Grain Refinement by Laser Welding of AA 5083 with Addition of Ti/B

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Abstract

Grain refinement was reported to improve the mechanical properties and reduce the hot crack susceptibility of aluminum welds. Some of today’s filler materials already contain grain refiners. However, their effectiveness will strongly depend on the boundary conditions of welding. The aim of this study is thus to determine the minimum content of Ti/B grain refiner, which is needed to achieve a small grain size with 100% globular grains of the weld metal for different welding conditions, particularly with respect to high welding speed and cooling rate by laser welding.

Controlled amounts of Tibor™ grain refiner (containing Ti and B in a ratio of 5:1) were introduced into the molten pool of AA 5083 by pre-deposited cast inserts under different welding conditions by laser welding. The results show that, despite the high cooling rate and great melt overheating, the laser weld could be grain refined to a mean grain size at ca. 22 µm. The minimal required Tibor™ concentration for complete grain refinement increases with welding speed. The WDX analysis has confirmed that the titanium aluminides are the nucleation site for equiaxed grains.

Keywords: Laser Welding; Grain Refinement; Aluminium; nucleation site; master alloy

1. Introduction

The grain refinement of aluminum welds involves a transition from coarse, columnar to small, globular grains. The refinement in grain size and shape leads not only to an improvement of mechanical properties but also to a reduction of the hot crack susceptibility in the weld. Substantial grain refinement in casting and weld is obtained by promoting the nucleation of grains during solidification. It can be achieved through providing many efficient heterogeneous nucleation sites in the melt, which builds the basis for grain refinement. Aluminum alloys are most common grain refined by Al-Ti and Al-Ti-B master alloys, which provides intermetallic aluminide particles of TiAl3 serving as nucleant substrates during solidification [1]. There is a debate over the nature of these nucleant particles in AlTiB alloys. A popular explanation of the mechanism suggests that a peritectic reaction envelops these particles in a layer of solid aluminum, which is an ideal substrate for nucleation [2]. However, the peritectic theory was not able to explain the grain refinement by Ti at a concentration less than the peritectic composition (~0.15% Ti), especially when small addition of B were made [3]. There has been a lot of debate about whether TiB2 particles themselves are effective nucleant sites for α-Al [4] or whether they may just provide substrates for Al3Ti to be stable
and thus responsible for the nucleation of α-Al at concentration below the peritectic composition [5]. Johnson et al. found out that solute elements are vitally important in the grain-refining process. They suggested that both the nucleants and the segregating solutes influence the grain refinement [6]. The extent of segregation is measured in terms of growth restricting factor (GRF) [7]. It was found out that the grain size can be described using a semi-empirical equation:

\[ d = \frac{a}{\sqrt{\text{pctTiB}_2}} + \frac{b}{Q} \]  

where \( d \) is the grain size and \( a \) and \( b \) are constants depending on the solidification conditions. The pctTiB\(_2\) is the content of the nucleant TiB\(_2\) particles in the melt. \( Q \) is the growth restriction factor (GRF), which was defined as the initial rate of development of constitutional undercooling with respect to fraction solid. It has been long realized that the segregating elements, especially titanium, restrict the growth of the solid-liquid interface, resulting in a significant grain refinement [8]. Recently, Easton and StJohn have shown that the effect of alloy content on grain size is well understood and predictable for a fixed particle addition in casting [9].

In the case of welding, especially laser welding [10] the high welding speed and the high energy density of the laser beam result in a very different solidification behavior than casting [11][12]. It leads to a different grain refinement behavior by welding process from that of casting [13]. Mousavi and Cross investigated the effect of titanium-boron additions on the solidification behavior of castings and welds of aluminum alloy 7108 and found that at low levels of Ti/B additions (<0.06 wt.% Ti) the casting grains were finer than those in the corresponding weld metal. Once sufficient particles were present, however, the weld metal grains became smaller than those in the casting, indicating a greater nucleating efficiency concurrent with the higher undercooling associated with welding.

2. Framework of this investigation

The effect of grain refiner (Ti/B) on the weld microstructures (size and shape of the grains) by laser welding process under different welding conditions were investigated in the present study. The aim for this study is to find out how grain refinement react to increasing content of grain refiner and to determine the minimal content of Ti/B that make a minimal grain size with 100% globular grains in the weld under different welding conditions.

3. Materials and experimental approaches

3.1. Materials

The raw materials used in the present study were AA 5083 and the master alloy Al-5Ti-1B (Table 1). Cast inserts will be made by adding different amounts of Tibor™ master alloy to the molten base alloy, chill-casting the mixture in a copper mold, and then machining 2 mm x 1.5 mm square inserts from the ingot. Inserts will then be pressed into a recess machined into the base metal, and this assembly will then be welded over (bead-on-plate), fusing together the insert and base metal (illustrated in Figure 1). The range of grain refiner additions in the inserts will include 0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70 wt.% Ti.

Table 1. Chemical compositions of the raw materials

| Compositions (wt. %) | AA 5083 | | | | | | | | Al-5Ti-1B |
|---|---|---|---|---|---|---|---|---|---|
| AA 5083 | Si | Mg | Fe | Mn | Cu | Cr | Ni | Ti | B |
| | 0.26 | 5.00 | 0.40 | 0.54 | 0.07 | 0.09 | 0.01 | 0.03 | - |
| Al-5Ti-1B | 0.06 | - | 0.11 | - | - | - | - | 4.98 | 1.00 |
3.2. Welding approaches

In order to introduce the Titanium/Boron into the molten pool, a wide weld was needed to melt the cast insert completely during welding. A Laser scanner was applied to meet this requirement.

The laser scans cross the welding direction, so that the inserts can be welded and an almost constant weld width can be made. Three different welding speeds were carried out and the laser power was then set to match the welding speed to realize a full penetration welding. The welding parameter are shown in Table 2. In this way, different solidification conditions were fulfilled, which would influence the grain refining effects [14].

Table 2. Welding parameter

| Group | Laser source | defocus | Focus spot diameter | Focal length | Shielding gas | Laser power | Welding speed | Scanner frequency |
|-------|--------------|---------|---------------------|--------------|---------------|--------------|---------------|-------------------|
| A     | TruDisk 8002 | -8 mm   | 250 µm              | 300 mm       | Argon: 20 L/min (welding gas) | P = 3.5 kW | v = 2 m/min | f = 200 Hz |
| B     |              |         |                     |              | Helium: 10 L/min (root gas)    | P = 6 kW | v = 4 m/min | f = 250 Hz |
| C     |              |         |                     |              |               | P = 8 kW   | v = 6 m/min | f = 250 Hz |

3.3. Measurement of the temperature and cooling in the weld

Thermocouples (type K) were used to measure the temperature in molten pool during laser welding. The cooling rate of the melt has been calculated according to the temperature curve.

3.4. Evaluation of the grain refinement

Investigation of the grain refinement was carried out by measurement of the size and proportion of the globular grains in the welds. The cross-sections of the welds were at first polished and then electro-etched. Metallographic photos of these specimens were taken under a light microscope at different magnifications using polarized light. The grain size measurement was done in the cross-section of the laser welds using the linear intercept method, calculating an average grain diameter over approximately 120 grain intercepts. The measurements were made at upper, middle and lower areas of the weld respectively. The mean grain size values were used to represent the overall effect of grain refinement.
3.5. Identification of the grain refiner in the welds

In order to identify the grain refiner in the laser welds, wavelength dispersive x-ray spectroscopy (WDX) was performed on one selected specimen which has the most Ti/B elements and the finest grain size of all.

4. Results

4.1. Cooling rate of the molten pool

Figure 2 shows for example a typical cooling curve in the middle of the molten pool in laser welding process. During welding the melt could reach a temperature over 1300 °C, indicating a very big overheating in the melt. The cooling rate can reach 1150 °C/s at solidification.

![Cooling curve](image)

Figure 2. Cooling curve in the middle of the molten pool by laser welding (Welding parameter: P = 6 kW; v = 4 m/min)

4.2. Grain structures

Figure 3 shows the cross-sections of the welds that were welded through Laser scanner with 0% and 0.5% Tibor™ (5Ti + 1B) additions in the inserts. Note that, AA 5083 contains already 0.03 % Ti. The Titanium content in the weld was calculated by the sum of the titanium from the base metal AA 5083 and the insert. It is clearly to see that there are more coarse columnar grains growing from the fusion boundary toward the centre of the fusion zone in the weld without Tibor™ additions. In contrast more fine and equiaxed grains were generated with Tibor™ addition. A weld with complete fine equiaxed grains can be achieved by 0.25% Titantium in the weld, Figure 3b.
4.3. Effect of Tibor™ additions

Figure 4 shows the micrographs in the centre of the weld cross-sections that showed in Figure 3. Globular grain structures with dendrites can be produced under both welding conditions. The addition of Tibor™ can significantly make a grain refinement in the weld.

Figure 5 shows the effect of the titanium addition on the mean grain size and the percentage of the equiaxed grains on the weld cross-section. With the increase of the titanium content, the mean grain size decreased steadily achieving a low level of 22 µm and meanwhile more globular grains were generated in the weld reaching a complete constitution of globular structure by 0.25 % titanium. It can also be confirmed that, the grain size will keep almost constant, if complete globular grains were achieved in the welds.
Figure 5. Grain refining effect of Tibor™ on laser welded alloy AA 5083 (Welding parameter: \( P = 6 \text{ kW} \); \( v = 4 \text{ m/min} \))

4.4. Effect of welding parameters

Figure 6 compares the effects of Tibor™ on the grain refinement in the welds which were made under different welding conditions with laser scanner. At each titanium content except the welds without Tibor™ addition, the mean globular grain size keeps almost constant by changing the welding parameters. However, the proportion of the globular grains increase with the welding speed and more titanium would be needed to realize a complete constitution of globular grains in the weld.
4.5. Identification the grain refiner

Figure 7 shows the WDX (wavelength dispersive X-ray spectroscopy) mappings of the main elements such as Mg, Al, and Ti in a grain refined weld. Figure 7c shows that, the titanium gathers together in particles. In Figure 7d, the distributions of these three elements are comprised. It can be seen that the titanium and aluminum contained particles are located in the centre of the aluminum dendrites, serving as a substrate for dendrite nucleation. The magnesium distributes between the aluminum dendrites.
5. Discussion

Based on the results, it is obvious that the Tibor™ additions help to realize a grain refinement in the welds. Not only the size of the equiaxed grains can be greatly reduced but also the grain shape in the weld can also be changed from columnar to equiaxed grains, Figure 5. The first grain refinement addition (ca. 0.06 wt% Ti) gave the largest decrease in grain size. Addition of further grain refiner had a smaller effect on further grain refinement. The mean grain size tends to keep constant after it reaches a minimum level at about 22 µm and will not continue to decrease with more Tibor™ additions in the welds. These phenomena are similar to the results from the literature both in casting [9] and arc welding [15].

Changing the welding parameters has not clearly influenced the size of the equiaxed grains or its dependence on the Tibor™ additions. However, by higher welding speed, more Tibor™ was needed to change the columnar grains to equiaxed structures, Figure 6. Comparing to the results by casting [7] with a cooling rate of 1 °C/s, the grains could maximal refined to ca. 200 µm which is much bigger than that by laser welding with the actual measured cooling rate by solidification at 1150 °C/s. The high cooling rate would have prevented the TiAl₃ particles that came from the cast insert from a complete dissolution.

It may be assumed that, those undissolved particles originally present in filler metal will eventually undergo a peritectic reaction upon cooling. This peritectic occurs at a temperature that is slightly above the liquidus temperature of the alloy (665°C):

\[(\text{Al})_L + \text{TiAl}_3 \rightarrow \alpha-\text{Al} \]  \hspace{1cm} (2)
This means that aluminide particles become coated with solid aluminum, which is the perfect substrate needed to nucleate new equiaxed grains[16]. Figure 7 shows the TiAl intermetallic phases concentrate in the middle of the $\alpha$-Al dendrites, providing a perfect nucleant site for the grains. It should be noted that if the aluminide particles are held in the liquid state for too long a time, e.g. by casting with a very low cooling rate, they will dissolve and cannot then participate in the peritectic reaction, a process referred to as fading. In addition, increasing the Tibor™ additions will introduce more TiAl$_3$ particles into the molten pool and therefore generate more nucleating sites for equiaxed grains. In the weld there will be more fine equiaxed but less columnar grains. Other than casting, by which the master alloy is usually added to the aluminum melt at 720 °C (Figure 8), the filler metal will be melted by laser welding at 1300 °C. This means that the TiAl$_3$ particles are more likely to dissolve by welding, which requires more Tibor™ addition for grain refinement than that of casting, by which usually only 0.01% Ti is needed [1]. Furthermore, to compensate the loss of materials through evaporation, one needs to bring more Tibor™ by laser welding. However, the grain size has its minimum level, at which more Tibor™ additions will not further refine the grain. On one hand, the grain refinement depends on the size of the undissolved particles originally present in the filler metal. The size and amount of the TiAl$_3$ particles which were introduced into the weld increase with the titanium content in the filler metal. Although they may become smaller or even dissolve into the liquidus by melt overheating, the new TiAl$_3$ phase will precipitate again and most would take the undissolved particles as substrates until the solute titanium content in the melt down to the liquidus point on the peritectic line. On the other hand, the minimal grain size is also determined by the amount of the nucleant particles that are present in the melt. One must note that not all the nucleant particles in the melt will take part in the peritectic reaction and thus work as nucleants. Therefore the low plateau of the grain size curves in function of titanium content in Figure 5 and Figure 6 indicate that there seems to be a maximal amount of the active nucleant particles for peritectic reactions and equiaxed grains. Further increasing of the Tibor™ additions will not improve the grain shape or reduce the grain size anymore.

![Al-Ti phase diagram](image)

Figure 8. Aluminum rich end of Al-Ti phase diagram [17]

If the weld which is all comprised of equiaxed grains with minimal grain size can be defined as a complete grain refined weld, the minimal Tibor™ addition that needed for complete grain refinement can be determined. Figure 9 shows the relationship between the minimal titanium content required for complete grain refinement and welding speeds. By higher welding speed more titanium are required to produce a complete grain refinement. Since more columnar would grow from the fusion lines (Figure 6) more Tibor™ were required to bring more nucleant sites for equiaxed grains in the molten pool.
6. Conclusion

The main conclusions of this study are:

• The Tibor™ addition can significantly grain refine the weld by laser welding on AA 5083. The grain size and shape depend on the amount of the Tibor™ addition. With increasing the Tibor™ addition more globular grains were generated and the grain size would be reduced until a complete grain refined weld which are all comprised of globular grains was achieved.

• At high concentration of Tibor™, the complete grain refined laser welds with minimal mean grain size at ca. 22 µm could be made.

• The minimal required Tibor™ concentrations for complete grain refinement at three different welding speeds were determined. At higher welding speed more Tibor™ addition are required to produce a complete grain refined weld.

• The WDX analysis confirmed that the titanium aluminide particles were located in the middle of the aluminum dendrites and therefore the substrate for the nucleation of the globular grains.

Acknowledgement

This work was accomplished within the Center of Competence for Welding of Aluminum Alloys - Centr-Al. The authors thank Mr. Schempp and the BAM for providing the cast inserts for the welding experiment. The authors appreciate the AIF for the financial support (Agreement No. 16.242N) and DVS for supporting the work.
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