Article ID: 1003 - 6326(2003)02 - 0289 - 05

Effect of pulse parameters on microstructure of joint in laser beam welding for SiC_p/6063 composite ①

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Abstract: The restraint effects of pulse frequency and pulse duty cycle on the precipitates of harmful needle-like Al_4C_3 phase were studied in CO_2 impulsed laser welding through the experiment on the SiC_p/6063 composite, and the microstructures of the weld under the different process parameters (pulse time from 1 ms to 20 ms, duty cycle from 50% to 91%) were analyzed. In order to compare, CO_2 continuous laser was conducted under the same efficiency. The results demonstrate that the proper laser pulse frequency and duty cycle can restrain the formation of Al_4C_3 effectively. However, the burning loss of SiC is more serious and the fluidity of molten pool is less in continuous laser welding than in impulsed laser welding.

Key words: laser beam welding; microstructure; aluminum metal matrix composites
CLC number: TB 331 **Document code:** A

1 INTRODUCTION

SiC particles reinforced composites, thanks to their low costs and high level of structural properties, are showing their potential in civil and military application. SiC particles reinforced aluminum matrix composites' wide application in aerospace and automotive are attributed to their performance of high specific strength, high specific stiffness, high elastic modulus and excellent wear resistance. The coefficient of thermal expansion and thermal conductivity can be regulated by changing the content and size of reinforcing particles and the content of matrix alloy, thus SiC particles reinforced composites are also suitable for microelectronic packaging[1, 2].

However, there are many crucial problems to be resolved in application of aluminum matrix composites, one of which is their limited application caused by their poor weldability. The primary reasons for their poor weldability were summarized as:

1) The great difference in both physical and chemical properties between the alloy matrix and reinforcing particles;

2) The high viscosity and poor mobility of molten pool during fusion welding can result in micropores and incomplete fusion;

3) It is well established that the matrix will react with reinforcing particles in molten pool during fusion welding, resulting in brittle combination and consequently decrease joint properties;

4) Technically, their welding is far more complicated than their preparation, and it is unlikely that a favorable interface is formed in welding.

Much research has been conducted on welding of aluminum matrix composites[3], largely on friction welding and diffusion welding. The weldability of SiC particles reinforced aluminum matrix composites has been investigated in friction welding[4, 5]. Results show that both inertia friction welding and continuous drive friction welding can produce high quality joints with uniform microstructures and promising mechanical properties, they are as far regarded as the most promising joining technique. However, their poor adaptability to the sizes and shapes of the components limits their wide application. Diffusion welding was studied widely, including the solid state diffusion welding without interlayer. Transient liquid phase diffusion boding has also been used to join SiC particles reinforced aluminum matrix composites, and the results were favorable[6-9]. However, diffusion boding was a complicated process in which vacuum and special equipment were required.

Fusion welding is the most flexible and versatile welding technology. Both traditional tungsten inert gas and metal inert gas welding techniques have been applied to join SiC particles reinforced aluminum matrix composites, but their industrial application is much limited because of the high viscosity of molten pool, the segregation and agglomeration of reinforcing particles, and especially the serious SiC particle disso-

① **Foundation item:** Project(59875016) supported by the National Natural Science Foundation of China
Received date: 2002 - 03 - 29; **Accepted date:** 2002 - 05 - 24
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lution which results in a large amount of coarse, needle-like Al_4C_3, Al_4SiC_4, $Al_4Si_2C_5$. At the same time, extensive investigation on welding of SiC particles reinforced aluminum matrix composites with high power laser beam and electron beam has been conducted[10-12] in order to produce ideal microstructure and joint strength. By means of pulsed laser beam with less heat input, the decomposition of SiC particles and formation of the needle-like deleterious Al_4C_3 can be constrained to some extent.

The formation of a large amount of needle-like deleterious aluminum carbides is very harmful to the mechanical properties of the weld. The brittle aluminum carbides greatly deteriorate the ductility and reduce fracture strength, and its susceptibility to moisture corrosion reduces the corrosion resistance of the weld. Therefore, it is crucial to restrain the formation of the harmful aluminum carbides in the efforts in joining SiC particles reinforced aluminum matrix composites. Here, through the pulse welding of $SiC_p/6063$ composites by CO_2 laser, the restraint of pulse frequency and pulse duty cycle on the formation of detrimental needle-like Al_4C_3 phases are studied.

2 EXPERIMENTAL

In this paper, $SiC_p/6063$ containing 15% (volume fraction) of SiC particles was prepared by means of stir-casting. The size of SiC particles was 15 - 20 μm. For welding, the material was made into specimens by wire cutting with the size of 30 mm × 10 mm × 1.5 mm. Prior to welding, the specimens were polished on 120# emery paper and were thoroughly cleaned with acetone.

The CO_2 gas laser device used for welding in this experiment, with rating power of 2 kW, can output both continuous and pulsed wave. The specimens, when welding, were in argon shielding atmosphere. The tensile test and observation of microstructure were conducted without postweld treatment. Transverse metallographic sections of the welds perpendicular to the welding direction were prepared using standard metallographic procedures and etched in Keller's reagent. Microstructures of the welds were observed by scanning electron microscope and phase composition was identified by X-ray energy dispersive spectroscopy.

3 RESULTS AND DISCUSSION

To compare, the parameters were selected as: power: 1 kW (peak power), welding speed 20 mm/s, laser output pulse on-time (t_H) 2 ms, 4 ms, 10 ms respectively, as shown in Table 1.

It can be seen that three groups of value are all high and some regularity is observed in tensile strength data in Table 1. With the change of pulse duty cycle, the similar regularity in strength of the joint for each group of specimens is found, namely strength of the joint is high when pulse duty cycle changes in certain range, while it is rather low outside the range. This is particularly evident in the third data group, where the highest strength of joint is achieved at pulse duty cycle of 63% - 77% and the joint strength is not favorable when out of this scope.

Table 1 Pulsed laser welding parameters

Pulse on-time/ms	Pulse off-time/ms	Pulse frequency/Hz	Duty cycle/%	Tensile strength/MPa
2	1	333	67	135.2
2	2	250	50	140.7
2	3	200	40	157.6
4	1	200	80	108
4	2	167	67	143
4	3	143	57	170.3
4	4	125	50	155.9
10	1	91	91	151.3
10	2	83	83	156.1
10	3	77	77	162.2
10	4	71	71	164.9
10	5	67	67	166.7
10	6	63	63	160.4
10	7	59	59	153.1
10	8	56	56	140.6
10	9	53	53	138.5
10	10	50	50	134.3

The joints were analyzed by scanning electron microscope to study the mechanism of effect between laser pulse and molten pool. Fig. 1 is micrograph of the weld at t_H = 10 ms, and different pulse off-time (t_L). It is shown in Fig. 1(a) that as a result of the short off-time (only 1 ms) and the duty cycle being 91%, the distribution of energy is comparatively concentrated and the density of energy is relatively high and the pulse effect is not evident. The decomposition of SiC is thus serious. The needle-like reaction products Al_4C_3 in this experiment are formed in the weld, sized 40 - 50 μm, through the reaction as:

$$4Al(l) + 3SiC(l) \rightarrow Al_4C_3(s) + 3Si(s) \quad (1)$$

As shown in Fig. 1(b), the off-time is 3 ms and the duty cycle is 77% at the moment. It is noted that under the condition of complete penetration and sufficient continuity of molten pool, the even power de-

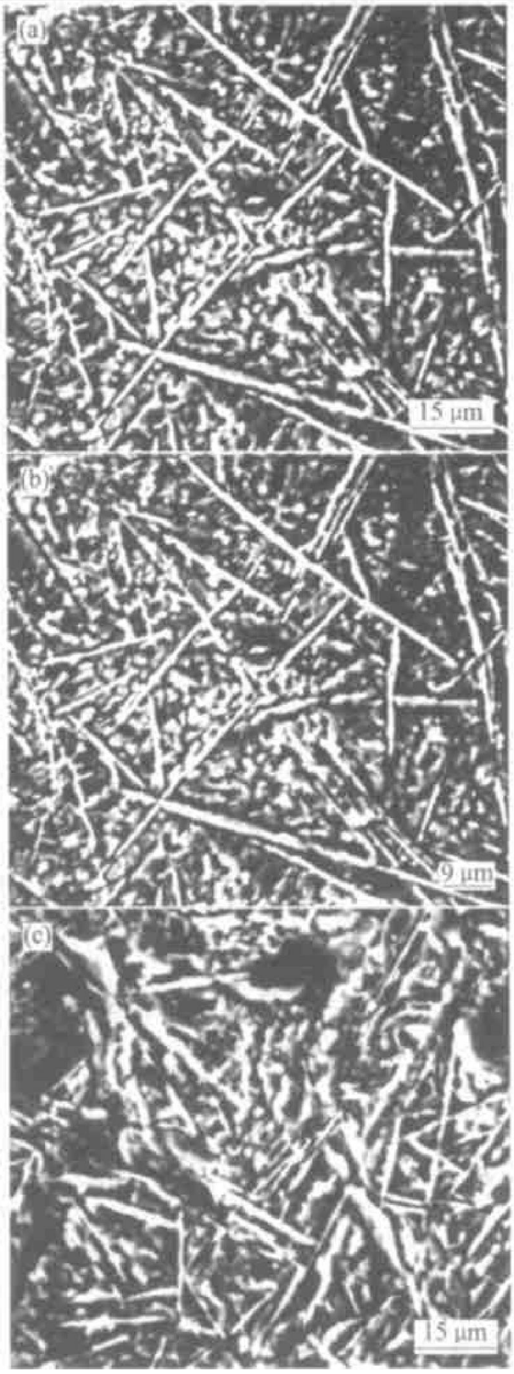

Fig. 1 Microstructures of SiC_p/6063Al MMC welded by pulsed laser for different pulse off-time(t_H= 10 ms)
(a) —1 ms; (b) —3 ms; (c) —10 ms;

creases as pulse off-time increases. Consequently, the temperature distribution is improved and the melting loss of SiC is restrained in most areas of the weld and the number and the size of the needle-like interface reaction products Al_4C_3 are decreased. The joint strength is improved further as illustrated in Fig. 1 (c). It can be seen from the transverse metallographic sections of the welds perpendicular to the welding direction only in some areas are the needle-like reaction products Al_4C_3 and the joint properties are further improved.

On the other hand, too long pulse off-time will lead to decrease of even power and excessive heat dissipation. Furthermore, the high value in viscosity of composites molten pool and low fluidity of molten pool make the continuity between molten pools poor.

In addition, it can be found in Fig. 1 that although much Al_4C_3 produces during impulsed laser welding, due to the stirring effect of laser impulse on molten pool, the fluidity of molten pool is improved. Under SEM, the structure of weld is compact and no micro-hole and gas-pore are found.

Experimentation and observation have shown that with the increase of laser pulse frequency (namely the decrease of pulse time and pulse off-time), the curve of strength of joint shows the upward tendency. Figs. 2 (a) and (b) are the SEM micrographs of the welds with laser pulse time of 2 ms and of 10 ms respectively and with duty cycle of 67%. As seen from the micrographs, despite the same value of duty cycle (67%), the higher frequency in former case decreases the melting loss of SiC particles and the needle-like reaction products are finer in size.

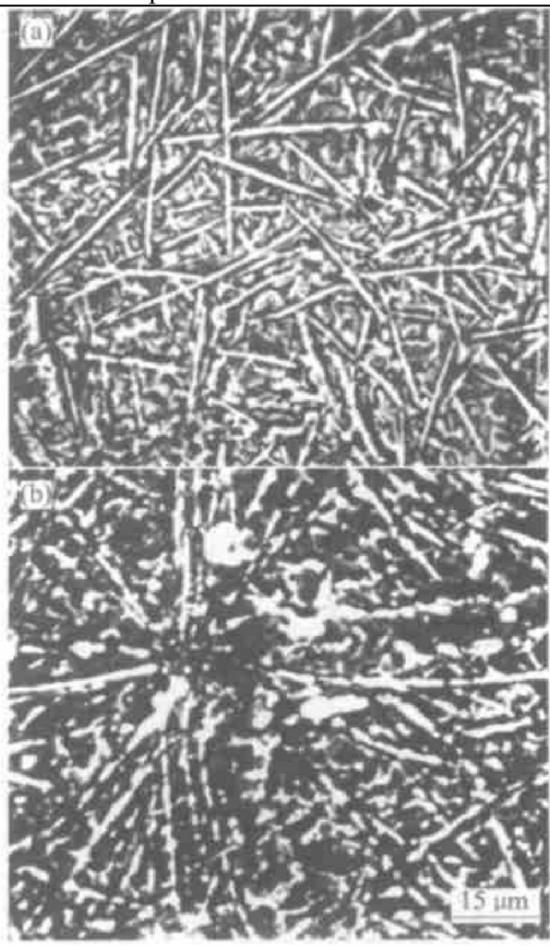

Fig. 2 Effect of different laser pulse frequency on microstructure of weld
(a) —2 ms; (b) —10 ms;

The effect of pulse frequency on weld is relevant to the heat input in welding. The high laser beam pulse frequency means the energy decrease of every pulse under the constant peak power, which then improves the temperature distribution of molten pool and restrains the interface reaction. The increased laser beam pulse frequency can also improve crystallization and eventually strengthen the weld. It is shown in Fig. 1, however, that the joint property does not always synchronize the increase of the frequency at every single stage. Under circumstances of little change in frequency, laser output duty cycle plays an important role in the joint properties and affects the energy distribution, the shape of molten pool, and the strength of the weld. It can be concluded that the laser pulse frequency and duty cycle are two correlated but differential parameters in SiC_p/6063 composite pulse laser beam welding.

For comparison, continuous laser beam welding for SiC_p/6063 composite was conducted with laser output power of 1 kW and welding speed of 20 mm/s. Fig. 3 shows the SEM micrograph under such condition. The serious melting loss of SiC reinforcing particles is shown in the micrograph and the needle-like Al_4C_3 is coarser than those in pulse welding. In addition, defects such as blowholes can be easily produced due to less disturbance by laser on the molten pool in continuous welding. At the same time, compared with Fig. 1 and Fig. 2, due to less stirring effect of continuous laser on molten pool, some defects such as gas-pore produce more easily, which surely reduces the properties of weld obviously.

Fig. 3 Microstructure of SiC/6063Al MMC welded by continuous welding

In order to study the effect of heat input on weld zone, TEM analysis was conducted in the heat-effected zone (Fig. 4). It is noted that the bond of SiC and matrix is so close that there are no evident defaults on the interfaces. However, some fine unattached particle-like reaction products are found on the interfaces and they nucleate and grow on the surface of SiC. According to the above study, the reaction products should be Al_4C_3, which were testified by the result of SAD pattern. This indicates that under the condition of continuous laser welding, higher heat input not only makes the decomposition of SiC particles in the weld serious but also brings interfacial reaction in the heat-effected zone during thermal cycle.

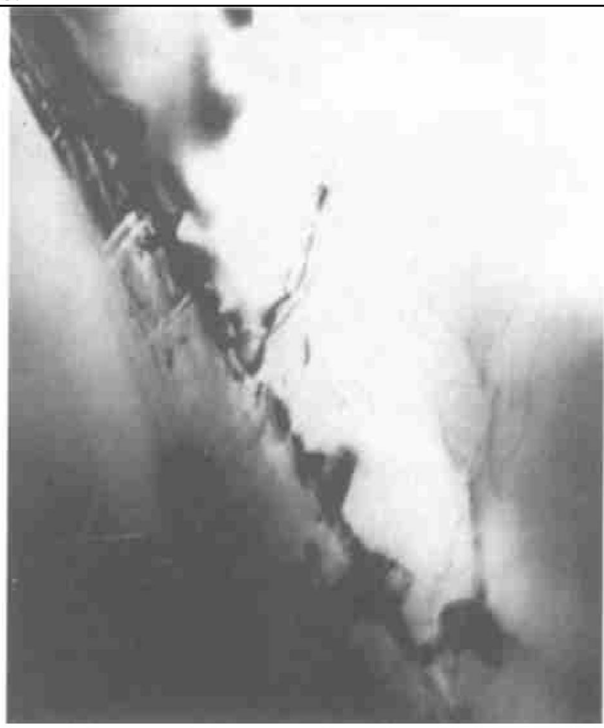

Fig. 4 TEM image of heat-effected zone of SiC_p/6063Al MMC welded by continuous laser

4 CONCLUSIONS

1) Under the condition of impulsed laser welding SiC_p/6063, the pulse frequency and the pulse duty cycle are coherent but differential parameters. The pulse frequency improved at proper level is favorable to the strength of joint. The pulse duty cycle plays an important role in certain scope of pulse frequency (for every pulse on-time). Both should be considered simultaneously in welding.

2) The produce of Al_4C_3 in the molten pool can be restrained effectively and the strength of joint can be improved by regulating laser pulse frequency and duty cycle. The optimal strength of joint can be achieved in case that the pulse on-time is 10ms and the duty cycle is 63%−77%.

3) In the comparative experiment, pulse laser welding demonstrated its advantage over CO_2 gas continuous laser welding in improving the fluidity of molten pool effectively, restraining the interface reaction of molten pool and improving consequently the properties of joint.

REFERENCES

[1] Allison J E, Cole G S. Metal-matrix composites in the automotive industry—Opportunities and challenges[J]. JOM, 1993, (1): 19 - 24.

[2] Lienert T J, Brandon E D, Lippold J C. Laser and electron beam welding of SiC_p reinforced aluminum A356 metal matrix composite [J]. Welding of Composite, 1993, 11(28): 1343 - 1346.

[3] NIU J T, MING L M, HAN L H. Actuality and outlook of welding of aluminum matrix composite[J]. Journal of Harbin Institute of Technology, 1999, 31(1): 130 - 132.

[4] Midling O T, Grong O. Process model for friction welding of Al-Mg-Si alloys and Al-SiC metal matrix composites[J]. Acta Metallurgica et Materialia, 1994, 42(5): 1595 - 1609.

[5] LIN C B, MU C K. Effect of joint design and volume fraction on friction welding properties of A360/SiC(P) Composites[J]. Welding Journal, 1999, 78(3): 100 - 108.

[6] Yokota T, Otsuka M. Solid phase welding of alloy AA6061 and SiCP reinforced alloy AA6061 at intermediate temperature [A]. Materials Science Forum Their Physical and Mechanical Properties Proceedings of the 1996 5th International Conference on Aluminium Alloys [C]. Grenoble: Transtec Publ Ltd, 1997, 242: 225 - 230.

[7] ZHANG X P, YE L. Investigation on diffusion bonding characteristics of SiC particulate reinforced aluminum metal matrix composites[J]. Applied Science and Manufacturing, 1999, 30(12): 1415 - 1421.

[8] Urena A, J M Gomez de Salazar. Diffusion bonding of an aluminium-copper alloy reinforced with silicon carbide particles (AA2014/SiC/13P) using metallic inter layers [J]. Scripta Materialia, 1996, 35(11): 1285 - 1293.

[9] LIU Li-ming, NIU Ji-tai, TIAN Yan-hong, et al. Diffusion bonding mechanism and microstructure of welded joint of aluminum matrix composite Al_2O_{3P}/6061 [J]. Trans Nonferrous Met Soc China, 1999, 9 (4): 826 - 830.

[10] Yue T M, Xu J H, Man H C. Pulsed Nd-YAG laser welding of a SiC particulate reinforced aluminium alloy composite[J]. Applied Composite Materials, 1997, 4 (1): 53 - 64.

[11] Chen Y L, Yu L G. Effect of 'In-Situ' weld-alloying on microstructure of laser beam welded SiC_p/6061Al metal matrix composite [A]. Proceedings of SPIE-The International Society for Optical Engineering High-Power Lasers in Manufacturing [C]. Osaka: 2000, 3888: 143 - 146.

[12] ZHANG De-ku, CHEN Yan-bin, NIU Ji-tai, et al. Mechanism of laser welding of SiC reinforced LD2 aluminum metal matrix composite [J]. China Welding, 2000, 10(2): 140 - 144. (in Chinese)

(Edited by LONG Huai-zhong)