STUDY ON SiC_P/6063Al COMPOSITES LASER WELDING PROCESS WITH $Al_{75}Cu_{20}Ti_5$ FOIL INTERLAYER

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Abstract:

This experiment chooses 6063 aluminum matrix composites containing 55~75% SiC particle reinforcing phase as the parent metal and $Al_{75}Cu_{20}Ti_5$ foil as the interlayer. The laser power, defocusing amounts and welding speed are discussed using three important parameters for the joint forming, microstructure and shear strength. The result shows that the weld width is mainly affected by laser power, and the weld penetration is almost determined by the defocusing amount. The welding speed has a certain influence on both weld width and weld penetration. When suitable laser heat input is adopted, superior weld appearance and satisfied shear strength could be obtained. The highest shear strength is 217MPa, with the laser power of 520W, the defocusing amounts of -1mm, and the welding speed of 1.5cm/s.

1 Introduction

The Aluminum metal matrix composites (Al-MMCs) with high volume fraction SiC are characterized by low density, high specific strength, high specific stiffness, high shear strength, low coefficient of thermal expansion, superb thermal conductivity, excellent thermal stability, good abrasion resistance and resistance to organic solvent erosion, which are proved to be a new promising material in the areas of aviation, aerospace, military, automobile, electronic information and precision machinery [1-3]. However, the most serious problem for application is its poor weld ability, on which material researchers have done a lot of research during the past 30 years [4-5]. However, it does not indicate distinguished achievements in welding or brazing of high volume fraction SiC reinforced Al-MMCs [6].The difficulties are in chemical-physical properties and unavoidable reaction between SiC and Al [7]. Due to good directivity and high power density of the laser beam, the connection parts will be completed in a very short time [8]. This article uses the advantages of laser welding and discusses the laser brazing process using SiCp/6063Al composites with $Al_{75}Cu_{20}Ti_5$ foil interlayer.

2 Experimental

The Al-MMCs used in this work contains 55~75 vol.% SiC particles with the diameter of 30~100 μm, as shown in Figure 1. Measured by differential scanning calorimetry (DSC), the solidus of the

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composite is 563 ℃, and liquidus is 654 ℃, as shown in Figure 2.

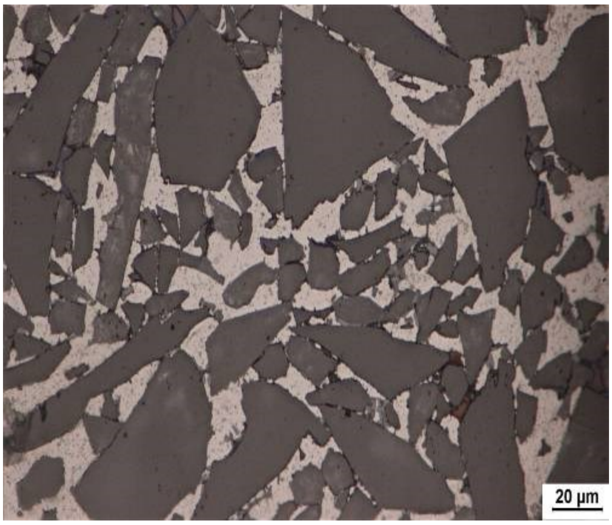

Figure 1. Microstructure of Al-MMCs.

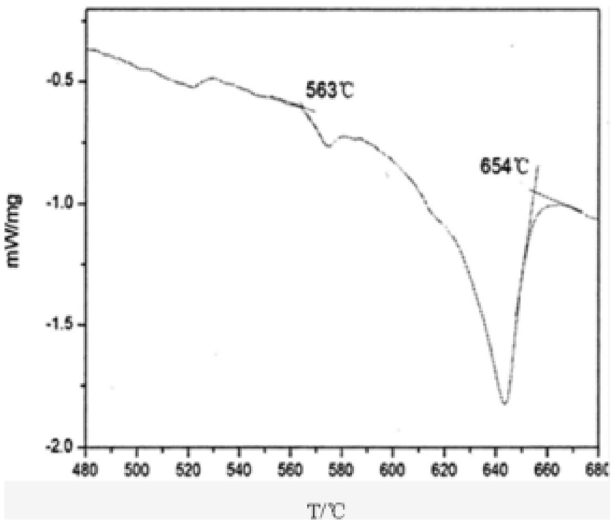

Figure 2. The melting temperature range of Al-MMCs.

The Al-MMCs was cut with an electric spark cutting machine into 70mm×30mm×1mm as upper parent material and 70mm×30mm×2mm as lower parent material. Figure 3 shows laser heating input with YAG laser and a sample assembly. Technical parameters of laser welding process are given in Table 1. According to our previous work [9, 10], the chosen interlayer is determined to be $Al_{75}Cu_{20}Ti_5$ foil with the thickness of about 50 μm, which is prepared by single roller rapid quenching method. Its microstructure is given in Figure 4.

After laser welding process, the shear strength test was performed in tensile testing machine. The specimen was cut into 20mm×10mm.The stretching rate is 1mm/s. The shear strength is calculated with/using the highest force divided by the action area.

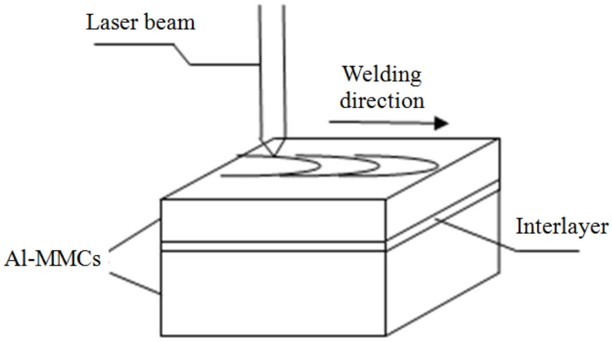

Figure 3. Heating input and sample assembly.

Table 1. Technical parameters of laser welding process

Laser frequency (Hz)	Laser energy (J)	Laser wavelength (nm)	Ar gas flow rate (L/min)
15.0	20.5	1064	6~7

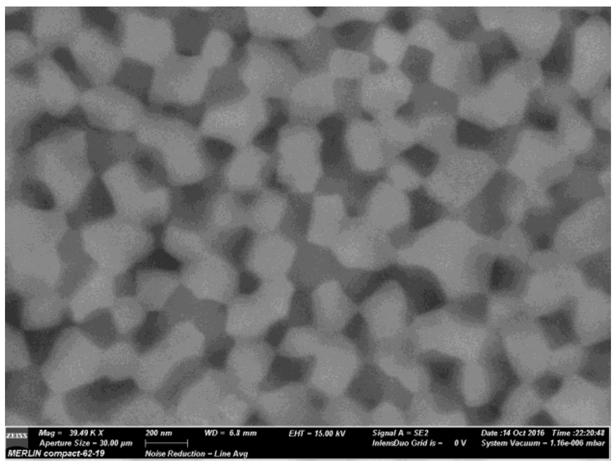

Figure 4. Microstructure of $Al_{75}Cu_{20}Ti_5$ foil.

3 Results and analysis

As well-known, the laser power level, defocusing amounts and welding speed are three main factors of laser welding. The forming, microstructure and shear strength of laser brazing joint affected by three parameters above will be discussed respectively. Fig.5 shows the joint forming parameters which contain "a" for weld reinforcement, "W" for weld width, "D" for weld depth.

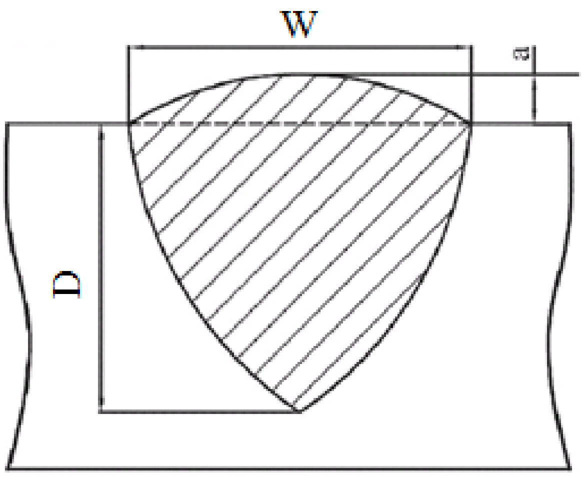

Figure 5. Diagram on characteristics of the laser welding joint.

3.1 Effect of laser power on joint forming, microstructure and mechanical properties

The laser power level is one of the most important parameters in the process of laser welding which controls the laser power density and line energy, determining thus the heat input directly. As shown in Table 2 and Figure 6, when the laser power level is high enough to form weld seam and when other factors are constants, the weld penetration is close to the weld width.

Table 2. Relationship between forming parameters and laser power

	D(mm)	W(mm)	a(mm)
P=480W	1.0	1.1	0.1
P=500W	1.2	1.3	0.1
P=520W	1.3	1.5	0.4
P=550W	1.4	1.7	0.2

Notes: The defocusing amount is -1mm and welding speed is 1 cm/s.

Both weld penetration and weld width improve along with an increase in the laser power, and the effect of weld width is greater than that of weld penetration. By increasing the laser power, a higher heat input could be obtained. It will cause weld heat conduction, thermal radiation and improved heat transfer ability, consequently resulting in the increased laser energy absorption and cooling rate reduction, which extends heat conduction and reaction time of molten pool to the upper parent material. Meanwhile, higher laser power level will also enhance the plasma density on the surface of base material, thereby raising the plasma and metal vapor temperature to increase molten pool heat radiation and heat transfer ability, causing further an increase in the weld width. However, the laser power level cannot be raised without limit. If the laser power is out of range, it will have a similar effect as cutting the parent material, which may cause difficulties in forming the brazing seam, as shown in Figure 6(d).

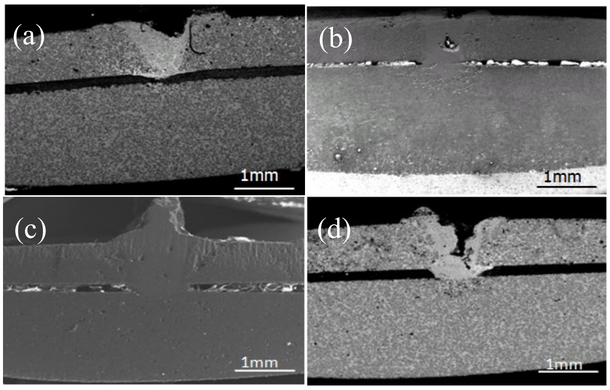

Figure 6. Cross-section joint appearances under different laser power when the defocusing amount is -1mm and welding speed is 1 cm/s (a) P=480W (b) P=500W (c) P=520W (d) P=550 W.

The microstructure of joints depends on welding heat input when other parameters remain constant. Figure 7 shows that the microstructures of joints under different laser power levels are relatively similar and are mostly composed of dendritic grain. With an increase in laser power, different microstructure of welding seam is dendrite coarsening and growing due to the higher heat input and lower cooling rate. At the same time, more heat energy will increase the highest temperature and prolong the time of permanence at high temperature in the molten pool. As a result, the dendritic grain of welding seam coarsens. When the laser power level is low, the metallurgical reaction in the seam is not feasible, which causes composition segregation, as shown in Figure 7(a).When the laser power level is appropriate, then an adequate metallurgical reaction, a very fine element distribution, and a uniform grain size could be achieved, which is the main reason for the superior shear strength, as shown in Figure 7(b) and (c). If the laser power continues to increase, not only the coarsening dendrite grain, but also a number of brittle phase Al_4C_3 formed by interfacial reaction between Al and SiC will reduce the shear strength of the joint, as shown in Figure 7(d).

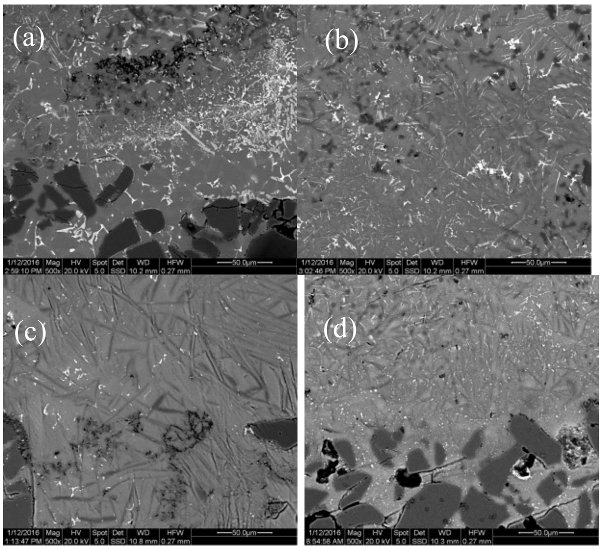

Figure 7. Transition region microstructure between Al and SiC of weld seam under different laser powers when the defocusing amount is -1mm and welding speed is 1 cm/s (a) P=480W (b) P=500W (c) P=520W (d) P=550 W.

As Figure 8 shows, by increasing the laser power, the shear strength of the joint firstly increases then decreases, and the peak value is 209 MPa when the laser power level has reached 520W.

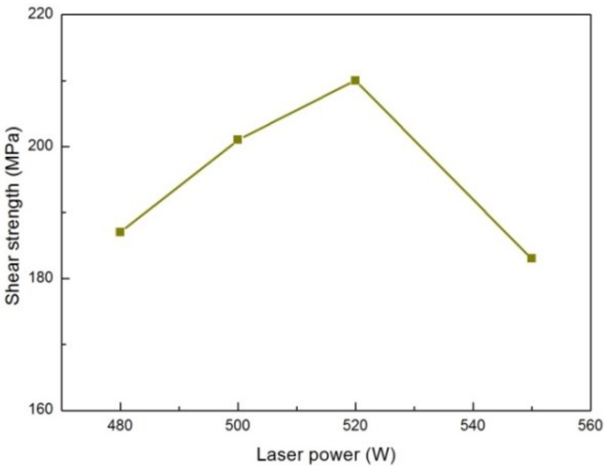

Figure 8. Relationship between shear strength and laser powers when the defocusing amount is -1mm and welding speed is 1 cm/s.

An analysis of shear fracture tests shows that the fracture position mostly appears at the interface of composite and interlayer when the laser power is insufficient to heat due to the lack of heat input. (to make metallurgical reaction feasible and effective). If the laser power is appropriate, the shear fracture position moves from the interface of composite and interlayer to the interlayer itself, and the joint shear strength improves. When laser power is over-raised, more defects-such as cracks, pores, holes, etc.-appear in the weld joint, meanwhile interfacial reaction occurs between Al and SiC. Finally, defect and brittle phase in the seam depress the shear strength.

3.2 Effect of defocusing amount on joint forming, microstructure and mechanical properties

As long as laser power and welding speed are unchanged so as to obtain required heat input for laser welding, reasonable laser irradiation position, or in other words, a suitable amount of defocus should be adjusted. . An amount of defocus is the distance between laser focusing point and the surface of parent material. When the laser focusing points are either above or under the surface of the parent material, they are called positive defocus or negative defocus. If the laser focusing point is exactly on the surface of the parent material, it is called zero defocus.

Table 3. Relationship between forming parameters and the defocusing amount

	D(mm)	W(mm)	a(mm)
Δf = +1.0mm	1.1	1.1	0.1
Δf = 0mm	1.3	1.2	0.3
Δf = -0.5mm	1.7	1.2	0.4
Δf = -1mm	1.9	1.3	0.2

Notes: The laser power is 500W and welding speed is 1 cm/s.

As shown in Table 3 and Figure 9(a), less weld penetration and cutting effect emerge in case of positive defocus. That is caused by the laser heat input concentrating almost on the surface of the parent material against the interlayer heat transfer . With the defocusing amount changing from positive to negative, the weld depth increases greater than the growth rate of the weld width. It does not determine the total welding heat input, but changes the line energy of the laser beam with various defocusing amounts. When the laser beam line energy is lower, metallic vapor from incomplete melting of metal spurts upward centrally, weakening the convection effect on the upper molten pool and reducing the heating effect of the laser beam to the bottom of the metal molten pool.

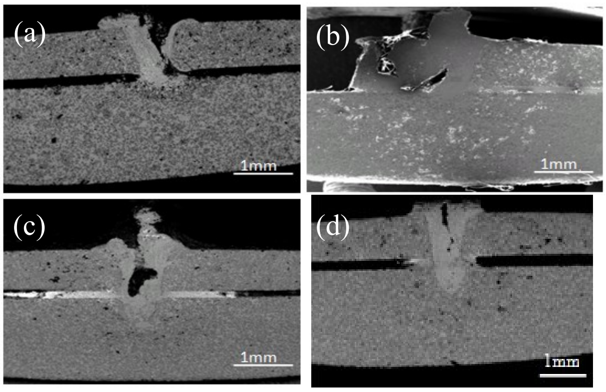

Figure 9. Cross-section joint appearances under different defocusing amounts when laser power level is 500W and welding speed is 1 cm/s (a) Δf = +1.0mm (b) Δf = 0mm (c) Δf = -0.5mm (d) Δf = -1.0mm.

When the laser focus is on the position of the interlayer, longer liquid time of weld seam enhances the heat conduction and prolongs time at high temperature at the bottom of the molten pool. As a result, it increases the depth and the elements of the interlayer can serve more effectively as diffusing barrier to parent material. It is emphasized that when using negative defocus, if unsuitable laser power and welding speed were used, there would be harmful holes and gaps in weld seam, as shown in Figure 9(c). When using positive defocus, there is not enough energy in the weld zone for element diffusion between interlayer and parent material, and then existing composition segregation phenomenon occurs, as shown in Fig. 10(a). When the defocusing amount is zero, the joint microstructure uniformity is improved. However, due to lack of heat input at the interlayer and weak movement of atoms in molten pool, unwetted parts on the SiC particles are regarded as phenomenon, as shown in Fig. 10(b). When choosing the negative defocus, with the laser focusing point close to the position of the interlayer, wetting and spreading ability of the interlayer improves, as shown in Fig. 10(c) and (d). The reason is that the energy increasing at the interlayer could reduce the effect of metal vapor against Al-MMCs absorbing heat, and enable transferring the laser energy to the parent material, thus elevating the interlayer's wetting and spreading ability on SiC particles.

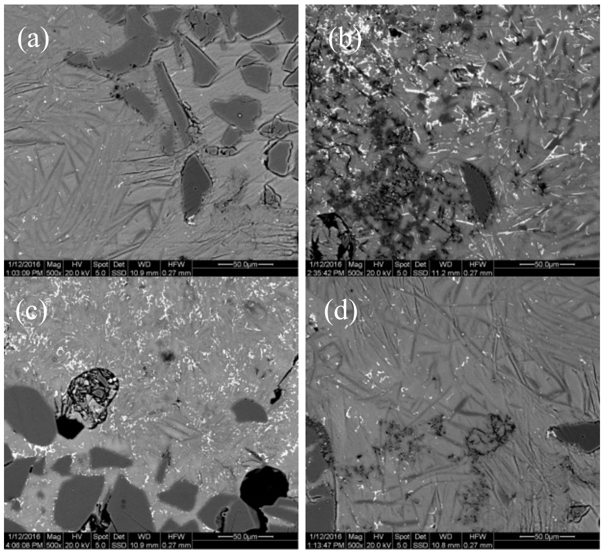

Figure 10. Transition region microstructure between Al and SiC of weld seam under different defocusing amounts when the laser power level is 500W and welding speed is 1 cm/s (a) Δf = +1.0mm (b) Δf = 0mm (c) Δf = -0.5mm (d) Δf = -1.0mm.

As shown in Figure 11, shear strength of the laser welding joint decreases from negative defocus to positive defocus, and the maximum shear strength (214MPa) is obtained in the case of the defocusing amount of -1mm.

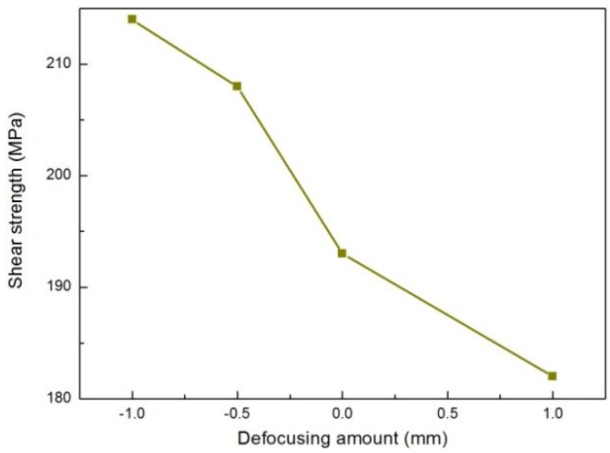

Figure 11. Relationship between shear strength and defocusing amount when laser power is 500W and welding speed is 1 cm/s.

An analysis of shear fracture shows that with an amount of defocus from positive to negative, the connection area on the lower parent material deepens. When the shear fracture occurs in the surface of lower parent material, the strength value is higher than that of the fracture, which happens in the interlayer itself. That is to say, an appropriate negative defocus will lead to adequate reaction between the interlayer and parent material, and compared to positive defocus and zero defocus it will result in an insufficient reaction .

3.3 Effect of welding speed on joint forming, microstructure and mechanical properties

Laser welding speed is the moving speed of the laser beam in welding process relative to welding specimens. The speed of laser beam determines the total heat input of the welding system partly. Normally,
the welding speed is mainly related to laser power: the higher the laser power level, the faster the welding beam moves. If the laser power is small, it has to be appropriate enough to reduce the welding speed.

Table 4. Relationship between forming parameters and welding speed

	D(mm)	W(mm)	a(mm)
v = 0.5cm/s	1.6	1.5	0.3
v = 1.0cm/s	1.5	1.4	0.1
v = 1.5cm/s	1.4	1.3	0.2
v = 2.0cm/s	1.3	1.3	0.1

Notes: The laser power is 520W and defocusing amount is -1mm.

As shown in Table 4 and Figure 12, if the laser power and defocusing amount are hold constant, the change of welding speed has a certain effect on the weld depth and width. When the welding speed reaches 0.5cm/s or is lower than that, the laser stays longer time on the upper base metal, increasing the welding depth and width. However, overhigh laser energy densities may result in similar laser cutting effect on welding seam, eventually leaving holes in it, as shown in Figure 12(a). When the welding speed is 2cm/s or higher than that due to energy shortage in the brazing seam, metallurgical reaction and elements transfer between the interlayer metal and parent material are incomplete, contributing to segregation, inclusion and other defects, as shown in Figure 12(d).When it comes to proper welding speed, the joint is compact and the surface is smooth, no obviously macroscopical defects observed, as shown in Figure 12(b) and (c).

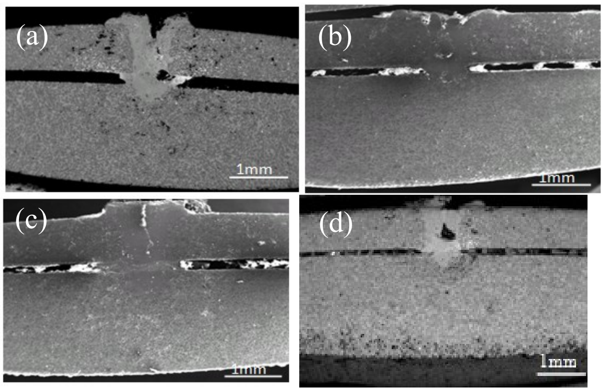

Figure 12. Cross-section joint appearances under different welding speed when laser power level is 520W and defocusing amount is -1mm (a) v = 0.5cm/s (b) v = 1.0cm/s (c) v = 1.5cm/s (d) v =2.0cm/s.

According to Figure 13 and Figure 14, the maximum shear strength of the laser welding joint is obtained with the welding speed of 1.5cm/s.

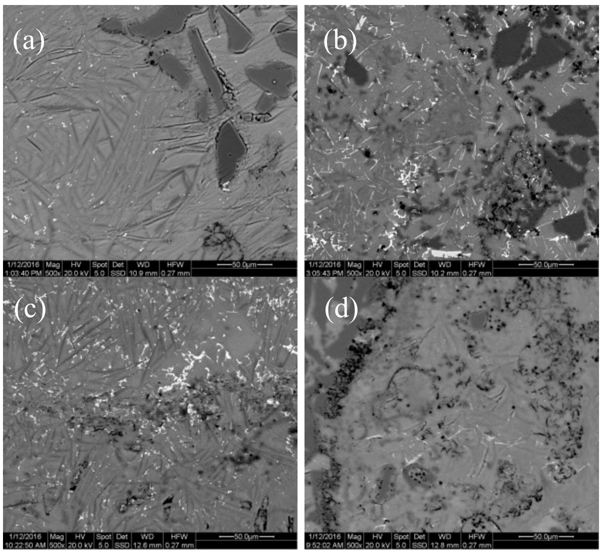

Figure 13. The *microstructure of the transition region between Al and SiC of weld seam under different welding speed when laser power level is 520W and defocusing amount is -1mm(a) v = 0.5cm/s (b) v = 1.0cm/s (c) v = 1.5cm/s (d) v =2.0cm/s.*

The analysis of the microstructure in Figure 13(a) shows that if welding speed is or under 0.5cm/s, high thermal energy in the seam will lead to the dendritic grain of welding seam coarsening constantly, because of the increase of maximum temperature and prolongation of the time permanence at high temperature of the molten pool. Overheating of the joint could form harmful holes in the weld seam, which also happens in the case of the excessive laser power. With an increase in welding speed, suitable thermal energy input declines the opportunity of burning loss and improves the wetting and spreading ability of the interlayer to SiC particles, as shown in Figure 13(b) and (c). When the welding speed is above 2.0cm/s, segregation and inclusion appear in the weld seam due to the incomplete element diffusion and metallurgical reaction between the interlayer and the parent material, as shown in Figure13(d).

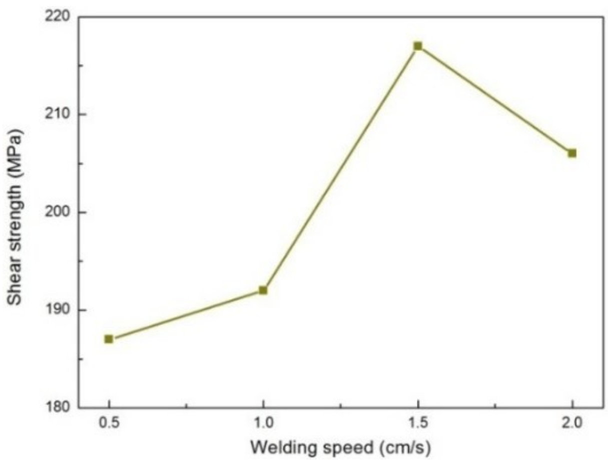

Figure 14. Relationship between shear strength and welding speed.

Above all, optimal process parameters and maximum shear strength of laser welding of SiC/6063Al matrix composites illustrated in Table 5 are based on orthogonal experiments with laser power, defocusing amount and welding speed.

Table 5. Optimum laser welding parameters and maximum shear strength

Laser power (W)	Defocusing amount (mm)	Welding speed (cm/s)	Maximum shear strength (MPa)
520	-1	1.5	217

4 Conclusion

Based on laser welding orthogonal experiments with laser power, defocusing amount and welding speed used on SiC/6063Al matrix composites, the influence of above mentioned three important parameters on the joint forming, microstructure and shear strength are discussed. The main results are shown as follows:

(1) The laser power directly affects heat input, and determines forming ability, microstructure and properties of the welding seam. Both weld depth and width improve with an increase in the laser power, and the effect on the latter is greater than that of the former. When the laser power is insufficient, it will cause porosity, segregation, and defects in unwetted parts; if it is excessive, coarse grains and fragmented phenomenon appear in the welding seam.

(2) In the case of positive defocus and zero defocus due to strong scattering effect of metal vapor in the molten pool, it will be difficult to form a high-quality joint with enough weld depth; when using proper negative defocus, a joint with nice appearance and satisfactory shear strength will be obtained.

(3) By adjusting appropriate welding speed, there will be right heat input on the welding samples. Low welding speed causes overheating on the surface of the Al-MMCs; If higher welding speed is used, segregation, inclusion and phenomenon of unwetted space in the weld seam will occur.

(4) The highest shear strength of 217 MPa has been achieved when the laser power level is 520W, the defocusing amount is -1mm, and the welding speed is 1.5cm/s.

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