Study on the Performance of Laser Welded joint of Aluminum alloys for Car Body

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ABSTRACT

Considering the fuel consumption of car, a light structure of aluminum alloys is desired for car body nowadays. However, fusion welding of aluminum alloys has some problems of reduction of joint efficiency, porosity formation and hot cracking. In the present work, investigation to improve the joint performance of laser welded joint has been carried out by addition of Cu, Ni, and Zr to A6N01 alloy welds. Aluminum alloy plate of 2.0mm in thickness with filler metal bar was welded by twin beam Nd: YAG laser facility (total power: 5kW). The filler metals were prepared by changing the chemical compositions for adding the elements into the weld metal. Thirteen filler metal bars were prepared and pre-placed into the base metal before welding. Ar gas shielding with a flow rate of 10 l/min was used. The defocusing distance is kept at 0 mm. At travel speeds of 3 to 9 m/min and at laser power of 5kW (front beam 2kW rear beam 3kW), full penetration welds were obtained, whereas at travel speeds of 12 to 18 m/min and same power, partial penetration was observed. The joint efficiency of laser-welded joint was improved by the addition of Cu, Ni, and Zr due to the solid solution hardening, grain refining and precipitation hardening. The type of hardening has been further considered by metallurgical examination.

KEYWORDS

A6N01, filler metal, additional element, laser welding, Nd: YAG laser

1. Introduction

In recent years, aluminum alloys have contributed in improving the performance of automobile vehicles by reducing their weight. Ability to recycle, saving on resources and environmental conservation are the reasons of increased attention aluminium alloys are attracting. Weight reduction is achieved not only by replacing the steel parts but the parts made up of conventional aluminium alloys by improved ones. Simultaneously development aiming at rationalization of welding assembly is actively pursued in fields such as high-speed railway vehicles and marine vessels(1). However, thermal conductivity of aluminum alloys is about three times higher than steels. This causes loss of heat due to conduction during welding of aluminium alloys, which in turn makes it necessary to use large amount of heat input. In addition, high thermal coefficient of thermal expansion causes inducement of internal stresses leading to distortion and solidification cracking depending on type of alloy. Because the hydrogen solubility in liquid phase is considerably higher than that in solid state, the porosity formation takes place easily. For all of these reasons, the weldability of aluminum alloys is said to be poor. Welding processes like arc welding, laser welding, electronic beam welding, spot welding etc. are used for joining of aluminum alloys. In arc welding, elaborate management of heat input is needed to improve the joint efficiency. Due to the radiation losses from the arc column to the surroundings, the effective heat input is about 50 - 70%. To achieve high welding efficiency, the amount of head input should be controlled. Even with such conditions, joint efficiency is about 80% in TIG welding and 85% in MIG welding. With high power density source, such as in electron beam welding, besides high travel speeds low heat input is possible, resulting in a narrow weld bead and heat affected zone (HAZ) with low distortion. In addition, there are advantages like ease of controlling the electron beam and contamination due to atmospheric gases is limited because of vacuum. However, the process has disadvantages such as size limitation due to vacuum chamber and generation of X-rays during welding.

In the present work, the effect of additional element on joint strength and the strengthening mechanism involved in laser welded joints of an aluminum alloy were studied. Twin-beam Nd: YAG laser facility was used for this purpose. Laser processing of aluminum alloys and copper alloys with CO2 laser are difficult due to their high reflectivity. YAG laser with shorter wavelength (1.06 μm) is used so that reflection from the surface is reduced. In recent years, high power YAG laser systems are developed from which high power laser beam is transmitted by optical fibers. These high power YAG lasers are expected to be widely used in manufacturing with suitable automation.

In general, laser welded joints of aluminum show low hardness values in the weld metal and HAZ as compared to base metal, which in turn reduce the joint strength. Therefore, it was decided initially to improve the joint strength by hardening the weld metal. Magnesium and silicon containing aluminium alloy A6N01 was used as base metal. It can be easily extruded to form complex cross sections and has good corrosion resistance. It finds its applications in railway vehicles, automobiles, and marine vessels(2)-(7).

Al-Si alloy was used as filler metal for bead-on-plate welding. Generally, crack susceptibility of aluminum alloy weld metal reaches to maximum when about 0.6 –0.8%Si is present in it. Therefore, the amount of Si in the filler metal was 12%, which exceeds the high crack susceptibility range(8)-(9). To strengthen weld metal of aluminum alloy, alloying elements causing solid solution hardening have to be selected. The respective atomic size factors for Cu and Ni are 10.5 and 12.6% with respect to Al, indicating that they can form solid solution with Al. Hence, the Cu containing and Ni containing filler metals with their amounts between 2 to 9% were used. Zr was added for grain refinement and precipitation hardening effect. Another group of filler metals was used to find the combined effect of Zr and Cu and Zr and Ni. Filler metals varying in composition in this way were used to study the effect of alloying elements on laser welded joint strength. Not only alloying addition but also changing the cooling rate by varying the travel speed was used to refine the grain size.

To investigate mechanical properties of the specimens, hardness test and tensile test were conducted. To study the metallurgical changes, macrostructures across the welded joint were observed and dendrite arm spacing (DAS) were measured.

2.Experimental Procedure

The base metal was hot extruded and rapidly cooled A6N01 aluminum alloy sheet with artificially aged to T5 temper designation (age hardened between 170 – 180°C for 8 hours). Its chemical composition is shown in Table 1.

Table 1 Chemical composition and mechanical property of A6N01

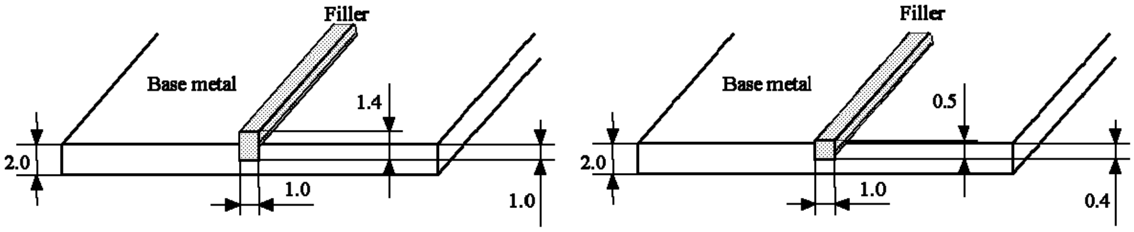
Materials	Element(mass%)									Mechanical property		
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	$\sigma_{0.2}$ (MPa)	$\sigma_{alt.}$ (MPa)	ε (%)
A6N01-T5	2.00	0.56	0.20	0.09	0.70	0.02	0.01	0.02	Bal.	245.0	275.0	12.0

The chemical composition of base filler metal Al-12%Si used is shown in Table 2. Additional alloying elements were added as explained above to this filler metal to find their effect on strength of the weld metal.

Table 2 Chemical composition of based filler metal Al-12Si

Filler metal	Element(mass%)									
	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sn	Ni	Al
Al-12Si	11.6	0.15	<0.005	<0.005	0.002	<0.005	<0.005	0.04	0.01	Bal.

The base metal sheet was machined with a central groove as shown in Fig.1 to place the filler metal with rectangular cross section prior to bead-on-plate laser welding. Two combinations of filler metal section and groove depth were used to achieve full penetration (Fig.1 (A)) with slow travel speeds of 3 to 9 m/min and partial penetration (Fig.1 (B)) with fast travel speeds of 12 to 18 m/min.



(A) For travel speed 3~9m/min

(B) For travel speed 12~18m/min

Fig.1 Setup of filler metals on base metal

The twin-beam Nd: YAG laser head with in-line configuration is shown in Fig.2. The laser beam is transmitted by an optical fiber to the head with distance of 0.6mm along the welding direction. The laser output of front beam was 2kW and that of rear beam was 3kW, giving total power of 5 kW. The defocusing distance was kept on 0 mm. Argon gas was used for shielding with flow rate of 10 l/min.

Vickers hardness was measured with 100 gf loads across the weld bead to find hardness distribution with interval distance of 0.15 mm between the successive indentations. In case of full penetration welds, the location of hardness measurement line was at the center of the sheet, whereas for partial penetration it was at the center of weld bead.

To measure the tensile strength of weld metal, test specimen was machined as shown in Fig.3. The width was 2mm and gage length was 12mm. The tensile test is performed without removing reinforcement of the weld bead. Three tensile test specimens were machined along the welded run from each specimen and the average tensile strength is reported. Two ton capacity universal testing machine was used with cross head speed of 1.0mm/min.

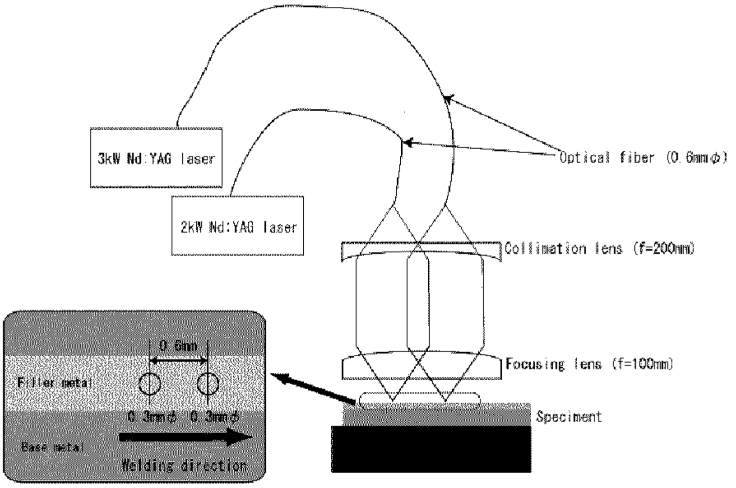


Fig.2 Schematic of twin beam Nd:YAG laser

'Dendrite arm spacing' (DAS) is measured based on microphotograph of weld metal. The clear distinction between primary arm and secondary arm cannot be made easily. Hence, linear intercept method is used and such measurement is called as 'dendrite cell size'. In the present work, dendrite cell size is measured but reported as dendrite arm spacing (DAS). Numbers of lines (m) were drawn with known total length (l_i) on the microphotograph and the total number of intercepts made by the dendrites was counted (n_i) as shown in the Fig. 4. To increase the accuracy of measurement, the total number of intersects was always over 200 measured on three microphotographs.

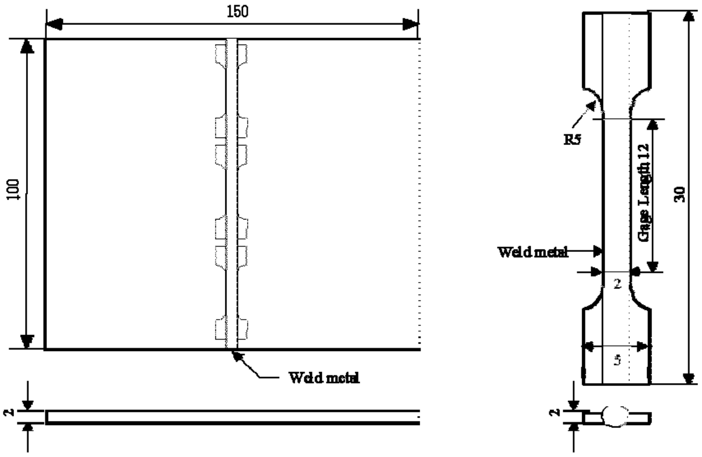
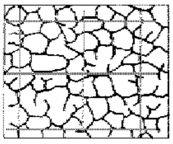


Fig.3 Schematic of tensile test specimen to measure tensile properties of weld metal

In order to consider the strengthening effect of alloying element in the welded joint, weld bead area was measured from the tracing of weld metal macrostructure. The dilution of the element in the weld metal zone was calculated using computer image analysis. From this result, the average content of alloying elements in weld metal is calculated by assuming uniform dissolution. This calculated average content of the alloying element was related to the tensile strength and hardness of the weld metal.



$d = \Sigma l_i / (\Sigma n_i - m)$

d : arm spacing(μm)

l_i : arm length

n_i : intersection number

m : number of lines

Fig.4 Schematic of DAS measurement by liner intercept method

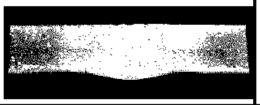
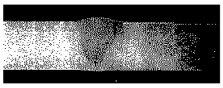
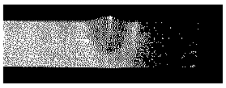
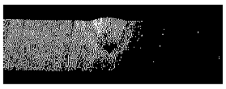
3.Results and discussion

The cross sections of laser welded joints of A6N01 alloy with Al-12Si base filler made at travel speeds of 3 to18m/min are shown in Fig.5. Some specimens show porosity, but the %porosity with respect to the weld metal is less than 1% and there are no cracks obtained in the weld metal. Full penetration is achieved for travel speeds between 3 and 9m/min, whereas partial penetration is obtained at the speeds faster than 9m/min. The bead width is also seen decreasing with the increase of travel speed.

The hardness distribution in the laser weld joint of A6N01 alloy made with Al-12Si filler metal containing Ni 5%-Zr3.0% at different travel speeds is shown in Fig. 6. At each travel speed, the hardness of heat-affected zone (HAZ) is low. However, the width of HAZ decreases as travel speed is increased. This effect is shown in Fig.7. At travel speed 18m/min, the width of HAZ decreased to 0.45mm. It is reported that if width of soft HAZ goes below 20% of plate thickness, it does not affect the strength of the welded joint. For a constant laser power, faster travel speed means reduction in laser heat input and the cooling rate becomes higher. This results in decreasing the width of the HAZ. It can also be noted from Fig.6 that, as travel speed increases, the hardness of weld metal increases.

Figure 8 shows the relation between average hardness of weld metal and calculated average content of the alloying elements.

The calculated average content of alloying elements is related to dilution. When travel speed is slow, the weld bead area is large giving increased dilution and calculated content of alloying element in the weld metal is low. In case of higher travel speeds, the area of weld bead becomes small giving low dilution and the calculated content of alloying element in weld metal is

Welding speed	Macro section	Welding speed	Macro section
3m/min		12m/min	
6m/min		15m/min	
9m/min		18m/min	

2mm

Fig.5 Cross section of laser weld of A6N01 alloy with Al-12Si base filler metal

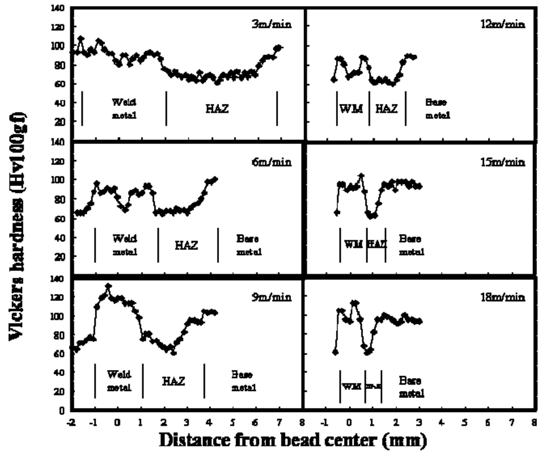


Fig.6 Hardness distribution in the laser welded joint of A6N01 alloy with Ni 5wt%-Zr3wt% in Al-12Si filler metal at different travel speeds

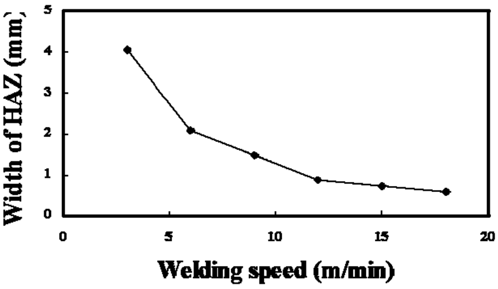
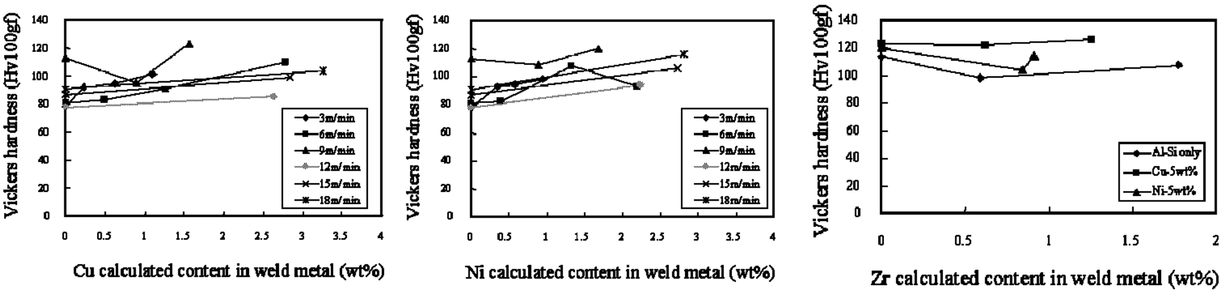


Fig7. Relationship between travel speed and width of HAZ

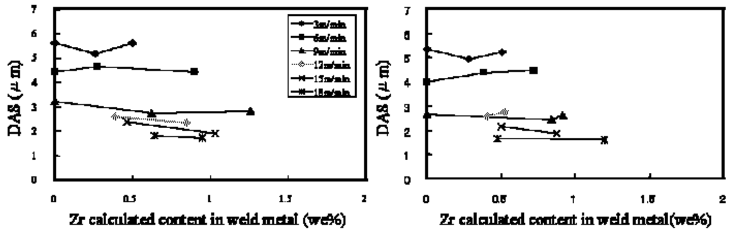


(a) Cu addition

(b) Ni addition

(c) Cu or Ni and Zr addition with travel speed 9m/min

Fig.8 Effect of alloying content in A6N01 weld metal on average weld hardness after laser welding high. When only Cu or only Ni is the alloying element in filler metal, the average hardness of weld metal increases with the calculated amount of theses elements. This indicates that solid solution hardening of weld metals has taken place. With only Cu or only Ni as additional alloying element and with travel speed of 9m/min, the average hardness of weld metal does not increase appreciably with increase in content element, but the hardness values are at the higher side as compared to other travel speeds (more than Hv 120). The effect of addition of Zr to the 3 types of filler metals namely Al-12Si, Al-12Si-5Cu and Al-12Si-5Ni on the average weld metal hardness is shown in Fig.8 (c). The hardness of weld metals are almost constant between 100 and 120Hv. In case of Al-12Si-5Cu filler metal, the hardness is about 120 Hv or higher.

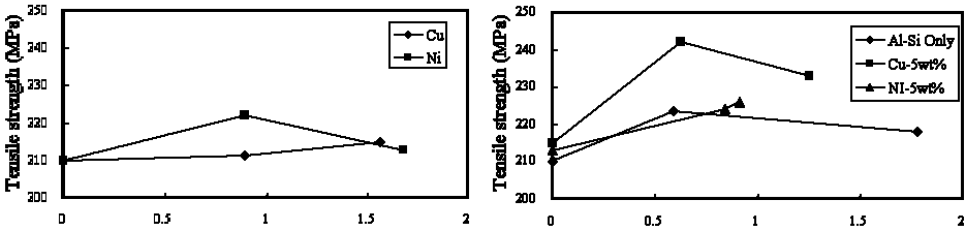


(a) Cu and Zr addition (d) Ni and Zr addition

Fig.9 Relationship between content of additional elements and DAS in A6N01 laser welded metal

Figure 9 (a) shows the relation between DAS and calculated content of Zr in the Al-12Si-5Cu filler metal. Similar relation is shown in Fig.9 (b) for filler metal Al-12Si-5Ni. In both cases, it can be noted that there is no change in DAS as Zr content increases but the effect of travel speed on DAS is clearly seen. As travel speed increases DAS decreases, indicating refinement of dendrites in the weld metal. As the travel speed increases, there is no time available for growth of dendrites; instead, the nucleation rate is fast which gives finer DAS. The finest DAS is 2 μm in case of the fastest travel speed of 18 m/min.

To understand the effect of average weld metal hardness and value of DAS on the tensile strength of the weld metal, the effect of calculated amount of additional alloying element dissolved in weld metal and respective tensile strength is shown in Fig.10. When only Cu or only Ni is added to the filler metal, there is no effect on the tensile strength with the increase of calculated amount of either Cu or Ni (Fig.10 (a)). However as seen in Fig.8 (a) and Fig.8 (b), the hardness increases with the increase of calculated amount of Cu or Ni. When Zr is added to the filler metal with and without Cu/Ni, its effect on weld metal tensile strength is shown in Fig.10 (b). This also shows that increase in the calculated amount of Zr dissolved in weld metal does not affect on the tensile strength. High tensile strength between 230 and 240 MPa was obtained in case of Al-12Si-5Cu filler metal containing Zr. However, for this filler metal with and without Zr, the hardness value was almost constant and was more than 120 Hv as seen in Fig.8 (d). In contrast to this observation, the pronounced effect of Zr addition on tensile strength can be seen in Fig.10 (b). The increased tensile strength with Zr and low tensile strength without Zr is evident. This indicates that not only solid solution hardening by Cu, but precipitation hardening by Zr helps in improving the weld metal strength.



(a) Cu or Ni addition (b) Zr only and Cu or Ni and Zr addition

Fig.10 Effect of alloying content in A6N01 weld metal on tensile strength after laser welding at 9m/min

4.Conclusion

The laser welding experiments were curried out to investigate the effect of alloying element to the mechanical properties of weld metal. From the results, following conclusions can be made.

1) By increasing travel speed, the width of soft HAZ decreases greatly. Especially when travel speed was 18

m/min, the width decreased to about 1/5 of plate thickness. This indicates the diminishing effect of HAZ on the strength of weld joint.

2) Hardness of weld metal was increased by increasing the content of Cu or Ni in filler metal. Particularly, when Cu and Zr were added to the Al-12Si filler metal, the hardness of weld metal was higher than 120 Hv, though base metal hardness was about Hv100.
3) The value of DAS decreased greatly by the increase in travel speed. However, the influence of addition of alloying elements has not been confirmed.
4) The tensile strength of weld metal increased by solid solution hardening of Cu and precipitation hardening of Zr. For the specimen welded with filler metal containing Cu and Zr, the high tensile strength was obtained between 230 and 240MPa.

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