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Laser processing of an aluminium AA6061 alloy involving injection of SiC particulate

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In the present laser processing work, the powder injection technique was investigated as a method for producing a surface metal matrix composite (MMC) containing large SiC particulates (SiC_p) (105–150 μm). This size is known to enhance the wear resistance of bulk aluminium-based composites. The effects of the laser-processing conditions, the powder feeding rate and the surface situations necessary to produce a well incorporated MMC on the surface were studied, and the microstructure examined. In previous work, laser processing involving the preplacement of SiC_p was developed to create an Al–SiC_p (≤ 45 μm) MMC layer on aluminium alloy surfaces. Some of these ideas were used in conjunction with the injection process in the present work to enhance the surface-wear resistance. The wear resistance of an MMC obtained by a single laser track with the injection technique was determined and compared with the base alloy and the MMC layer produced by the preplacement technique.

1. Introduction

Aluminium alloys have been widely used in industry, particularly in automotive and aircraft industries, because of their low densities and attractive bulk properties. Often it is not necessary for the surface properties to be identical to bulk properties, and the advantages of a functional gradient material become apparent. To enhance surface hardness and to improve wear resistance, there has been increasing attention paid to high-power laser surface modification processes. Hard particle cladding, using either injection or preplacement of the particles, is one of the very important techniques in laser processing. Although the injection technique was reported to inject particles with a wide range of particle sizes (5–700 μm) in some alloys, such as in titanium alloys [1–3], Stellite alloys [4], a magnesium alloy [5], and an aluminium alloy containing a high content of silicon (12 at %) [6], applications of the particle cladding laser process in the aluminium alloys containing a low level of silicon (0.7%), such as the AA6000 alloys, have been confined to the preplacement technique [7–10] because aluminium alloys have an extremely low laser-energy absorption, and the preplacement technique can provide the energy needed both for the formation of a liquid surface and subsequently an MMC.

With preplaced SiC particulate (SiC_p) or a mixture of SiC_p and aluminium powder, a smooth Al–SiC_p metal matrix composite (MMC) layer could be successfully created on the surface of aluminium-base alloys [7–10]. Using the optimum laser processing conditions, the SiC_p was well distributed and embedded in the MMC layer, and the layer was well incorporated with the base alloy [7–10]. More importantly, from data on 9 mm wide treated regions, the experiments suggested that an MMC layer could be produced over the whole surface by overlapping the laser tracks [10]. Unfortunately, the preplacement technique was effective only when the size of SiC_p was 45 μm or below, and when a larger size was used as the reinforcement particle in the preplaced layer, the process was not successful [7]. This is because the formation of the MMC needs a sufficient capillary force between the solid SiC_p and the liquid aluminium during the laser processing, and in the initial experiments, when the size of SiC_p was over 45 μm, the capillary force was insufficient to form a well-incorporated MMC during the very short lifetime of the liquid. However, it is well established that a large size of SiC_p is preferable for a high wear resistance in an Al–SiC_p MMC [11, 12]. Therefore, in the present work, the injection technique was investigated as a means of developing an MMC layer containing SiC_p greater than 45 μm in size.

2. Experimental procedure

AA6061 aluminium alloy was used as the base alloy, because this has attracted much attention in bulk aluminium composites. The composition of the AA6061 alloy is shown in Table I. $SiC_p \leq 105$ or 150 μm, was used as the reinforcement for injection. There were three conditions of the injected materials relative to the surfaces: (1) SiC_p injected on the base alloy surface, (2) a mixture of SiC_p (40%) and AA6061 powder (60%, ≤ 40 μm) injected on the base alloy surface, and (3) this mixture injected on preplaced SiC_p (60%, ≤6 μm), AA6061 (40%, ≤40 μm) on the surface.

TABLE I The composition of AA6061 alloy(wt%)

Fe	Si	Mg	Cu	Mn	Cr	Al
0.21	0.7	1.02	0.27	0.04	0.2	Bal.

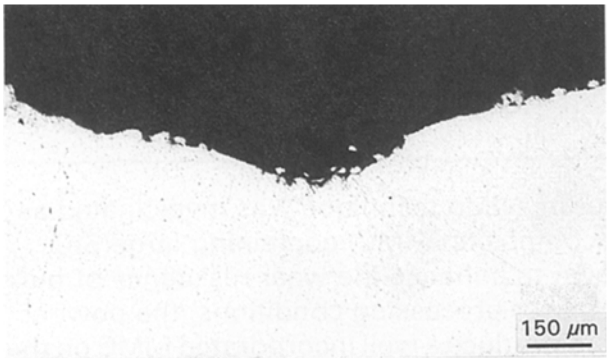

Figure 1 A typical micrograph showing a base alloy surface laser treated at $q = 2.8$ kW, $r_B = 2$ mm and $v = 20$ mm s^{-1}, and 105 μm SiC_p injected at a feeding rate of 5 g min^{-1}. The dark region in the upper part of the micrograph is the mounting compound.

The thickness of the preplaced layer was about 50 μm, and the base alloy specimens were 6 mm thick for all the experiments in the present work. The preplaced mixture was blended with a binder, an organic solution, and painted on the surface prior to laser injecting. A stationary, continuous 5 kW CO_2 laser beam at Culham Laboratory, AEA Abingdon, with an annular energy profile was used, and the specimens were moved under the beam on a work-table to produce all the tracks processed in the present work. A powder feeder (Plasma Technik, Twin 10C) was used at the feeding rate of 5–10 g min^{-1}. Pure and dry argon gas at 50 l min^{-1} through a nozzle of 4 mm internal diameter was used to carry the powder and to protect the powder and the laser glazing area against oxidation. The laser-beam power, q, set at 2.8 kW, the radius of the laser beam r_B, 1.0–2.5 mm, and the velocity of the specimen, v, 5–20 mm s^{-1}, were used in the laser processing. Therefore, the laser energy density $E = q/(r_B v)$ (MJ m^{-2}), referring to the energy intensity [13], could be determined from q, r_B and v.

Wear tests were carried out on a simple pin-on-disc machine using a constant load of 0.5 kg and speed of 0.236 m s^{-1}. The specimens were cleaned in methanol and blown dry with air before testing against P600 SiC grit paper, which was replaced at constant distances during the wear tests. Weight losses were measured after a known sliding distance by weighing the samples to an accuracy of 10^{-5}g. All the tests were carried out at room temperature under dry sliding conditions in air.

The transverse sections of laser-treated specimens were examined using an optical microscope. An image analyser was used to estimate the volume fraction of SiC_p in the MMC layer. An SEM with an associated EDX with a light element facility was used to detect the phases formed during the processing.

3. Results and discussion
3.1. SiC_p injected on the base alloy

When a low feeding rate (5 g min^{-1}) and a low laser energy density (70 MJ m^{-2}) were used, no MMC layer was formed on the surface. This situation is shown in Fig. 1. The concave surface indicated that a molten zone was generated during the processing. Because aluminium has an extremely low energy absorption from the laser, without the injected SiC_p, the surface would not melt at such a low energy density [9]. Therefore, the melt must be formed by the energy transferred from the SiC_p dragged from the base alloy by a capillary force, and then peeled off the surface during the specimen preparation. This was confirmed by the micrograph in Fig. 2 obtained from a surface treated at a higher energy density (280 MJ m^{-2}) but with the lower feeding rate (5 g min^{-1}). SiC_p was agglomerated with the solidified aluminium melt over a large concave surface, and between the agglomerated mixture and the surface there was a large cavity. Obviously, the melt was dragged by the SiC_p, and if the agglomerated mixture peeled off again during

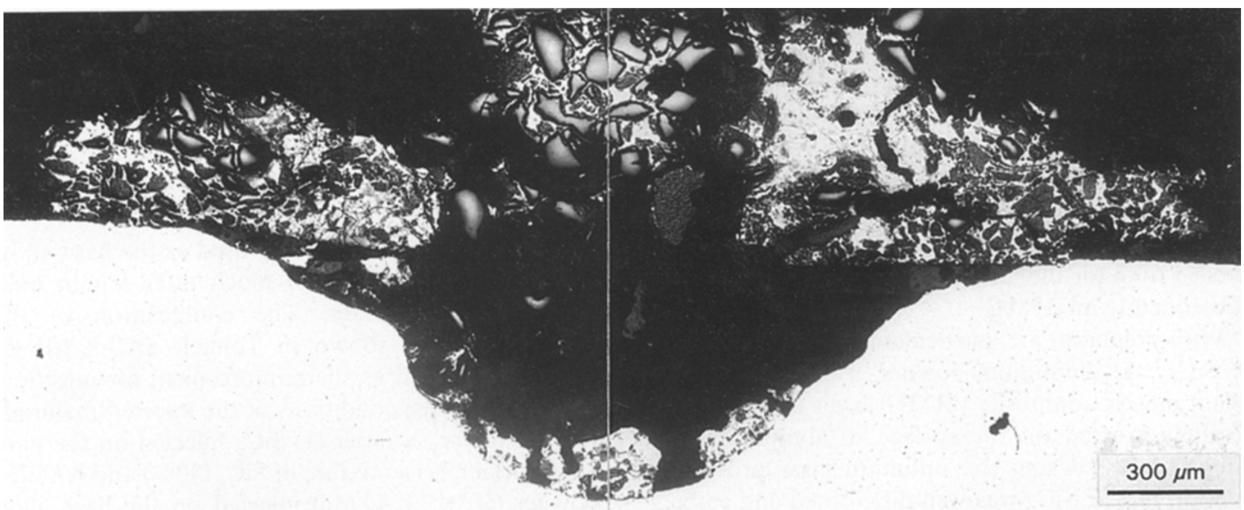

Figure 2 A typical micrograph showing a base alloy surface laser treated at $q = 2.8$ kW, $r_B = 1$ mm and $v = 10$ mm s^{-1} and 105 μm SiC_p injected at a feeding rate of 5 g min^{-1}.

the specimen preparation, the surface would have remained with a similar morphology to that in Fig. 1.

3.2. SiC_p (150 μm) and aluminium alloy powder injected on the base aluminium alloy surface

Figs 1 and 2 suggest that injecting a mixture of AA6061 powder with the SiC_p might be a better method to produce an MMC layer, because the AA6061 powder should supply the liquid phase needed to provide the matrix for the MMC layer, and thereby eliminate the cavity, which is due to the base alloy being used as a source of MMC matrix in the experiments described above.

A typical micrograph in Fig. 3, shows that an uneven MMC layer, with a convex surface, was produced on the base alloy. The SiC_p was well distributed and embedded in the matrix but the MMC was, in fact, separated from the base alloy along the line marked Y–Z. This was previously considered to be caused by either too low a laser energy density or too high a feeding rate. Therefore, in the next experiment, a higher laser energy density ($187\ \mathrm{MJ\,m^{-2}}$) and a lower feeding rate ($5\ \mathrm{g\,min^{-1}}$) were used. The result was a slight improvement, Fig. 4. It is believed that

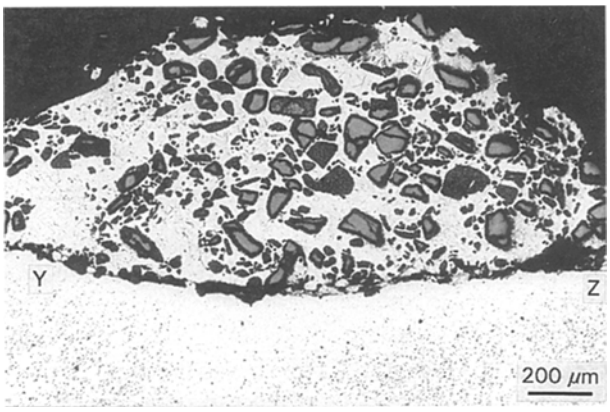

Figure 3 A micrograph from a specimen laser treated at $q = 2.8$ kW, $r_B = 2$ mm and $v = 15\ \mathrm{mm\,s^{-1}}$, and a mixture, 60% 150 μm SiC_p and 40% AA6061 powder, injected at a feeding rate of $10\ \mathrm{g\,min^{-1}}$. The MMC layer is separated from the base alloy along the line Y–Z.

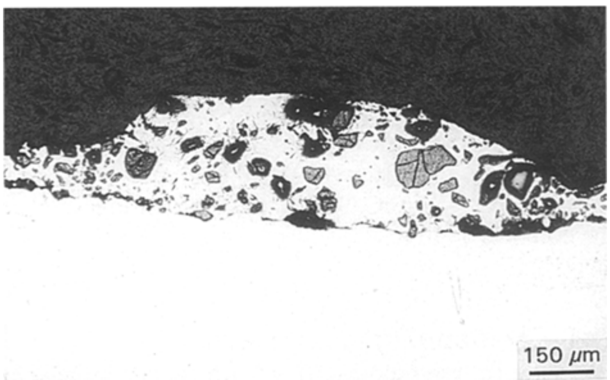

Figure 4 A micrograph from a specimen laser treated at $q = 2.8$ kW, $r_B = 1.5$ mm and $v = 10\ \mathrm{mm\,s^{-1}}$, and a mixture, 60% 150 μm SiC_p and 40% 40 μm AA6061 powder, injected at a feeding rate of $5\ \mathrm{g\,min^{-1}}$.

a good incorporation between the injected MMC and the base alloy requires an optimum generation of liquid in the surface layer of the base alloy composition to support the SiC_p. When a mixture of SiC_p and AA6061 powder was injected on the base alloy, the energy absorbed by the base alloy was mainly from the SiC_p, and must have decreased significantly because of a lower fraction of SiC_p in the injected mixture, compared with the situation where SiC_p alone was injected on the base alloy. This, together with the extremely low laser energy absorption of the base alloy itself, resulted in a less than optimum situation of liquid surface than was necessary for the required incorporation between the MMC layer and the base alloy.

3.3. A mixture (SiC_p–150 μm) injected on to a mixture (SiC_p–6 μm) preplaced on the alloy surface.

In previous work, SiC_p and aluminium powder preplacement has been successfully used to increase the energy absorption and provide liquid aluminium for the base alloy to form an MMC layer [7–10]. Here the preplacement technique was again used to provide a higher energy absorption and a suitable liquid surface for the base alloy in the injection process.

With preplaced SiC_p and AA6061 powder, an improved incorporated MMC layer with the base alloy was obtained, Fig. 5. In the previous work it was reported for the SiC_p preplacement technique [8, 10], that under specific laser conditions there was a well-incorporated MMC region at the beam centre and poorly incorporated regions on both sides beyond the well incorporated region in the microstructure obtained by a single laser track. This is also observed in Fig. 5, and suggests that with either the preplacement or the injection techniques a critical thermal intensity is necessary for the development of a well-incorporated MMC on the surface. Fig. 5 also shows a convex surface of the MMC layer, as also seen in Figs 3 and 4. Also found in Fig. 5 were two different morphologies of SiC_p, one grey and smooth, and the other dark and

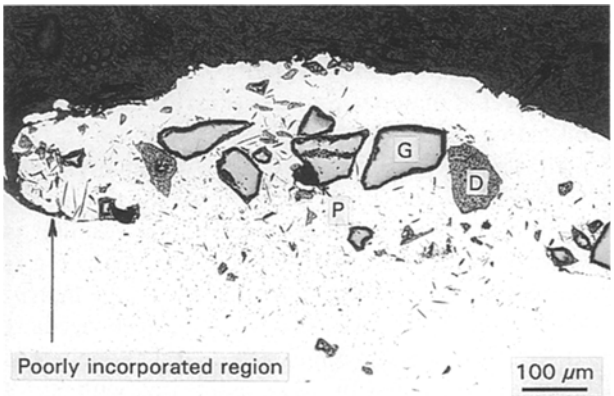

Figure 5 A micrograph from a mixture, 60% 6 μm SiC_p and 40% 40 μm AA6061 powder, preplaced specimen; laser treated at $q = 2.8$ kW, $r_B = 1.5$ mm and $v = 15\ \mathrm{mm\,s^{-1}}$, and a mixture, 60% 150 μm SiC_p and 40% AA6061 powder, injected at a feeding rate of $5\ \mathrm{g\,min^{-1}}$.

mottled. Both the grey (G) and the dark (D) particles were detected with the EDX associated with SEM, and found to contain the same level of silicon and carbon, but the dark SiC_p was thought to have reacted with the liquid to a greater extent than the lighter phase. The volume fraction of the SiC_p was estimated by image analysis to be 30 vol % in the MMC. Porosity (P) was found in the MMC. The preplaced SiC_p region was not retained as in earlier work [7–10] but in the central molten zone under the beam, some precipitates and small SiC_p particulates were observed. Moreover, a large SiC_p in the MMC was likely to be cracked in the injection processing. This is because SiC_p has a high laser-energy absorption, and when SiC_p is laser glazed during injecting, the energy absorbed by SiC_p could not be efficiently transferred to the surroundings due to few contacts between SiC_p and AA6061 particles, and therefore the SiC_p was rapidly heated up. The rapid heating and the high temperature reached would result in a dramatic increase in the internal stress of the SiC_p, and the larger the size of the SiC_p, the higher the internal stress level, which was more likely to result in cracks in the largest SiC_p. The amount of energy absorbed by SiC_p will depend also on the position of the SiC_p in the mixture when injected. In other words, the level of energy absorbed by the same size of SiC_p is not uniform. Therefore, only those SiC_p which absorbed a high laser energy, may have cracked, but if most of the absorbed energy was transferred to the aluminium alloy particles, the SiC_p particles may remain intact and have a greater tendency to react with the liquid, giving the dark mottled features seen in Fig. 5.

Increasing the powder feeding rate increased the thickness of the MMC, but the degree of incorporation between the MMC and the base alloy deteriorated. It was considered that when more powder was injected on the surface, the energy absorbed by the injected material was increased, which was used to form a thicker MMC, but that by the surface was reduced. This is because SiC_p has a high laser-energy absorption but a low thermal conductivity, and the surface could receive more energy only when the preplaced SiC_p performs as an energy source instead of a heat conductor through which energy is transferred from the injected material to the surface. Therefore, when more powder was injected on to the SiC_p preplaced surface, the surface absorbed less energy due to more injected material, and therefore developed a less conducting region between the laser and the surface, which was insufficient to form a well-incorporated interface. Increasing the laser-energy density together with increasing the powder feeding rate resulted in a very complex microstructure. This is shown in Fig. 6. More SiC_p reacted with, or dissolved into, the matrix. Al_4SiC_4 (dark-grey platelets), Al_4C_3 (black needles), and free silicon (grey regular particles) formed. The phases were detected by EDX associated with SEM. The morphologies and the spectra of these phases were the same as those obtained in the SiC_p preplacement technique reported previously [10]. In fact, the dark-grey Al_4SiC_4 platelet was also identified by SAED associated with TEM [8] and using X-ray diffractometry by Viala *et al.* [14], as was the Al_4C_3 needle phase [10, 14]. The Al_4C_3 needles were poorly embedded in the matrix and easily peeled off during the specimen preparation, resulting in cracks. This is shown in Fig. 7. There are two areas in Fig. 6. The one above the line *Y–Z* shows fewer SiC_p particles and more free silicon and Al_4SiC_4, and the region below *Y–Z* more SiC_p and Al_4C_3 needles. Because the upper area was closer to the laser, it would be expected to be a higher temperature region than the lower one during the laser processing. This is in good agreement with the work by Viala *et al.* [14], where Al_4C_3 was reported to form from liquid, $L \rightarrow Al_4C_3 + SiC$, in the temperature range 940–1620 K, and Al_4SiC_4, $4Al + 4SiC \rightarrow Al_4SiC_4 + 3Si$, at temperatures higher or equal to 1670 K.

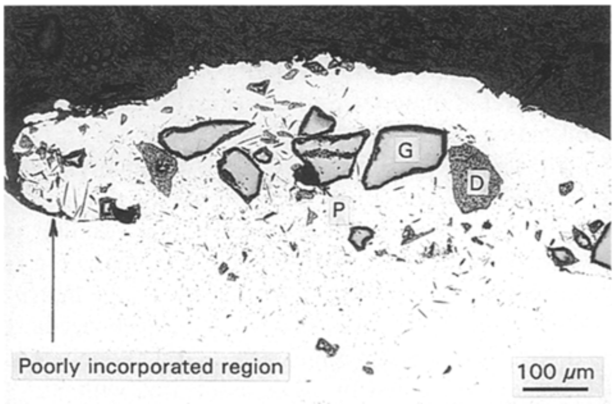

Figure 6 A typical microstructure obtained when a high laser-energy density ($E = 280$ MJ mm^{-1}) was used. Al_4SiC_4 formed as dark grey platelets, Al_4C_3 as black needles, and free silicon as regular light-grey particles. The specimen was preplaced with 60% 6 μm SiC_p and 40% 40 μm AA6061 powder, laser treated at $q = 2.8$ kW, $r_B = 1$ mm and $v = 10$ mm s^{-1}, and a mixture, 60% 150 μm SiC_p and 40% AA6061 powder, injected at a feeding rate of 10 g min^{-1}.

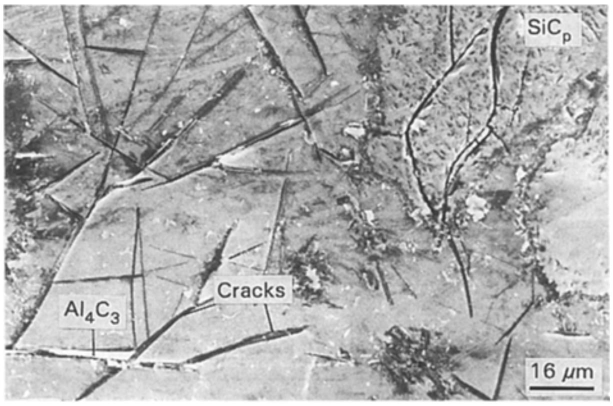

Figure 7 Scanning electron micrograph showing that Al_4C_3 needles were poorly embedded, or peeled off and left cracks in the matrix.

3.4. Overlapping laser tracks

To obtain a well-incorporated MMC over a large area of the surface, the poorly incorporated MMC region, like that in Fig. 5, should be eliminated, and this may be achieved by overlapping the laser tracks and therefore remelting part of the initial track. The preliminary

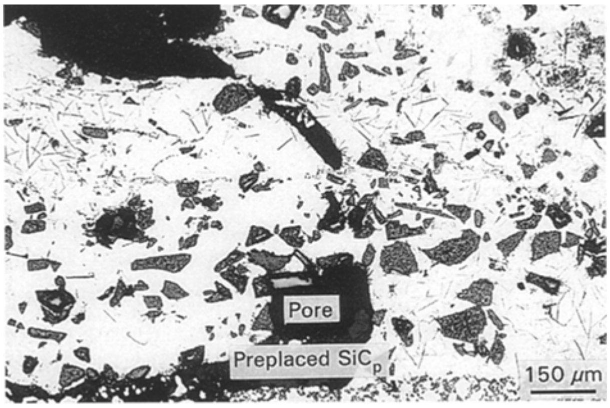

Figure 8 A typical micrograph showing large porosity in the overlapped area of two laser tracks; a preplaced specimen with 60% 6 μm SiC_p and 40% 40 μm AA6061 powder, laser treated at $q = 2.8$ kW, $r_B = 2$ mm and $v = 15$ mm s^{-1}, and a mixture, 60% 150 μm SiC_p and 40% AA6061 powder, injected at a feeding rate of 5 g min^{-1}.

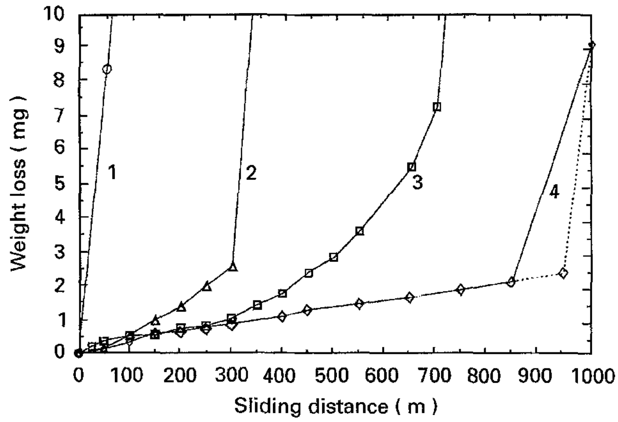

Figure 9 Wear test results: (1) for the base alloy (○), (2) for a 200 μm thick MMC layer containing 57 vol % of 6 μ m SiC_p produced with the preplacement technique (Δ), (3) for the MMC containing 30 vol % 150 μm SiC_p, shown in Fig. 5, produced with the injection technique (□), and (4) for a 200 μm thick MMC layer containing 57 vol % 45 μm SiC_p produced with the preplacement technique (◇)

experiments undertaken in this study did not produce a satisfactory MMC layer. A typical micrograph in Fig. 8 shows a large fraction of porosity in the overlapped area of two laser tracks. The porosity was thought to result from the effect of the oxidized MMC surface of the first track due to the unsuccessful design of the protection system. In the present experimental system, argon gas carrying the powder was used to protect the laser glazing surface. The laser-treated area which has just moved from under the beam may be less efficiently protected by the gas, and therefore more easily oxidized. To obtain a well-incorporated MMC by using the injection technique for overlapping laser tracks, a specific experimental system has to be designed to protect the treated areas as well as the area being treated. Obviously a system which can protect the whole specimen would be desirable.

3.5. Wear resistance

Because overlapping laser tracks produced in conjunction with the injection technique failed to produce a well-incorporated MMC on the surface with the present experimental system, the laser-treated specimen obtained by a single track, the microstructure of which is shown in Fig. 5, was used for the wear test, and the result compared with the base alloy, and those results previously reported for the preplacement technique [7]. The wear data are shown in Fig. 9, where wear graph 1 is for the base alloy, graph 2 the specimen with SiC_p (6 μm, 57 vol %) preplaced MMC, graph 3 the specimen with SiC_p ($\leq$ 150 μm, 30 vol %) injected MMC, and graph 4 that with SiC_p (45 μm, 57 vol%) preplaced MMC.

Using the pin-on-disc test, all the specimens with an MMC on the surface showed a significant increase in the sliding wear resistance compared with the base alloy. The SiC_p preplaced specimens showed two distinct sections in their wear graphs: one of a low slope and the other of a high slope. The slopes of the wear graphs are considered to be the wear rate (mg m^{-1}). Therefore, the low slope section of the graph recorded the wear resistance of the MMC, and the high slope section showed that the MMC was worn away and the wear occurred in the base alloy matrix. It was believed that the last section (from 850–1000 m) of the solid line in graph 4 should be extended by the dotted line, as shown in Fig. 9, adding a hypothetical value for one more testing point (at 950 m). Thus, the slopes of the last section of all the graphs would then show the same value, i.e. the wear rate of the base alloy, as expected. Graph 3 shows a transition period between the first and the second sections, or a changing wear rate at different thickness of the MMC. This is attributed to the effects of a poor distribution of SiC_p and a non-uniform thickness of the MMC, and to the phases formed in the molten zone during laser processing. After the first 50 m of wear sliding, the injected specimen had the highest wear rate of 0.0074 mg m^{-1} compared with 0.003 and 0.0026 mg m^{-1} for the 6 and 45 μm SiC_p preplaced MMCs, respectively, and in the next 200 m sliding distance (from 50–250 m), the injected specimen showed the lowest wear rate of 0.0023 mg m^{-1}, while the 6 and 45 μm SiC_p preplaced MMCs showed 0.0093 and 0.0034 mg m^{-1}, respectively. The total wear resistance of the injected MMC was higher than that of the 6 μm preplaced SiC_p MMC. This must result from the effect of a large size of the injected SiC_p, as the volume fraction of SiC_p was 57 vol% for the 6 μm SiC_p preplaced specimen and about 30 vol% for the injected specimen. Graph 4 showed the highest wear resistance because of the high volume fraction of SiC_p which was well distributed in the MMC layer in this case. In addition, although the injected MMC contained a large size of SiC_p, the cracked SiC_p's and the porosity in the MMC may have had a negative effect on the wear resistance.

4. Conclusion

Because of the extremely low laser-energy absorption of aluminium alloys, a good incorporation of the SiC_p and the base alloy was difficult to achieve by injecting SiC_p on to the base alloy surface. With a small size of

SiC_p preplaced on the surface, this situation was improved. Further, an MMC containing SiC_p up to 150 μm was produced on the surface by injecting the SiC_p with AA6061 powder and using a single laser track. The thickness of the MMC produced via the injection technique was controlled by the powder feed rate. The feed rate must be limited in the present process to ensure the development of a sufficient conduction area between the laser and the surface and to produce a required liquid surface on the base alloy, and therefore the thickness of the resultant MMC was also limited. It is recommended that overlapping of laser tracks should be carried out under a system which can protect the whole specimen against the oxidation during the laser processing.

It was found that when a large size of SiC_p was used in the injected MMC, the carbide tended to be cracked. Although the large SiC_p increased the sliding wear resistance, the cracks in the SiC_p and the porosity in the MMC were responsible for a wear resistance lower than that of preplaced MMC containing 45 μm SiC_p. Therefore, the application of the injection technique in the Al–SiC_p system will depend on whether the cracks on SiC_p can be avoided and whether the overlapping laser technique to produce wider areas can be successfully employed.

As in the preplacement processing studied previously [10], Al_4SiC_4, Al_4C_3 and free silicon could form in the high-temperature region of an MMC during the laser treatment when a high energy density was used.

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