Pulsed Nd:YAG Laser Welding of Al-Si Controlled Expansion Alloys and Aluminum 4047

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ABSTRACT

Aluminum Silicon alloys are lightweight, high thermal conductivity alloys that are increasingly being used for RF & microwave packages, electro-optical housing, power device base plates and other critical heat sinking applications. The manufacture of these packages requires the Al-Si body containing the electronics to be hermetic sealed using Aluminum 4047 lids. The heat sensitivity of the weld requires the use of a pulsed laser, however welding alloys with a silicon content over 27% becomes increasingly problematic due to cracking of the Al-Si alloy. This is due to the weakness of the Al-Si alloy under the solidification forces of the weld. The thermal performance advantage of the higher silicon content alloys has great potential for significantly improving power handling of the packages. Therefore, a welding process was developed using pulse shaping and a minimized average power approach that eliminated cracking in alloys with up to 40% silicon In addition a novel concept is introduced that enabled crack free welding of 70% silicon alloys.

INTRODUCTION

Aluminum Silicon alloys are binary alloys of silicon and aluminum, produced by Sandvik Osprey by a proprietary spray forming process. These controlled expansion alloys are offered in a range of weight proportions of silicon and aluminum from 70Si-30Al to 27Si-73Al, with CTE's 7.5 to 16 ppm/°C respectively. The specific applications of these alloys in summarized in Table 1. Aside from tailoring the CTE, the key advantages these alloys over materials such as kovar and CuW are reduced weight, high stiffness and ease of manufacture [1].

Composition	CTE 20 –500 C (ppm)	Sandvik Osprey designation	Applications
Si-30%Al	7	CE7	RF & microwave packages, Electro-Optical housing, power device base plates.
Si-40%Al	9	CE11	
Si-50Al	11	CE13	General electronic packaging, heating blocks in die bonders, components for inertial systems.
Al-42%Si	13	CE17	
Al-27%Si	17	CE27	

Table 1 Composition and applications for the range of Al-Si alloys.

In constructing a housing or package the body containing the components must be hermetically sealed under vacuum to ensure component operational reliability and longevity. The lid of the package is aluminum, typically 4047 or 6061, as these alloys contain high percentages of silicon. Laser welding is the preferred joining technology; as arc based techniques overheat the solder and internal electronics of the package.

In order to successfully laser weld the alloys beyond a silicon content of 27%, the heat input must be minimized and the thermal cycle carefully controlled. Figure 1 shows a typical weld result, using un-optimized welding conditions. The unique problem in welding these two materials is the composite nature of the Al-Si alloy, and that cracking does not occur in the weld material, rather immediately adjacent to the weld metal in the Al-Si alloy. In all previous examples that used pulse shaping to overcome cracking, the mode was hot cracking in the weld material [2-3]. The pulse shapes proposed simply extended or slowly reduced the thermal heating effects on the weld material, in this instance the pulse shaping must address the stress field created in the Al-Si.

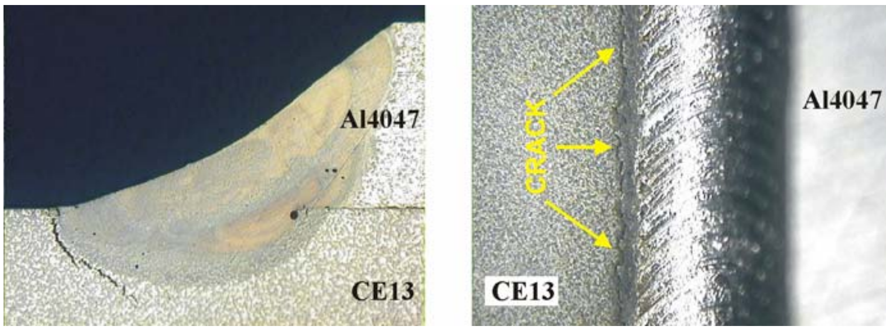


Figure 1 Cross section of an un-optimized seam weld indicating the location of crack, that occurs outside of the weld in the heat affected zone of the Al-Si. A top view of the weld shows the crack clearly running the length of the seam

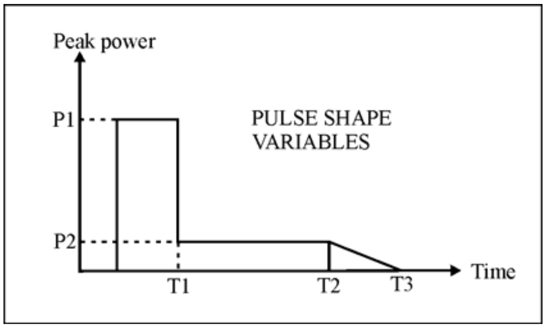
EXPERIMENTAL

The objective of the experimentation was to assess the feasibility of welding Al-Si controlled expansion alloys with increasing Si contents to 4047 aluminum. The specific experimental goals were as follows –

- Benchmarking studies on CE13, 40 % silicon alloys, to produce to assess cracking mode and sensitivity of weld cracking and quality to laser and process parameters as summarized in Table 2.

Parameter	**Level**
Average Power (W)	18 - 270
Peak Power (kW)	1 - 8
Square Pulse Width (ms)	0.3 - 20
Repetition Rate (Hz)	5 - 40
Welding Speed (in/s)	0.03 – 0.2
Gas Shroud (cfh)	None – 55
Weld Offset (in)	0 – 0.01

- Investigate the feasibility of laser pulse shaping to weld 40 -70% silicon alloys. The general pulse shapes used was an annealing pulse, with variables P1, P2, T1,T2 and T3.



A Unitek Miyachi LW400A laser was used, using a 600 micron stepped index fiber and an FX focus head assembly with a collimation/focus ratio of 1.2:1. During the trials the focus head was angled around 40 degrees to the normal. The aluminum lids were 0.02" thick with milled edges to provide a consistent weld interface for the fillet / edge butt welds. Prior to each seam weld, a number of tack welds were used to avoid the lid from distorting. For component hermetic seam sealing applications a glove box is used, however for convenience these trials were completed in air using a diffused argon gas shroud. In terms of assessing the response of weld cracking this was not significant.

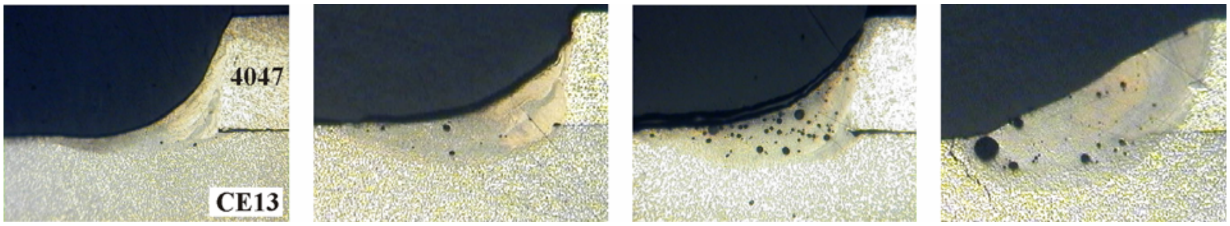
The welds were analyzed for cracking by visually inspecting the weld surface using an optical microscope, and examining the weld cross section by sectioning the welds.

RESULTS

Weld Benchmarking

Parameter	**Response to cracking**
Average Power (W)	Higher average power induced more cracking
Peak Power (kW)	Higher peak powers with shorter pulse duration tend to reduce cracking
Pulse Width (ms)	Shorter pulse widths reduced cracking
Repetition Rate (Hz)	Lower rates reduced cracking
Welding Speed (in/s)	Intermediate speeds reduced cracking
Gas Shroud (cfh)	Pressure had no effect on cracking, but caused porosity with too low or high pressures
Weld Offset (in)	Weld cracking reduced with increasing offset

The benchmarking results indicate that high pulse repetition rates and long pulse durations increase cracking potential. In these trials only a very small processing window existed that produced crack free welds. The conditions were at minimal average heat input conditions; using 6kW peak power, 1ms pulse width, 10 Hz repetition rate, at 0.1"/s welding speed. A summary of results are shown in Figure 2. Although free of cracks the weld is slightly undercut, potentially weakening the mechanical strength. When the laser was offset into the Al-Si, as shown in Figure 2b, the resulting weld was crack free, but the joining area is reduced. Other results in Figure 2 show the effect of too little or excessive gas pressure, and the cracked weld resulting from using a pulse with low peak power and long pulse width durations.



(A) **(B)** **(C)** **(D)**

Figure 2 Cross sections of seam welds in CE13 (Al-40%Si) at various conditions. (A) 8kW, 1ms, 10 Hz, 0.1”/s. (B) Offset into Al-Si alloy; 5kW, 1ms, 17 Hz, 0.15”/s (C) Insufficient or excessive gas pressure (D) 2kW, 20ms, 10 Hz, 0.1”/s.

Laser Pulse Shaping

From the work completed in the bench mark studies the pulse shape needed to reflect the requirements of short welding pulse durations and high peak powers. In addition, the pulse repetition rate and welding speed must also provide an 80-90% overlap for hermeticity, minimized average power and create a sufficiently large weld volume. The pulse variables were centered around a short initial spike that created the weld, followed by a lower peak power tail. The use of pulse shaping proved effective in increasing the process window of the CE13 40% silicon alloy, but did not prove successful in welding alloys with greater silicon content. The optimal pulse shape is shown in Figure 3, with a 7.5kW peak power ramp up for 0.3s duration followed by a 1.1kW peak power cool down for 3ms. The pulse repetition rate and welding speed were 13Hz and 0.08”/s respectively.

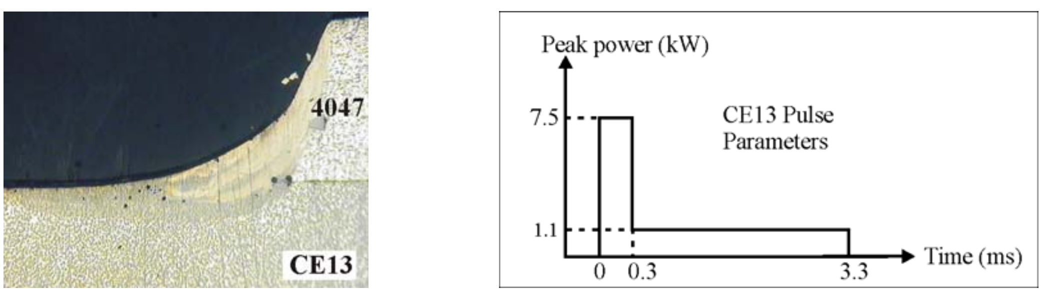


Figure 3 Cross section of CE13 weld with the pulse shape used.

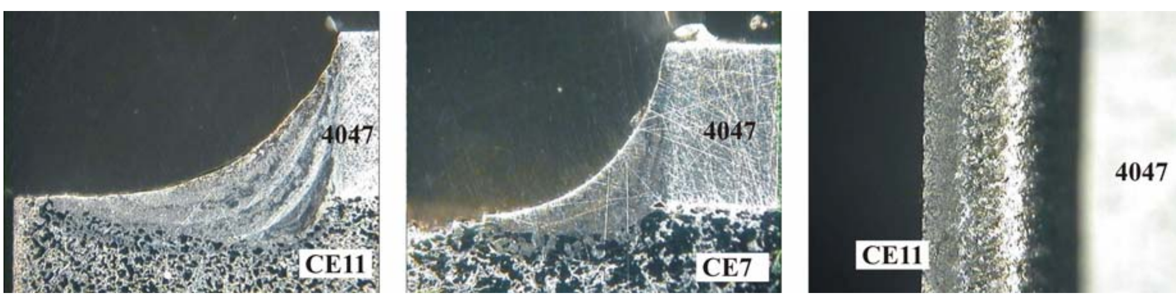
DISCUSSION

In the experimental work laser process parameters were determined to produce consistent crack free welds in CE13, 40% silicon alloy. Beyond 40% silicon content welding is problematic due to the high crack sensitivity of the alloys under weld solidification forces. In contrast to hot cracking that occurs instantaneously, and cold cracking that occurs sometime after the weld has solidifies, these cracks occur instantaneously after welding outside of the weld and primary heat affected zone area. In addition, the cracks do not appear to propagate into the weld material or heat affected zone.

Weld solidification forces encompass two distinctly different parts. Most commonly discussed are the forces created as the weld solidifies from a liquid to solid. The second part is the thermal gradient in the material immediately surrounding the weld that creates internal stresses of compression and tension. The CTE of aluminum 4047 is 16ppm/°C compared with 7 ppm/°C for CE7, therefore a mismatch of CTE provides the necessary shrinkage forces. However, if a bead on plate weld is laid down on the CE7 only, the weld cracks on both sides in the exact same place adjacent to the heat affected zone. This would indicate that weld shrinkage may not be the dominant cracking mechanism. It also may be argued that as a large amount of silicon exits in and around the weld area, the expansion of silicon with decreasing temperatures counteracts the shrinkage forces.

It has been shown that using arc technology with a silicon based filler material can produce crack free welds in high silicon content alloys[4]. One key difference between arc and pulsed laser welding is the heat input into the part and subsequent thermal gradients. Arc welding is a slow process that through conduction heats up a large area surrounding the weld, in contrast, pulsed laser welding uses millisecond pulses to heat only a highly localized area around the weld. Therefore the temperature gradients produced in pulsed laser welding are very high, setting up highly stressed areas within a short distance from the weld. In addition the laser exerts a very rapid thermal weld cycle on a material, possibly creating thermal shock. The Al-Si alloy with relatively large silicon deposits in an aluminum matrix are susceptible to cracking under such stresses that would be at a maximum next to the heat affected zone. As these deposits increase in size with increasing silicon content, the likelihood of the deposit spanning the highly stressed zone increases, and thus the cracking susceptibility increases.

In attempting to prove this theory some welds were completed with the lid positioned close to the edge of the alloy. The close proximity of the edge effectively modifies the isotherms around the weld, such that the thermal gradient is reduced and re-orientated. The result, shown in Figure 4, clearly shows crack free welds in the highest silicon content alloy CE7. In addition the laser parameters process windows for lower silicon content alloys was significantly increased.



(A) **(B)** **(C)**

Figure 4 Welds completed with lid positioned 0.04" from the alloy edge. (A) CE11, with 50% silicon content (B) CE7 with 70% silicon content (C) Plan view of CE11 seam showing crack free weld.

The basic method for the edge weld versus regular in plane weld is shown in Figure 5. The edge weld isotherms are modified by the edge boundary preventing the high radial thermal gradients and associated stresses. The proximity of the edge also creates a thermal insulation that may reduce the effect of thermal shock. However, this does not appear to be the dominant mechanism as the heat build up would take time and the edge welds are crack free from the start of the weld.

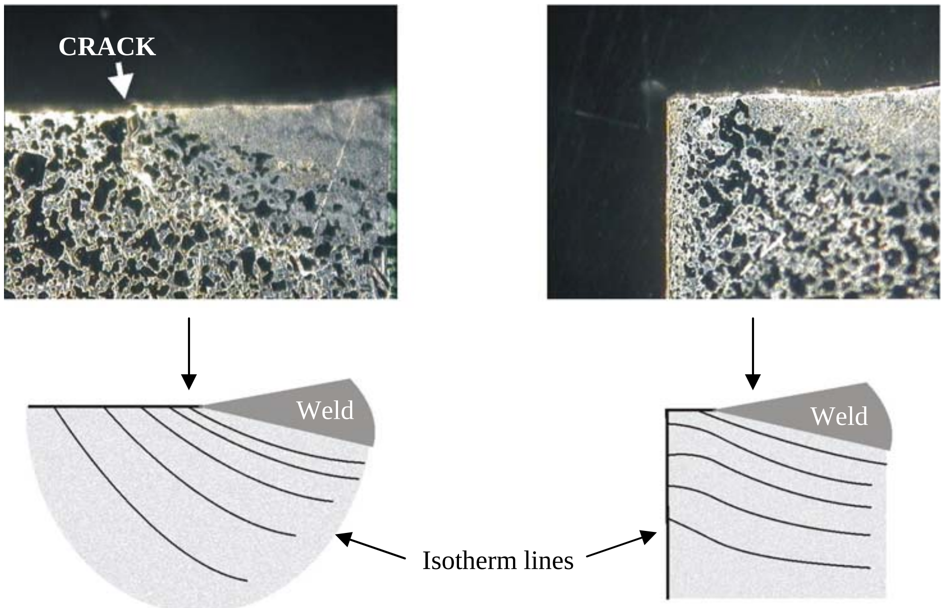


Figure 5 Micrographs of the a CE11, 50% silicon alloy, weld edge at x300 magnification, both for away from edge and at edge welds. The schematic sketches show the isotherm lines and how the edge weld modifies these to prevent the stress field adjacent to the weld.

The implementation of the edge welding technique for commercial manufacture of Al-Si packages is currently being undertaken. Although welding every package in this way may not be possible, modifications to the package in the form of troughs and channels could may be possible, especially considering the ease of machining the Al-Si alloys.

CONCLUSION

The welding of Al-Si alloys with a silicon content greater than 40% shows a high susceptibility to cracking. These cracks occur adjacent to the weld in the Al-Si alloy. It is proposed that the cracking mechanism is primarily due to the high thermal gradients pulsed laser welding, and the subsequent stresses induced. By moving the weld to the edge of the alloy, and modifying the heat flow and internal stresses crack free welds were able to be produced in alloys with up to 70% silicon content.

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REFERENCES

1. Jacobsen, D.M., Ogilvy, A.J.W & Leatham, A.G. ‘Controlled expansion alloys offer manufacturing advantages for high-tech applications’.????
2. Michaud, E.J, Kerr, H.W & Weckman, D.C. ‘Temporal pulse shaping and solidification cracking in laser welding Al-Cu alloys’. Trends in Welding Research, Proc. Of the 4th Int conf, pp153-158, 1995.
3. Matsunawa , A, Katayama, S., Ikeda, H., & Nishizawa, K. ‘Effect of pulse shaping on defect reduction in pulsed laser welding’, Proceedings of ICALEO, pp547-556, 1992.
4. Ogilvy, A.J.W. Private communication. July 2004.