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Effect of Laser Surface Modification (LSM) on laser energy absorption for laser brazing

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Abstract. Since the development of the laser in the 1960s a rapid development of research interests in science and technology took place. Since then, the need of laser application in industrials such as automotive, aerospace and electronics is increasing because of several advantages like automation worthiness, noncontact processing and product quality improvement. In this present study, the effect of Laser Surface Modification (LSM) on pure copper plate towards the laser energy absorption during indirect laser brazing process was studied. The laser brazing experiment was conducted inside a chamber under controlled vacuum pressure with 400Pa and irradiated with constant 140 Watt laser power. The defocusing features for laser brazing was used in order to find better focal position. Accordingly, the focal length for this laser brazing experiment was set to the focus point at 124 mm from the focal plane. Meanwhile, during LSM process, laser parameters such as laser scanning speed and focus length have been kept constant throughout the surface modification process. Yet, the laser power and laser frequency have been varied from 9 Watt to 27 Watt and 10 kHz to 80 kHz respectively. Apparently, surface roughness due to surface removal and oxide layer formation were presented during LSM process. These two surface integrities were found to be the factors of increasing laser energy absorption. It was discovered that an increase in surface roughness and oxide layer formation can absorb more laser energy which then results an increase in brazing temperature during laser brazing. This is because, increasing surface roughness will scatter the laser energy over a larger surface area, multiply the reflections in the surface irregularities while the oxide layer will enhance the interference phenomena of laser energy occurring inside the oxide layer. Both mechanisms increase laser energy absorptivity during laser brazing which results a high brazing temperature.

Keywords. Laser Brazing; Laser Energy Absorption; Laser Surface Modification

1. Introduction

During this past few decades, the application fields of laser brazing in industrial including automotive, aerospace and electronics have been expanding due to several advantages in comparison with other brazing methods. For instance, in terms of processing time, laser brazing consumes much shorter compared with few hours during conventional furnace brazing [1]. Additionally, laser brazing is preferred when joining high sensitivity and precision products as it can localize the heat input within a specific area [2].

Laser brazing can be operated in two different configurations which are direct and indirect. It can be categorized as operating in either mode, depending on how the laser melts the filler material. Direct laser brazing is performed by directly radiating the laser on the filler material, thus heating and melting the filler materials. The filler is usually in form of wire. On the other hand, during indirect laser brazing, the filler material is heated and melted by radiating the laser on the based materials first. The heat then transfers to filler materials to melt it. These two laser brazing configurations are shown in the following figures 1. With respect to heat supply for the brazing process, indirect method requires high laser power in order to obtain same joining quality [3].

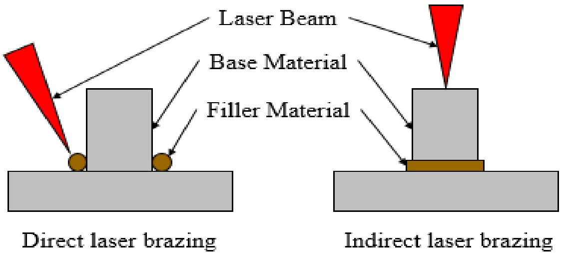

Figure 1. Direct and indirect laser brazing configuration.

Nevertheless, the laser energy needed to melt the filler materials are all depending on the laser-material interaction, for instance, the spectral absorptivity [4]. In laser brazing, an understanding of the fundamental laser energy absorption mechanisms plays a vital role in determining the optimum parameters and conditions.

For example, the defocused distance was found to have a significant influence on appearance, microstructure and mechanical properties [5]. It was discovered that, at focus point distance, where the diameter of the laser becomes smallest, the photon can produce enough laser energy to melt the metal in short time [6] compared to other defocusing distance.

Apart from that, the composition of the filler material and brazing temperature are also found to influence the brazing joints as they can improve wetting angle and joining strength [7, 8]. This is due to it is highly depending on the energy absorptance. As the laser energy is transferred to the metal, it will heat up the metal resulting in increment of temperature. Despite that, due to the nature of high reflectivity of laser beam on materials, especially metal, limits the laser energy absorption [9]. Subsequently, this laser-material interaction affects the laser energy efficiency, considering more energy wasted and reflected away towards ambient instead of absorbed and contributed to the process.

However, by modifying the materials surface integrity, namely surface roughness and oxide layer formation, the interaction between laser and surface of the material can be improved [10, 11]. Therefore, increasing the laser energy absorption, resulting in high energy efficiency and low laser power requirement. The effect of surface integrity on the laser energy absorption are illustrated in Figure 2. The increase in surface roughness will scatter the laser energy over a larger surface area, multiply the reflections in the surface irregularities. Besides, the formation of a thicker oxide layer will enhance the interference phenomena of laser energy occurring inside the oxide layer. Additionally, it was discovered that oxide metal has better laser energy absorption coefficient compared to metal surface [12]. Both surface conditions will increase the total laser energy absorbed by the material, resulting a higher energy efficiency during the laser brazing process.

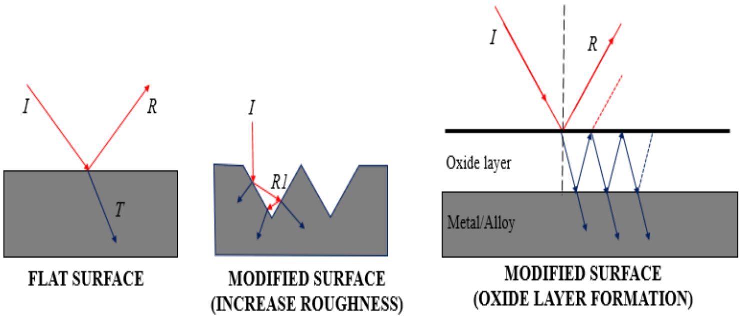

Figure 2. Unmodified and modified surfaces.

One of the well-known and practical methods in modifying the surface of a material is Laser Surface Modification (LSM). This process owns several advantages compared to conventional surface modification processes such as surface plasma-spraying, electropolishing, anodic oxidation, and acid etching. For instance, easily automated, high process precision and high speed [13]. During LSM process, the molecular particle at the material surface is ablated and removed by radiating short intense bursts of a laser beam with high intensity to break the molecular chemical bonds and thus resulting microgrooves that will increase the surface roughness. Simultaneously, the targeted surface will react with oxygen gas, and oxide layer is formed and presented in particular colour or lustre. By applying LSM, both increase in surface roughness and oxide layer formation can be achieved by a single process. Hence, it makes LSM the most suitable methods to achieve consistent surface modification for understanding and improving the laser energy absorption mechanism during laser brazing process.

The intention of this present work carried out was to find out the possible LSM parameters to obtain high surface roughness and more oxide layer formation in order to increase the laser energy absorption for laser brazing application. Also, an attempt to produce high brazing temperature by using low power fiber laser has been conducted where the peak power was set to 140W which is considered low in laser brazing application.

2. Experimental setup

The material used in this experiment was (99.99 %) pure coppers plate with dimensions of 60 mm length × 10 mm width × 1 mm thickness and its chemical properties is presented in table 1. The samples were grinded with 600 grit Silicone Carbide sanding paper to remove any residues such as coating and dirt on the sample's surface. Afterwards, samples must be cleaned with acetone prior to processing. The purpose of the acetone usage on cleaning process is to degrease any residual oil contamination on the sample's surfaces. Subsequently, the copper surface will be modified using LSM.

Table 1. Pure copper properties.

Pure Copper	Properties
Density	8.3 gcm^{-3}
Melting point	1084°C, 1984.32°F, 1357.77 K
Electrical Conductivity	16.78 nΩ•m
Thermal Conductivity	401 W.m^{-1}.K^{-1}

Laser Surface Modification process were carried out by using fiber laser machine which has 30 W peak power. The machine was operated in pulsed mode. A 10 mm x10 mm copper surface is marked with vertical etched lines. The distance between the lines was set to 1µm. The experimental setup for LSM process can be seen in Figure 3.

Furthermore, LSM parameters such as laser scanning speed and focus length were kept constant through the whole experiment while laser power and frequency were varied from 9-27 Watt and 10-80 kHz respectively. The laser input variables for LSM are shown in table 2.

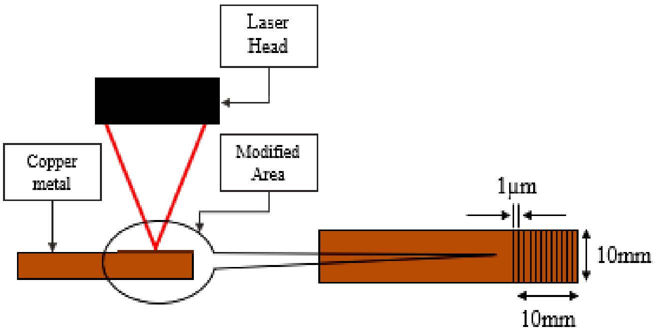

Figure 3. Experimental setup for LSM.

Table 2. Parameter for laser surface modification.

Specification	Parameter
Power	9, 12, 15, 21 and 27 Watt
Frequency	10, 20, 50 and 80 kHz
Laser Speed	500 mm/s

Upon LSM process, the area irradiated with the laser will be removed and reacted with oxygen, thus, produced a rough surface and formed oxide layer on the copper surface. The cross section of the modified area after LSM process was studied in order to determine the value of the surface roughness by using image processing software.

The oxide layer formation after LSM process was studied according to the colour appearance. All samples were pictured on the same light intensity and converted into black and white (B&W) contrast in order to determine the percentage of the contrast. The black and white scale can be referred in Figure 4, where 100 % was set to be the most oxide layer formation while 0 % will be considered as no oxide layer formation.

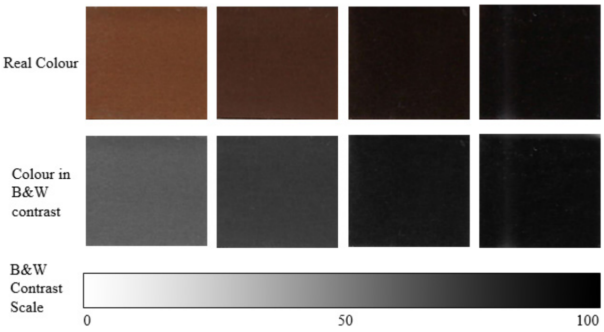

Figure 4. Example of B&W contrast scale.

For laser brazing process, IPG YLM 200/2000 fiber laser machine which has 200 W peak power was used in the experiment. The whole experiment was conducted in a vacuum chamber with constant 400 Pa pressure and ±0.05/s leak rate. Besides, the laser power was set to 140 Watt. Moreover, an infrared thermometer was used to measure the brazing temperature due to non-contact measurement, long lasting and consistent yet precise device. However, this device has limitation in terms of measurement reading where it can measure the temperature with range of 385 °C to 1000 °C only.

Before starting the experimental work for laser brazing, the focus point on the copper plate must be studied. The focal lengths used were ranged from 120 to 128 mm. Beam diameter from the laser spot was measured at each focal length by using image processing software.

After determining the focal distance between the plane and the workpiece for laser brazing, the experimental setup for the process has been conducted. The location for temperature measurement and the laser brazing beam can be seen in Figure 5. Alumina silica and wood were in order to prevent heat dissipation as both materials have low thermal conductivity.

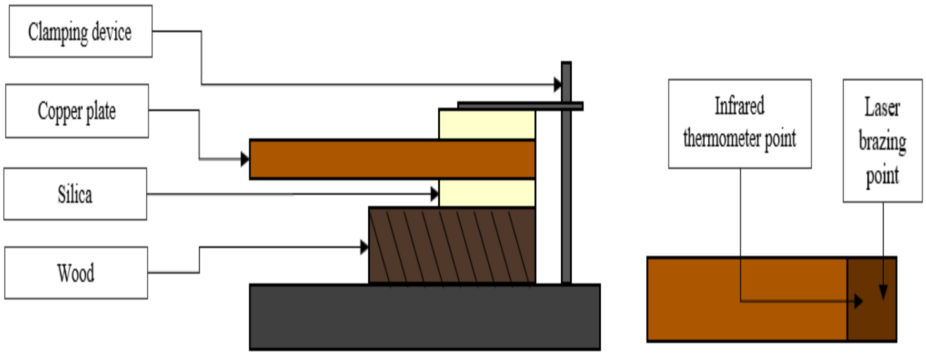

Figure 5. Experimental setup for laser brazing.

3. Results and discussion

3.1. Focal point experiment

Table 3 shows the result in finding the highest brazing temperature and the smallest beam diameter according to the focal points of laser beam on pure copper surface. From the tabulated data, a graph of brazing temperature and spot diameter versus focal length with the range of 2 mm between them was constructed as shown in Figure 6.

The graph presents that as the laser defocused change towards focal length 124 mm, the beam spot diameter becomes smaller. Plus, the brazing temperature achieves higher degree when the laser is pointed at focal length 124 mm compared to other defocused positions. This is due to increment in laser power density which will improve the depth penetration towards the surface when radiated at focus point. This will then lead to the increment of brazing temperature in comparison with other focal length.

Hence, from the graph below, the focus point for this laser brazing experiment was at focal length, FL = 124 mm with beam diameter of 392.33 µm. Therefore, the focus point for laser brazing experiment is set to 0 (FP= 0) at focal length 124 mm.

Table 3. Result of focal length.

Focal Length (mm)	Beam Diameter (µm)	Brazing Temperature (°C)
120	463.67	660
122	429.67	694
124	392.33	715
126	418.33	703
128	439.00	690

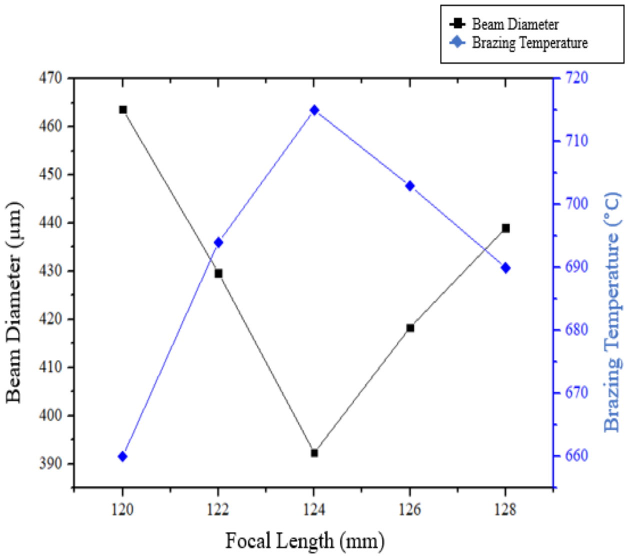

Figure 6. Relationship between brazing temperature, beam diameter and focal length.

3.2. Effect of LSM power on surface roughness and oxide layer formation

The result of surface roughness and oxide layer formation when radiated with variable LSM laser power can be seen in table 4. The LSM laser power was varied from 9-27 Watt. The percentage of B&W contrast can be referred in figure 7. The data from the table and figure was concluded in the graph.

Table 4. Result of variable LSM Power.

Power (W)	Frequency (kHz)	Surface roughness (µm)	B&W contrast (%)
0	0	0	20
9	20	94.13	20
12	20	101.53	60
15	20	104.87	78
21	20	115.90	91
27	20	139.90	95

According to the graph in figure 7, the surface roughness and the percentage of B&W contrast increases with increasing LSM laser power. This is due to the fact that, higher laser power ables to supply more laser energy during the process and removes more surface from the material. When the surface removal increases, it creates microgrooves which changes the texture of the surface. The surface roughness will then increase as there is more surface removed.

Furthermore, increasing LSM laser power also results an increment in oxide layer formation. This can be noticed with the reference of B&W contrast percentage in table 4 and figure 7. As the LSM laser power increases, the laser energy supplied increases, more surface layer will react with oxygen and form oxide layer upon solidification and cooling, thus, turn the copper surface into darker colour.

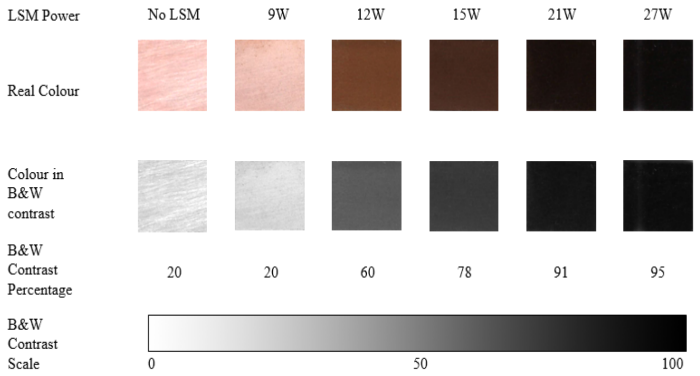

Figure 7. Oxide layer formation with variable LSM power.

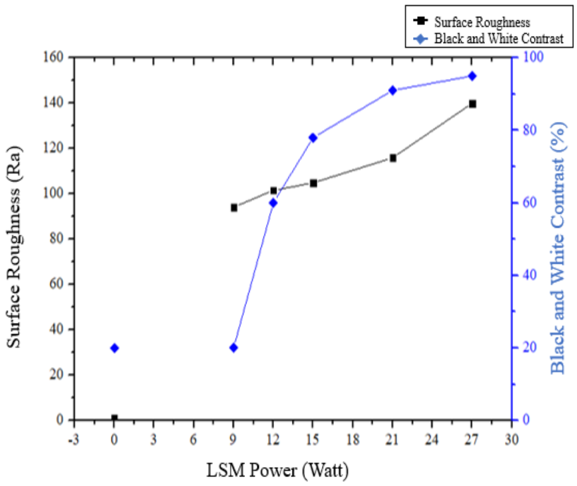

Figure 8. Effect of LSM Power.

Hence, it can be concluded that, there is significant effect when applying variable LSM laser powers on a copper plate. High surface roughness and more oxide layer formation were found when modifying the surface using high LSM laser power.

3.3. Effect of LSM frequency on surface roughness and oxide layer formation

The result of surface roughness and oxide layer formation when radiated with variable LSM laser frequency can be seen in the figures and table below. The LSM frequency was varied from 10-80 kHz. The result of the oxide layer formation based on percentage of B&W contrast can be referred in Figure 9. The data from the table and figure was concluded in the graph.

Table 5. Result of variable LSM Frequency.

Power (W)	Frequency (kHz)	Surface roughness (µm)	B&W contrast (%)
0	0	0	20
27	10	142.07	96
27	20	139.90	95
27	50	136.60	84
27	80	134.03	55

It shows that, when varying LSM frequency on the copper surface, the surface roughness and B&W contrast result different value depending on its rate. Based on the graph, the surface roughness increases with decreasing LSM laser frequency. This is because at lower laser frequency, the heating effect will be deepened on the surface. Accordingly, it will remove deeper layer and turn the surface to be rougher.

Apart from that, the deeper penetration from low laser frequency also causes the copper surface to form more oxide layer and change the copper plate to darker colour. The appearance of the copper surface can be observed from figure 9.

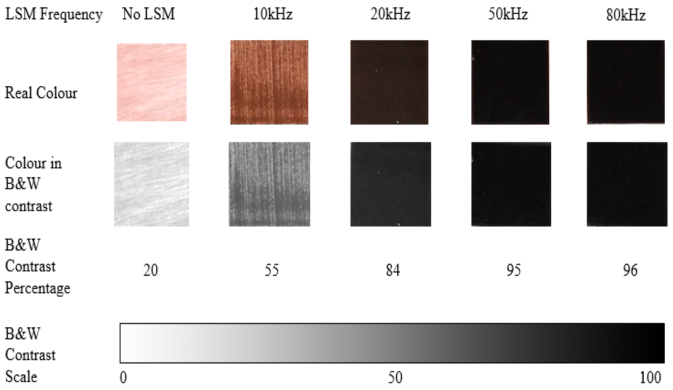

Figure 9. Oxide layer formation with variable LSM frequency.

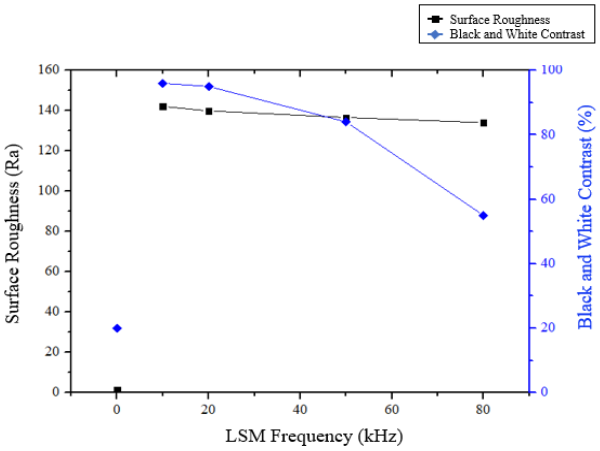

Figure 10. Effect of LSM frequency.

Therefore, it can be observed that, when modifying pure copper plate with low LSM laser frequency, it will result a high surface roughness and form more oxide layer.

3.4. Effect of surface roughness towards brazing temperature

The result of brazing temperature from different surface roughness can be seen in the following table. The data from the table 6 was presented in the graph.

Table 6. Result of LSM laser power on surface roughness and brazing temperature.

Power (W)	Surface roughness (µm)	Temperature (°C)
0	0	<385
9	94.13	<385
12	101.53	703
15	104.87	714
21	115.90	720
27	139.90	726

Based on the graph in figure 10, as the surface roughness increases, the brazing temperature increases as well. This is because, an increase in surface roughness will scatter the laser energy over a larger surface area of the copper plate, multiply the reflections in the surface irregularities and leading to enhanced laser energy absorption. The laser energy absorbed is then converted into heat energy which results the increment for brazing temperature. The highest brazing temperature (726 °C) is achieved when the surface roughness is at 139.90 µm.

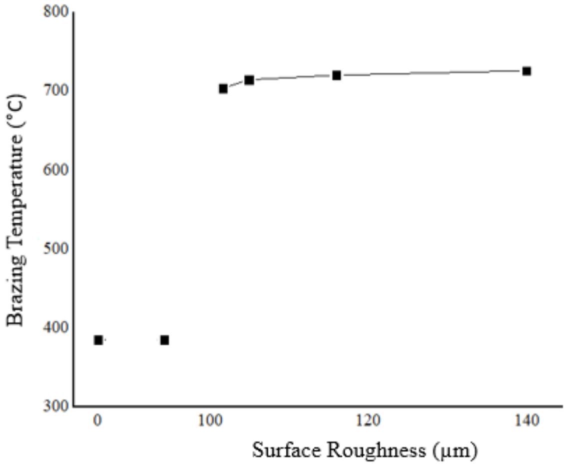

Figure 11. Graph of surface roughness vs brazing temperature.

On the other hand, when there is no LSM applied before laser brazing process which means the surface has an ideal roughness with Ra≈0, the brazing temperature is too low. It proves that, when the laser energy strikes a flat surface, most of the laser energy will bounce off from the surface and reflected back into the ambient.

Therefore, as the surface roughness increases, the brazing temperature will increase as well due to increase in laser energy absorption.

3.5. Effect of oxide layer formation towards brazing temperature

The result of brazing temperature from different black and white contrast correlated to oxide formation can be seen in table 7. The data from the table was presented in the graph.

Table 7. Result of LSM laser frequency on surface roughness and brazing temperature.

Frequency (kHz)	B&W contrast (%)	Temperature (°C)
0	20	<385
10	96	727
20	95	726
50	84	704
80	55	695

As reported in the graph below, as the oxide colour in B&W contrast increases, the brazing temperature increases as well. The increase in oxide layer formation can absorb more laser energy. This is because, when a laser beam irradiates an oxide layer, the laser energy is 'caught' by the oxide layer which may further elevate the heat absorption. As a result, the brazing temperature increases as the oxide layer formation increases. The highest brazing temperature (727 °C) is recorded when the oxide layer has 96% of B&W contrast.

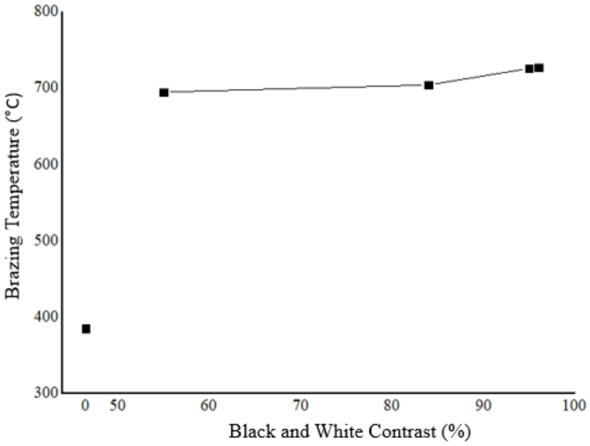

Figure 12. Graph of B&W contrast vs brazing temperature.

However, when there is no LSM process applied before laser brazing process, the thin oxide layer on the copper plate is not enough to absorb large amount of laser energy and hence, most of the laser energy supplied is wasted into the ambient and not contributing towards the process. Hence, it results a lower brazing temperature compared to other oxide layer formation.

Accordingly, the laser energy absorptivity during laser brazing increases when radiating at surface that has more oxide layer and as a result, the brazing temperature will increase as well.

4. Conclusion

The effect of Laser Surface Modification on pure copper plate towards the laser energy absorption during indirect laser brazing process was studied. There is significant effect on surface integrity such as surface roughness and oxide layer formation when applying laser surface modification. A high LSM laser power and low LSM laser frequency increases both surface roughness and oxidation layer formation.

Both surface integrities will increase laser energy absorption, resulting a high total laser energy absorbed during laser brazing and thus, a high brazing temperature.

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