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Comparative study between furnace brazing and laser brazing

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Abstract. Nowadays, brazing has been widely used in many industries, especially in the automotive application. The brazing process is introduced as it can be used to join the different metals together without melting the parent material. In this present study, furnace brazing and laser brazing of Ti-6Al- 4V titanium alloy and 316 L stainless steel (SS) with silver-based, BAg 8-1.5Ti filler metal were studied. There are significantly different between furnace brazing, also known as conventional brazing method and laser brazing in terms of joining strength and microstructure reaction. Furnace brazing was performed at 870°C and 880°C with 30 minutes of heating duration. Meanwhile, laser brazing was performed using a 200Watt continuous wave laser with varying laser power. Both of brazing method was conducted with a vacuum pressure of 3×10^{-3} Pa. Besides, to maintain the accuracy of the temperature measurement of laser brazing, an infrared thermometer is used. The tensile test was conducted to analyse the mechanical properties. The cross-sections of the brazed joints have been examined using an optical microscope. The brazed joints of the furnace brazing show an average tensile strength of 55.89 kPa for 880°C and 43.16 kPa for 870°C. Nonetheless, the maximum tensile strength of laser brazed joints was 27.95 kPa, which is lower than furnace brazed joints.

1. Introduction

Brazing is one of the most traditional methods for joining dissimilar materials due to its simple operation, great repeatability, and relatively small thermal impact on a substrate [1]. The brazing process is applied to join two metals (similar or dissimilar) using heat and filler metals which have a melting temperature of above (450◦C) [2, 3]. The joining of two metals made by heating them to the melting point of the filler metal to ensure that molten filler flows through the capillary action between the two mating surface [2]. Brazing makes a metallurgical bond between the filler metal and the surfaces of the two metals being joined [4]. Nevertheless, brazing includes insignificant microstructural changes and thermal distortion of the base metal, which makes it desirable over welding in many manufacturing circumstances [5]. Brazing method has been typically used when high joint strength is required. However, it is challenging to achieve a good joint [6].

Some of the prominent types of brazing techniques are furnace brazing and laser brazing. Generally, furnace brazing is a semi-automated process which allows joining of genuinely complex multi-joint assemblies. It offers the adaptability to join a wide range of metals. Vacuum furnace brazing additionally called as conventional furnace brazing, is the right choice for bonding materials challenging to join by a traditional welding process. In contrast, laser brazing is a combination of laser heating and brazing with filler metal, which has the basic characteristics of brazing [7]. Some of the advantages of laser processes are that they allow not only localized fusion with a constraint of 'heat affected zones', but also the possibility of automation and ideal control of the quality of the joints [8]. Consequently, laser brazing is becoming a well-established laser joining technique that is completely incorporated into industrial production lines [9]. It offers efficient and attractive solutions to the automotive sector due to its high strength and smooth surfaces. Moreover, laser brazing, as well as furnace brazing, is used for a diverse array of applications, including aerospace components, automotive components, and biomedical assemblies [10].

Comparing between furnace brazing and laser brazing, it has a few comparisons, including brazing processing time, energy efficiency, heat distribution, and adoption cost. Focusing on the brazing process, conventional furnace brazing is a prolonged process with the unnecessary heating of the whole job at high temperature. Meanwhile, laser brazing possesses a short and fast process because only the selected part should be heated, and the amount of heat input is small. Also, laser brazing has distinct advantages that pay off the long term, legitimating the higher costs for the technology. Most significant benefits are high processing speeds and low heat input [11]. Nevertheless, conventional furnace brazing is suitable for mass production of small parts and does not require flux or post-cleaning. It can allow inert or vacuum atmospheres protecting from oxidation. Of little difference, lasers eliminate the need to heat the whole part and far more energy-efficient. Laser- braze parts are available for immediate onward processing with minimal cool- downtime.

Depending on the brazing temperature and time, an increase in the content of the active element causes a decrease in the joint strength. These issues emerge because conventional furnace brazing requires long treatment times in order to ensure the heating and cooling of the whole segment [12]. These issues are suppressed by laser brazing due to the fast heating and cooling time of a few moments. In the brazing process, brazing temperature is one of the parameters that influencing the joining strength. The effect of the brazing temperature on the microstructure of brazed joints is not so unambiguous. Microstructures may be different due to the rapid cooling and heating during the process as well as the strength of the joint.

On the other hand, the higher the brazing temperature is, the more intensive reaction occurs between the filler metal and base metal. Consequently, the thicker intermetallic layer might be formed at the interface [13]. Tight process (time/ temperature) control and the chance of a clean metallurgical joint at the beginning of brazing are attractive attributes. Above all, brazing is a relatively quick process that offers adequate strength in the joint of dissimilar materials [14]. However, when joining Ti to steel, it is restricted by their minimal solid solubility (0.1 at. %) at ambient conditions and common solid solubility in liquid conditions [15]. The research focused on joining of dissimilar material (316L SS and titanium alloy, Ti6Al4V) by using silver-based (BAg 8-1.5Ti) filler metal alloy to investigate the comparison between the effect of laser power and furnace brazing temperature on joining strength of furnace brazing and laser brazing. Also, the microstructure interaction between the base metal and filler metals are comprehensively studied.

2. Method and materials

Dissimilar metals of a 316L stainless steel plate and a Ti-6Al-4V titanium rod were employed in the brazing process. The samples were divided into rectangular plates with 50 mm × 10 mm × 2 mm dimension for stainless steel. And 6 mm × 6 mm dimension for Ti-6Al-4V. These specimens were then, grind using grinding papers 800 grit and subsequently were cleaned by acetone before brazing. The physical and mechanical properties of the materials and their chemical composition are recorded in table 1 and table 2, separately. The filler metal used was BAg- 8 1.5Ti with thickness was around 100 µm. The filler metal was cut into 5 mm × 5 mm and cleaned in acetone prior to brazing. Afterward, it is sandwiched between the overlapped areas of the base metals, as shown in figure 1.

Table 1. Physical and Mechanical properties of alloys

Alloy	Melting point (^{0}C)	Thermal conductivity (W/ (m.K))	Tensile strength (MPa)
Ti-6Al-4V	1604	6.7	950

316L SS	1375	16.2	515
BAg 8- 1.5 Ti	790	-	-

Table 2. Chemical composition of the alloys used

Material	Chemical composition (wt.%)								
Ti-6Al-4V	V	Al	C	O	N	Fe	H	Ti	
	3.83	6.01	0.008	0.088	0.003	0.083	0.002	Bal.	
316L SS	C	Mn	Si	P	S	Cr	Ni	Mo	Fe
	0.03	2.00	0.75	0.045	0.03	16.0-18.0	10.0-14.0	2.00-3.00	Bal.
BAg 8- 1.5 Ti	Ag	Cu	Ti						
	71.25	27.25	1.5						

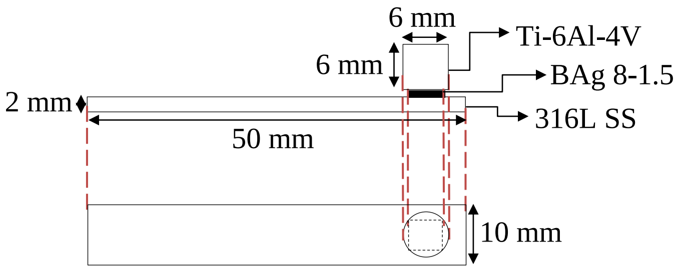

Figure 1. Schematic of material configuration (T-joint)

Subsequently, titanium rod will undergo laser surface modification (LSM) to modify the surface roughness which will contribute to the high absorption of heat during the laser brazing process using laser surface marking machine, operated in pulse mode. The laser marked the titanium rod surface within 7 mm in diameter. After the LSM process, the materials will be set up, as shown in figure 1. Since the surface area of 316L SS plate is big, it was arranged to be at the bottom of the Ti rod to reduce the energy disperse towards the material.

The furnace brazing was performed with pressure vacuum of 3×10^{-3} Pa. For this reason, the parts were heated in a vacuum furnace up to 880°C for 30 minutes (heating rate: 29.33°C/ min) as illustrated in figure 3(a). The samples were easily and quickly cooled at the room temperature in a vacuum furnace. Three samples each were furnace brazed for assessing the process. Meanwhile, laser brazing, a continuous wave of the fiber laser machine with a maximum laser power of 200 Watt, is used. The experiment was carried out in a vacuum chamber to avoid oxidation during the brazing process. The laser beam was focused on the surface of the titanium rod and irradiated at an angle of 18°. The parameters used in this study are shown in table 3.

Table 3. Furnace brazing and laser brazing parameter

Parameter	Furnace brazing	Laser brazing
Brazing temperature/ Laser power	870°C, 880°C	140 W, 150 W
Heating duration	30 mins; 5 mins HT	60 s
Vacuum pressure	3×10^{-3} Pa	3×10^{-3} Pa
Cooling rate	Natural cooling	Natural cooling

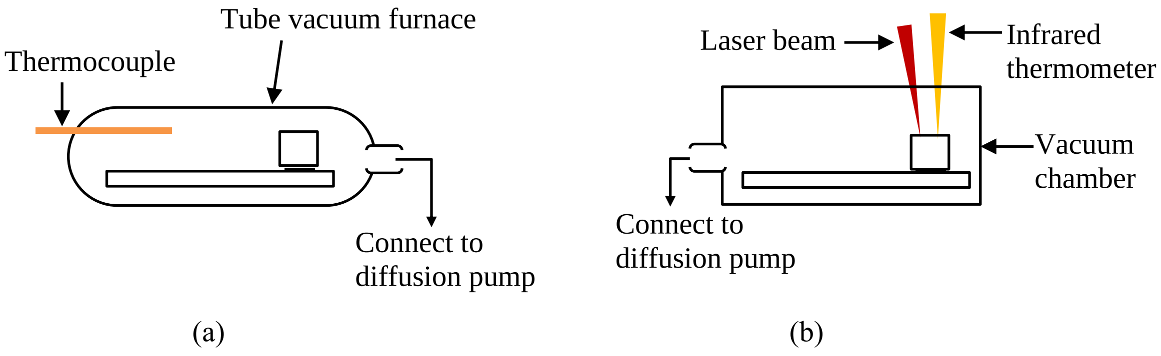

Figure 2. Set up of (a) Conventional furnace brazing; (b) Laser brazing

Besides, to maintain the accuracy of the temperature measurement of laser brazing, an infrared thermometer CTLM2HBF300- C3 Micro-Epsilon with temperature limitation of 385°C- 1600°C was used due to non-contact measurement which measured the surface temperature based on the emitted energy of the specimens. Brazing temperature was influencing the brazing joints as they can improve joining strength because of it is exceptionally relying upon the energy absorbance. Concerning furnace brazing, it was not a big deal since the temperature set will heat the whole sample; thus, the temperature will be the same. The temperature for laser brazing was measured at one point on the titanium rod where the laser beam is irradiated. The laser temperature sensor is set nearby the laser beam on the titanium rod surface, as shown in figure 2(b). As the laser energy is transmitted to the metal, the metal heats up, resulting in an increase of temperature as seen in figure 3(b). During the laser brazing, regardless of the workpiece fixture, the instantaneous melting of the material by laser and the subsequent cooling process behind the beam trigger thermal cycles.

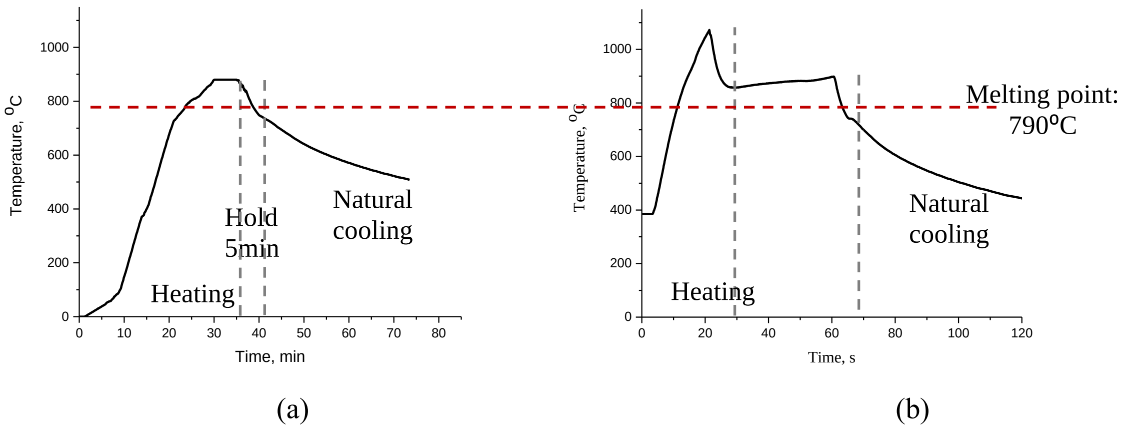

Figure 3. Temperature profile for (a) Furnace brazing; (b) Laser brazing

The tensile test was conducted using Universal Testing Machine to assess the joint strength of the samples. Figure 4 illustrates the schematic configuration of the shear test. The chosen samples were cut, mounted, polished and etched for microscopic evaluation. The cross-section of the brazed joints was etched with the chemical composition of the Killers' Etchant for titanium rod and Adler's Etchant for stainless steel 316L for about approximately 20 seconds. Meanwhile, for AgCuTi filler metal microstructure, a nitric acid solution is used and immersed for 10 seconds. The samples were checked using a 3D measuring laser microscope to observe and identify the pattern for both methods of the brazing process.

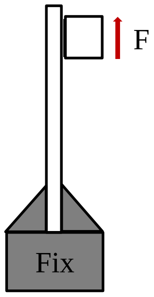

Figure 4. Schematic of the shear test

3. Results and discussions

3.1. The microstructure of furnace brazing joints

The microstructure of the brazed joints at 870°C and 880°C for 30 minutes are shown in figure 5. The microstructure of the brazed joint gradually changed with an increase in brazing temperature. There are also reaction layers between the brazed alloy and the growth of the interfacial reaction layer, which resulted in the loss of elements in the braze alloy. The microstructure of the brazed joints changed significantly with diminishing brazing temperatures to 870°C. The microstructure examined at a relatively high brazing temperature of 880°C is shown in figure 5(c) and (d). The titanium microstructure is an equiaxed pattern. Each parameter has almost the same titanium microstructure pattern. The different pattern of this microstructure will indeed show the differences in the joining strength. Besides, it should be acknowledged that erosion may occur in the furnace brazing process because of a long process time than the laser brazing process time.

(a) (b) (c) (d)

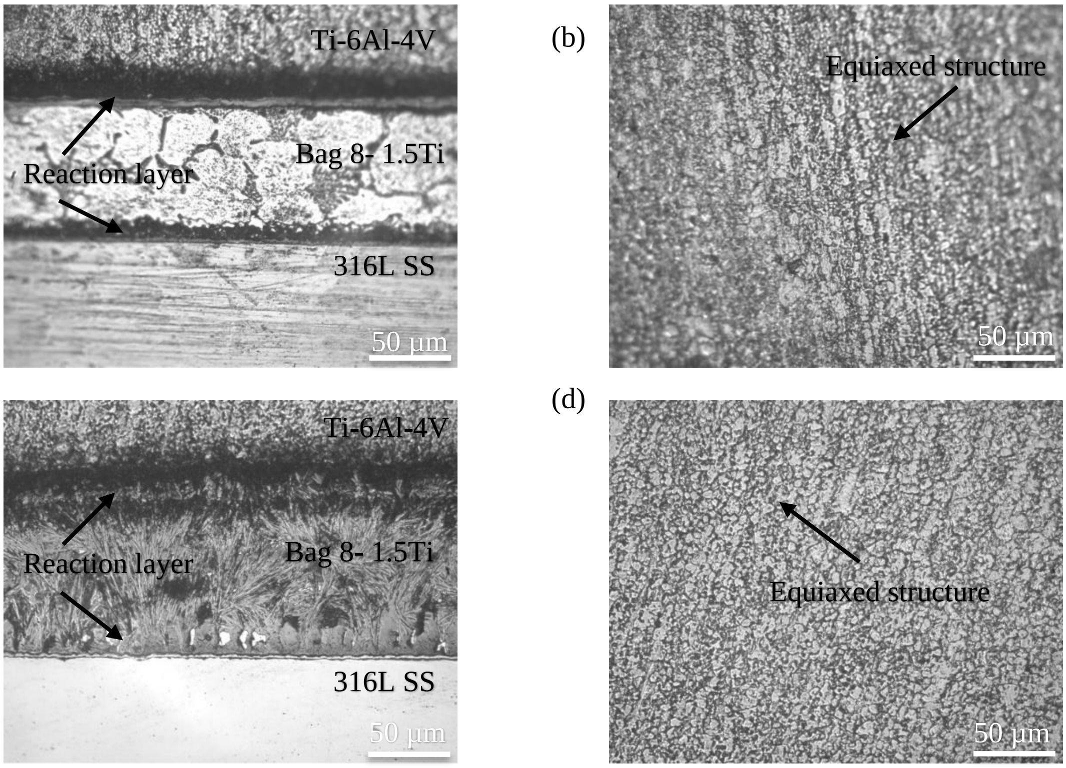

Figure 5. (a) Interface microstructure at 870°C (50X); (b) Titanium microstructure at 870°C (50X); (c) Interface microstructure at 880°C (50X); (d) Titanium microstructure at 880°C (50X)

3.2. The microstructure of the laser brazed joints

Figure 6 portrays the microstructure of the cross-section of the laser brazed samples performed with different laser power. In this figure, it can be seen the titanium microstructure look like Widmanstatten pattern, also known as Thomson structures which indicate that the molten metal cooled very slow. Apart from that, the Widmanstatten pattern form because of the development of the new phases within the grain boundaries of the parent metal, which lead to the increasing of the hardness and brittleness of the metal. Subsequently, the pattern for each parameter looks alike. As for filler metal, the microstructures are different where it is a bit rough when power used is 140 Watt compared to the power of 150 Watt. However, with the growth of reaction between Ti and SS, as with the increase in the thickness of IMC layer, vacancies for voids presumably become to an ever- increasing extent, likely form in IMC layer which may decrease the joint strength.

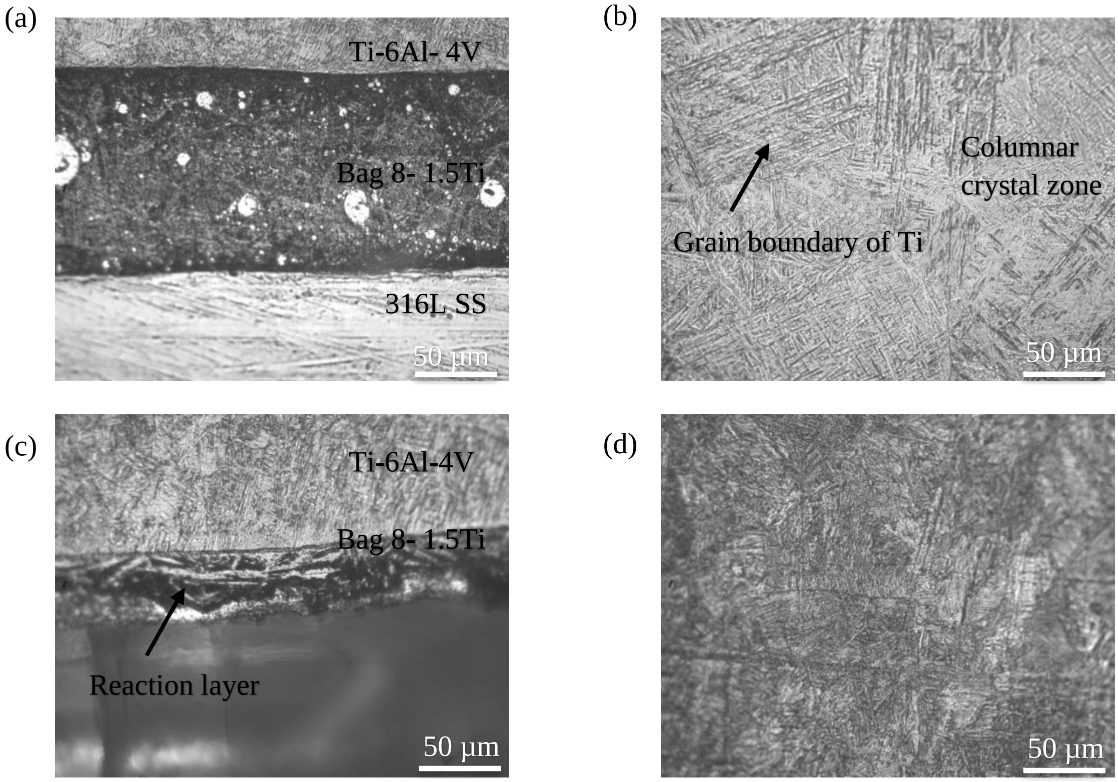

Figure 6. (a) Interface microstructure at 140 W (50X); (b) Titanium microstructure at 140 W (50X); (c) Interface microstructure at 150 W (50X); (d) Titanium microstructure at 150 W (50X)

The observed microstructure was a difference due to the different thermal behaviour of each parameter used. The reason is the used of the low energy density, a low laser power, lower peak temperature and shorter thermal cycle. Thus, the quenching effect that was realized by thermal transmission through the substrate was strong. The thickness of interfacial reaction layers, as shown in figure 5 and 6, was found to depend on the temperature and time. The microstructure also was affected by the heating and cooling rate. However, the significantly enhanced cooling rate and solidification rate refined microstructure and will promote the phase transformation as well. Therefore, the microstructure of laser brazed samples is different from the furnace brazed ones.

3.3. Tensile shear strength

With an increase in brazing temperature and laser power, the shear strength of joints showed a general ability to increase. The average shear results obtained are displayed in figure 7. The tensile strength of brazed furnace samples is shown in table 4. The highest tensile strength of the brazed sample of the furnace was 55.89 KPa. The tensile strength of the ideal laser brazed sample is therefore approximately

41.77% lower than the tensile strength for furnace brazed samples. However, based on figure 7, the graph's pattern indicates that the tensile strength increases when laser power and furnace temperature increase to 150 Watt and 880°C, respectively.

The microstructure affects the tensile strength values. As the filler metal spreads completely over the brazed region, the thickness of the reaction layer and alloying the elements are the most critical parameters for the joint strength. Subsequently, the filler metal was not spread entirely, and there is very minimal reaction layer form in laser brazing with laser power of 140 Watt. Hence, the tensile strength is low among the others. The low joint strength, however, is also attributed to the thermally induced stresses created due to stress concentration generating as a result of a variation in the phase present and thermal expansion coefficient. For the laser brazed sample, the maximum tensile strength, 32.54 kPa, is obtained at a laser power of 150 Watt and a duration of 60 s.

Table 4. Tensile shear strength of furnace brazed samples

Furnace temperature, °C	870	880
Tensile strength (KPa)	43.16	55.89

Table 5. Tensile shear strength of laser brazing samples

Laser power, Watt	140	150
Tensile strength (KPa)	27.95	32.54

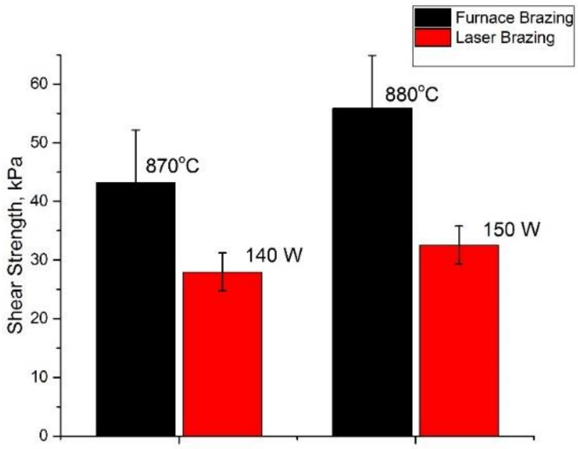

Figure 7. Shear strength of furnace brazing and laser brazing

Comparing the overall tensile strength of the brazed joint between furnace brazing and laser brazing, it is clearly shown that the furnace brazing has a higher joint strength. It might be due to the difference in heating rate and the cooling rate, which also plays a crucial role other than the microstructure in determining the joint strength. After all, laser brazing can be said having a faster heating rate and cooling rate, which would degrade the mechanical properties compared to the furnace brazing.

From a microstructural perspective, the difference in joint strength with the brazing parameters was, to a great extent, depending on the joint microstructure. The thickness and type of reaction layer between the brazed alloy are basics factors in determining the brazed joint strength. Clearly, the thickness of the layers increased with an increase in brazing temperature and time. It is suggested that the shear strength of the joint was affected by the formation of the required reaction layer in order to achieve good strength for the joint and the growth of the interaction layer, which degrades the strength.

4. Conclusions

The current study assessed the microstructure and effect of furnace brazing temperature and laser power on the joining strength of the brazed joints between the titanium alloy and stainless steel with BAg 8-1.5Ti filler metal. There is an effect of increasing the brazing temperature either using laser or furnace as a heating method.

The difference in joint strength with the brazing parameters was largely based on the thickness of the reaction layer. The maximum shear strength test can be achieved at 55.89 kPa when using furnace brazing at temperature 880°C meanwhile the lowest shear strength test can be observed at 27.95 kPa when using laser power of 140 Watt of laser brazing.

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