Investigation on laser brazing AA6056 Al alloy to XC18 low-carbon steel

Jianjun Ding (丁健君)[1], Feiqun Li (李飞群)[1], Feng Qu (瞿 丰)[1], Patrice Peyre[2], and Remy Fabbro[2]

[1]*College of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200030*

[2]*Cooperation Laser Franco-Allemande, 94114 ARCUEIL, France*

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Based on the studies of influence of YAG laser heating conditions for Al alloy melt and steel on wettability, the mechanics of the laser overlap braze welding of 6056 Al and XC18 steel sheet has been investigated. Under the temperature range which is above the melting point of the Al alloy and below the melting point of the steel, two dissimilar metals can be joined by means of laser braze welding. There is no crack observed in the joining area, i.e. Al-Fe intermetallic phase ($Fe_3Al/FeAl/FeAl_3/Fe_2Al_5$) layer formed by solution and diffusion between liquid-solid interface. The temperature range can be defined as the process temperatures of laser braze welding of Al-Fe materials. Selecting a higher laser heating temperature can improve the wettability of Al melt to steel surface, but the intermetallic phase layer is also thicker. When the laser heating temperature is so high that the joining surface of steel is melted, there is a crack trend in the joining area.

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There is a large difference in mechanical and physical properties such as electrical conductivity, thermal conductivity, strength, and specific gravity between Al and its alloy and steel (iron). So some complementarities with their respective advantages between both of them are very useful in industrial application. In a longer term, the joining methods of Al and Fe materials have been explored by scientists in order to obtain the lightweight mechanical structures with a comprehensive property, which is very valuable especially for automobile and aircraft manufactures. But as we know, it is very difficult to join Al and Fe materials with the traditional processing methods, since a large temperature difference (> 800 °C) between their melting points, and the cracks produced by brittle intermetallic compounds such as Fe_2Al_5 and $FeAl_3$ in joining area are almost unavoidable during the joining process. In the recent decade, the concerned scientists have explored the feasibility by using the infrared laser beam as a rapid heating source. The initial method is that, laser beam just irradiates on the surface of steel piece, then the heated steel piece transfers the thermal energy to Al piece by heat conduction. When the Al material reaches the melting point or above, the Al melt has an appropriate wettability onto iron surface, a successful Al-Fe joining is realized[1]. Some researchers considered that, in general when the thickness of the Al/Fe intermetallic compound layer formed by diffusion reaction reaches 10 μm or above, the brittle cracks can be observed in the joining layer[2-4].

Based on this method, we design an integration heating method for Al/Fe laser brazing, which is called "ride-edge" laser heating. Since the melting point of steel is much higher than that of Al and its alloy above 800 °C, during the laser brazing the beam spot travelling along the edge of steel sheet can be divided by the edge into two parts. It is easy to control the allotment of beam energy to get a finer laser overlap brazing, the most of laser beam energy is for steel to raise surface temperature and active, and the other is for Al metal to get an available melt bulk. During the laser brazing, the thermal energy for the melted Al comes not only from conduction effect through a touch with steel but also directly from beam irradiation. The advantages of this brazing method are that laser energy can be utilized effectively, the melting of Al and wettability do not depend on a very reliable touch area between two sheets, and the heating rate of materials and brazing rate are enhanced which is of benefit to the microstructure and property of interface joining layer. The experiments show that the heating temperature range of the materials in laser joining zone for the feasible laser brazing is about 800 °C which is above the melting point of Al materials and below the melting point of steel materials. When the temperature of laser joining zone is at an upper limit of the temperature range, the Al melt has a better wettability to steel and the thickness of the joining layer is higher, however the brittle cracking trend is upward. Furthermore when the surface temperature of steel reaches its melting point, the cracking will be unavoidable in the joining zone. However adjusting the distribution of beam energy can control the heating temperature, the overall laser power, and beam travelling speed. The cracking trend depends not only on the thickness of laser joining layer, in substance it is related to the composition of intermetallic compound layer. In the experiments, no crack defect was observed in a laser brazing specimen with 27-μm joining layer. In this paper, the laser brazing method and physical metallurgical process are introduced, and the influences of laser processing parameters on wettability of Al melt to steel and the thickness of intermetallic compound are analyzed.

The principle configuration of laser brazing is shown in Fig. 1. The 1.2-mm-thick XC18 low-carbon steel sheet is fixed onto the 0.9-mm-thick AA6056 Al alloy sheet by the clamp. The overlap width of two sheets is 10 mm. A focused YAG laser beam with 1000-W laser power and Φ6-mm beam spot is adopted as the heating source. The laser beam travels along the edge outline of steel to heat the overlap area. In general, the beam spot in 2/3 diameter irradiates on steel, and the other in 1/3 diameter irradiates on Al alloy. Argon is used as a protective atmosphere to cover the irradiated area. Figure 2 is the photograph of laser overlap brazing area.

In order to eliminate the influence of oxidation film on metal surfaces of AA6056 and XC18 on wettability, the "Nocolok flux" powder was solubilized in alcohol as the soldering flux agent for laser brazing. Before laser brazing, the soldering solution is precoated on the overlap interface of both metals. The melting point of the flux powder is about 565 – 572 °C. The composition of the "Nocolok flux" powder is listed in Table 1.

As we know that it is almost impossible to take a melt welding for the two dissimilar metals by traditional heating source, since the melting point of steel is much higher than that of Al and its alloy. All the research results including this paper testify that under laser heating, the joining layer is composed of several Al/Fe intermetallic compounds in which some brittle structures with a cracking trend are unavoidable. When the both metals are in a liquid status under laser heating, the most of compounds are brittle phases with a serious cracking trend. However, in some degree it may be improved by adjusting laser-processing parameters (laser power, laser heating temperature, etc.)[5].

During the foregoing experiments, the laser beam spot just irradiates on steel surface. At first the temperature of the steel in the overlap location rises, therewith the temperature of the Al alloy which is in touch with the heating steel is raised up to its melting point through thermal conducting effect to get wettability metallurgical joining with steel surface. In fact, this kind of laser heating configuration has a disadvantage that it cannot always keep an ideal touch between two materials in overlap area. However, the controllability of laser power and selectivity of laser heating area provide a possibility to resolve the pivotal problems of dissimilar physical properties in melting point, optical absorptivity, and thermal conductivity between both materials. As mentioned above, the "ride-edge" laser heating method can obtain a reasonable distribution of heating energy on both materials by varying the position of beam spot. The most of beam energy are used for steel to balance the thermal gradient between two materials. The distribution proportions of laser beam energy depend on the characteristics and thicknesses of materials and joining requirements. To the available laser joining process (without an obvious cracking trend) for the two dissimilar metals, the hypostasis of the laser joining is braze welding that steel materials are not molten to avoid an Al/Fe melt reaction which may lead to a cracking in joining layer during the solidification-crystallization process. So the laser joining process between Al alloy and steel can be defined as the laser braze welding; and the corresponding temperature range of the laser braze welding for Al alloy is above its melting point and below its boiling point, for steel is above the melting point of the Al alloy below its melting point.

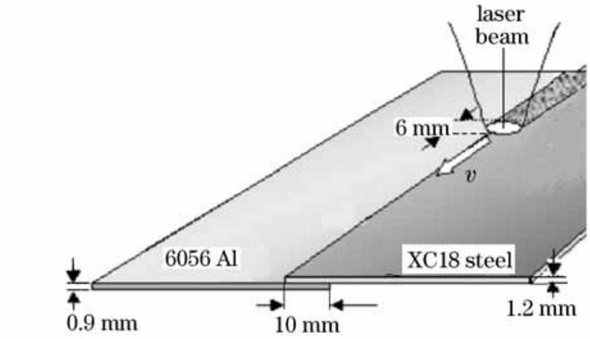

Fig. 1. The schematic illustration of laser brazing.

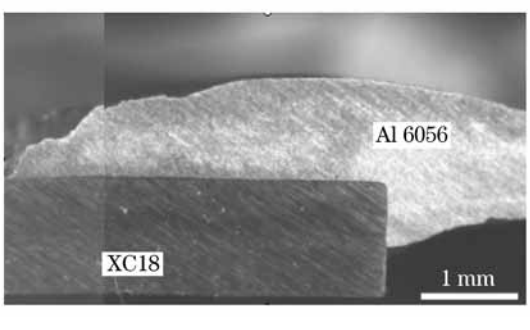

Fig. 2. The cross section of overlap joining area after laser brazing.

The metallurgical process of braze welding includes solubilizing and diffusing between the two metals. From the diffusion equation, diffusion coefficient is a function of temperature. If the laser heating temperature of the metal materials in overlap area is located at the upper positions of the temperature range of the laser braze welding, it is helpful to improving the surface activities and diffusing abilities of the two metals and to reducing the surface tension. Thus, the wettability of Al alloy melt can be effectively improved and the touching status between two metal sheets before laser irradiation has no need of a very strict tightness. Although the interface joining layer is thicker under a higher temperature range, the cracking phenomena in the joining layer are not observed in the experiments.

An experimental method is designed, as shown in Fig. 3, to find out the influence of laser heating conditions on wettability of Al alloy melt to steel. In the experiment, argon was used as protective gas, a precoat of soldering flux was prepared on the interface, and the 350-W YAG laser beam irradiates upward with a Φ6-mm beam spot on center of the square XC18 steel plate ($30\times30\times1.5$ mm^3) where the Al columnar in $\Phi5$ mm$\times$2.5 mm was put on center of the steel plate. The change of the wetting angle shows the wettability of Al melt on steel under varied heating durations. The heating temperature of the centre of the steel plate could be calculated through the finite element analog computation based on the practical measurement values from the thermocouple, which was

Table 1. Composition of the Flux Nocolok Powder

Composition	K	Al	F	Fe	Ca	LOH
wt.-%	28 – 31	16 – 18	49 – 53	0.03 max	0.2 max	2.0 max

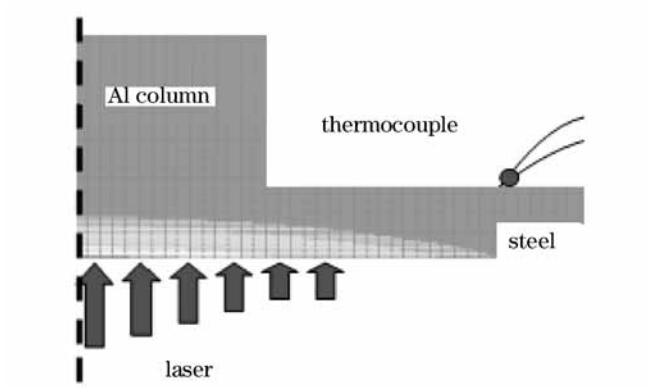

Fig. 3. The schematic illustration of wettability test of Al melt to steel under laser heating.

Table 2. Wetting Angles and Interface Joining Layer Thicknesses under Various Laser Heating Conditions

Specimen	1	2	3
Irradiation Duration (s)	18	15	13
Wetting Angle (deg.)	31.9	31.7	79.2
Thickness of Joining Layer (μm)	27	11	7
Measurement Temperature (°C)	700	520	440
Analog Computation Temperature (°C)	1080	960	780

fixed on the steel plate in a 6-mm distance from the center. The concerned test conditions are listed in Table 2.

The experimental results indicate that the wettability depends on the temperature level of the metals in the brazing area. The higher the laser heating temperature is, the smaller the wetting angle is, i.e. the wettability is in a better condition. From the micrographs of the cross sections of the specimens 1, 2, and 3, it can be observed that the thickness of joining layer was related to the laser heating duration. In the experiment, the crack was not found in the sweep electron micrograph (SEM) while the thickness of Al-Fe intermetallic layer reached 27 μm at the temperature of 1080 °C and the heating duration was 18 s, which is shown in Fig. 4. But crack would emerge at the edge of the joining area when there are melting traces on the steel's surface, the maximum value of the microhardness of the joining area can reach HV825, which is the structure hardness of the generated brittle phase Fe_2Al_5.

As shown in Fig. 1, the laser energy is distributed into two parts by the edge of the steel sheet, the majority of beam energy directly acts on the steel sheet and the other on Al metal. Formation of Al melt is the integrated result under laser beam acting on the two metals synchronously. While irradiation is going along, steel firstly reaches the melting point of Al because of its higher absorptivity to YAG laser than Al and the heat energy is conducted to Al metal. Meanwhile Al metal is directly heated by the other beam energy. Then the Al melt with a higher temperature can wet adequately the surface of the hot steel in overlap area, and also spread upwards along the lateral surface of steel conquering its own weight till the half of steel plate thickness. So the brazing area increases observably.

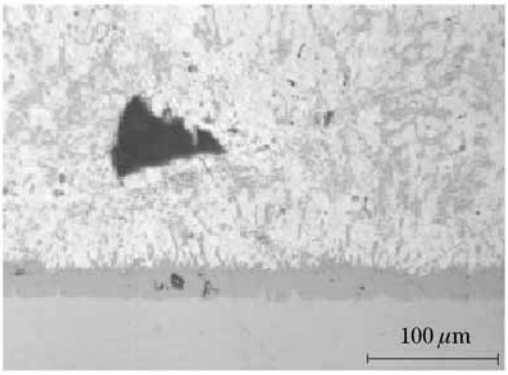

Fig. 4. SEM photograph of joining area (No. 1 sample).

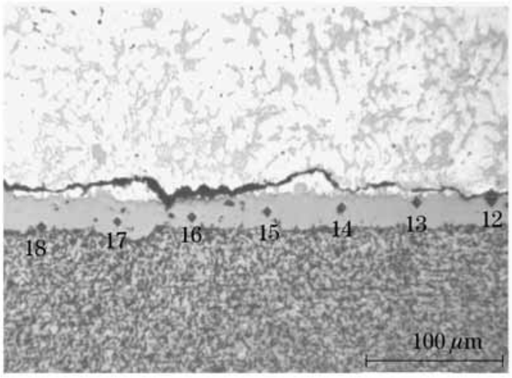

Fig. 5. SEM photograph of joining area when steel has a melting state.

It is well known that Al has a low absorptivity to infrared beam at the solid state, but the absorptivity rises sharply when it is going to be melted, so the "ride-edge" laser heating can augment volume of Al alloy melt in a shorter time. Meanwhile a sufficient volume of Al alloy melt can increase the conduction area between Al metal and the heated steel, thereby the thermal energy from laser beam acting on the steel plate could make a contribution in increasing Al alloy melt to promote the progress of wetting and diffusing between Al and steel materials.

The formation of Al alloy melt is achieved by both direct radiation of the laser beam and heat conduction from the heated steel. Molten Al can continuously spread along the overlap path of the two metals with the movement of the laser beam. The "ride-edge" laser heating process improves the heating efficiency and enlarges the temperature gradient between the laser irradiating area and other area, which results in a relatively high cooling rate of melt to refine the recrystallization structures. The results by means of the energy dispersive spectrum (EDS) analysis show that the intermetallic compounds in the laser brazing layer are mainly Fe_3Al, FeAl, $FeAl_3$, and Fe_2Al_5, and the latter two are of brittle phase. But the structure crack has not been observed as the joining layer thickness is about 30 μm, it may be owed to that the grains are not so coarse under the cooling effect.

For this kind of laser laminose sheet joining, the wet driving force of Al alloy melt on the steel surface under a higher temperature and a shorter heating duration can conquer not only the sole weight of the melt, but also the influence of the inevitable offsetting touch in the lapping faces on the continuity and stability of laser braze welding seam.

In summary, we get the following conclusions. 1) In the condition of inert ambience and the usage of appropriative brazing flux, the laser overlap braze welding of AA6056 Al alloy and XC18 steel sheet could be actualized by means of the laser "ride-edge" heating. Since there is the higher heating efficiency and recrystallization rate during the laser braze welding, the cracking trend in laser joining area is also reduced. 2) The temperature range, which is above the melting point of Al alloy and below the melting point of steel, can be defined as the process temperatures for laser braze welding of Al-Fe materials. When the temperature is located at an upper limit of the range, it is useful to improve the fluidity of Al melt and the wettability of Al melt on steel, and the thickness of intermetallic compounds layer thickens but without obvious cracking trend. When the laser heating temperature is up to the melting point of steel, there is a melt trace on the joining area of steel, the crack must be found in the joining area. 3) Under a given condition, the distribution proportion of laser beam energy for the "ride-edge" laser braze welding depends on thickness, properties of the two dissimilar metals, and joining requirement, and the heating temperatures can be adjusted within the process temperature range of laser braze welding. 4) The laser braze welding has potential applications in industry since there is a large difference in mechanical and physical properties between Al and its alloy and steel.

J. Ding's e-mail address is jjding@sjtu.edu.cn.

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