Laser Beam Welded T-Joints of 6013 Aluminium Alloy Sheet

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Abstract

T-joints of 1.6 mm thick 6013 sheet were produced using a 3 kW Nd:YAG laser and different aluminium filler powders. Pores were observed in the fusion zone exhibiting a dendritic microstructure with interdendritic regions rich in silicon and copper. Using highly-alloyed filler powders, microhardness measured in the fusion zone exceeded that of the base alloy 6013-T4. A post-weld heat treatment to the T6 temper increased the hardness, indicating precipitation of strengthening phases in the fusion zone. Tensile strengths of T-joints in the as welded T4 condition were in the range from 65 to 80% of the ultimate tensile strength of the parent sheet 6013-T4. Increase in strength due to post-weld heat treatment was moderate. The corrosion behaviour of welds exposed to an intermittent acidified salt spray fog was similar to that observed for the base material.

1. Introduction

Aluminium alloys exhibit a good strength-to-weight ratio, favouring their use for lightweight structures in the transportation industry. Offering high speed and flexibility, laser beam welding is an important joining technology, which is particularly appropriate for heat treatable aluminium alloys [1]. The low heat input results in low distortion and narrow fusion and heat affected zones. Weld qualities have achieved a high level, enabling the substitution of the conventional riveted stringer-skin joint by laser beam welding [2]. A welded integrally stiffened shell has been introduced in the lower fuselage of the aircraft A318 [3]. Weldable 6xxx aluminium alloys, such as 6013 and 6056, are used for stringer and skin. Weldability of aluminium alloys, i.e. hot cracking susceptibility, porosity formation and joint performance, depends primarily upon the composition of base alloys and filler metals [4]. The aim of the present work was to study the microstructure, hardness, tensile strength, and the corrosion behaviour of T-joints of the alloy 6013 produced by Nd:YAG laser beam welding using different filler powders.

2. Experimental

The material used was a 1.6 mm thick sheet of the alloy 6013 in the tempers T4 and T6. T-butt welds were produced using a 3 kW Nd:YAG laser and helium shielding gas. Argon atomised powders of the aluminium alloys AlSi12, AlSi20, AlSi40, AlMgSi1, AlSi10Mg, AlSi12Mg5, and Al4.5MgMn were used as filler metals (composition of the alloys in weight

percentage). Particle size ranged from 45 to 150 μ m. Dimensions of the basal sheet and stringer to be welded were 400×100 and 400×50 mm², respectively. T-shape joints were realized by double pass welding subsequently along the two edges. The welds were investigated in the as welded T4 and T6 conditions and after a post-weld heat treatment to the T6 temper (4h at 191°C). Hardness was measured on polished surfaces with a load of 4.9 N. Composition analysis was performed using a scanning electron microscope with an Oxford EDS detector. The acceleration voltage was 20 kV. Tensile strength of the T-joint was determined using 25 mm wide strips machined from the T-shaped assembly. During the mechanical test the stringer was pulled off the basal sheet being rigidly clamped. Triplicate specimens were tested. Strength values were calculated dividing the maximum load applied by the cross-section of the stringer. The corrosion behaviour was evaluated performing acidified salt spray tests according to ASTM G85, Annex 2. Exposure time period was 2 weeks.

3. Results and Discussion

Figure 1 shows macrographs of T-joints laser beam welded using the filler powders AlSi10Mg (a) and AlSi12Mg5 (b). Metallography revealed generally full penetration welds. Sometimes, small crevices were observed in the fusion centre exhibiting a sharp edge near the original surface of basal sheet. At these defects, the components were probably not completely fused. The basal sheet suffered a slight distortion. Hot cracks were not observed in the metallographic sections, but pores were found in the fusion zone.



Figure 1: Macrographs of T-shape joints welded using the filler powders AlSi10Mg (a) and AlSi12 Mg5 (b).

Figure 2 shows scanning electron micrographs of slightly etched metallographic sections of a 6013 joint welded using the filler powder AlSi10Mg. The fusion zone exhibited a cellular dendritic solidification structure. A partially melted zone was found adjacent to the fusion boundaries. Its width extended over two to three grains. The chemical composition of the fusion zone was determined by EDX analysis. Results are given in Table 1. To determine average concentrations of the alloying elements, raster analysis was performed, scanning an area of $15 \times 20 \ \mu\text{m}^2$. The content of silicon in the fusion zone increased with increasing silicon content of the filler powders. The magnesium concentration was also higher in comparison to the base alloy, when magnesium rich filler metals were used. Similar amounts of copper and manganese were measured in the fusion zone and in the parent material. The iron content resulted from impurities in the filler powders. As found by spot analysis, the dendritic cores were enriched with the filler alloying elements silicon and magnesium. The interdendritic regions contained several phases (the composition of the interdendritic region is the mean of five measurements). These phases were rich in Si, Cu,

Mg, Mn, and Fe, being probably eutectic formed by the alloying elements of the filler powders and the parent material.

Values of the Vickers hardness HV0.5 measured in the fusion zone of T-joints made with different filler powders are listed in Table 2. The mean of ten measurements is given. The lowest hardness was found with joints welded using the filler powder AIMg4.5Mn. The hardness increased with increasing content of alloying elements in the filler metals. The highest values were determined in welds made with AISi40 and AISi12Mg5. A post-weld heat treatment increased the hardness in the fusion zone due to precipitation of strengthening precipitates. The increment ranged between 14 and 21 HV0.5, indicating an approximately similar age hardening effect in all joints. For welds in the as welded T6 condition, similar values were measured to those in the as welded T4 condition. The hardness increase with higher content of alloying elements in the filler powders might be associated with solid solution hardening of silicon and, to a lesser extent, of magnesium and to an increasing amount of eutectic and other intermetallic phases.



Figure 2: Scanning electron micrographs of the fusion zone of a T-joint welded using the filler powder AlSi10Mg, showing the dendritic solidification structure at different magnifications (a, b). Porosity (a) was typically found in joints laser beam welded using aluminium filler powders.

Tensile strengths of the T-joints are presented in Table 3. For welds in the as welded T4 condition, values ranging from 214 to 282 MPa were determined, corresponding to joint efficiencies between 62 and 82%. A marked dependence of strength upon the alloying elements of the filler powders was not observed. The increase in strength due to a postweld heat treatment was moderate, not exceeding 80% of the ultimate tensile strength of 6013-T6 sheet. A significant improvement in strength of the fusion zone was not observed for 6013-T6 joints which were post-weld heat treated at 191°C for 4h (second peak-aged temper T62). Failure occurred in the fusion zone. Cracks propagated very often close to the fusion boundaries, suggesting that crack initiation occurred near the partially melted zones. Fractographic examinations revealed a ductile dimple like fracture. On the fractures surfaces, pores and secondary cracks were observed (Figure 3). These secondary cracks were probably hot tears, indicating that the occurrence of hot cracking in laser beam welds of 6013 sheet was not completely eliminated by the filler powders used. The large pores being about 100 µm and higher in size (Fig. 3c) probably resulted from the instability of the keyhole [5]. This type of porosity was observed particularly in welds made with filler powders containing a high content of magnesium (AIMg4.5Mn, AISi12Mg5). The smaller pores found on the fracture surfaces of all specimens tested might be associated with hydrogen (Figs. 2a, 3b).

Table 1: Composition of the base alloy 6013 and of joints welded using different filler powders, as determined by EDX spectroscopy. Raster and spot analyses were carried out in the fusion zone and in different regions of the solidification microstructure, respectively (concentration in wt.-%).

| Filler Powder | | AI | Mg | Si | Cu | Mn | Fe |
|---------------|-----------------------|-------|------|-------|------|------|------|
| base alloy | | 97.15 | 0.87 | 0.74 | 0.96 | 0.28 | |
| AlSi12 | Fusion zone | 95.32 | 0.78 | 2.30 | 0.95 | 0.33 | 0.32 |
| | Dendrite | 96.78 | 0.73 | 1.18 | 0.75 | 0.35 | 0.21 |
| | Interdendritic region | 86.62 | 1.05 | 5.40 | 3.29 | 1.20 | 2.44 |
| AISi20 | Fusion zone | 93.46 | 0.70 | 4.38 | 0.86 | 0.31 | 0.29 |
| | Dendrite | 94.95 | 0.74 | 2.90 | 0.78 | 0.36 | 0.27 |
| | Interdendritic region | 89.47 | 1.05 | 6.06 | 2.28 | 0.45 | 0.71 |
| AISi40 | Fusion zone | 89.64 | 0.68 | 8.26 | 0.83 | 0.31 | 0.28 |
| | Dendrite | 93.66 | 0.58 | 4.63 | 0.72 | 0.24 | 0.17 |
| | Interdendritic region | 81.52 | 1.29 | 11.29 | 4.72 | 0.51 | 0.68 |
| AIMgSi1 | Fusion zone | 94.59 | 0.78 | 3.06 | 0.90 | 0.36 | 0.31 |
| | Dendrite | 95.58 | 0.69 | 2.25 | 0.84 | 0.34 | 0.30 |
| | Interdendritic region | 89.91 | 0.81 | 4.74 | 3.40 | 0.48 | 0.67 |
| AISi10Mg | Fusion zone | 95.60 | 0.99 | 1.85 | 0.91 | 0.36 | 0.29 |
| | Dendrite | 95.83 | 1.10 | 1.77 | 0.72 | 0.33 | 0.25 |
| | Interdendritic region | 90.06 | 1.07 | 4.14 | 3.17 | 0.53 | 1.04 |
| AISi12Mg5 | Fusion zone | 94.79 | 1.23 | 2.58 | 0.83 | 0.32 | 0.25 |
| | Dendrite | 95.36 | 1.35 | 2.12 | 0.68 | 0.27 | 0.22 |
| | Interdendritic region | 88.02 | 1.32 | 4.97 | 3.76 | 0.73 | 1.21 |
| AIMg4.5Mn | Fusion zone | 96.32 | 1.40 | 0.81 | 0.75 | 0.44 | 0.28 |
| | Dendrite | 96.81 | 1.45 | 0.52 | 0.56 | 0.42 | 0.24 |
| | Interdendritic region | 90.75 | 1.30 | 2.12 | 3.10 | 0.74 | 2.01 |

Table 2: Vickers hardness (HV0.5) measured in the fusion zone of 6013 joints in different heat treatment conditions welded using various filler powders.

| Filler Powder | T4 as welded | T6 post weld heat treated | T6 as welded |
|-------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| AlSi12 AlSi20 AlSi40 AlMgSi1 AlSi10Mg AlSi12Mg5 AlMg4.5Mn base alloy | 96 ± 3 104 ± 5 119 ± 5 106 ± 4 105 ± 9 118 ± 9 91 ± 3 102 ± 4 | $117 \pm 4 \\ 119 \pm 6 \\ 133 \pm 6 \\ 121 \pm 3 \\ 126 \pm 7 \\ 136 \pm 6 \\ 106 \pm 4 \\ 132 \pm 6$ | 96 ± 3 100 ± 8 116 ± 6 103 ± 3 105 ± 10 89 ± 3 |

Table 3: Tensile strength (in MPa) of 6013 T-joints in different heat treatment conditions welded using various filler powders.

| Filler Powder | T4 as welded | T6 post-weld heat treated | T6 as welded | T62 post-weld heat treated |
|-------------------------------------------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|----------------------------------------|----------------------------------------|
| AlSi12 AlSi20 AlSi40 AlMgSi1 AlSi10Mg AlSi12Mg5 AlMg4.5Mn base alloy | 274 262 258 282 273 243 214 345 | 296 280 283 301 290 284 245 397 | 266 256 295 306 315 222 | 264 281 297 306 311 235 |



Figure 3: Scanning electron fractographs of 6013 joints welded using the filler powders AlSi12 (a), AlSi20 (b), and AlSi12Mg5 (c, d), showing pores and hot tears.

As illustrated in Figure 4a, specimens of T-shape welds suffered pitting when exposed to an intermittent acidified salt spray fog. According to visual inspection, the corrosion attack was similar to that observed with the parent material. An influence of the different filler powders on the corrosion performance, in particular due to galvanic coupling, was not found. For 6013-T6 welds in the as welded condition, a zone with a width of about 1 mm was observed adjacent to the fusion boundary being not attacked by corrosion. This zone was not found when the joints were post-weld heat treated 4 h at 191°C (T62 temper). Testing the rear side of the basal sheet (opposite to the welded stringer), a zone being not corroded was also observed for specimens machined from T-joints in the as-welded T6 condition, indicating that the heat affected zone extended through the whole thickness of the basal sheet (Figure 4c). Obviously, the heat input during laser beam welding was sufficiently high to dissolve the strengthening precipitates of the peak-aged microstructure in the heat affected zone. Subsequent aging at room temperature in the region near the fusion boundary resulted in a microstructure being similar to the T4 temper. The corrosion potentials of 6013 sheet in the tempers T4 and T6 were -0.444 and -0.486 mV_{NHE}, respectively, as measured according to the standard test method ASTM G69. Being more active, the peak-aged parent material might provide cathodic protection to the region near the fusion zone exhibiting a naturally aged microstructure.



Figure 4: Pitting corrosion on specimens machined from T shape welds after two weeks of exposure to an intermittent acidified salt spray fog: top side with fusion zone (a), rear side of the basal sheet of T-joints in the as welded T4 (b) and as welded T6 (c) conditions.

4. Conclusions

- T-shape welds of 1.6 mm thick 6013 sheet were produced by double pass laser beam welding using silicon rich filler powders.
- The fusion zone exhibited a dendritic solidification structure with interdendritic regions enriched with silicon and copper.
- Pores were observed in the fusion zone, being the prevailing weld defect.
- Hardness measured in the fusion zone increased with increasing silicon and magnesium content of the filler powders.
- An increase of hardness was found in the fusion zone of joints post-weld heat treated to the T6 temper, resulting from precipitation of strengthening phases.
- Tensile strengths of the T-shape welds in the as welded T4 condition ranged from 65 to 80% of the ultimate tensile strength of the base alloy 6013-T4. Increase in strength resulting from a post-weld heat treatment was moderate.
- When exposed to an intermittent acidified salt spray fog, 6013 welds in the different heat treatment conditions were susceptible to pitting corrosion. The corrosion behaviour of the T-joints was similar to that of the base material.

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