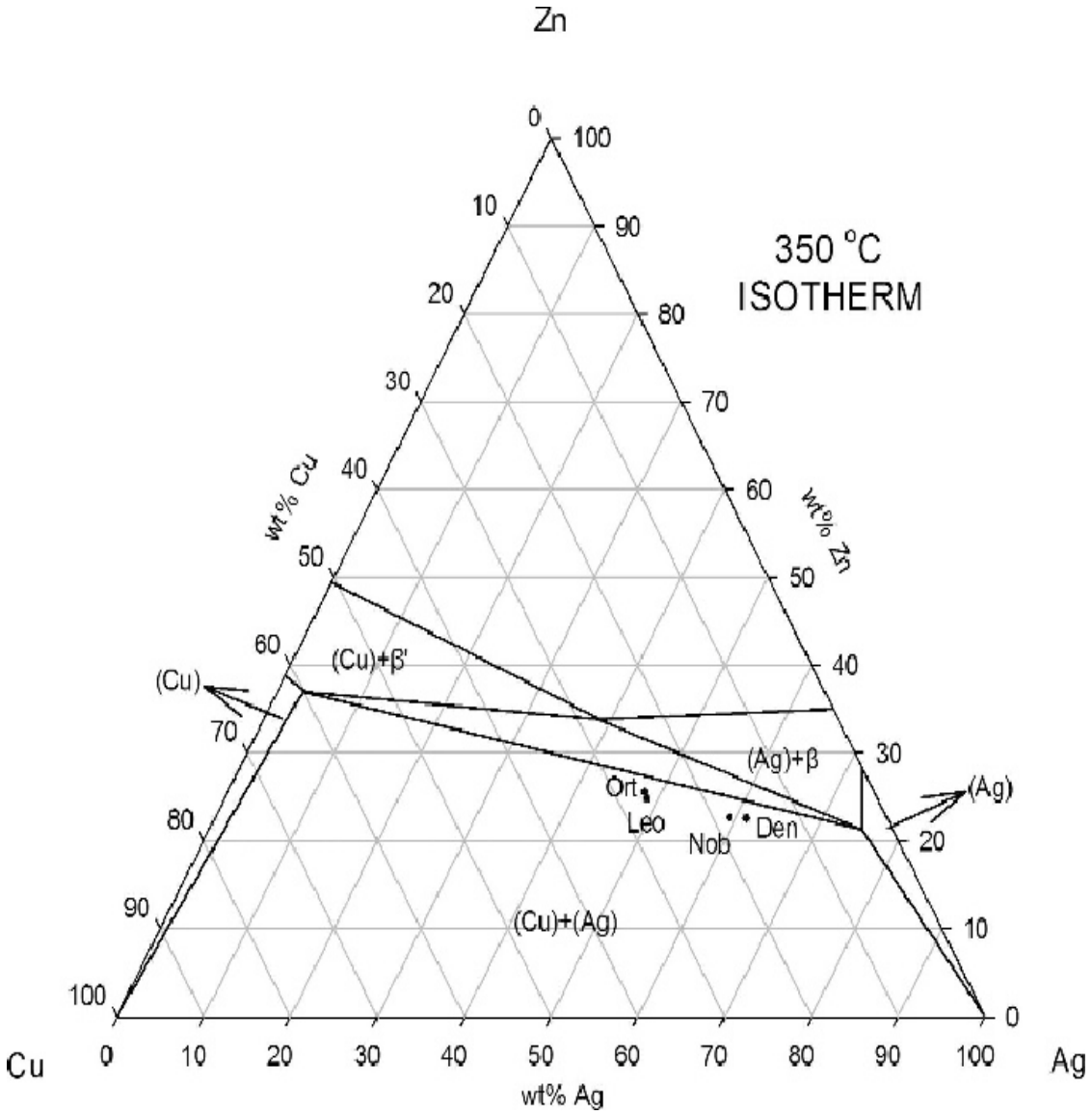


Figure (2.10): Isotherm diagram for the silver-copper-zinc ternary system [43].

The elements that are commonly used to lower the melting and flow temperatures of copper-silver brazing filler metals, zinc is by far the most helpful wetting agent

for joining alloys based on iron, cobalt, or nickel. Alone, or in combination with cadmium or tin, zinc produces filler metals that wet the iron-group metals. Lap joints are generally used with joint clearances for filler metal (Ag20) is (0.075-0.2 mm [47].

The selection of the Ag20 filler metals is for low-melting filler metal with a brazing range of (779 to 835˚C (1435 to 1535 ˚F) as show in Figure (2.10) and good flow and wetting properties. It is used primarily for food equipment because it is free of cadmium and low in zinc. It also provides a good color match with silvery metals and alloys [47].

2.8.3 BAg-8 Filler Metal

When alloyed with copper in a proportion of 72% silver-28% copper to yield brazing filler metal AWS BAg-8, silver forms a eutectic with a melting point of (779°C). Brazing filler metal AWS BAg-8 is suitable for furnace brazing in a protective atmosphere without the use of a flux as well as for brazing procedures requiring a flux. It is usually used on copper or copper alloys. When molten, AWS BAg-8 is very fluid and may flow out over the workpiece surfaces during some furnace brazing applications. It can also be used on stainless steel, carbon steel, and nickel-based alloys, although it's wetting action on these metals is slow. Higher brazing temperatures will improve flow and wetting on these base metals. Brazing filler metal AWS BAg-8 is cadmium free. Lap joints are generally used with joint clearances of (0.05-0.15mm) [15].

2.9. Literature Review

In 2001, NISHIO K. et al. [44] studied the tensile strength, the fatigue strength and the impact characteristics of the joints of the spheroidal graphite cast iron produced by the solid state bonding method and found that the mechanical characteristics of the joints were comparable to those of the base metal. With respect to practical uses, it is considered that the brazing method with a brazing sheet is easier than the solid state bonding for bonding of the cast iron. The spheroidal graphite cast irons were bonded with Ni-base brazing sheets using the high frequency induction heating apparatus. Those sheets were sheet one (Ni-Cr-Si-B system), sheet two (Ni-Si-B system) and sheet three (Ni-P system) in the thickness of 40μm. Main results obtained are as follows: When the surface roughness was 2.3μm, the tensile strength of the joints bonded with MBF 15 was nearly equal to that of the base metal. When the surface roughness was 13.9μm, however, all of the joints were tensile-fractured at the bonded zone because small shrinkages were formed at the center of the bonded zone. The tensile strength of the joints bonded in argon was a little lower than that of the joints bonded in vacuum with MBF 15 and MBF 60. However, the strength of the joints bonded in air was decreased considerably because the oxides of Cr were produced in the center of the melting zone.

In 2004, L.X. Zhang et al. [45] investigated a brazing of TiC cermet to cast iron which was carried out at 950 ˚C for 5 – 30 min using Ag – Cu – Zn filler metal. The formation phases, interface structures and shear strengths of the joints were investigated. The experiment result and analysis identify that three new phases, namely Cu base solid solution, Ag base solid solution and (Fe, Ni) have formed during the brazing of TiC cermet to iron. The interface structure of the joints can be expressed as TiC cermet/Cu base solid solution/Ag base solid solution a little

Cu base solid solution/Cu base solid solution (Fe, Ni)/cast iron. The highest shear strength of the joints is 292MPa, obtained with a brazing time of 20 min.

In 2009, Ahmed O. Jasim et al. [46] investigated the brazing with ductile filler metal (Ag-base alloy) and epoxy adhesive are more reliability to join carbon steel / gray cast iron with high shear strength and more uniform stresses with less defects. A gray cast iron-to-low carbon steel cylindrical lap joint was studied: a steel rod brazed and adhesive inside cast iron tube using BAg-7 braze alloy and epoxy adhesive. The shear strength of joints of varying lengths was made, maximum shear strength obtained at a thinner clearance(0.05mm) when the overlap length 15mm in brazing, while in adhesive, shear strength increases when the clearance increases, the length of overlap increases (up to 20mm).

In 2017, M. Mičian, R. Koňár. [47] Studied the brazing of graphitic cast iron which was investigated, particularly using conventional flame brazing with a CuZn-based filler metal (CuZn40SnSi – brass alloy).The experimental part presents the results of performance assessment of brazed joints on other than CuZn basis using silicone (CuSi3Mn1) or aluminium bronze (CuAl10Fe). TIG electrical arc was used as a source of heat to melt these filler materials. The results show satisfactory brazed joints with a CuAl10Fe filler metal, while pre-heating is not necessary, which favors this method greatly while repairing sizeable castings. The technological procedure recommends the use of AC current with an increased frequency and a modified balance between positive and negative electric arc polarity to focus the heat on a filler metal without melting the base material. The suitability of the joint is evaluated on the basis of visual inspection, mechanic and metallographic testing.

In 2018, Satnam Singh et al. [48] Studied the feasibility of joining cast iron through novel microwave heating using susceptor (i.e. microwave hybrid heating), The joints were developed in domestic microwave applicator at 2.45 GHz frequency and 900 W. Nickel based powder slurry was placed between the faying surfaces for obtaining the joint. Results revealed that uniform and dense joint of 0.5 mm thickness were obtained. Obtained joints revealed metallurgical bonding of nickel powder with faying surfaces of base metal. This metallurgical bonding resulted into wavy interface and this was due to dilution of the base metal along the joint region. The EDS analysis confirms the uniform distribution of elements in the joint region and SEM results revealed that some porosity (in the range of 1.5–1.88%) was observed in the joint region. Tensile strength of microwave joined cast iron was 90% of the base metal strength. This was due to the development of high strength intermetallics and presence of nickel metal in the joint region. Microhardness at joint region was 201.7 ± 18 HV and 315 ± 10 HV along HAZ, whereas microhardness of bulk cast iron was 184 ± 4 HV. Microwave processed samples fractured along the HAZ region.

In 2020, A.F. Looty et al. [49] studied the diffusion brazing mechanism of two dissimilar alloys Ni 270 and ductile cast iron (DCI) by BAg-5 and BAg-7 filler metal with bonding time of 10 min was investigated. Shear strength test was performed to evaluate mechanical properties. The bonding phase for joining side nickel by using the two type of filler metal alloy BAg-5 and BAg-7 is the NiCu phase with shear strength about 70 Mpa, and the bonding phase for joining side ductile cast iron by using the two type of filler metal alloy BAg-5 and BAg-7 is the Fe3Si and SiC phase with shear strength about 40 Mpa. The joining of nickel 270 plate and ductile cast iron by using BAg-5 filler metal alloy shows an Eutectic structure at the middle of filler zone ,which lead to great affinity between nickel

element with copper. The optimum shear strength of 43 MPa was achieved for the bond made by BAg-7 filler metal.

2.9.1 Summary of Literature Review

Table (2.1) shows the differences between the present work and some works presented in the literature review.

Table (2.1): The Differences between the present work and some works presented in the literature review.

Study	Metals	Variable	Technique and Filler type	Joint Strength	IMC_S
The current study	D.C.I G.C.I	Type of Filler	Furnace, Ag20 and Bag-8	Max=286.624	Cu-Zn phase, Ag-Cu eutectic alloy
NISHIO K. (2001)	D.C.I-Ni	Surface roughness	Solid state bonding + Brazing Sheet one Sheet two Sheet three		
Zhang L.X. (2004)	TiC cermet-cast	Time	Ag-Cu-Zn	Max=292Mpa	Cu-base (SS)

	iron				Ag-base (SS)
Jasim A.O. (2009)	Carbon Steel-G.C.I	Gap	Furnace Bag-7 Epoxy adhesive		Ag-Cu phase
Mician M. (2017)	G.C.I		Flame brazing Cu-Zn-based		
Satnam singh (2018)	Cast iron		Microwave brazing Ni- based powder	90%base metal strength	
Looty A.F.	Ni270-D.C.I		Furnace brazing Bag-5 Bag-7	Max=43Mpa by Bag-7	NiCu phase Eutectic NiCu Fe_3Si phase SiC

The two filler metal types used in the current investigation were Ag20 and BAg-8, and the brazing was done between cast irons of similar metals with a 0.1mm gap between them.

Chapter Three

Experimental Part

3.1 Introduction

The present chapter offers the details of the experimental work, and explains the whole circumstances of the conducted tests. The joining of cast irons were carried out by furnace, which needs the vacuum or inert gas, using two types of filler alloys Ag20 and BAg-8 which work at brazing temperature of 820℃ and 780℃ respectively. The brazed joints are tested through the microhardness test and the compression test for evaluating their strength, XRD for predicting the new phase development EDS, SEM and OM. The summary of the whole program employed in the current experimental work is manifested in Figure (3.1).

3.2 The Materials Used

The materials used in the present research are two types of cast irons (ductile and grey). The chemical composition analysis of the material used was carried out by a spectral analysis device at the General Company for Inspection and Engineering Rehabilitation-Baghdad. The device is made on 2009 in Germany, a model is Spectromax. Table (3.1) shows the chemical composition analysis for cast irons and filler metals. Table (3.2) shows Physical and technical properties of Ag20 and BAg-8 filler metals used in the experiment.

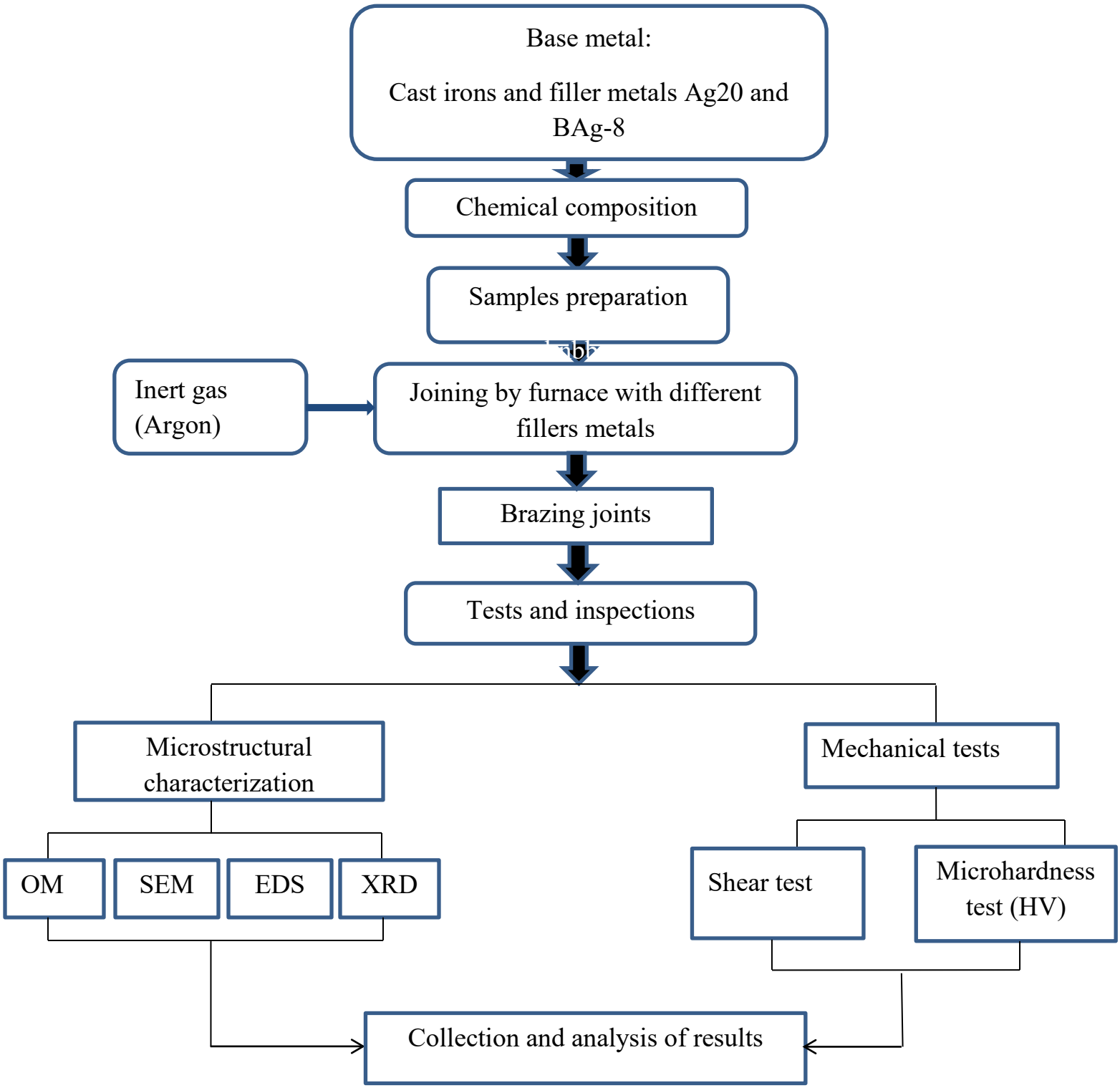


Figure (3.1): Flow-chart of experimental steps for the present study.

Table (3.1): The chemical composition in (wt%) of materials used.

Element %	C%	Ag %	Mn %	Si%	Cu %	S%	P%	Al %	Zn %	Cr%	Ni%	Ti%	Mg %	Fe%
Ductile cast iron	3.75		0.25	2.223		0.013	0.021			0.073	0.025	0.447	0.043	Bal.
Grey cast iron	3.04		0.42	2.58	0.05	0.11	0.068	0.13				0.11		Bal.
Ag20		20		0.15	44				36					
BAg-8		72			28									

Table (3.2): Physical and technical properties of Ag20 and BAg-8 filler metals used in the experiments [43].

Filler metals	Melting temperature (solidus)	Melting temperature(liquidus)	Brazing temperature	Density	Tensile strength	Recommended joint gap	Service temp.
Ag20	690 °C	810 °C	820 °C	8.7 g/cm^3	43kg/mm^2	0.075-0.2 mm	-200/ +200 °C
BAg-8	780 °C (eutectic)	780 °C	780 °C	10 g/cm^3	35 kg/mm^2	0.05-0.15mm	-200/ +200 °C

3.3 Samples Preparation and Design of Brazing Joint

The silver base brazing filler metals (BAg-8) has been received as a sheet, with a diameter of 10mm and 20cm in length, while (Ag20) has been receive as a rod, with a diameter of 2mm and 40 cm in length [51].

The materials used in the present research are ductile cast irons and grey cast irons with a diameter of 25mm and a length of 25mm, and the rod (diameter=10mm, length=15mm) to form lap joint as shown in Figure (3.3 and 3.4), with a different filler metals were BAg-8 and Ag20.

The cast irons bases were turned with an internal diameter of 10 mm for inserting the rod of cast irons. The internal diameters of cast iron bases were then finished by (0.1mm) to form the gaps between cast irons, and thus to apply the fillers (BAg-8 and Ag20). This is the lap joint between cast irons.

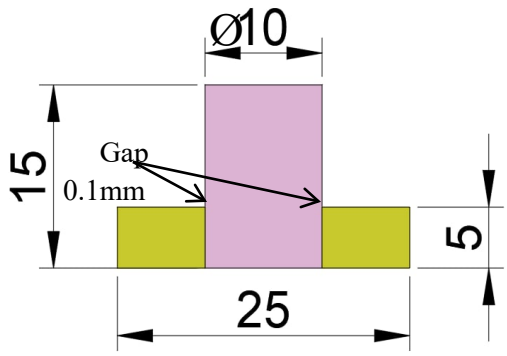


Figure (3.3): Schematic for the lap joint design.

Figure (3.4): Samples after the chemical treatment.

3.4 Chemical Treatment of Cast Iron

The machining of cast iron smears the cut surfaces with graphite, making it difficult to wet with the brazing filler metal. During brazing, silver and copper brazing filler metals fail to wet the graphite flakes or nodules. Thus, the graphite must be removed from the surfaces prior to brazing. Brazing filler metals that contain chromium, titanium, or other carbide formers will wet and bond to the graphite. Brazing filler metals such as AWS BNi-2 can be used without the normal cleaning process to remove the graphite [43].

3.5 Furnace Treatment

An electrical furnace as shown in Figure (3.5) was used in the present work for brazing. The device type is Sola Basic 51222, LINDBERG 304 HART STAEET. WATERTOWN 53094, and the process were done at the laboratories of the Metallurgical Eng. Department / College of Materials Engineering / University of Babylon. The furnace chamber is fabricated from the alumina. The furnace is thermally insulated via castable cement, with many glass wood layers to prevent the heat dissipation outside its chamber. The furnace has a maximum temperature of 1200℃.

Figure (3.5): The furnace used in the present work.

In chemical treatment, the surfaces have been prepared for brazing and cleaned to remove free graphite from components. The process of cleaning was carried out in a molten salt bath operating at 460-480°C in the furnace. The bath composition consists of 75% sodium hydroxide, 5% sodium chloride, 5% sodium fluoride, 14%sodium carbonate. These percentages were weighed by a sensitive balance shown in Figure (3.6), mixed together and put in container (Figure 3.7) with the samples for 20 min using hand agitation. Preparation was completed by rinsing the cast irons in hot water to remove the salt and then drying. The salts oxidize the surface graphite, leaving the metal surface with a thin layer of iron oxide. After that, the samples were cooled and washed with distilled water and dried.

Figure (3.6): Sensitive balance.

Figure (3.7): Container of the chemical treatment.

3.5 Brazing Equipment

3.5.1 Microwave Brazing

Microwave applicator Fixed frequency, Multimode (Make: LG and Model: Charcoal), Frequency was 2.45 GHz (fixed), with 900W maximum power rating was used for the development of joints. Table (3.3) represents the process parameters used in the experiments. The process of microwave hybrid heating for obtaining cast iron joint is shown in Fig. (3.8). The faying surfaces were filled with a powder slurry and were placed on a refractory brick, and the joint region was

covered with a graphite sheet of 1 mm thickness. The complete joint region was covered with charcoal powder to provide susceptor heating. Charcoal initially interacts with microwaves such that by the conventional heating takes place, and heat is transferred to the interfacial powder.

The formation of joint is also affected by the gap between faying surfaces. If higher gap is maintained, then there are chances of slurry leakage from the joint region, and reduced gap can limit the powder quantity required for joint formation. A gap of 0.1 mm was filled with nickel-resin slurry between the faying surfaces. It is important to maintain slurry between the joint edges during heating, so limited resin is added to form a paste with no fluidity.

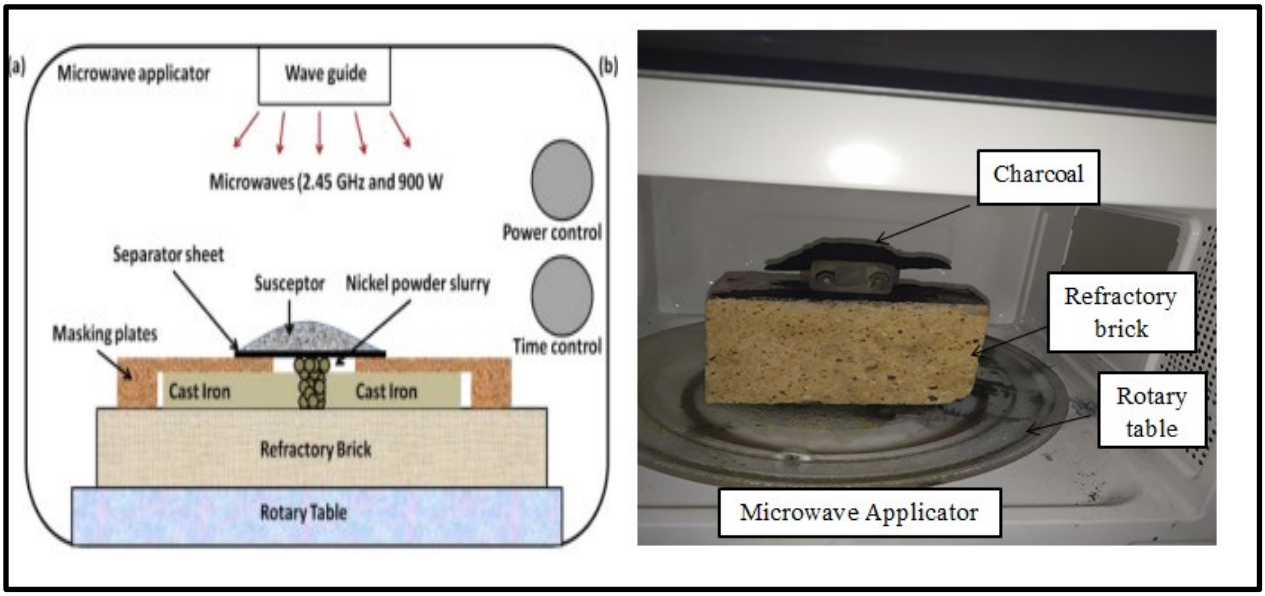


Figure (3.8): A processing of joint in microwave applicator [44].

Methodology and Equipment

The experiment performed employs different equipment and materials for the purpose of microwave processing of metallic materials chosen on the basis of previous works and studies. These are described below:

- **Multimode Microwave Oven** with 2.45GHz and 900W power supply was used in order to supply microwave energy at the junction of the base metals having a capacity of 34 liters.

- **Resin-** A standard resin adhesive used for binding Ni based powder with the sample material.

- **Acetone** is used as an important solvent used for cleaning purposes in laboratory.

- **Sand paper or glass paper** is used to remove small amount of material from surface, either to make smother or to remove a layer of material.

- **Susceptor materials** used for initial coupling of microwave with metallic materials, as the susceptor medium. It has ability to absorb microwave material, thus providing intense spot heating. This is also used to prevent direct contact of metals to microwave which may call arching.

- **Slurry** is a mixture of corresponding nickel powder and adhesive. Metallic powder gets heated up through conventional mode of heat transfer from the heated charcoal.

Experimentation

The following steps were followed for the experimentation:

- Sample surface were cleaned with sand paper in an acetone bath prior to applying the interface layer.

- Slurry was made by corresponding metallic powder with resin and was uniformly placed at the interface surface between the two pieces of cast iron.

- Susceptor material was used to avoid direct exposure of metals with microwave.
- Applied slurry sample is placed into pressing mechanism and then put into microwave oven, where it was heated under controlled timing and temperature mode as shown in Figure (3.9).

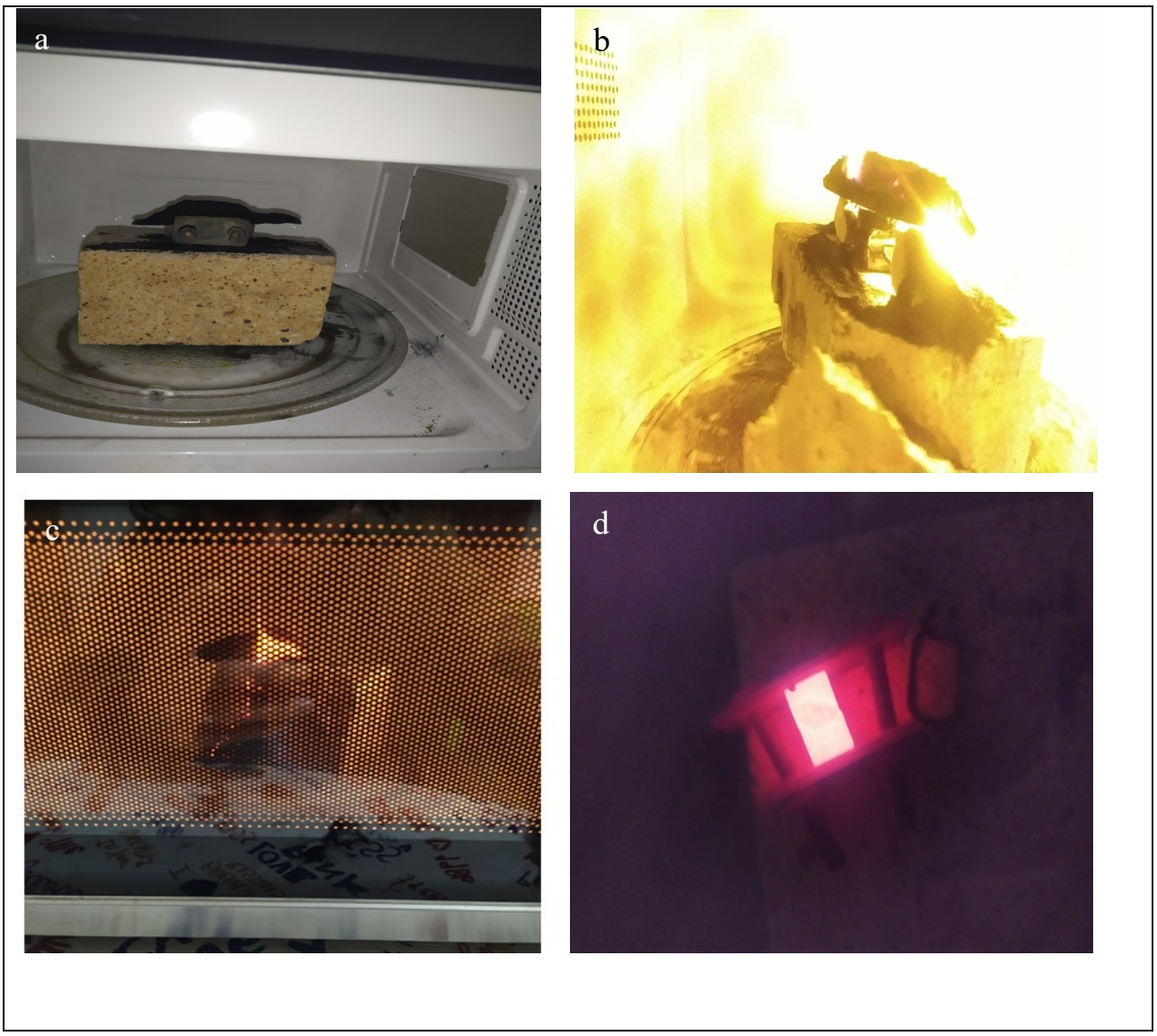


Figure (3.9): The experimental samples during the Microwave processing (a) preparation sample for brazing, (b) burning of charcoal, (c) arching of charcoal, (d) red hot of sample.

Different experimental observations were recorded during different parametrical regulations: the materials used in the present research were ductile cast irons with slurry of Ni powder and resin. Susceptor materials were wooden; coconut shell charcoal. The Sheet of graphite was used in different thickness (1, 1.5, and 2mm). Surface of samples (flat, notched). Power of microwave was 700, 900W, and other variables as shown in Table 3.3.

Table (3.3): Experimental details of Microwave Brazing

Exp. No	Exposure time (in min)	Results
1	5	Not hot , not joined
2	7	No arching, charcoal was heated up but no burning was observed
3	8	Red hot , not melting, and not joined
4	8.5	Red hot , not joined
5	9	Arching (spark), burning of charcoal, specimen reached to red hot condition but no melting was observed
6	10	Arching (spark), burning of charcoal, specimen reached to red hot condition with little melting was observed, not joined

In this work, the joining of cast iron using microwave energy was unsuccessful, perhaps because microwaves used were domestic.

3.5.2 Furnace Brazing

An electrical furnace was used in the present work for brazing (Figure 3.10). The device type was Tube furnace EQ-GSL-1600X single zone series uses high power electric, and the process was done at the laboratories of the Metallurgical Eng. Department / College of Materials Engineering / University of Babylon. Tube of furnace made of ceramic was used to provide a protection under the argon gas at a rate of 3l/min. The furnace has a maximum temperature of 1250℃.

3.5.3 Brazing Conditions

The samples of cast irons were brazed using the Ag20 and BAg-8 fillers inside a resistance heated furnace. The filler was cut into pieces and placed on the gap around the cast iron. A bubbler at the outlet of the furnace provided visual confirmation that the gas was flowing through the furnace chamber. The samples were heated to 820, 780˚C and held at that temperature for 15 minutes to equilibrate homogenize of sample. Temperature and time were selected experimentally after holding time; the samples were cooled by slow cooling (furnace cooling). Argon was closed on the samples that cooling in a furnace until (200 ˚C), and it was completely cool to room temperature (30 ˚C).

Figure (3.10): The furnace used in the brazing operation.

Brazing operations were done by furnace. Six samples were selected to the compression-shear tests and these include all the variables in Table (3.4). Samples were selected for metallographic analyses and hardness testing across the gap (G) 0.1mm (between cast irons). Figure (3.11) shows the samples before brazing.

Table (3.4): Process parameters for Brazing Cast Iron Joints.

No. of Exp.	Base metals	Filler metals	Temp. (˚C)	Time (min)
1	D.C.I / D.C.I	Ag20	820	15
		BAg-8	780	
2	G.C.I / G.C.I	Ag20	820	15

		BAg-8	780	
3	D.C.I / G.C.I	Ag20	820	15
		BAg-8	780	

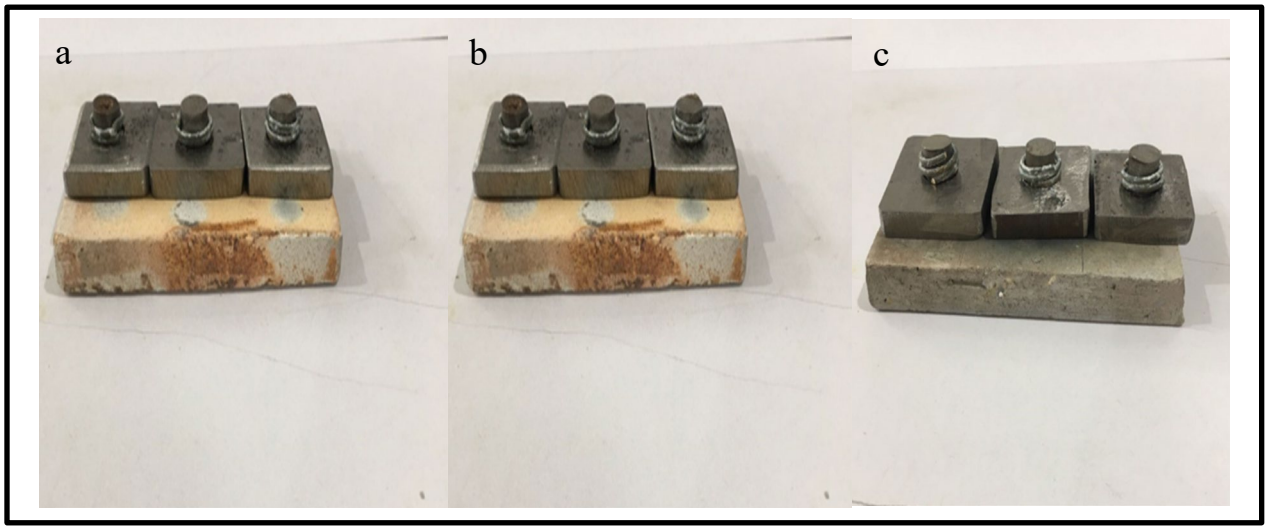


Figure (3.11): The samples before brazing, (a) ductile cast irons (b) grey cast irons (c) ductile/grey cast irons.

3.6. Test of Shear Strength

The shear strength test of cast iron brazed assemblies was carried out by loading the assemblies in compression, using universal testing machine shown in Figure (3.12). A uniform compression rate (1 mm/min) was used for the shear strength test. The load-displacement data was collected using a recorder.

The compression-shear test samples were tested using (Microcomputer Controlled Electronic Universal Testing Machine) model (WDW-200E), the device was made in China. The machine is located in the Laboratory of Strength / Department of

Metallurgical Engineering / College of the Materials Engineering / University of Babylon.

Figure (3.12): Universal testing machine.

3.7 Microscopy

The samples for microstructural test were prepared inconsistently with the standard metallographic techniques. The ultimate objective of such techniques is to obtain a flat scratch-free, mirror-like surface. Optical microscopy (OM) and scanning electron microscopy (SEM) were used for this purpose. The mating sample surfaces were prepared using the conventional grinding starting at grade 180 and going to 3000 in stages. The chemical etchant used to disclose the metallographic structure of the bond and the neighboring base metals was etching

solution (2% HCl, 5% $FeCl_3$, 93% methanol) for 2 seconds for Ag20 filler metal, and (0.5% HF, 1.5% $FeCl_2$, 98% methanol) for 1min for BAg-8 filler metal. Directly beyond the etching process, all samples were washed by water and then dried by hot air. All samples were prepared at the laboratories of the Metallurgical Eng. Department / College of Materials Engineering / University of Babylon.

3.7.1 Optical Microscopy

The microstructure for the brazing joints which consist of cast irons and alloy filler metals (Ag20 and BAg-8) were observed by the (OM), using MMM-800RF. device made in Japan, present in College of Materials Engineering / University of Babylon, shown in Figure (3.13).

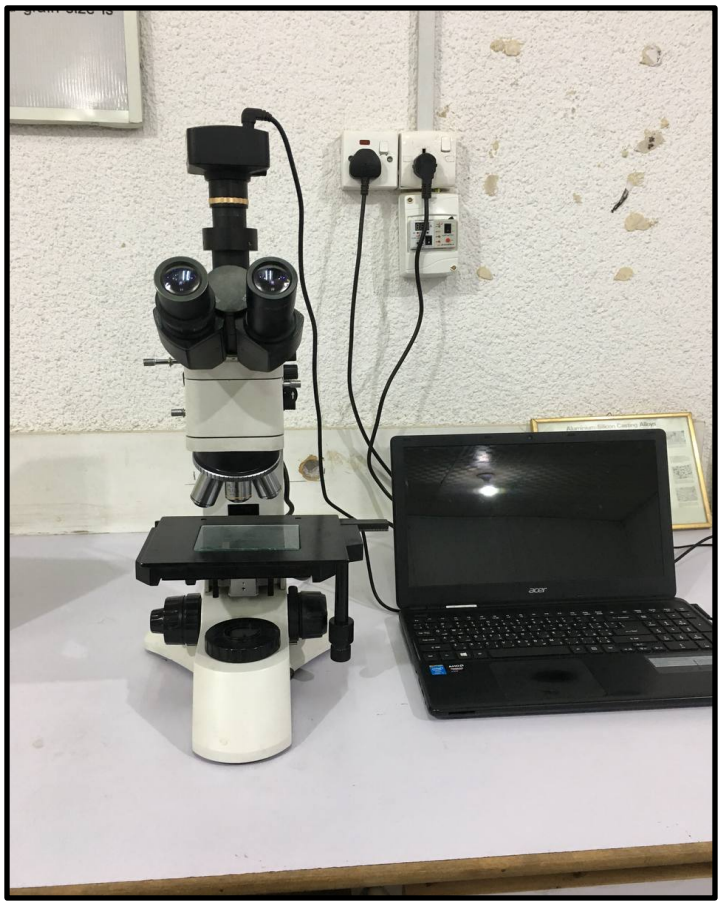


Figure (3.13): Optical microscopy.

3.7.2 Scanning Electron Microscopy (SEM) with Energy Dispersion Spectrometer (EDS).

The scanning electron microscop, model Tescan, and the energy dispersive spectrometer detector that linked to the SEM used for obtaining the elemental analysis were utilized. The resulted images were taken at various magnifications relevant to the required information. This test was used for microstructural characterization and composition analysis at the brazing alloys and the interface between the cast irons and brazing alloys. The SEM was performed in the Laboratories of the Applied Sciences Department, University of Technology, using an SEM device shown in Figure (3.14).

Figure (3.14): Scanning electron microscope.

3.7.3. The X-ray Diffraction (XRD)

The XRD method was employed to evaluate the phases that developed in the base materials and through the joint of the brazed alloys. This test was achieved by the XRD instrument, model ADX-2500 XRD-2010, made in Japan, using Cu target = 30 mA, voltage = 40 kV, a range of scan = (20-90) deg., and a speed of scan = (5) deg.min-1 . The analysis of the X-ray diffraction of the materials was done, and the comparison of the outputs with the standard XRD charts was carried out. The XRD was performed in the Laboratories of Ceramic engineering in College of Materials Engineering / University of Babylon which is shown in Figure (3.15).

Figure (3.15): X-Ray diffraction device.

3.8 Microhardness Measurements

Vickers microhardness method was used to measure the hardness of the brazing joint at a loading of (200 g) and hold for (10 seconds). The value of hardness has been taken at base metals, and brazed alloy. Hardness values (HV) were obtained by using the following equation:

$$HV=1.8544\times P/d^2 \quad \text{..... (3.1)}$$

Where: p= applied load, Kg, d=average length of diagonals, mm, HV is the number of Vickers hardness in (kg/mm^2).

This test achieved by using Digital Micro Vickers Hardness Testing Machine type TH714 Twster made in China, which is located in the metallography laboratory in the College of Materials Engineering / University of Babylon as shown in Figure (3.16).

Figure (3.16): Vickers hardness tester.

Chapter four

Results and Discussion

4.1 Introduction

The chapter contains all the results of mechanical tests (shear, microhardness), microstructure characterization by an optical and scanning electron microscopy with energy dispersive spectrometer of the similar and dissimilar joints and discussion of these results.

4.2 X-Ray Characterization of Brazing Joints

Figures (4.1 and 4.2) show the X-ray diffraction (XRD) analyses, in which the picks are drawn between intensity and theta-2theta (0-110 deg) for the sample that has slow cooling from furnace. XRD analyzed the joint of D.C.I/D.C.I that brazed in the furnace and slow cooling. The peaks of copper (α) were due to the Cu-rich phase in the brazing zone formed during brazing when the cast iron brazing by Ag20 filler metals. Thus, the XRD pattern did not identify the formation of the intermetallic phases or oxidation.

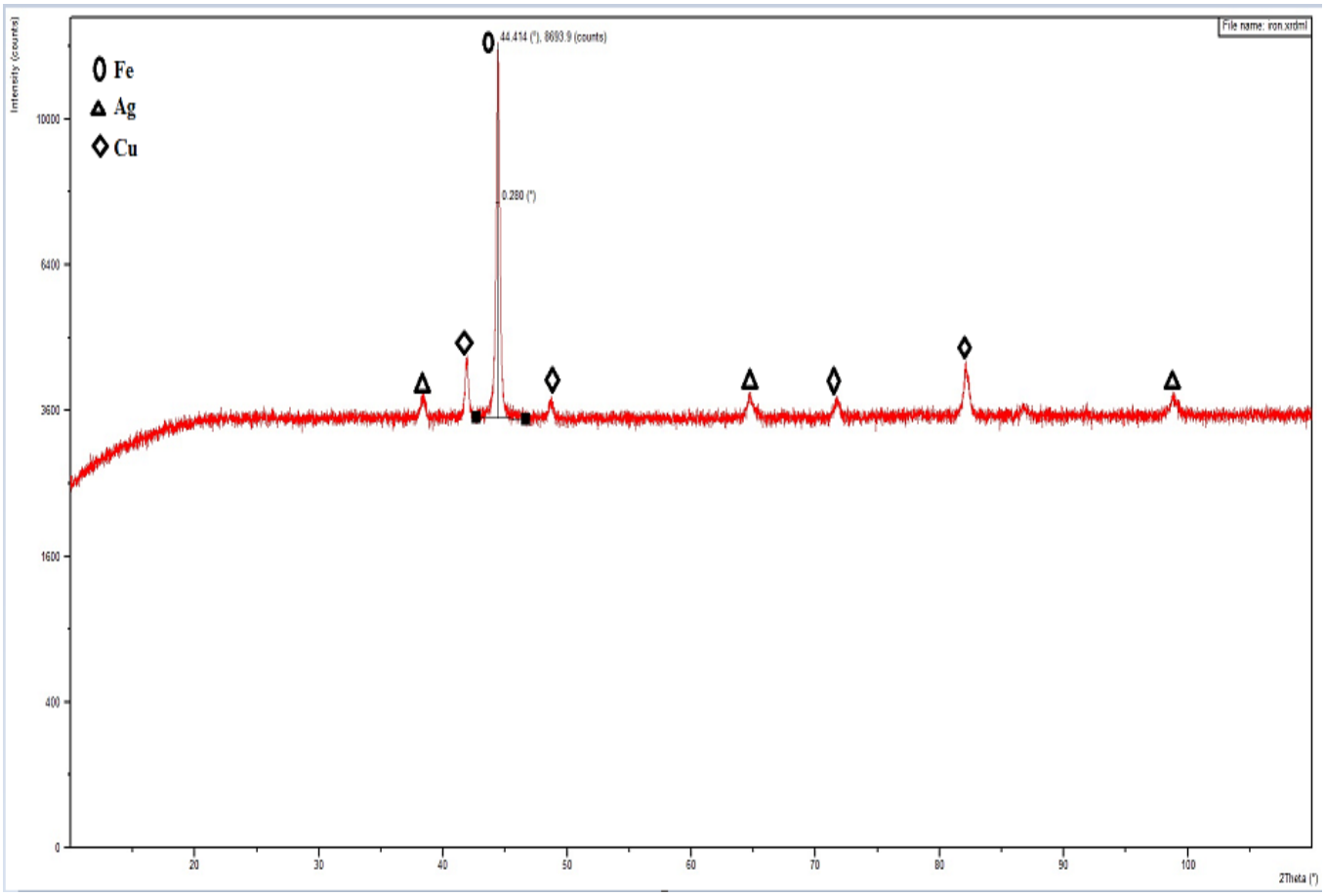


Figure (4.1): XRD pattern of the ductile cast iron/ ductile cast iron joint that brazed by Ag20 filler metals.

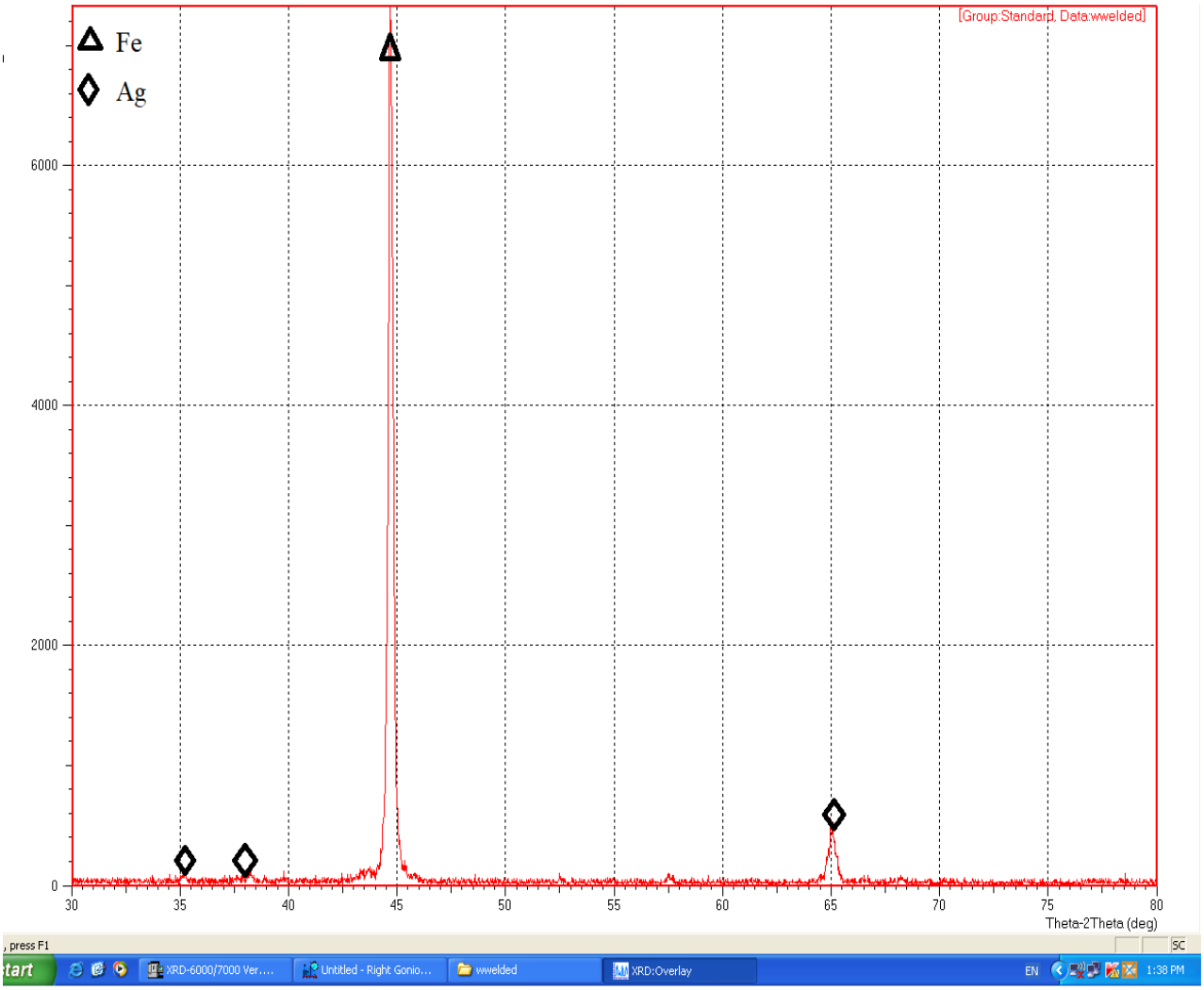


Figure (4.2): XRD pattern of the ductile cast iron/ grey cast iron joint that brazed by BAg-8 filler metals.

The XRD patterns did not identify the formation of the intermetallic phases. The peak corresponding to Ag was assigned to the Ag-Cu (Ag-rich) phase present in the brazing zone.

4.3 Microstructure Evaluation

4.3.1 Microstructure of Base Metals

Figure (4.3) shows an optical micrograph for the base metals that were used in this work. The base metals were produced by casting (as received).

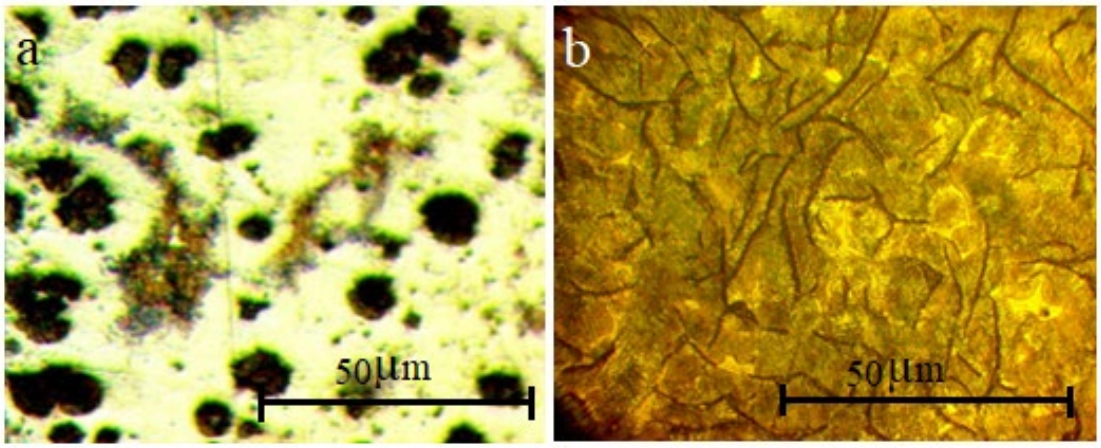


Figure (4.3) Optical micrograph for base metals (a) ductile cast iron and (b) grey cast iron.

It is observed from the figure that the ductile iron contains more uniform of nodular graphite, and the matrix has more ferrite phase. Grey cast iron shows a flake shape graphite and the matrix has more lamellar perlite.

4.3.2 Microstructure of the Ductile Cast Iron Joints

From optical microscopy (OM), different microstructures (Figures 4.4 – 4.7) were obtained.

Figure (4.4) shows the microstructure of ductile to ductile brazed joint using Ag20 filler alloy. Large amount of Cu was observed in the brazing alloy, which is greater than the amounts of Ag and Zn, indicating that a Cu- based solid

solution has formed according to the Cu-Zn diagram. In the white phases of the brazing alloy, there was a lamellar eutectic of Cu and Ag. It is also observed that the nodularity of graphite is less uniform, and may be converted to compact shape of graphite. The changing in shape of graphite may be due to the high temperature of the brazing process.

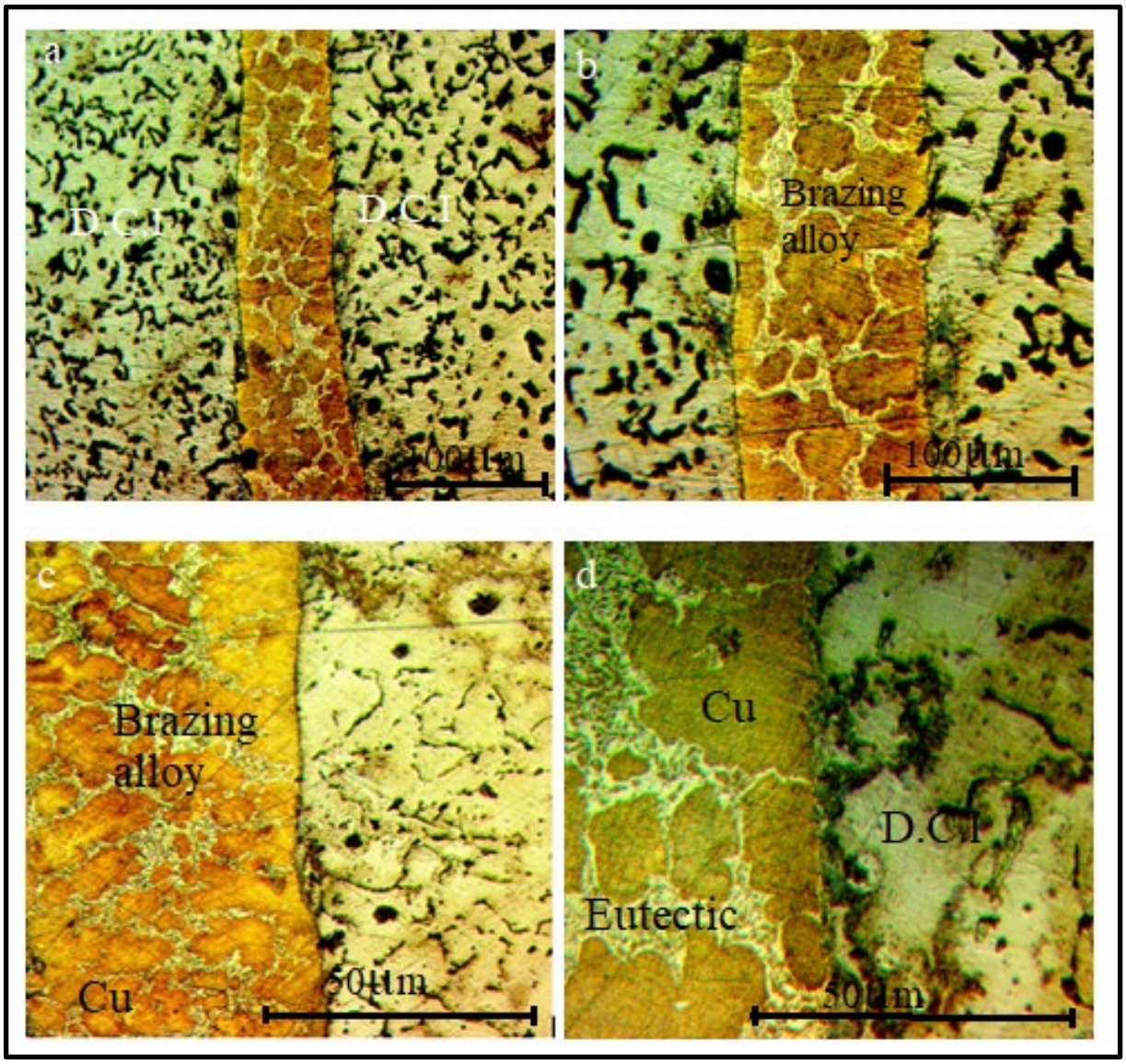


Figure (4.4): Optical micrograph for ductile cast iron braced using Ag20 filler metals using different magnifications.

The reaction of the brazed cast iron joints at the interface can be divided into two stages. In the first stage, the Ag20 brazing filler metal melts when the temperature reaches its melting point. Diffusion and segregation of elements occur during the phase transformation of liquid to solid and solid to solid transformations. A little of Zinc dissolves in the Copper and becomes Copper based solid solution at the brazing alloy. A small amount of carbon diffuses to the brazing filler metal from the cast iron, as does a small amount of Copper from both sides of the brazing filler metal, while Silver travels freely in the brazing filler metal. The diffusion of iron and Copper in the second stage results in a small quantity of Fe diffusing into the brazing filler metal and a lot of Copper (solid solution) aggregates on both sides, while a considerable amount of Silver is left in the center of the brazing filler metal and forms an eutectic with Copper, as shown in Figure (4.4), these result are approximately closed to the result of A. F. Lotty (2020) [49].

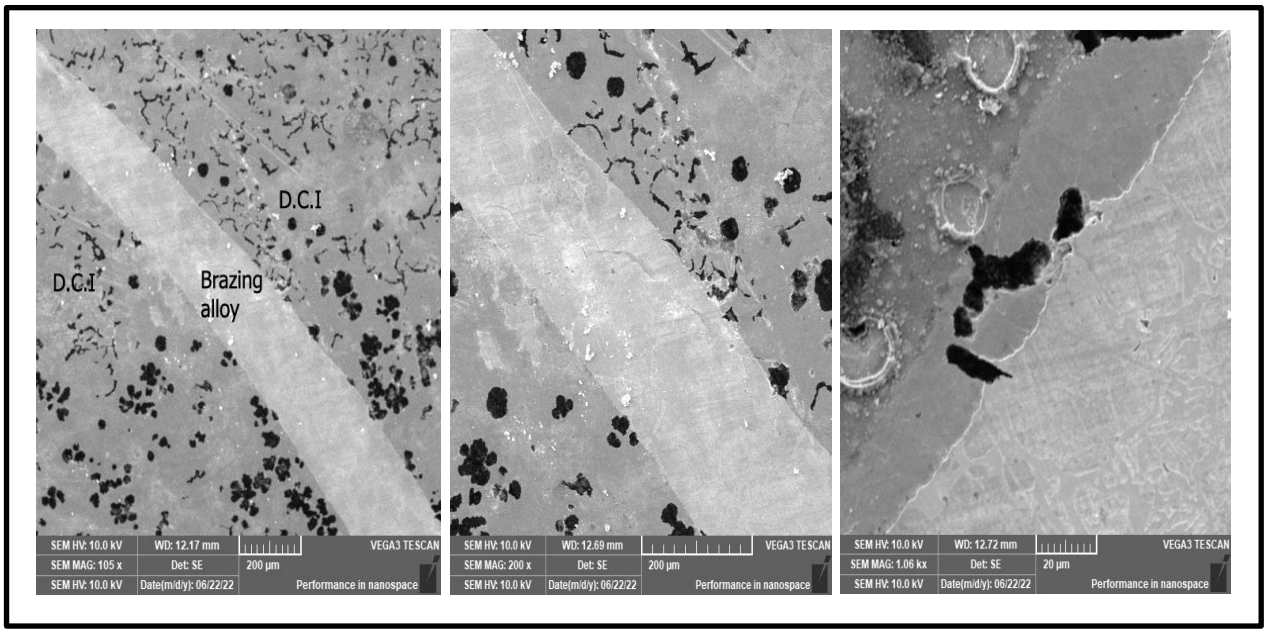


Figure (4.5): SEM for the ductile cast iron brazed by Ag20 filler metal using different magnifications.

From Figures (4.6 and 4.7), BAg-8 filler alloy consists of (72% Ag and 28% Cu); this chemical composition exhibited a eutectic microstructure as a lamellar form of coupling growth of two phases of Ag- rich (bright) and (α)copper- rich (dark) phases according to the Ag-Cu diagram in Figure (2.9).

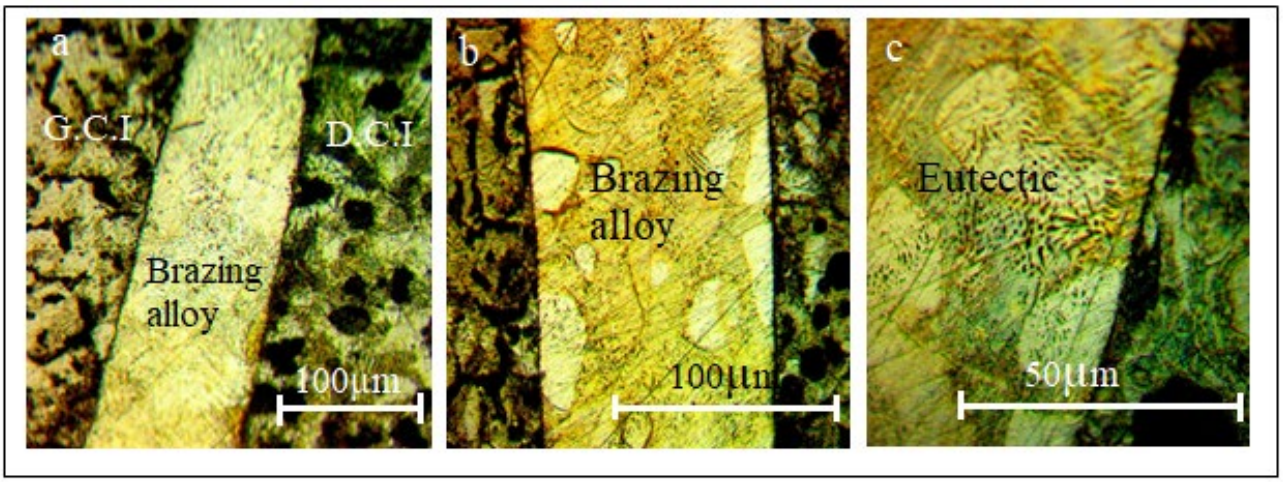


Figure (4.6): Optical micrographs for ductile cast iron brazed using BAg-8 filler metal using different magnifications.

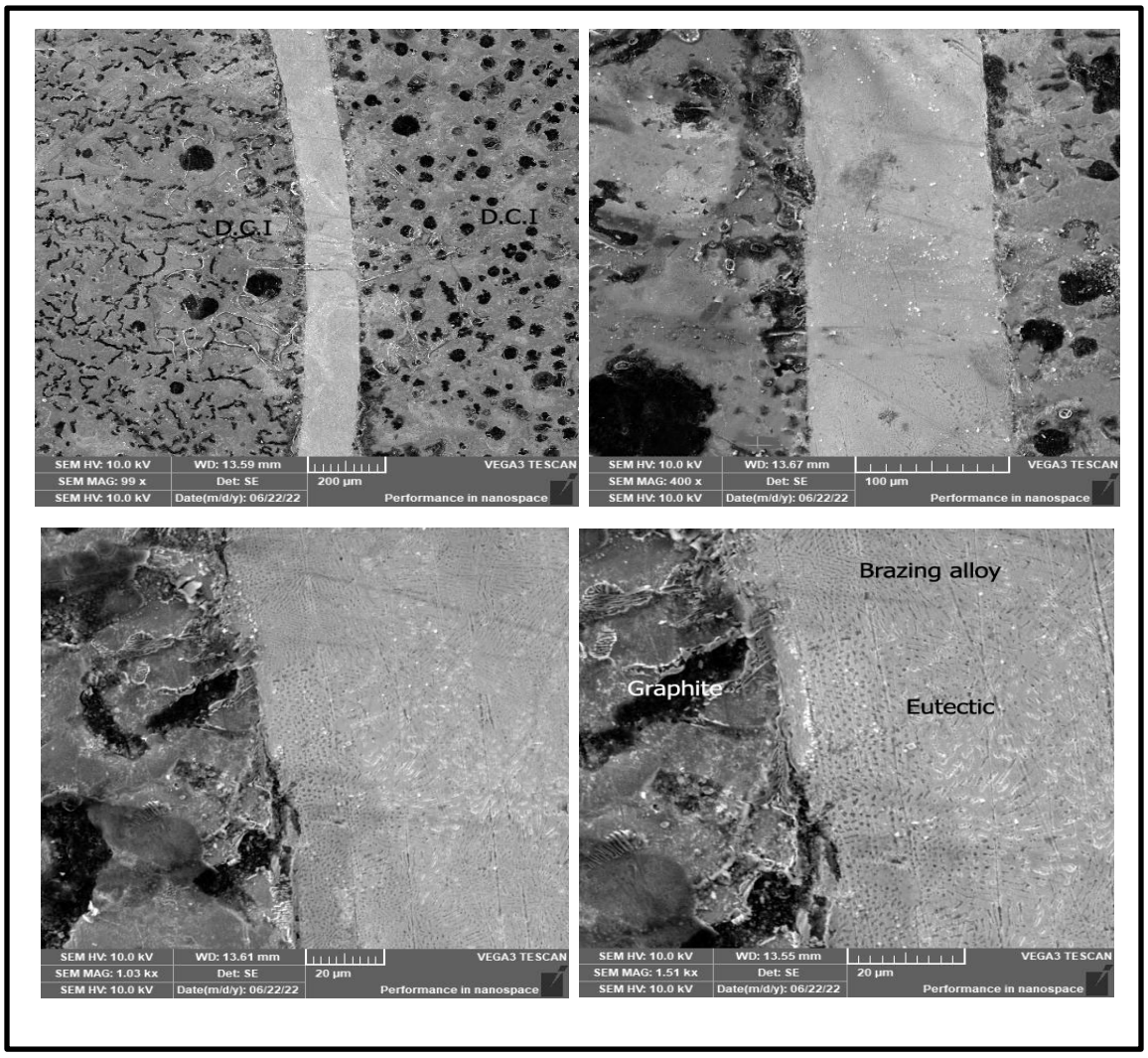


Figure (4.7): SEM for ductile cast irons brazed by BAg-8 filler metal using different magnifications.

4.3.3 Microstructure of the Grey Cast Iron Joints

From optical microscopy, different microstructures (Figure 4.8 and 4.9) were obtained. It is clear that no porosity or debonding at the interface between the filler metal and grey cast irons. This may be due to the suitable heating and type of filler.

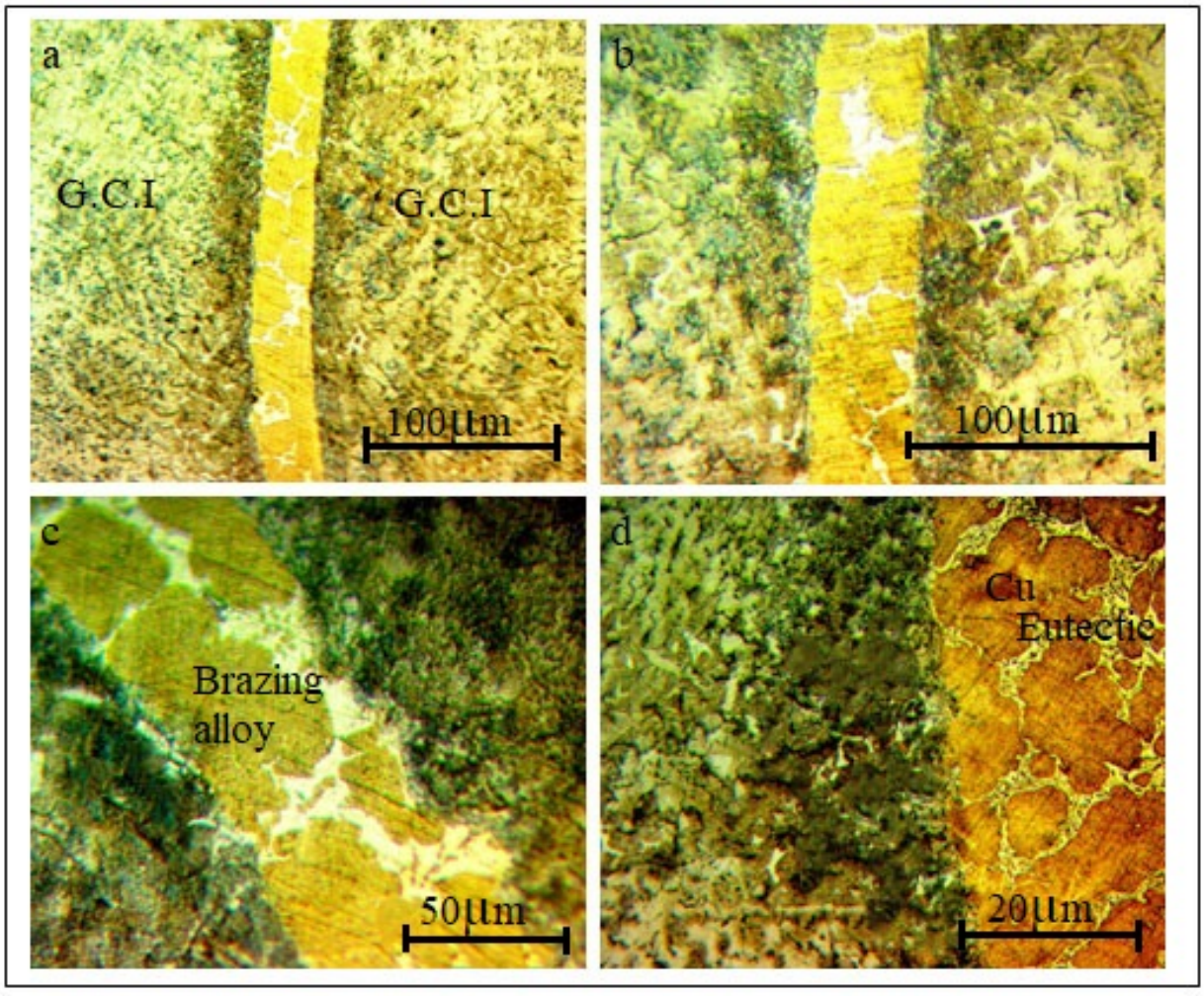


Figure (4.8): Optical micrograph for grey cast irons brazed by (Ag20 filler metal using different magnifications.

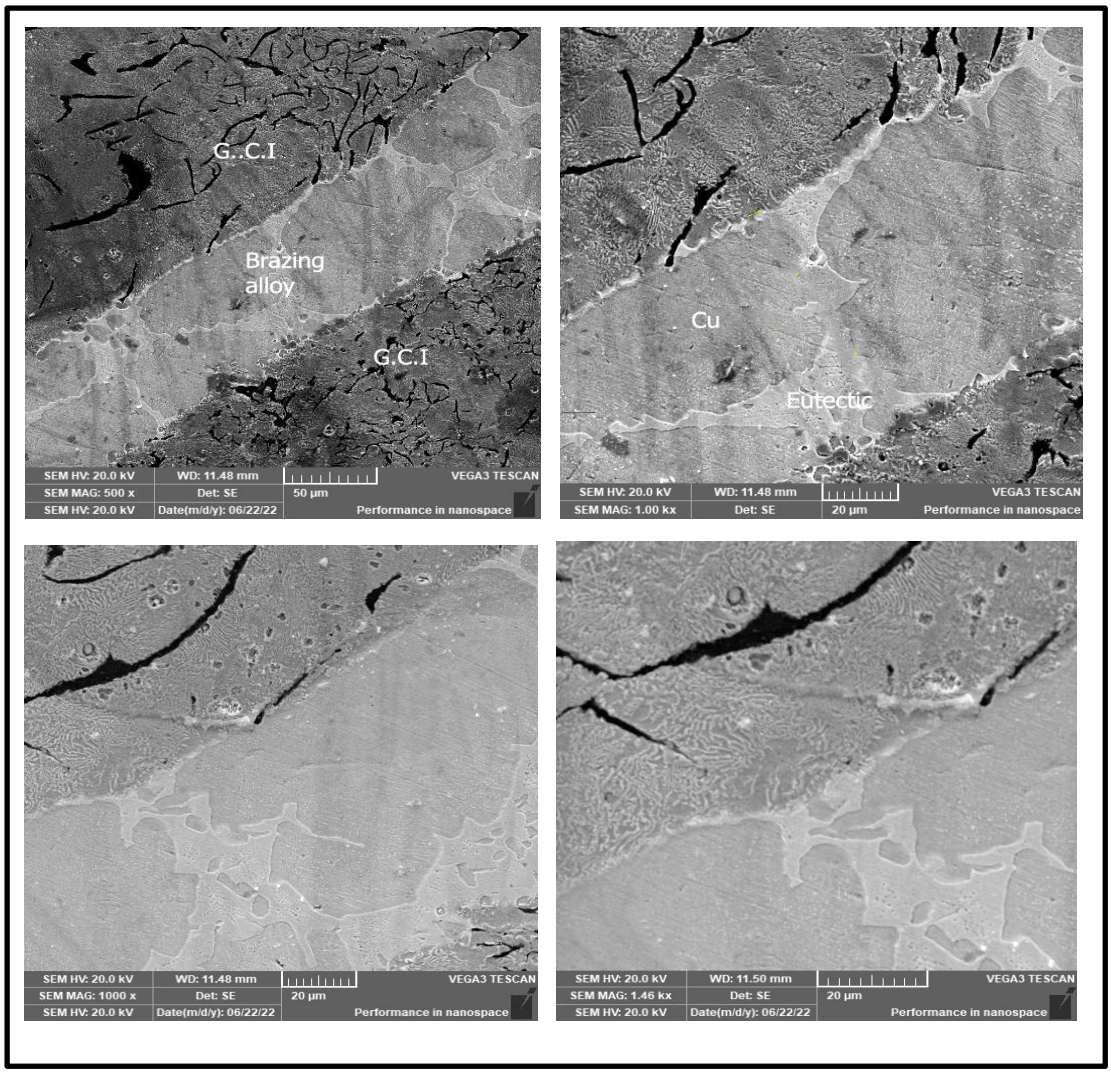


Figure (4.9): SEM for the grey cast irons brazed by Ag20 filler metal using different magnifications.

Figure (4.10) shows the microstructure of the brazed similar grey cast iron joint using B-Ag8 filler alloy. It is observed an alloy according to the Ag–Cu

diagram, the eutectic (Zebra) of Ag and Cu, Ag- rich (bright) and copper- rich (dark) phases.

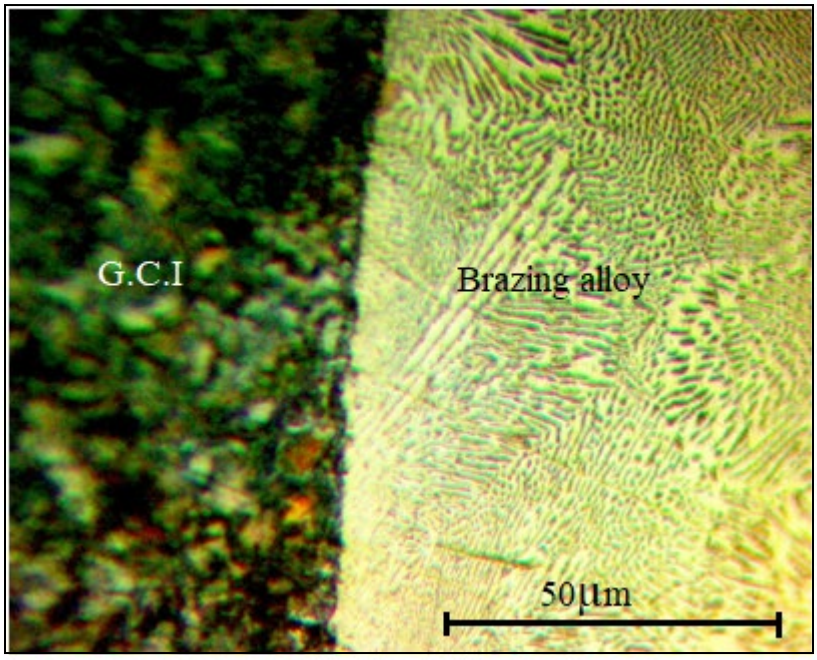


Figure (4.10): Optical micrographs for grey cast iron brazed by BAg-8 filler metal.

4.3.4 Microstructure of the D.C.I/Brazing Alloy/Grey Cast Iron Joints

From OM, different microstructures were obtained, as shown in Figure (4.11 and 4.12). The samples brazed with Ag20 filler metals have copper base solid solution (Cu (α)) with eutectic of Ag- rich (bright) and copper- rich (dark) phases.

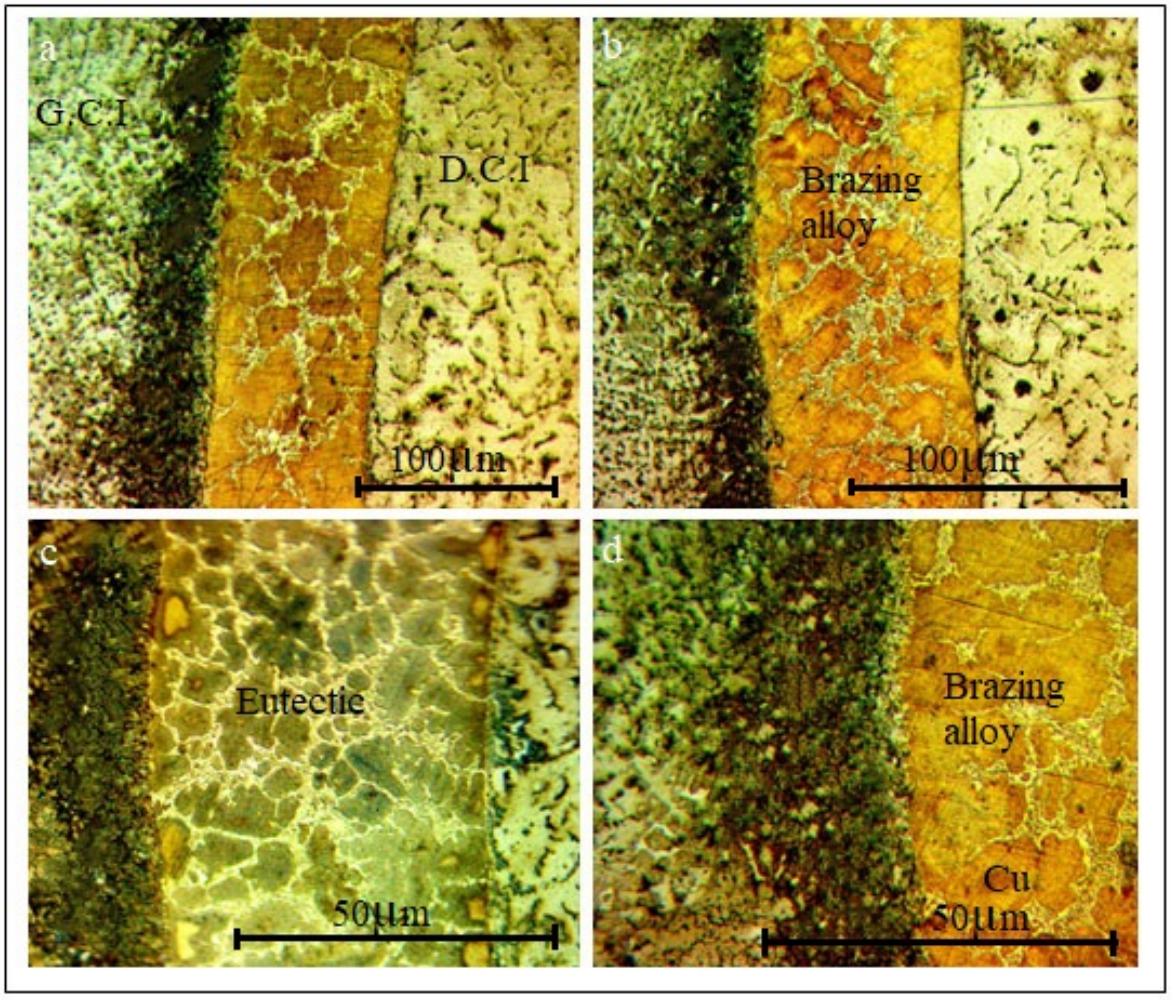


Figure (4.11): Optical micrographs for ductile/grey cast irons brazed by Ag20 filler metal using different magnifications.

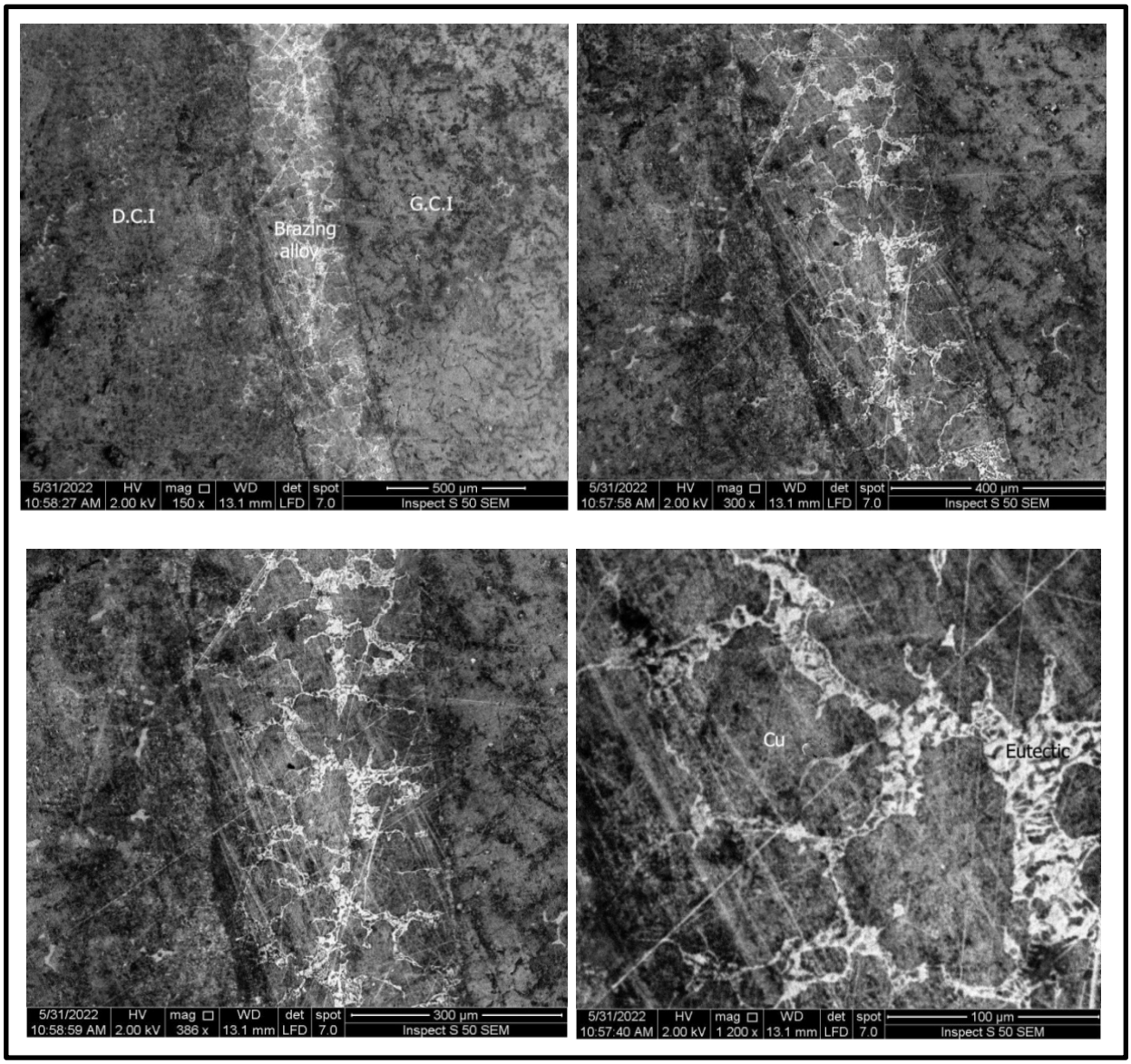


Figure (4.12): SEM for the ductile/grey cast irons brazed by Ag20 filler metal using different magnifications.

Figure (4.13) shows the microstructure of the brazing alloy according to the Ag–Cu diagram, the eutectic (Zebra) of Ag and Cu, Ag- rich (bright) and copper-rich (dark) phases. It is also observed that the nodularity of graphite is still uniform after brazing process by using BAg-8 filler metals. It may be converted to compact shape with Ag20 because the brazing temperature of BAg-8 (780 ˚C)

less than Ag20 filler metals (820 ˚C), and this temperature may be enough to change the graphite shape. Figure (4.14) shows the SEM of brazed ductile /grey cast iron joint.

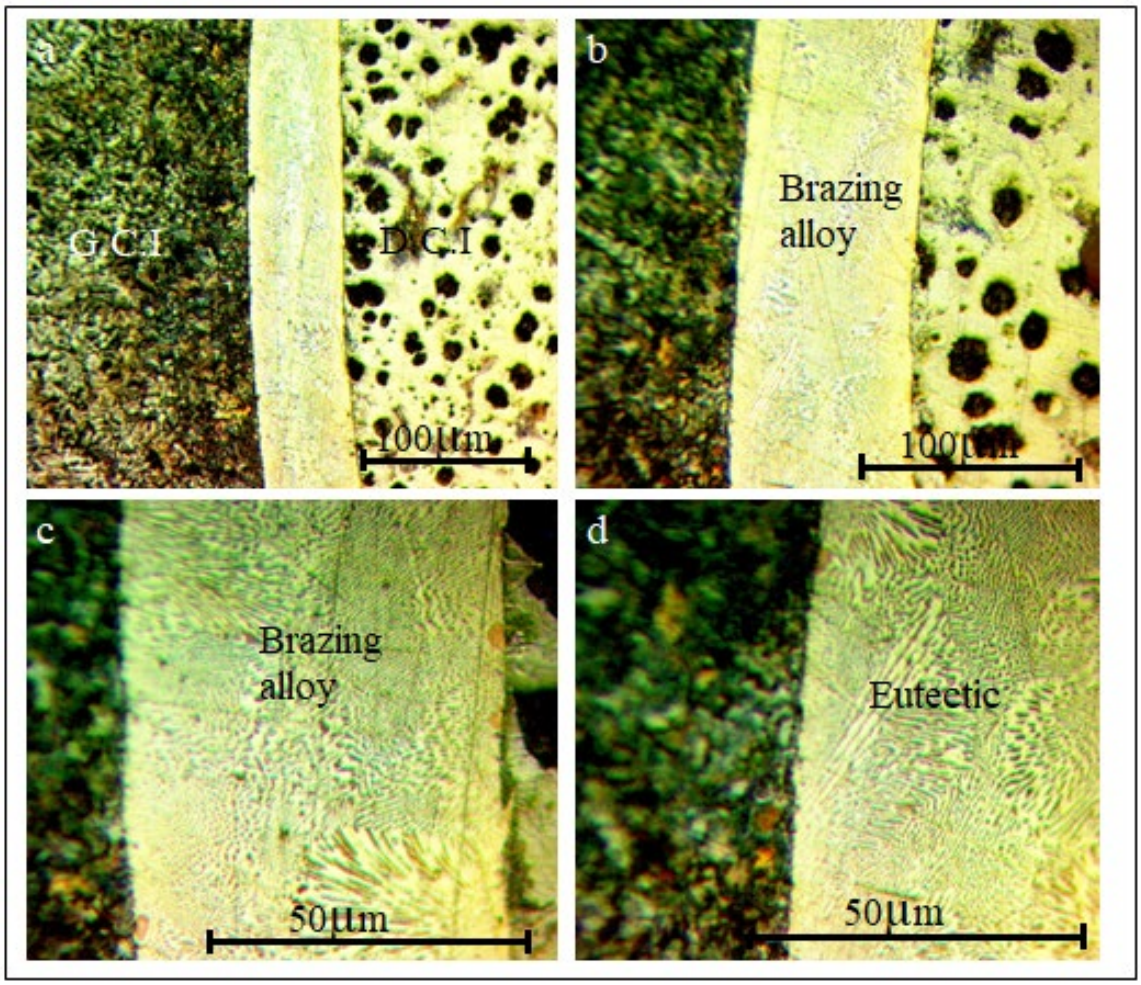


Figure (4.13): optical micrographs for ductile/grey cast irons brazed by BAg-8 filler metals using different magnifications.

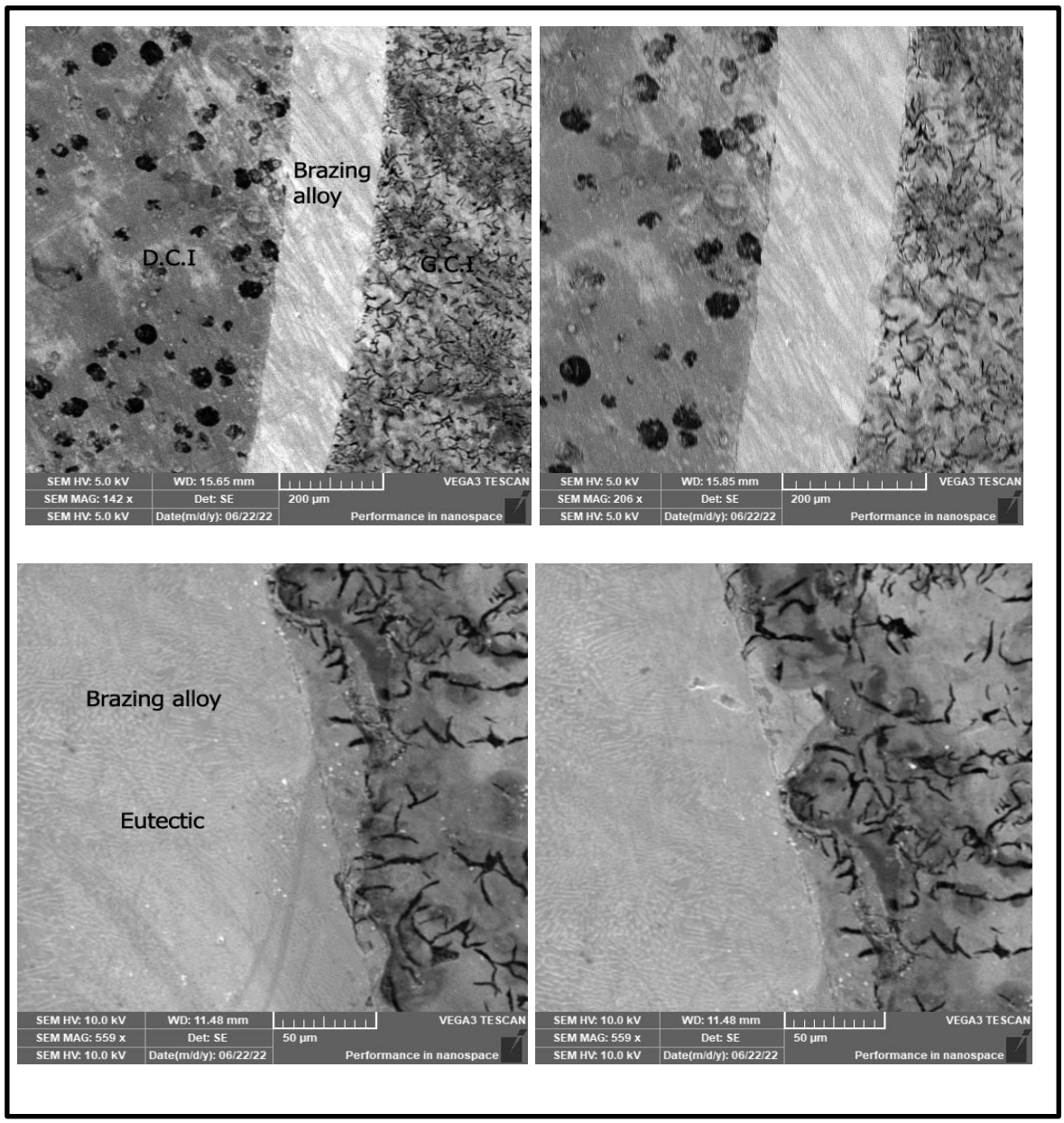


Figure (4.14): SEM for the ductile/grey cast irons brazed by BAg-8 filler metals using different magnifications.

4.4 Energy Dispersive Spectrometer (EDS)

The highest value of Fe presented at the interface between ductile cast iron and brazing alloy were (46.7%) when brazing by Ag20 filler metal, while the value of Cu was (30.8%). The other elements were lessees values as show in Table (4.1). Figures (4.15 and 4.16) shows EDS line and EDS mapping.

Table (4.1): Percentage of Elements of Data Mapping Analysis.

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
Si	4.3	0.2	2.0	0.1
Fe	46.7	0.3	43.2	0.3
Cu	30.8	0.3	32.4	0.4
Zn	14.3	0.3	15.5	0.4
Ag	3.9	0.1	6.9	0.1

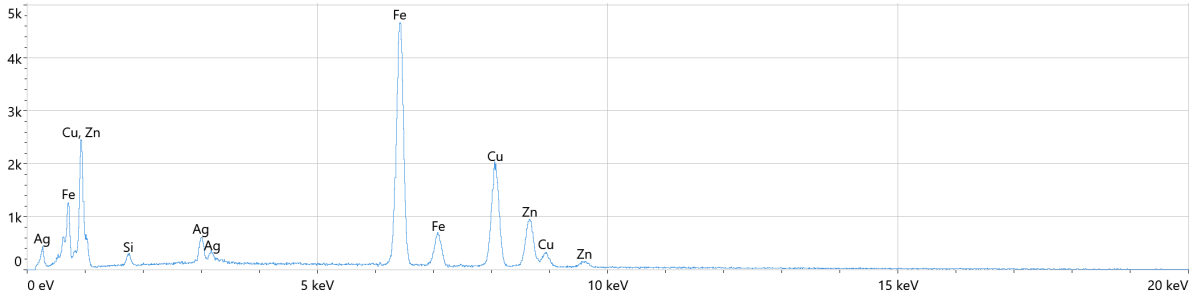
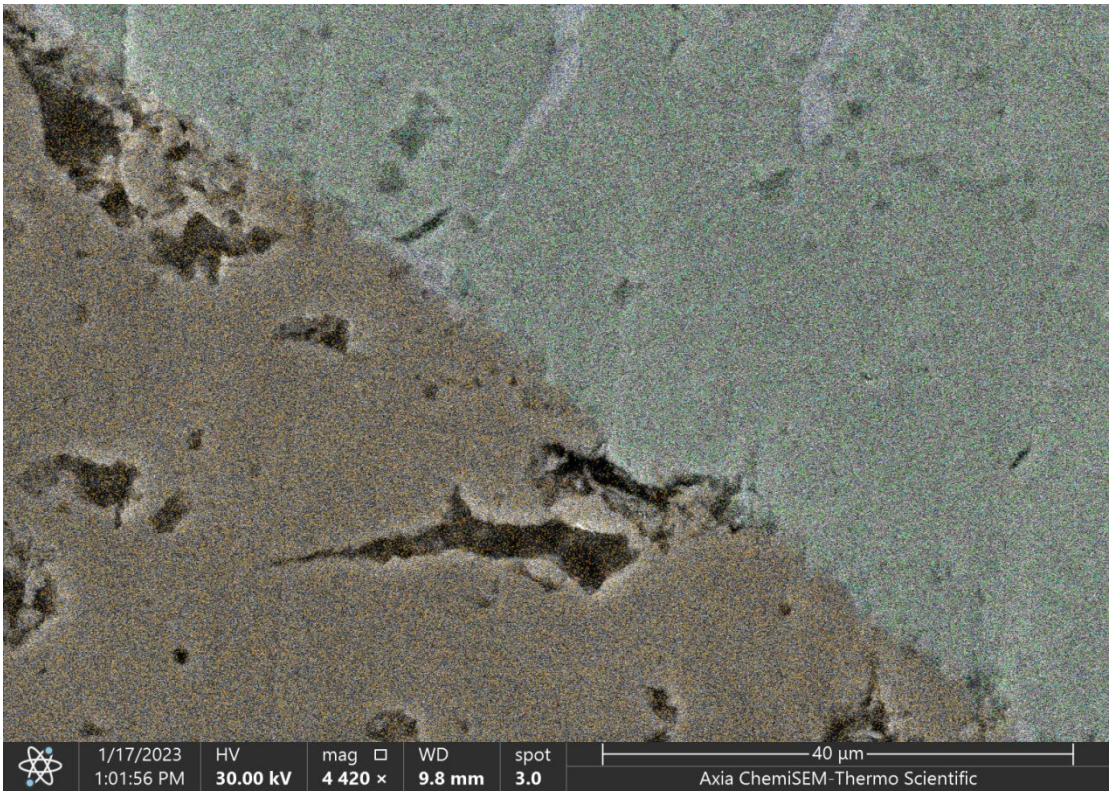


Figure (4.15): Energy dispersive spectroscopy (EDS) line scan for sample D.C.I to G.C.I bonded using Ag20 filler metal.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1:01:56 PM
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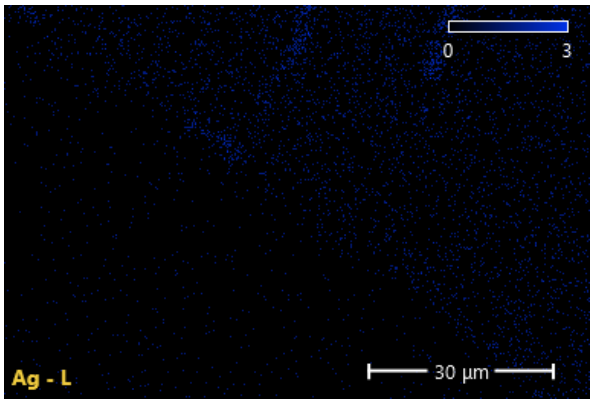
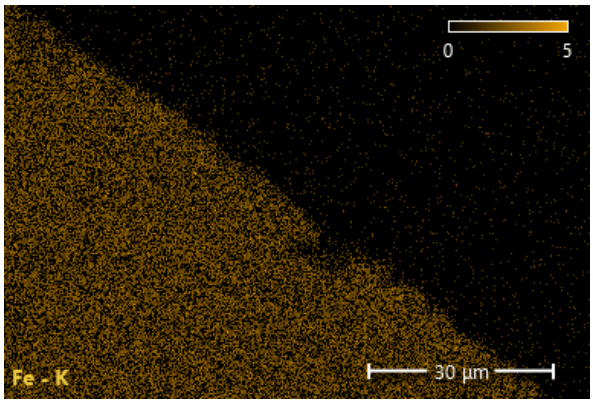
Axia ChemiSEM-Thermo Scientific


0
3
Ag - L
30 µm


0
5
Fe - K
30 µm

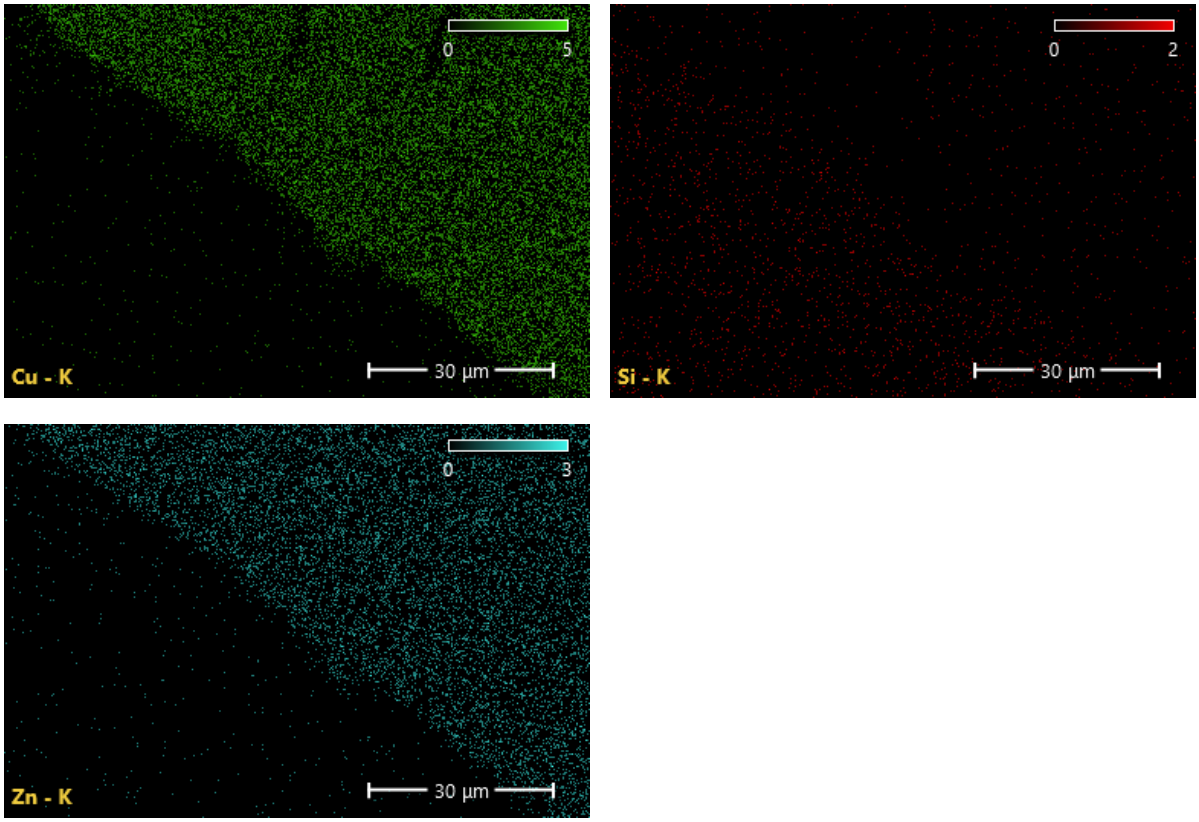
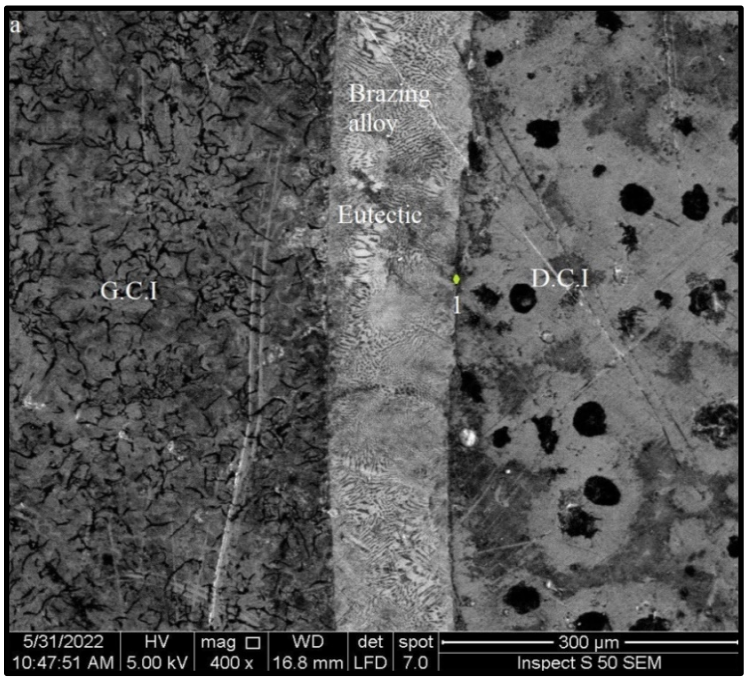


Figure (4.16): EDS micro-points analyses for the ductile/grey cast irons brazed by Ag20 filler metals.

The highest value of Fe presented in the cast iron was (63.90%) at the interface between brazing alloy and ductile cast iron when brazing by Bag-8 filler metal, while the value of C was (9.47%). The other elements were less values as show in (Table 4.2). Ag has a value from the EDS point which is (2.59%) at the same point, copper and silicon had the high value (10.30%, 4.20%), respectively and Manganese have a value (4.73%). The silver appears with bright color in SEM Micrograph, as shown in Figure (4.16). While the highest value of copper appears with dark color.

Table (4.2): Percentage of Elements in One- Point of EDS Analysis.

Point	Fe wt%	C wt%	Cu wt%	Ag wt%	Si wt%	Ti wt%	Mn wt%
1	63.90	9.47	10.30	2.59	4.20	4.82	4.73



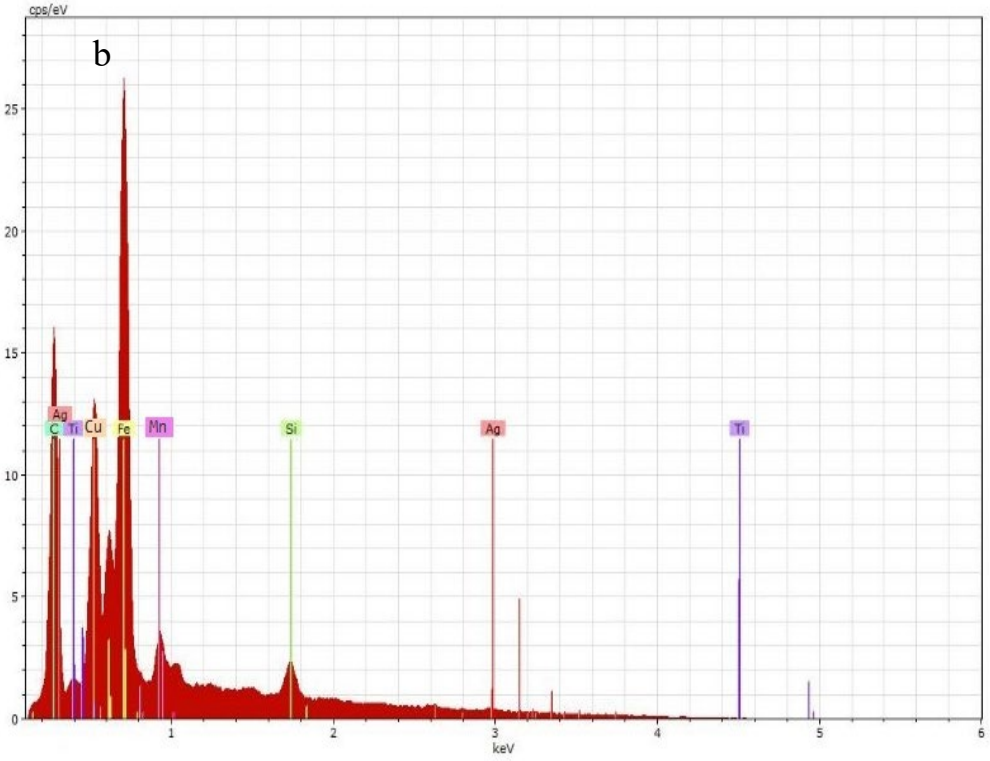


Figure (4.17): EDS micro-points analyses (a) sem to the point on the cross section of dissimilar joint at the interface by using BAg-8 filler alloy (b) the percent of elements in wt. % for this point.

4.5 Mechanical Testing

4.5.1 Compression-Shear Test of Brazing Joints

A compression shear strength test was performed at room temperature to determine the strength of the brazed joints. The values of the shear force for the cast iron joints are affected by the brazing filler for two types of cast irons.

Therefore, it was noticed that the shear strength of the joints using Ag20 as a filler alloy is higher that produced using BAg-8 (Figure 4.18) due to the quantity of copper (44%) in the Ag20 filler metal, whereas the amount of copper

in the BAg-8 filler metal is only 28% as (Table 3.3). Silver –copper compounds are relatively ductile, silver and silver alloys are used as brazing filler metals to produce brazed joints [3].

The recommended joint clearances for filler metals (Ag20 and BAg-8) according to AWS-ASTM classifications are (0.075-0.2 mm and 0.05-0.15mm) respectively. If clearances are smaller than those recommended, the joint strength may decrease as a result of excessive voids, flux inclusions, and other factors. Larger clearances are provided for more machining flexibility, but they also result in weaker joints and waste filler metal [51].

Table (4.3) presents the effect of brazing filler on the joint shear strength by using furnace for brazing two types of cast irons: (ductile cast iron (D.C.I) and grey cast iron (G.C.I)). Brazing temperature and time were set up of (820, 780˚C, 15 min, for Ag20 and BAg-8 respectively, from experimental work).

Table (4.3): Effect of Brazing Filler on the Joint Strength.

Base metals	Type of filler	Shear strength (MPa)
D.C.I/D.C.I	Ag20	286.624
D.C.I/D.C.I	BAg-8	189.745
G.C.I/G.C.I	Ag20	155.159
G.C.I/G.C.I	BAg-8	97.707
D.C.I/G.C.I	Ag20	276.878
D.C.I/G.C.I	BAg-8	185.223

Table (4.3) shows sharp contrast in shear strength values between the ductile cast iron joints and grey cast irons for the two types of brazing filler metals that brazed in furnace. The failure mode of the joints occurred in brazing alloys for both ductile cast iron joints and grey cast iron joints. It is observed, that the joints produced using Ag20 have more shear strength those produced using BAg-8 due to the presence of more contain of Zn and more strength by solid solution of copper due to the more stress field created around solid solution and more distortion of the lattice occurs due to solid solution strengthen by Zn content as shown in Table (4.3).

Figure (4.18) and (4.19) show the sharp contrast in shear strength values, among the brazed joints using Ag20 and BAg-8 filler alloys respectively.

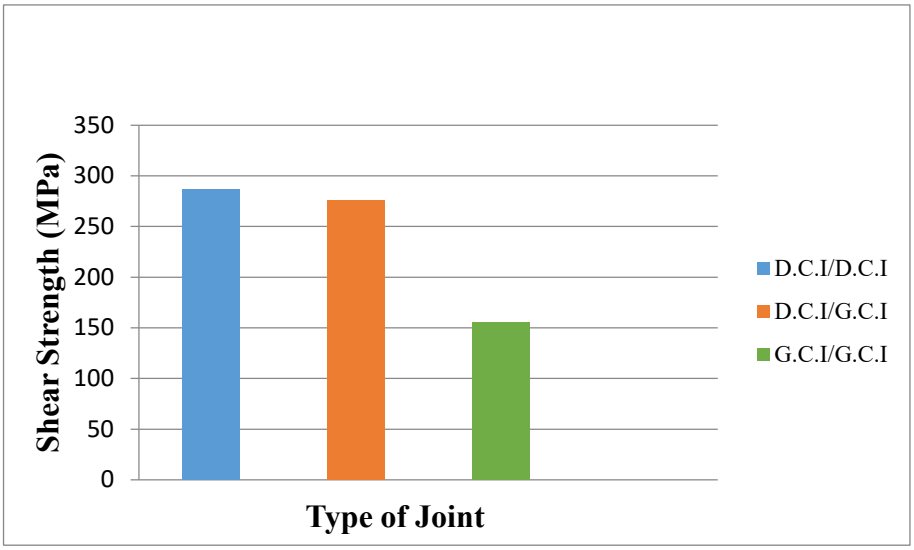


Figure (4.18): Shear strength of the cast iron joints using (Ag20) filler alloy.

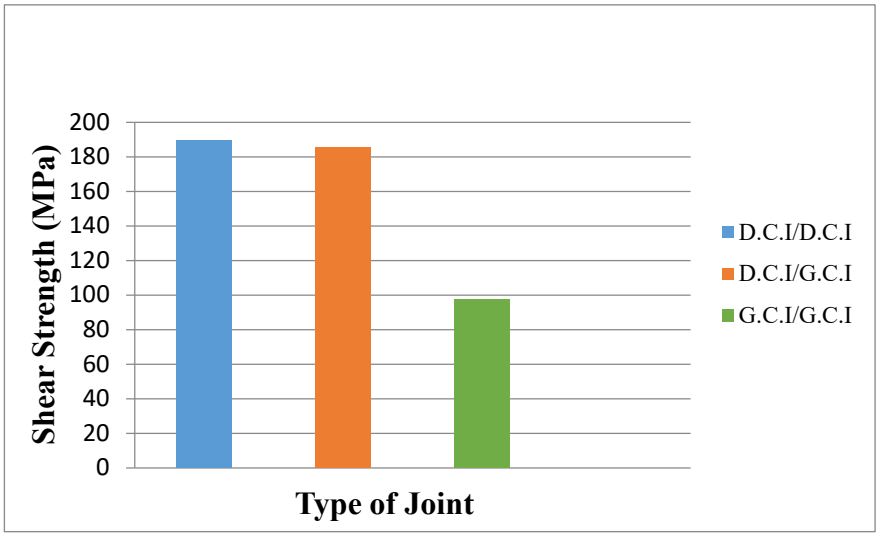


Figure (4.19): Shear strength of cast iron the joints using (BAg-8) filler alloy.

Figure (4.18) and (4.19) show that the type of filler metal affected the shear strength values. The Ag20filler metal was perfect and stronger than other filler to more adhesion work.

4.5.2 Microhardness Tests

Table (4.4) presents the results of the Vickers microhardness (HV) test for the brazed cast iron joints. The hardness was measured at the brazing alloy for all samples, and the gap between metals was 0.1mm. The cast irons had the highest hardness values, followed by the brazing alloy. It was noticed that the hardness of the Ag20joints was more than that of the joints bonded by BAg-8 ((Figure 4.20 and 4.21), as a result of the greater amount of zinc that distort the lattice of solid solution due to hinder the dislocation movement [47].

Table (4.4): Effect of Brazing Filler metals on the Hardness of Joints.

Base metals	Type of filler	Hardness HV
D.C.I/D.C.I	Ag20	126
D.C.I/D.C.I	BAg-8	104
G.C.I/G.C.I	Ag20	143
G.C.I/G.C.I	BAg-8	98
D.C.I/G.C.I	Ag20	148
D.C.I/G.C.I	BAg-8	87

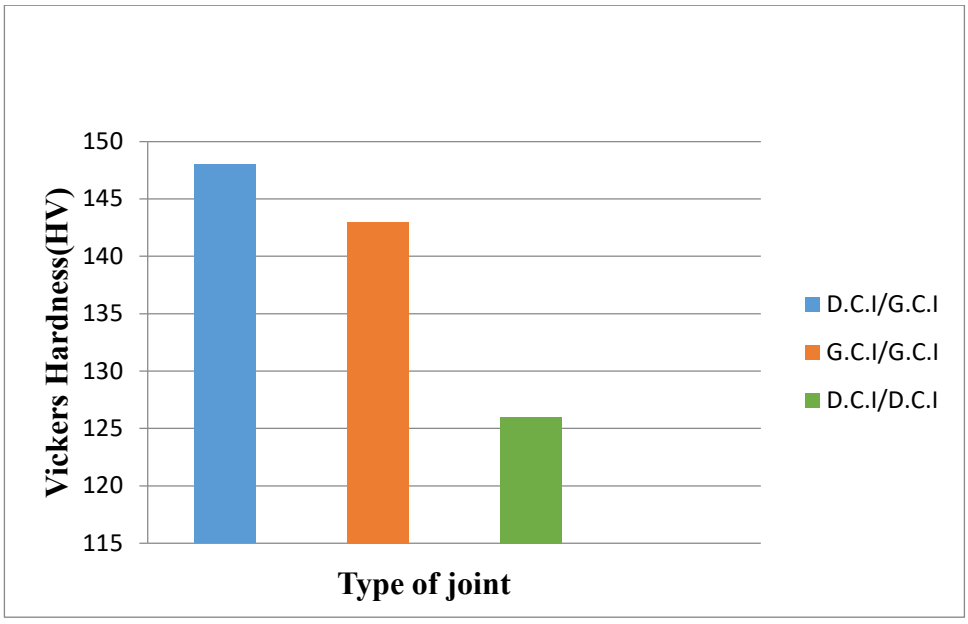


Figure (4.20): Microhardness test results for Ag20 joints

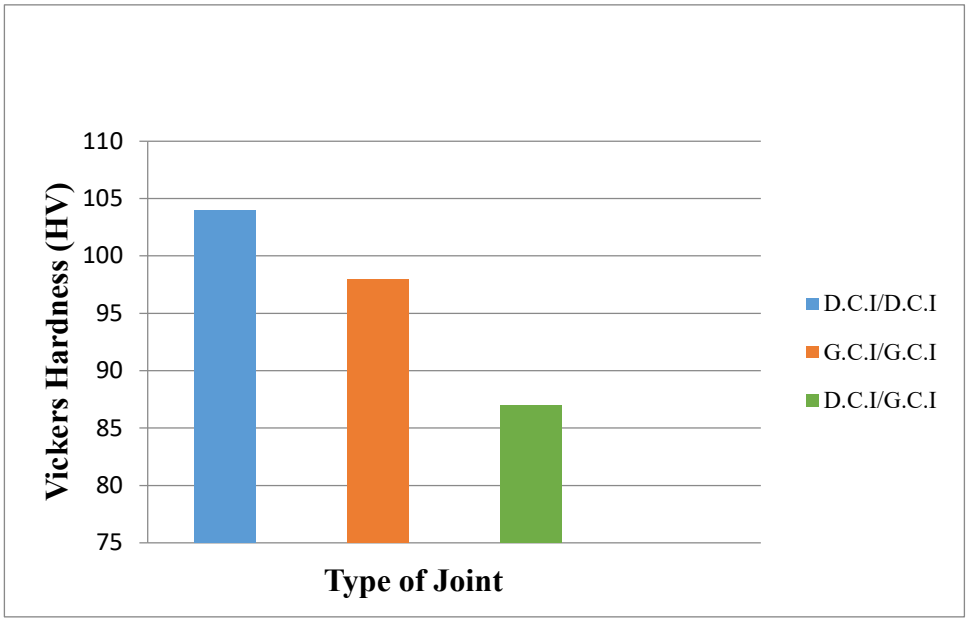


Figure (4.21): Microhardness test results for BAg-8 joints

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

The joining of similar ductile cast iron, similar grey cast iron and dissimilar ductile cast iron to grey cast iron is performed by furnace brazing using brazing filler metals Ag20 and BAg-8 as a rod and foil respectively. The brazed joints were tested through the microhardness and the compression tests for evaluating their shear strength, XRD for predicting the phases developed, in addition to EDS, SEM, and OM.

Accordingly, the results of the present study, can be concluded as follow:

1. D.C.I and D.C.I, G.C.I and G.C.I, and D.G.I and G.C.I concentric lap joint made with Ag20 and BAg-8 brazing alloys failed at the brazing alloys when stressed in shear.
2. The highest value of shear strength and hardness was found in the samples that were brazed with Ag20 filler metal.
3. Cleaning cast irons by fused salts before brazing enhanced the wettability between them and satisfactory joints were obtained.
4. Ductile to ductile cast irons brazed with both filler alloys exhibited the highest value of shear strength (286.624 MPa).
5. The XRD patterns did not identify the formation of the intermetallic phases or oxidation. From X-ray diffraction analysis, presence of α (Cu) solid solution phase between ductile cast iron and grey cast iron was when brazing done by Ag20 filler metals, and Ag base solid solution lamellar eutectic consists of silver and copper was when cast irons brazed by BAg-8.

6. The shape of graphite in D.C.I changed from its nodular to compacted shape during brazing process.
7. The nodular graphite in D.C.I migrated from its original site towards the interface during brazing process.

5.2 Recommendations for Future Work

1. Studying the effects of time or temperature on the furnace sample.
2. Using Bag-7 filler metals to brazing cast irons.
3. Studying the effects of torch brazing on the same work.
4. Using the chemical treatment before brazing.
5- Studying the brazing of cast iron to steel or other alloys.

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Appendix A

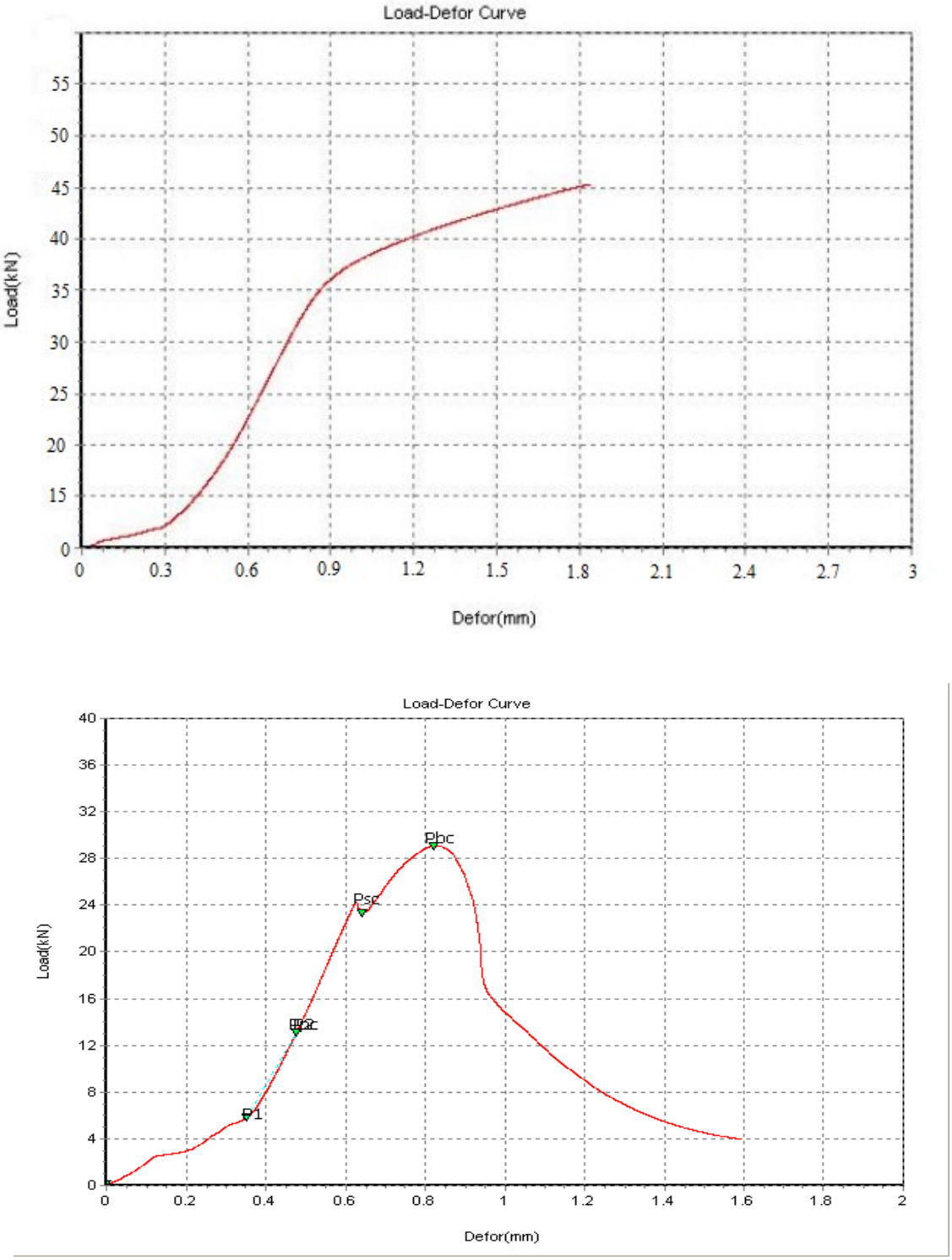


Figure (1): Load-Deformation Curve of the Joints Ductile Cast Iron / Ductile Cast Iron by Ag20 and BAg-8 Filler Metal

Appendix A

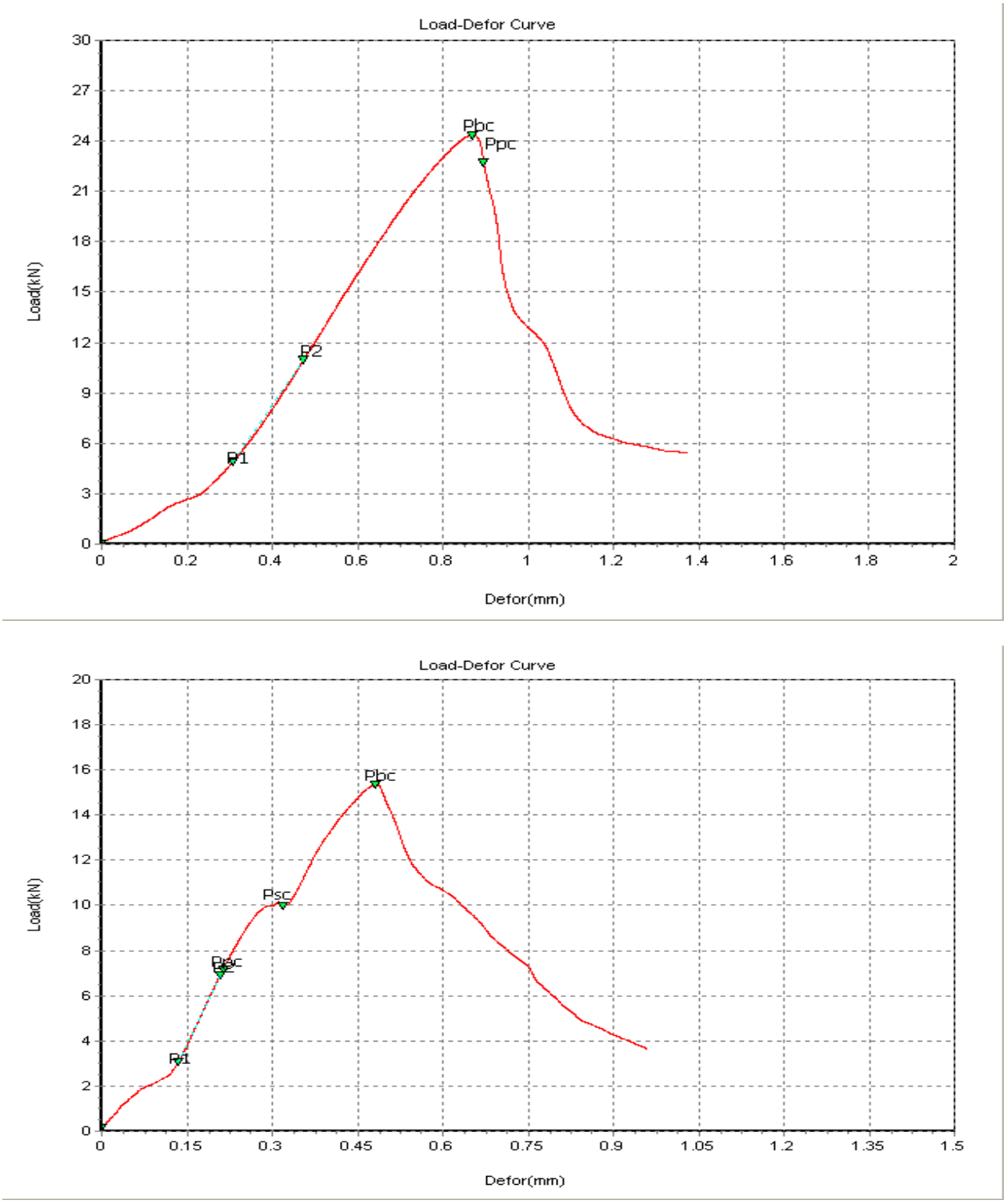
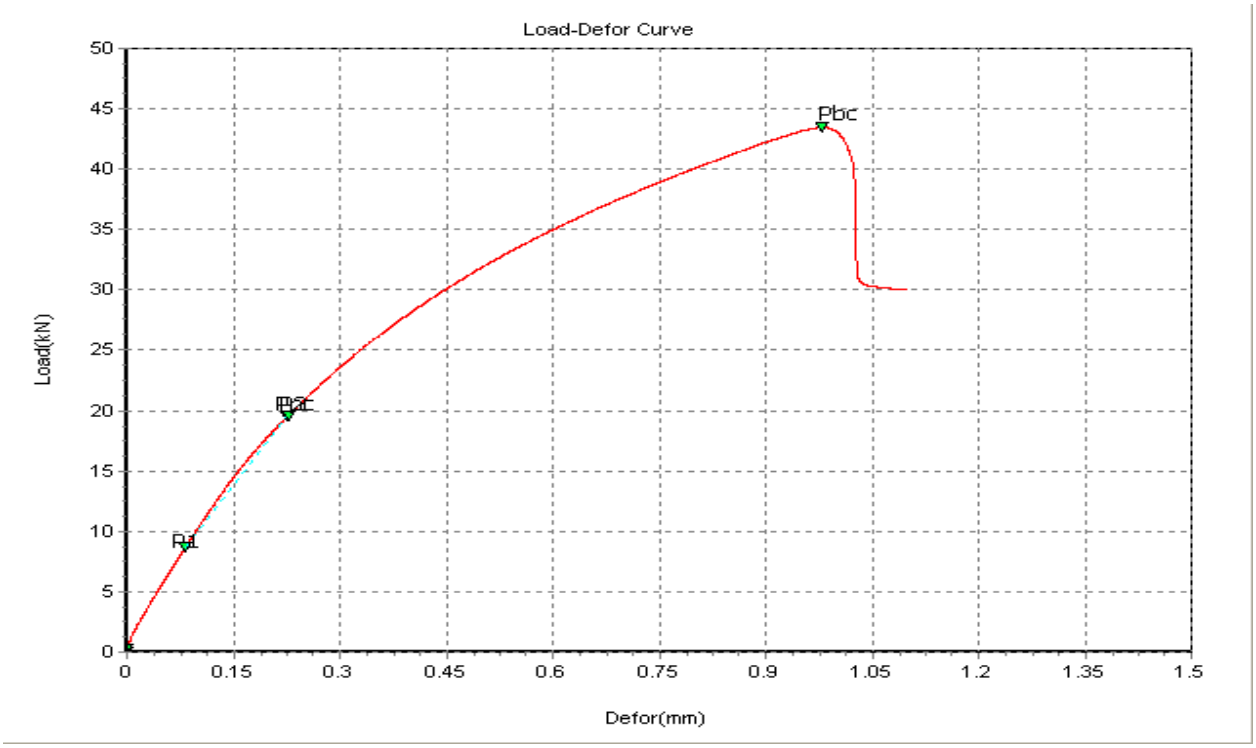


Figure (1): Load-Deformation Curve of the Joints Grey Cast Iron / Grey Cast Iron by Ag20 and Bag-8 Filler Metal.

Appendix A



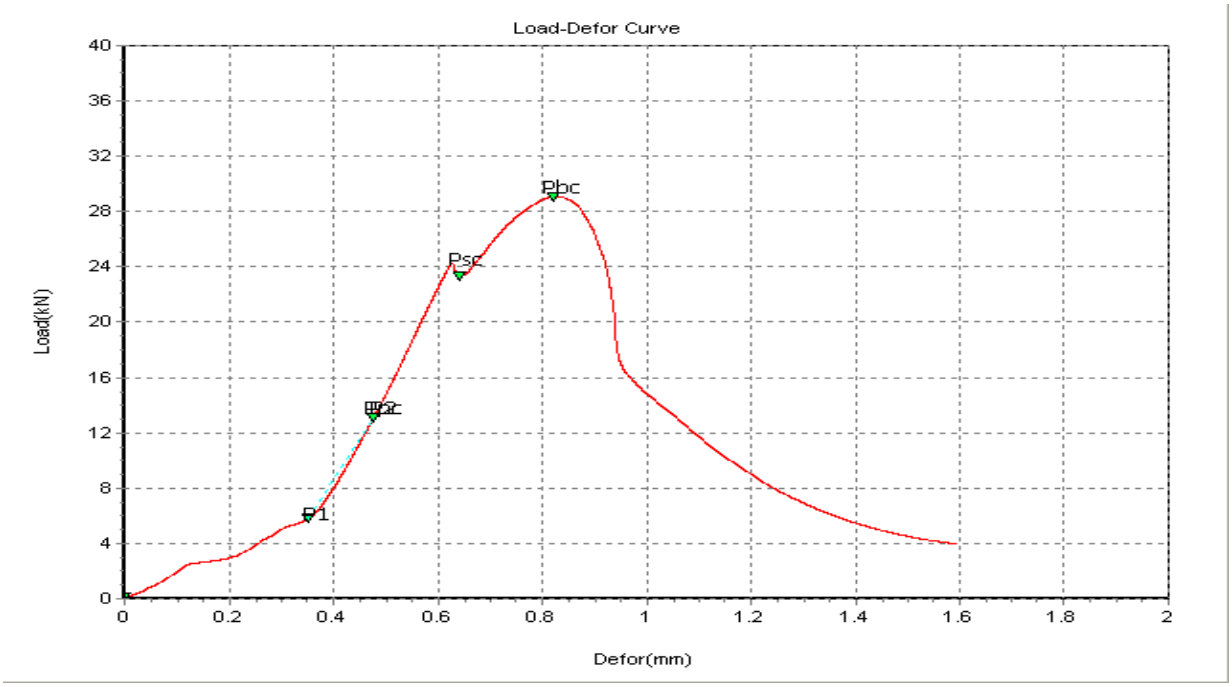


Figure (1): Load-Deformation Curve of the Joints Ductile Cast Iron / Grey Cast Iron by Ag20 and Bag-8 Filler Metal.

الخلاصة

في هذا البحث يتم ربط حديد الزهر عن طريق الربط بالمونه باستخدام نوعين من معادن الملئ (الحشو) Ag20 وBAg-8. كلا المعدنين المستخدمين من حديد الزهر يتداخلان للربط بطول 5 ملم وسماحه بين المعدنين 0.1 ملم. وقد تم ربط المعدنين بالفرن الكهربائي في جو محمي بغاز الاركون الخامل بدرجة حراره 780˚C , 820 ˚C ولمدة 15 دقيقه.

تم دراسة البنيه المجهريه للربط بالمجهر الضوئي والمجهر الالكتروني الماسح مع مطياف تشتيت الطاقة (SEM&EDS) وقد استخدم التحليل الطيفي (X-Ray) لتحديد الاطوار الناتجه من الربط بينما تم دراسة الخواص الميكانيكية باختبار القص بالضغط لمعرفة مقاومة الربط والصلاده الميكرويه.

اظهرت النتائج ان اعلى مقاومة ربط كانت في النماذج التي تم ربطها بواسطة معدن الملئ Ag20 بينما كانت تسلسل اعلى قيمة مقاومة قص للنماذج تحت نفس الظروف هي كالتالي D.C.I/D.C.I, D.C.I/G.C.I واخيرا G.C.I/G.C.I.

البنيه المجهريه بينت وجود محلول جامد غني بالنحاس ((Cu(SS)) وكذلك طبقات من اليوتكتك للماده الرابطة عندما يتم الربط بواسطة Ag20. بينما النماذج التي تم ربطها بواسطة BAg-8 يتكون تركيبها المجهري من طبقات يوتكتك متعاقبه من النحاس والفضه. البنيه المجهريه تكشف عن تغير شكل الكرافيت في حديد الزهر المطيلي D.C.I من الشكل العقدي (nodular) الى الشكل المضغوط (compacted) خلال عمليات الربط. كما يهاجر الكرافيت من موقعه الاصلي باتجاه الحد الفاصل بين سبيكة الربط (brazing alloy) وحديد الزهر المطيلي.

التحليل الطيفي (XRD) لا يشير الى وجود مركبات شبه معدنيه او أكاسيد. XRD يشير الى وجود محلول جامد غني بالنحاس (α) في حالة ربط حديد الزهر المطيلي مع حديد الزهر الرمادي بواسطة Ag20. ومحلول جامد من النحاس والفضه غني بالفضه في حالة استخدام BAg-8.

Chapter one

Introduction

Chapter two

Theoretical part

Chapter Three

Experiential part

Chapter Four

Results and Discussions

Chapter Five

Conclusions and Recommendations for future woks

References

Abstract