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Mechanical Integrity of Printed Circuit Heat Exchanger

Ali M. Aljelawy*
Ph.D. student
University of technology
Baghdad, Iraq
engaljelawy@gmail.com

Amer M. Aldabbagh
Assist. Prof
University of technology
Baghdad, Iraq
Aamermajeed@yahoo.com

Falah F. Hatem
Assist. Prof
University of technology
Baghdad, Iraq
falahhatem59@yahoo.com

ABSTRACT

The printed circuit heat exchanger is a plate type heat exchanger with a high performance and compact size. Heat exchangers such as this need a unique form of bonding and other techniques to be used in their construction. In this study, the process of joining plates, diffusion bonding, was performed and studied. A special furnace was manufactured for bonding purposes. The bonding process of copper metal was carried out under specific conditions of a high temperature up to 700 ^{o}C, high pressure of 3.45 MPa, and in an inert environment (Argon gas) to make tensile samples. The tensile samples are cylindrical shapes containing groves representing the flow channels in the printed circuit heat exchanger and checking their tensile strength in addition to the standard shape of the tensile specimen to check the yield and ultimate strength of the copper. A higher tensile strength was obtained for diffusion bonded specimens than the yield strength of copper, up to 1.35 times the copper yield strength. The tensile strength decreases with the increase in the number of groves and the decrease in the distance between one grove and another. This is because the stress is concentrated in the sharp corners. A prototype heat exchanger of two plates and a header to be tested for its compressive strength was also manufactured. The results showed that the bond bears an air pressure of up to 8 bar without fail. It was also found to withstand a hydraulic pressure of up to 60 bar until it reached failure.

Keywords: Heat exchanger; Diffusion bonding; printed circuit heat exchanger; mechanical integrity

المتانة الميكانيكية للمبادل الحراري للدائرة المطبوعة

*** علي محمد الجيلاوي**
طالب دكتوراه
الجامعة التكنولوجية

عامر مجيد الدباغ
استاذ مساعد
الجامعة التكنولوجية

فلاح فاخر حاتم
استاذ مساعد
الجامعة التكنولوجية

*Corresponding author

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الخلاصة

يعتبر المبادل الحراري للدائرة المطبوعة نوعًا واعدًا من المبادلات الحرارية من نوع بلات نظرًا لأدائه العالي وصغر حجمه. لكن تصنيع هذا النوع من المبادلات الحرارية يتطلب نوعًا خاصًا من الترابط وعمليات أخرى. في هذه الدراسة تمت دراسة عملية ربط الصفائح وترابط الانتشار. تم إجراء عملية الترابط لمعدن النحاس في ظل ظروف معينة من درجات الحرارة المرتفعة والضغط العالي والبيئة الخاملة لعمل عينات الشد. تكون عينات الشد على شكل أسطواني تحتوي على بساتين تمثل قنوات التدفق في المبادل الحراري للدائرة المطبوعة وللتحقق من قوة شدها. بالإضافة إلى الشكل القياسي لعينة الشد للتحقق من المحصول والقوة النهائية للنحاس. تم الحصول على مقاومة شد أعلى من مقاومة الخضوع للنحاس. تتناقص قوة الشد مع زيادة عدد البساتين وبتقليل المسافة بين بستان وآخر لأن الضغط يتركز في المناطق الحادة. كما تم تصنيع نموذج أولي لمبادل حراري من لوحين ورأس ليتم اختباره من حيث قوته الانضغاطية. حيث أظهرت النتائج أن السند يتحمل ضغط هواء يصل إلى 8 بار دون أن يفشل. كما وجد أنه يتحمل ضغط هيدروليكي يصل إلى 60 بار حتى يصل إلى الفشل.

الكلمات الرئيسية: مبادل حراري, ترابط الانتشار, المبادل الحراري للدائرة المطبوعة, المتانة الميكانيكية

1. INTRODUCTION

PCHE has an interesting and distinctive design that requires specific, precise manufacturing techniques. However, these technologies are somewhat monopolized by the companies developing this type of heat exchanger, which is supposed to prompt specialists to research its manufacture and find the best and simpler ways to manufacture it. These techniques are highly precise and professional; few researchers mention them in the field of PCHE fabrication and mechanical integrity. In addition, this type of exchanger is a promising type, and few researchers have paid attention to its mechanical resistance.

(Oh and Kim, 2008) used an ABAQUS two-dimensional model to perform a stress analysis on a PCHE and examined numerous heat exchanger stress behavior effects. They discovered that the lifetime of a PCHE was roughly 35 years at an operating temperature of 900 °C and that the offset channel arrangement design lowered the stress concentration by up to 50%, thus leading to a large improvement in PCHE lifetime. This research also concluded that a three-dimensional stress analysis was necessary to obtain more accurate findings.

(Mylavarapu et al., 2012) used diffusion bonding to manufacture two heat exchangers out of Alloy 617 plates. To promote the bonding, an interlayer of 2.5 Micrometer thick of pure nickel was deposited electrolytically between the two faying surfaces before diffusion bonding. The existence of stable surface oxides of titanium and aluminum on Alloy 617 plates led to the necessity for a Ni interlayer. Because nickel is a high melting temperature ductile metal that can handle extreme service temperatures, it was selected as an interlayer material. The bonding was done in a vacuum chamber with a starting vacuum of less than 0.013 Pa, and the pieces were heated to roughly 1120 °C in stages, each with a different rate of temperature increase and holding pressure. The bonded pieces were kept for 4 hours, and the bonding pressure changed from 6.8 to 10.2 MPa.

(Lee and Lee, 2014) performed a numerical study to investigate the structural integrity of intermediate PCHE for Sodium-cooled Fast Reactor (SFR) with Supercritical CO_2 (sCO_2). The stress fields of typical PCHE channels were simulated using ANSYS-Mechanical, with temperature fields imported from FLUENT simulation. The predominant source of stress is discovered to be mechanical stress caused by pressure loading. Because the plasticity reduces the local stress concentration at the PCHE channel tips, the PCHE type intermediate heat exchangers manufactured of SS316 are expected to cope with the ASME design requirements, owing to the structural temperature being below the effective creep-inducing limit reliably. The PCHE real life time for SFR-sCO_2 is expected to be impacted by the changes in the mechanical properties of

SS316 caused by the reactions with sCO_2, such as wall thickness changes and the creation of oxide films, and gaseous species diffusion inside the PCHE body.
(Shirzadi, 2019) performed a study on the diffusion bonding of aluminum plates using gallium assistance to overcome the stable aluminum oxides. The plates were machined by wire cut to produce the flow channels. The welded plates were then tested by bending and tensile tests.
In this study, diffusion bonding of free oxygen copper was performed for the printed circuit heat exchanger to investigate the mechanical integrity of the bond.

2. DIFFUSION BONDING

Diffusion bonding is a solid-state bonding when two basically flat surfaces are kept together under applied pressing load for a period of time at an increased temperature generally above (0.5-0.8) Tm (melting temperature) until a bond is formed **(Khaleel, 2018) and (Adnan Jumaa Alewi, 2010)**. The pressure must be sufficient to cause contact between two components that need bonding, resulting in micro deformation of the contact area of the pieces. At the same time, the temperature is used to increase the energy of atoms to motivate them to move from one surface to another. All of this must be done in a controlled environment away from oxygen.

There are many parameters that influence the quality of diffusion bonding, such as the bonding temperature, pressure, bonding time, and surface roughness and oxides. All parameters can be easily controlled during the bonding process except the surface oxides, which may need special techniques to reduce or eliminate their effects. Oxide layers on faying surfaces may influence the ability of some materials to form solid-state diffusion bonds. Certain oxide layers dissolve in the bulk of the metal or break down at the bonding temperature (for example, those of steel, copper, titanium, tantalum, and zirconium), allowing for easy establishment of metal-to-metal contact at the interface **(Shirzadi, 1997)**. On the other hand, if the oxide layer is chemically stable, as is the case with aluminum-based materials, forming a metallic bond may be challenging. The existence of a chemically stable aluminum oxide surface layer is the primary limitation in the majority of welding operations. Studies have been made to achieve a high-strength diffusion bonding of different materials.

In the present work, and at the beginning, aluminum was supposed to be the base metal for PCHE, but dealing with aluminum is difficult because of the stable oxides on its surface. These oxides can be removed, but they return to form very quickly. They are oxides with high melting points. One of the methods used to overcome oxides for diffusion bonding is the transient liquid phase diffusion bonding (TLDF) which is not solid-state welding. In this method, microfilm of another material is coated or electroplated on the base material and then diffusion bonded. As a result, a small melting region formed because of the formation of the eutectic phase, which has a lower melting point of the base material, which will break the oxides layer. But, also aluminum is hard to electroplate, and guess what? The reason is the oxides.
So, after these attempts to use aluminum in diffusion bonding, the decision was made to change the material. The most common material used in heat exchangers was copper. Then copper was used as the base material for diffusion bonding for its high thermal characteristics for heat transfer processes.

2.2 Diffusion bonding process

In order to perform the diffusion bonding process, special conditions for this process need to be provided, such as a high temperature and pressure, as well as a non-oxidizing atmosphere, are required. Also, it requires special processes to prepare the samples to be bonded. All of these conditions were provided by the manufacturer of the diffusion bonding system, and the components of this system will be presented.

2.2.1 Diffusion facility

A diffusion bonding facility consists mainly of three parts: the heating system, loading system, and deoxidizing system; these components are shown in **Fig. (1a) and (1b)**. The heating system is simply a furnace. The furnace consists of a high insulating chamber made of refractory bricks. To provide the furnace with sufficient heat, a Ni-Cr heater was used, which was wrapped and distributed within grooves in the inner walls of the furnace. The characteristics of the heater are 8 meters in length, 1.5 mm in diameter, and a power of 2000 watts. A thermostat control system and a type K thermocouple insulated ceramic material were used to control the temperature inside the furnace.

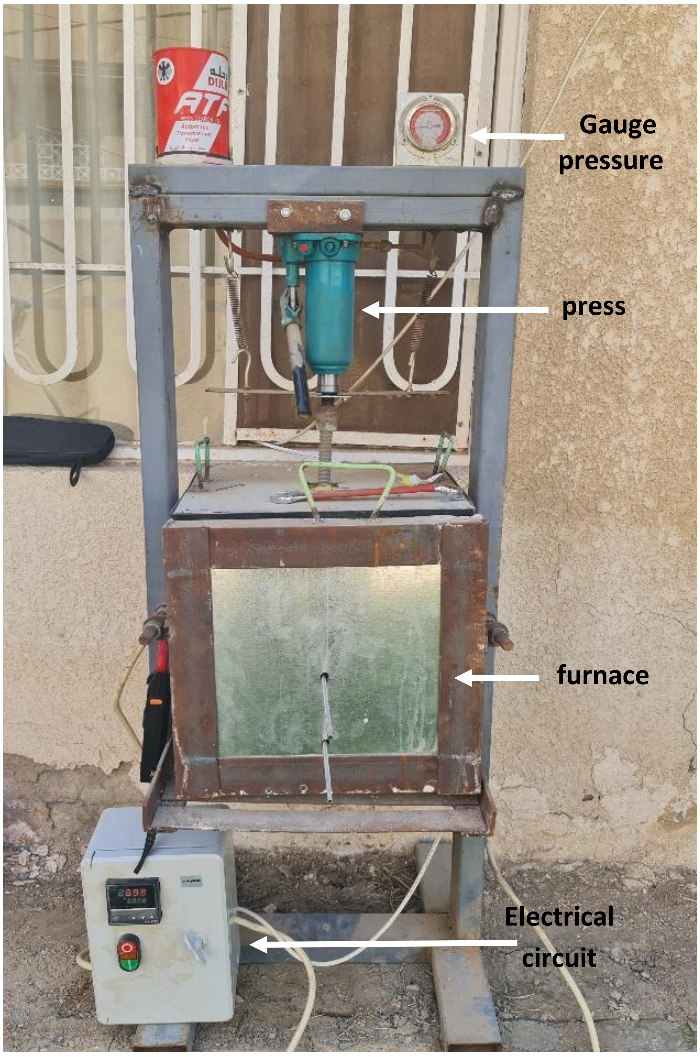


Figure (1a) diffusion bonding furnace

Figure (1b) furnace chamber

The other important point in diffusion bonding is the pressure load system. A hydraulic press was used with a capacity of 4 tons (each ton equals 10.4 MPa according to the piston area of 9.6 cm^2).

The press shaft enters the furnace through a hole in furnace ceiling.
To provide a non-oxidizing atmosphere, a retort was used. The retort is a closed chamber with two opening ports, upper and lower, which are continuously supplied with relatively heavy gas such as argon from the lower port to let the air inside the chamber exit from the upper port.

2.2.2 Surface preparation

The surfaces to be joined must be flat, smooth, and free of impurities. As a result, the surface of all specimens has been ground to achieve a suitably flat bonding surface. Specimens' surfaces have been ground by using different silicon carbide paper grades (400, 600, 1000, 2000, and 3000). Grinding was performed by a portable grinder machine, as shown in **Fig. (2 a)**.
Surface roughness after grinding was measured using a portable device as in **Fig. (2b)**, and it was found that the roughness value of the samples was between 0.6 and 0.8 micrometers.
Then, an ultrasonic bath apparatus was used to clean the specimens with acetone for 5 minutes to eliminate any contaminations that had adhered to the specimens, as shown in **Fig. (2c)**.

Figure (2a) portable grinder machine

Figure (2b) ultrasonic bath

Figure (2c) portable surface roughness device

2.2.3 Diffusion conditions and procedure

Diffusion bonding was carried out at a temperature of 700 °C, a pressure load of 3.45 MPa, and for 30 min, as recommended by **(Elmer et al., 2001)**. Several steps must be followed to perform diffusion bonding and can be listed sequentially as follows:

1- After preparing the specimens, they are placed in the jaw designed to hold and fix them and must be ensured that they are in contact with the surfaces to be connected; then, they are placed inside the retort.
2- The oven door is closed and set at a temperature of 700 °C, and the Argon gas bottle is opened with a low flow rate into the retort chamber.
3- When the temperature reaches the required value, the pressure load is applied with a value of 3.45 MPa for 30 min, and the diffusion bonding duration begins when the load is applied
4- Turning off the oven, remove the load up, and leave it to cool
5- When the temperature reaches a low value, the argon gas valve can be closed.

Some of the results of diffusion bonding work are shown in **Fig. (3)**.

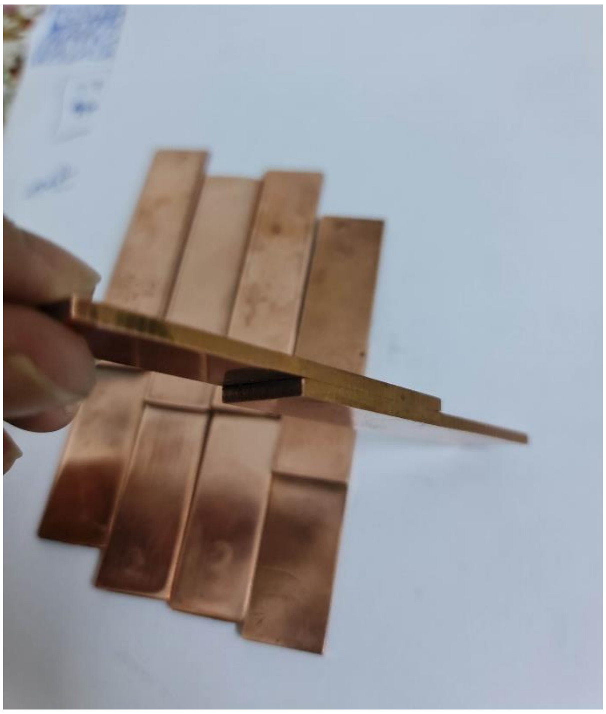


Figure (3a) diffusion bonded samples

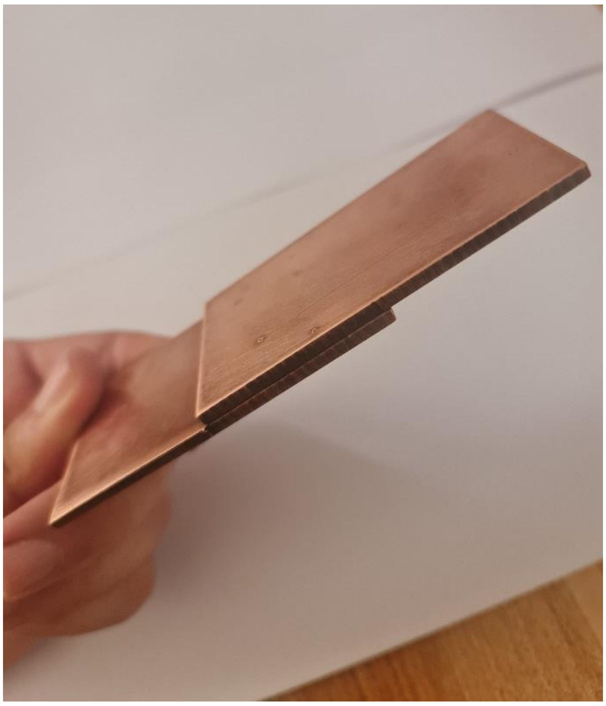


Figure (3b) diffusion bonded samples2

2.3 Tests and examination

2.3.1 Tensile test

A copper rod was machined to 20 mm diameter and then cut into cylindrical parts of 30 mm length, and then the joint surfaces were machined, simulating the flow channels of the PCHE with different numbers of channels or, in other words, with different cutting ratios as shown in **Fig. (4a)** to prepare for the diffusion bonding process. Then, the samples were diffusion bonded under the conditions mentioned previously. **Fig. (5)** shows the diffusion bonded samples.

Tensile strength tests on base metal and bonded specimens have been performed. The base metal has been machined into the standard tensile test specimen according to **(ASTM E8-E8M)** shown in **Fig. (4b)**. The bonded specimens were made from two cylindrical shapes as mentioned above. The tensile strength test was conducted using the tensile test unit (WDW -200E) shown in **Fig. (6)** with a crosshead speed of 0.2 mm/min in the Production and Metallurgy Engineering Department at the University of Technology. The yield strength and ultimate tensile strength were obtained from this test and listed in **Table 1**. Results showed that the tensile strength of the bonding samples is higher than the yield strength of the base material. When the cut ratio is increased, the tensile strength decreased due to the stress concentrations in the bonding areas. A small decrease in the bond strength is obtained at the same cut ratio but keeping the cut slots a little close to each other as in sample number 4.

Table 1: Measured tensile strength of Cu base metal diffusion bonded samples.

Sample no.	No. of slots	Cut shape	Area cut ratio Ac/A	Ultimate strength (Mpa)	Yield strength (Mpa)
Base metal	-----		----	219	44
1	3		36%	59.7	---
2	4		45%	55.2	---
3	5		57%	52.1	---
4	3		36%	58.1	---

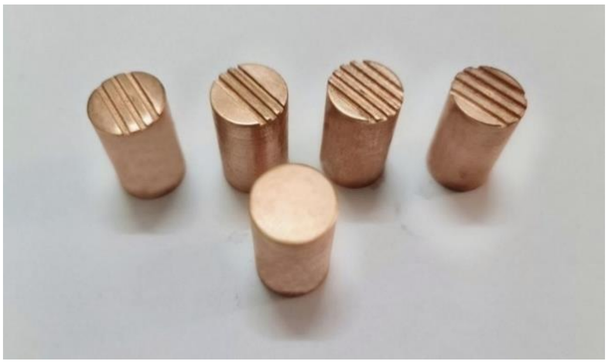


Figure (4a) diffusion bonding samples with different cutting ratios

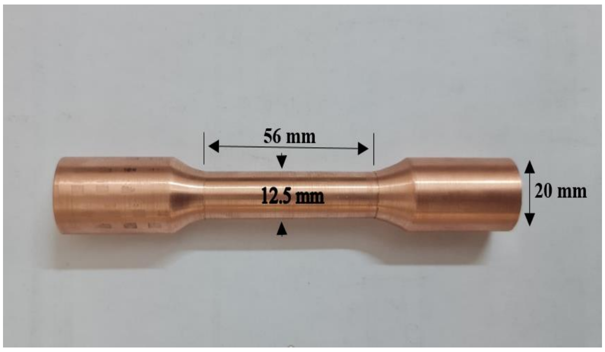


Figure (4b) the standard tensile test specimen

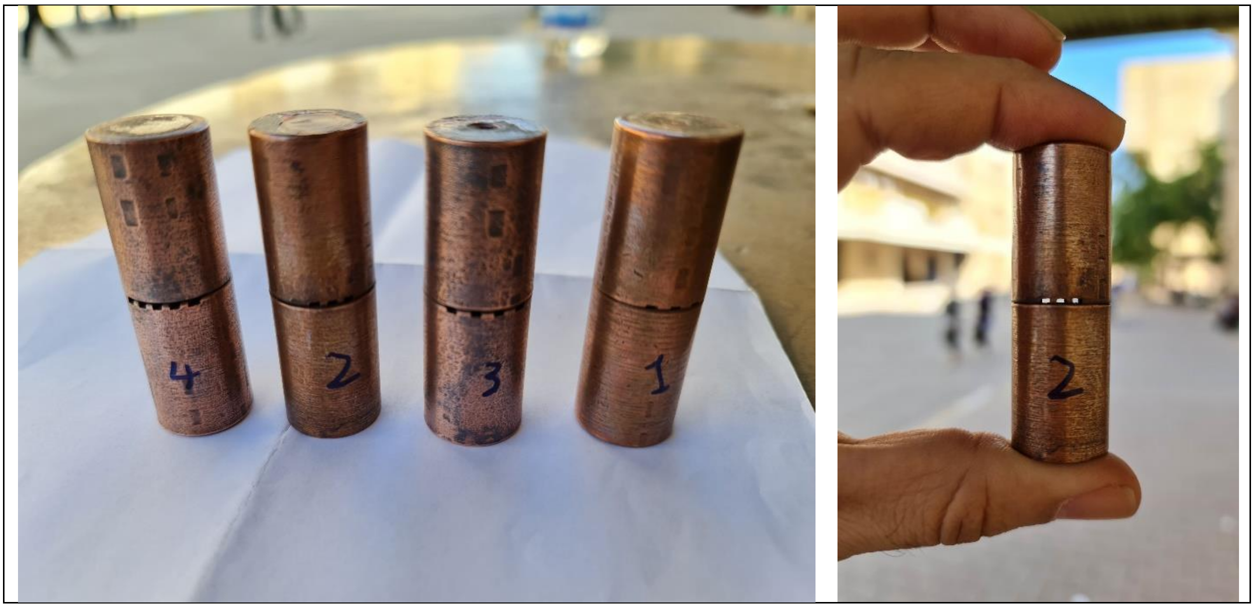


Figure (5) diffusion bonded samples with a different area cut ratios

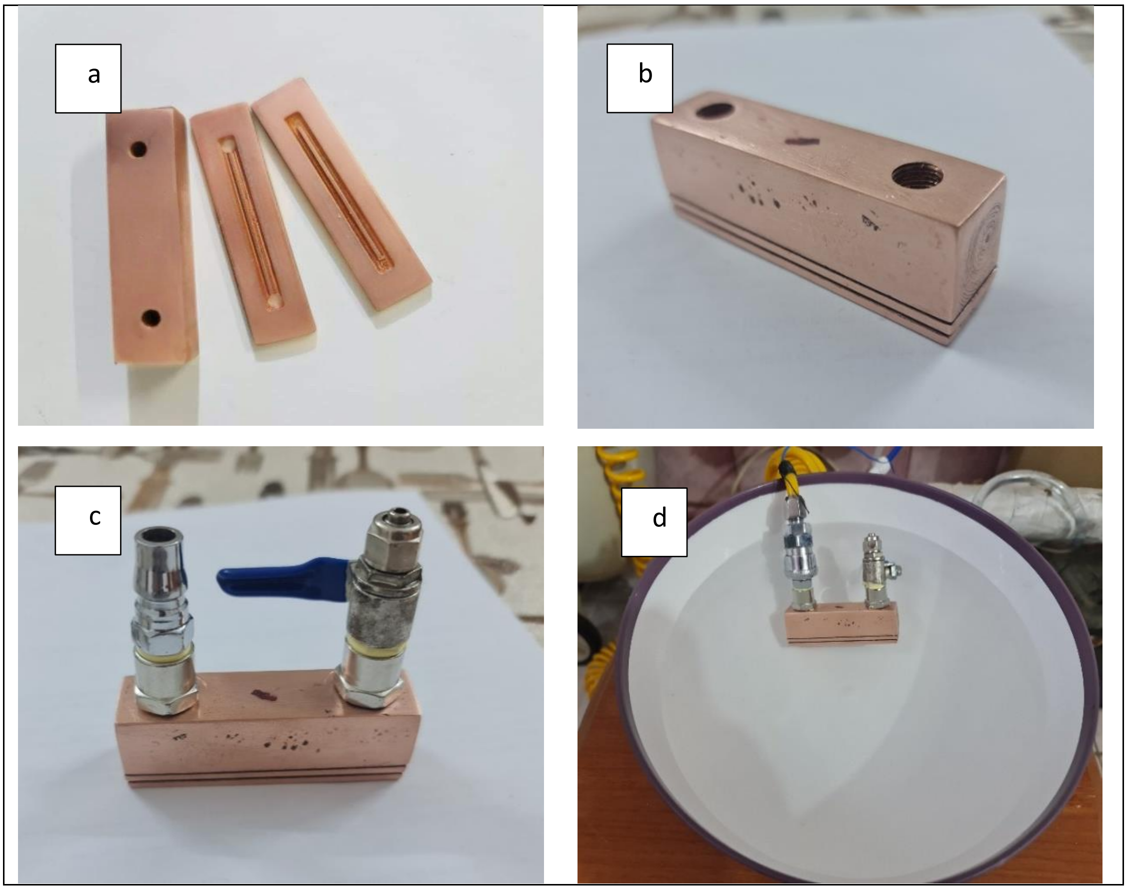
Figure (6a) tensile test device

Figure (6b) specimen tensile test

2.3.2 Compression test

It is important to know that the tensile test may not provide accurate knowledge of the strength of the heat exchanger because there may be certain weak points and strong ones. Therefore, another test was adopted, which is the compression test.

A mini heat exchanger was manufactured by diffusion bonding consisting of two copper plates with two channels on their surfaces and an upper copper block to facilitate the process of connecting the inlet and outlet fittings of the testing fluid, as shown in **Fig. (7a)**. The bonding process was carried out under the same welding conditions as the previous tensile samples resulting the mini heat exchanger block, as shown in **Fig. (7b)**. The inlet was connected to a quick coupling fitting, and the outlet was connected to a valve, as in **Fig. (7c)**.
Then, the pressure test process at the first stage was carried out with a high pressure air from a compressor at different pressures from (1-8) bar, where the mini heat exchanger is immersed in a basin of water to see if there is air leakage as shown in **Fig. (7d)**. And at each pressure value, waiting for half an hour is to prove that the bond certainly bears that pressure value. It was found from the test results that the mini heat exchanger has fully withstood these pressures. So, the test moved to the second stage.
The second stage of the compression test was by hydraulic pressure using a manual hydraulic pump, as shown in **Fig. (7f)**. The pump is connected to the mini-exchanger by a quick coupling adapter equipped with a pressure gauge up to 600 bar, as in **Fig. (7e)**. Then, a little oil is pumped into the mini-exchanger with the exit valve open to let out any remnants of air inside the mini-exchanger, and then the valve is closed to complete the test process. The pressure is gradually raised by pumping the oil through the pump.



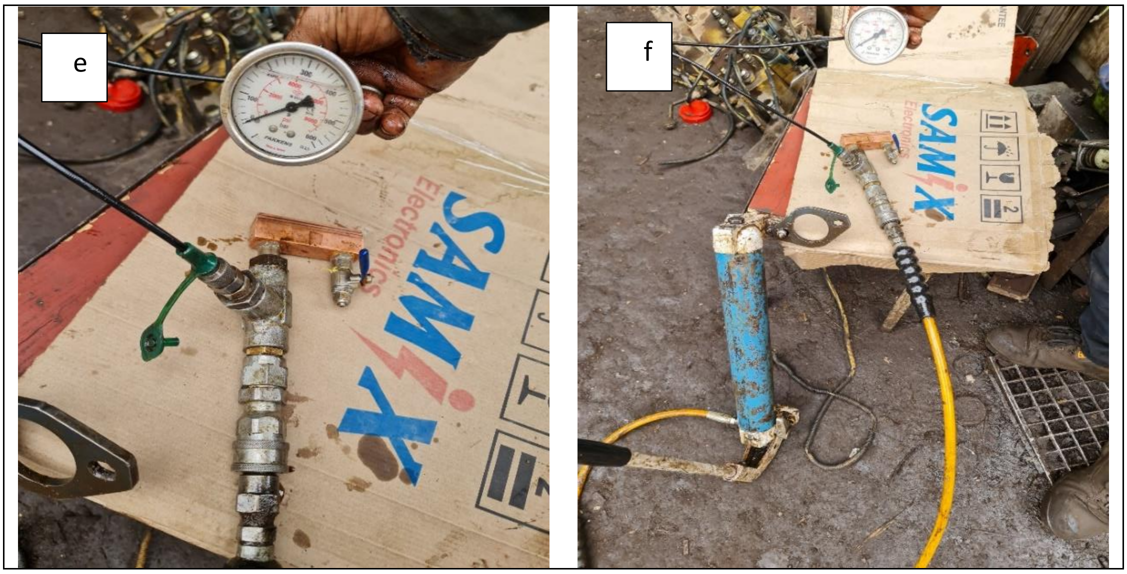


Figure (7) a- prototype exchanger parts b- Diffusion bonded exchanger prototype. c- Exchanger prototype with fittings. d- Exchanger prototype dipped in water. e- Hydraulic adapter. f- Hydraulic pump

The results of the test showed that the mini exchanger withstands up to 60 bar, and then it started leaking a little oil, so the test was stopped.

2.3.3 PCHE block prototype

A prototype of PCHE block was manufactured by diffusion bonding, using copper plates of dimensions of 8 cm *4 cm * 3 mm. In the beginning, the flow channels were machined at the surface of the copper plates with dimensions (2 mm wide *1 mm depth), as shown in **Fig. (8)**. The plates surfaces were prepared for diffusion bonding as mentioned previously. Then, they were stacked one on top of the other, fixed with the jaws, as in **Fig. (9)**, and entered the oven to bake. The PCHE block prototype is shown in **Fig. (10)**.

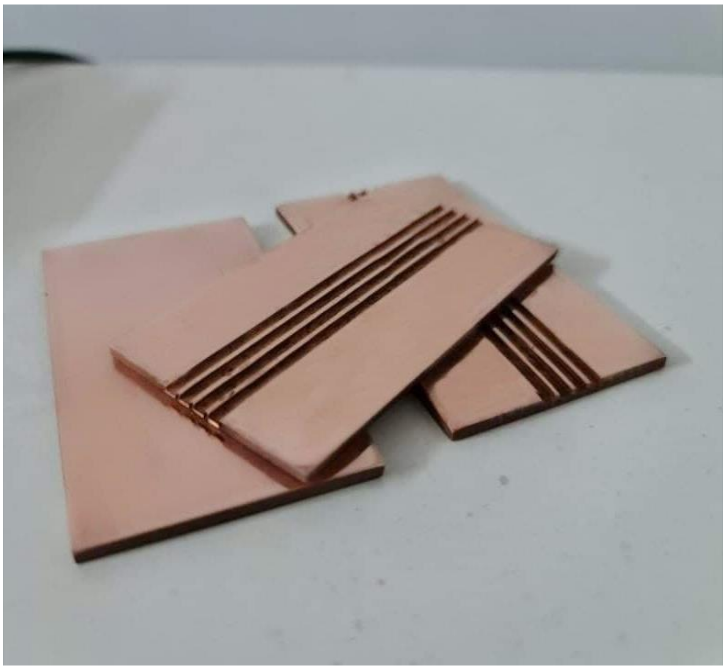


Figure (8) prototype plates

Figure (9) fixing the plates

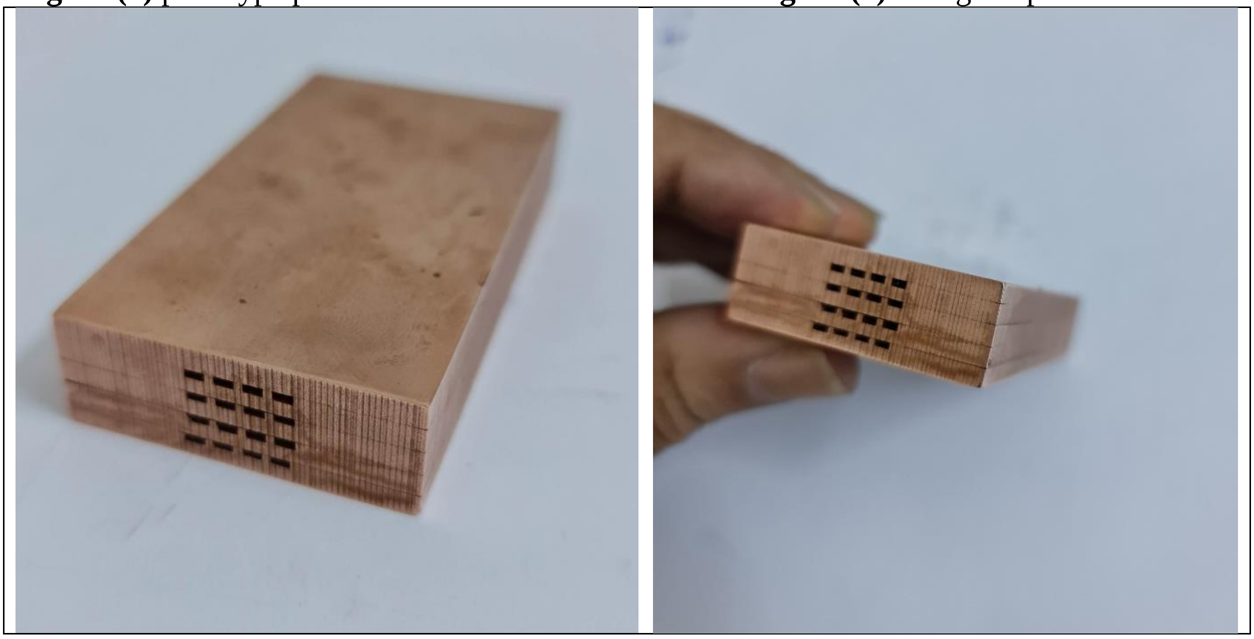


Figure (10) PCHE prototype block

4. CONCLUSIONS

In this study, the process of joining the plates of the printed circuit heat exchanger, diffusion bonding, was performed and studied. A special furnace was manufactured for bonding purposes. The diffusion bonding process of copper metal was carried out under specific conditions to make tensile samples containing groves representing the flow channels in the heat exchanger and to check their tensile strength. A higher tensile strength was obtained than the yield strength of copper. Tensile test of the diffusion bonded specimens containing channels gives a higher tensile strength up to 35 % than that of copper yield strength, but lower than the ultimate strength. Compression test of the mini model of PCHE shows that the mini-model withstands a high Pneumatic pressure of 8 bar without reaching failure and a high hydraulic pressure of 60 bar at which it starts leaking.

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