

Improvement of Wear Resistance of Aluminum Alloy Surface by Forming Si Alloyed Layer with PTA Process †

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Abstract

High Si alloyed layer up to 67mass% and of 5mm in thickness has been successfully formed on aluminum alloy A5083 by mean of Plasma Transferred Arc (PTA) process. Uniform distribution of fine primary Si particle with grain size of 20 to 40 μm was obtained in the alloyed layer of which Si content ranged from 30 to 50 mass%. Wear resistance of alloyed layer was improved with depending on volume fraction of primary Si particle, V_{Si} and was remarkably increased at 20-30% V_{Si} , but no more improvement in wear resistance than this was obtained even in higher V_{Si} .

KEY WORDS: (Aluminum Alloy) (Surface Hardening) (Si powder) (Wear) (Plasma Transferred Arc Welding)

1. Introduction

Aluminum alloy have been given attention as light structural materials. However, wear resistance of aluminum alloy is much inferior than ferro-materials. Authors have pointed out that plasma transferred arc welding (PTA) was a beneficial process for the improvement of wear resistance of aluminum alloy by making thick hardened layer on its surface. Until now, the formation of composite and alloyed layer by the addition of ceramics or metal powders or by the simultaneous addition of both powders have been investigated and the metallurgical and mechanical characteristics have been examined¹⁻⁵.

In the previous report^{4,5}, it was made clear that copper (Cu) was effective to form alloyed layer easily and in addition, to add good anti-wear property. This beneficial effect of Cu is closely related to eutectic reaction with aluminum. There are same elements having eutectic reaction with aluminum such as Si, Ca, Ge and La beside Cu. Among them, Si is one of the major alloying element for anti-wear and heat-resistance aluminum alloys, especially as hyper-eutectic Al-Si alloys.

In this type of alloy, in order to improve the wear-resistance, it is very important to make fine primary Si

particles and to disperse them densely in Al matrix. With conventional casting process, however, alloying content of Si is limited to about 20 mass% in maximum due to comparably lower casting temperature than liquidus temperature of highly contained Si alloy, and primary Si particles are likely to become to the coarse plate-like shape, which much degrade the mechanical property of the alloy.

On the contrary, according to the previous report⁴, the temperature of molten pool with PTA process was much higher than conventional casting temperature, and in addition, solidification rate at PTA process was much higher than at conventional casting. Therefore it is expected that these two features of PTA process enable the formation of alloyed layer with high Si content and dense dispersion of fine primary Si particle.

The purpose of this study is to make highly contained Si alloyed layer on Al surface to improve anti-wear property by using PTA process with Si powder. The effect of process parameters on the formation of desirable alloyed layer and the hardness and wear property of alloyed layer have been investigated in relation to Si content and structure of alloyed layer.

2. Material used and experimental procedure

2.1 Material used

† Received on July 30, 1993

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Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

Aluminum alloy A5083(Al- 4.15 mass%Mg - 0.47 mass%Mn alloy) plate with 150mm in length x 100mm in width x 12mm in thickness was used as base metal, and Si powder with 99.9% in purity and 60-150 μ m in grain size was used as alloying element in PTA process. Si powder used is a polygon shape with sharp edges because of crushed powder as shown in Fig. 1.

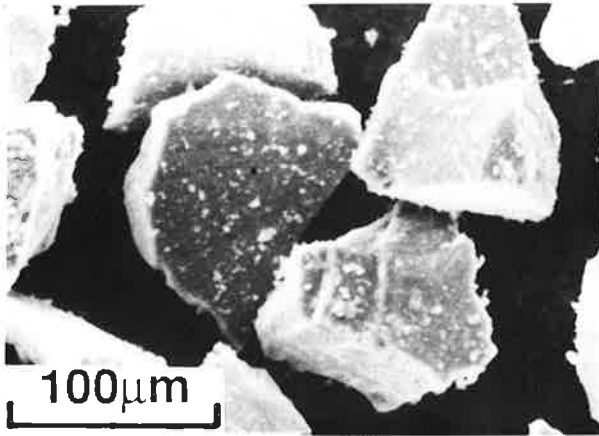


Fig. 1 Morphology of Si powder used, purity:99.9%, grain size:60-150 μ m.

2.2 Experimental procedure

2.2.1 PTA alloying process

The same PTA process as used in the previous report⁴⁾ was again used in this study. Surface layer of base metal is melted continuously by plasma Transferred Arc with a constant travel speed of a plasma torch, and simultaneously Si powder is fed into molten pool through plasma torch and plasma arc, and then react with molten aluminum to make alloyed layer on base metal surface.

An inverter type alternate and direct current plasma transferred arc equipment was used for PTA process. According to the result in the previous report⁷⁾, direct current with electrode negative (DCEN) and He gas were selected as polarity and plasma and shielding gases respectively, because surface alloyed layer was much easy to be obtained in wide condition range by this process condition⁶⁾.

As alloying condition, plasma arc current ranged from 175A to 250A, powder feeding rate was varied from 5 to 20g/min, torch travel speed was 500mm/min and the distance between a tip of torch and base metal surface was 8mm. Pilot, shielding and powder carrier gases of He were 6, 45 and 6 l/min, respectively.

2.2.2 Structural observation of alloyed layer

A crosssection of alloyed layer was polished with 0.3 μ m alumina and electrolytically etched in 3% HBF₄

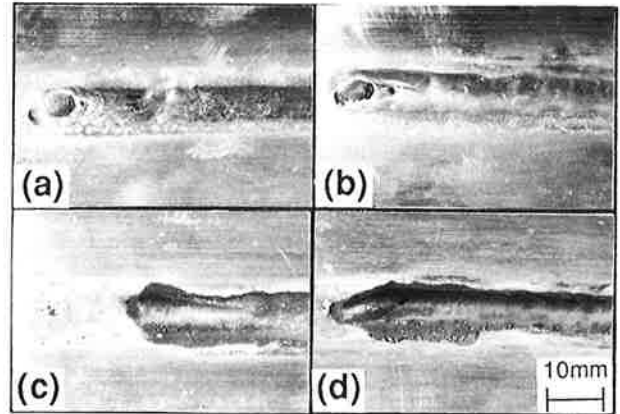


Fig. 2 Typical appearance of Si alloyed bead made by PTA process with various powder feeding rate (a)5, (b)10, (c)15 and (d)20g/min at 200A and 500mm/min.

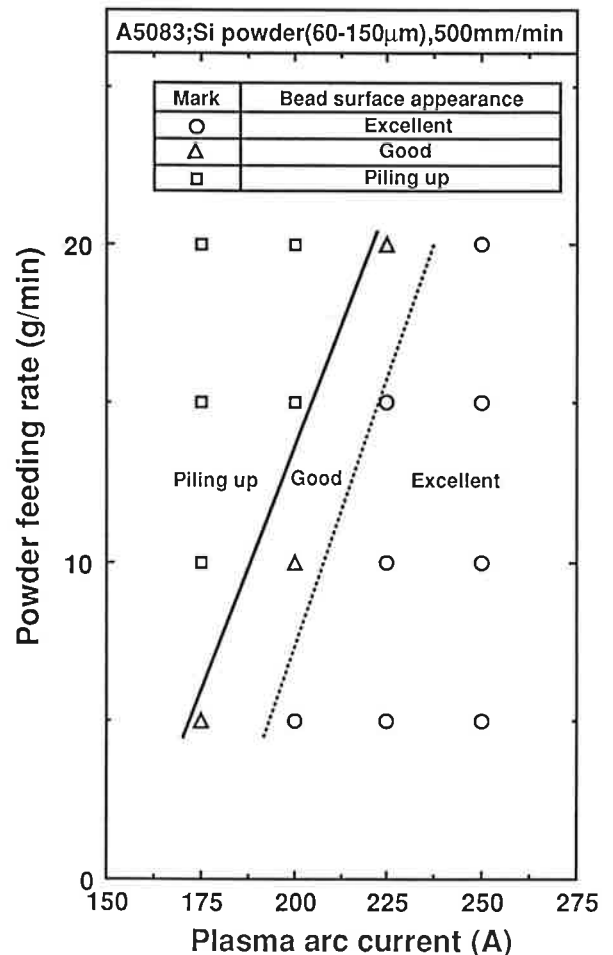


Fig. 3 Combined effect of powder feeding rate and plasma arc current on surface morphology of alloyed layers.

water solution (15V, 10s), and after then optical and scanning electron microscopic observations, element distribution measurement by EPMA and phase identification by EPMA and X-ray diffractometry were performed.

2.2.3 Hardness and wear resistance measurements

Hardness of alloyed layer was measured with Vicker's microhardness tester with 9.8N load on crosssection. Wear resistance of alloyed layer was measured with Ogoshi-type wear tester as following manner : A rotating counter disk of SUJ2 (Hv 650) with 30mm in diameter was pressed on a polished surface of alloyed layer under the constant test condition of 10N in wear load, 4.36m/s in rotating speed and 100m in wear distance and then the wear volume was measured.

3. Experimental result and discussions

3.1 Surface appearance and crosssectional shape of alloyed layer

Figure 2 shows the typical surface appearance of alloyed layer with different powder feeding rates.

Smooth surface appearance as shown in (a) was obtained with low powder feeding rate, but as increasing

powder feeding rate, surface appearance become rough in (b) and excess powders were piled up on the surface and easy to be peel off in (c) and (d).

Figure 3 shows schematically the combined effect of plasma arc current and powder feeding rate on the surface appearance of alloyed layer, of which surface condition was divided into 3 types designated by each marks in figure according as the previous report⁴⁾.

The optimum condition range with a smooth surface was obtained with more than 200A, and the optimum range of powder feeding rate was enlarged by the increasing plasma arc current.

This reason is considered to be related to the size of molten pool.

Figure 4 shows the combined effect of powder feeding rate and plasma arc current on the crosssectional macrostructure of Si alloyed layer. Penetration shape depended mainly on plasma arc current, and both penetration depth and width increased with increasing plasma arc current. The other hand, powder feeding rate has little influence on the penetration depth.

Alloying condition of Si in fusion zone depended on both plasma arc current and powder feeding rate.

At lower current than 200A and higher powder feeding rate than 15g/min the melted Si powders were deposited

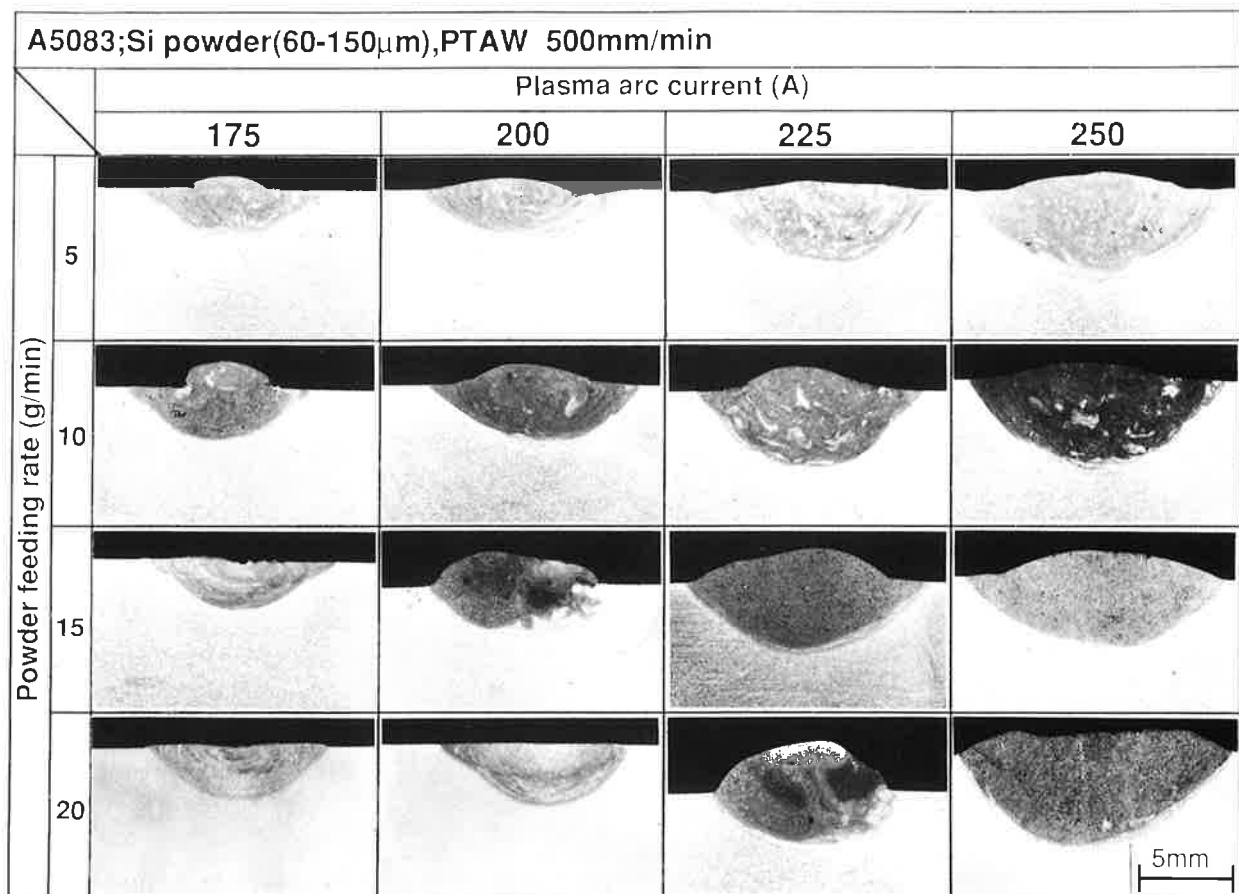


Fig. 4 Combined effect of powder feeding rate and plasma arc current on macrostructure of crosssection of alloyed layers.

on the plate surface without no formation of alloyed layer because of insufficient fusion of base metal. However, at higher plasma arc current than 225A, alloyed layer was formed in the base metal even with higher powder feeding rate.

3.2 Structure and composition of alloyed layer

As shown in Fig. 4, un-uniform structure of mixed with some white bands and islands was formed with low powder feeding rate as 5 to 10g/min. As increasing powder feeding rate, white structure was likely to decrease and disappeared at higher current than 225A.

Figure 5(a), (b), (c) and (d) shows microstructural change on crosssection of alloyed layer with different powder feeding rate of 5,10,15 and 20 g/min, respectively. The top and bottom of each photo correspond to the top surface and bottom fusion boundary of alloyed layer, respectively.

Figure 6 shows typical microstructure with high magnification.

With lower powder feeding rate than 10g/min, white band and island-like structures were observed as shown in Fig. 5(a) and (b) because of macrosegregation caused by molten metal flow in molten pool. However, with higher powder feeding rate than 15g/min, these white structures disappeared and uniform distribution of fine primary Si particle (white particle in Fig. 5(c) and gray particle in Fig. 6(c)) was obtained in whole alloyed layer, though with excess powder feeding rate as 20g/min primary Si changed to coarse plate-like shape as shown in Fig. 6(d) and segregated in the bottom part of alloyed layer.

Figure 7 shows the Al-Si phase diagram and SEM microstructure with different powder feeding rate. Si content of (a),(b),(c) and (d) corresponded to 5, 10, 15 and 20g/min of powder feeding rate, respectively. By EPMA analysis and X-ray diffractometry, the alloyed layer (a) exhibited hypo-eutectic structure which was composed of primary α -Al surrounded by α -Al+Si eutectic.

The structures in (b), (c) and (d) were hyper-eutectic one.

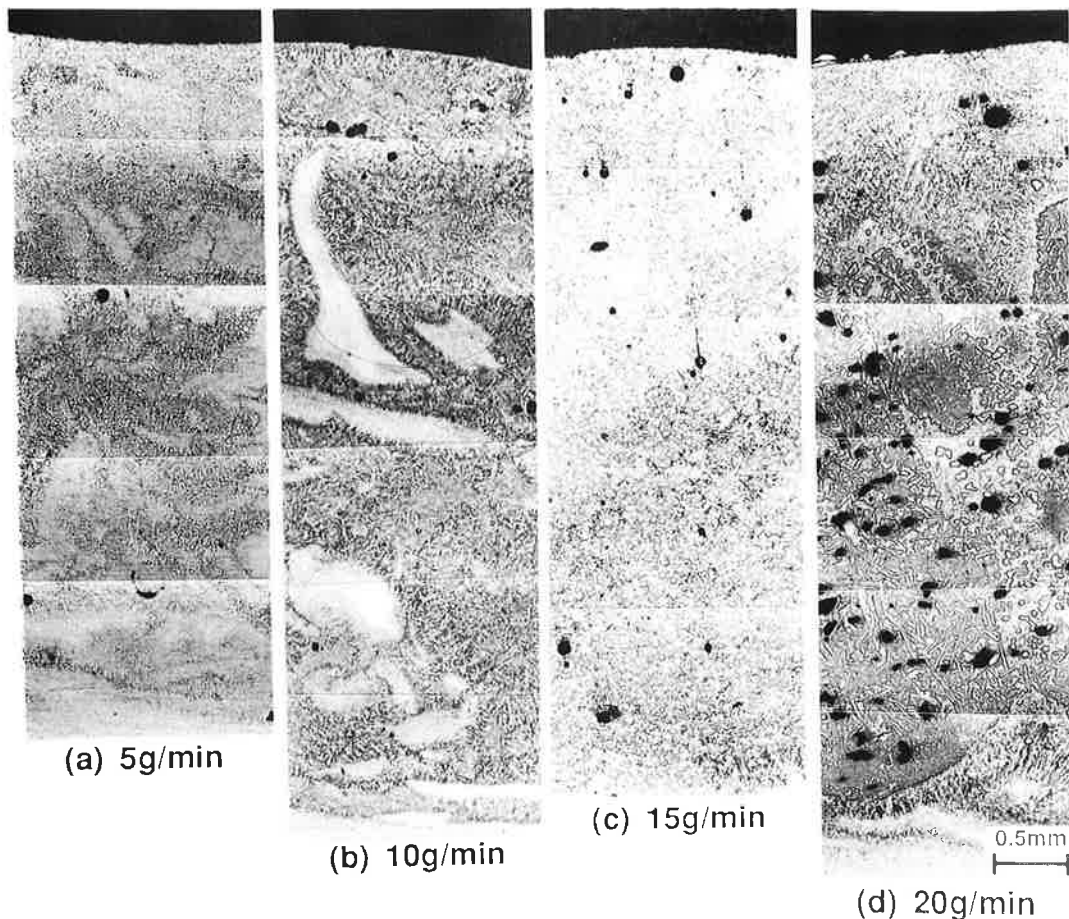


Fig. 5 Crosssectional microstructure of Si alloyed layer by PTA process with 225A and 500mm/min, (a)5, (b)10, (c)15 and (d)20g/min.

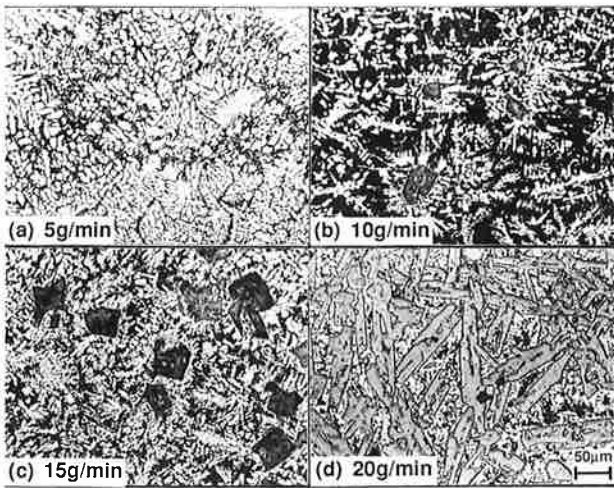


Fig. 6 Typical microstructure of Si alloyed layer by PTA process with 225A and 500mm/min, (a)5, (b)10, (c)15 and (d) 20g/min.

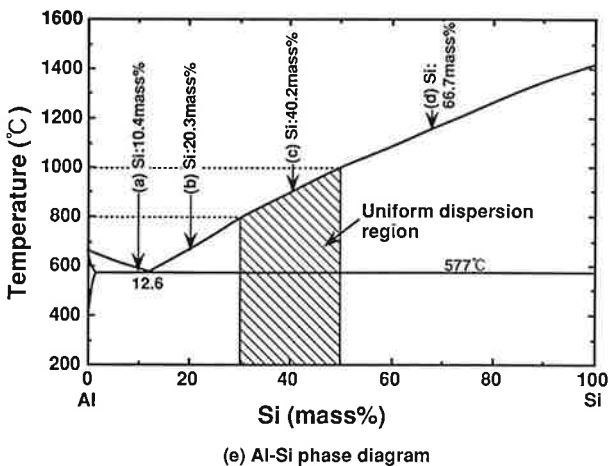
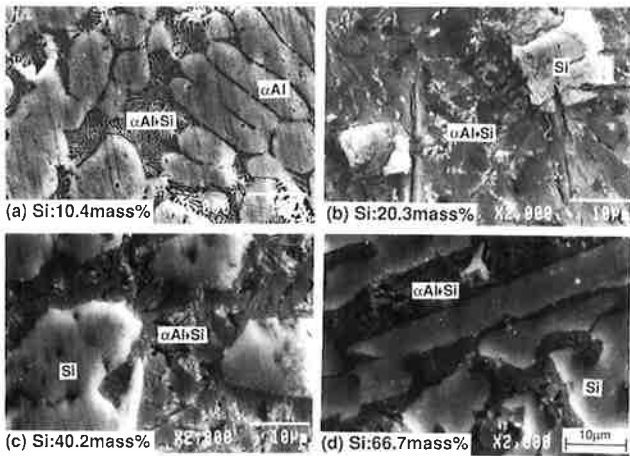


Fig. 7 SEM microstructure with mean Si content of alloyed layer showing relationship between Al-Si phase diagram.

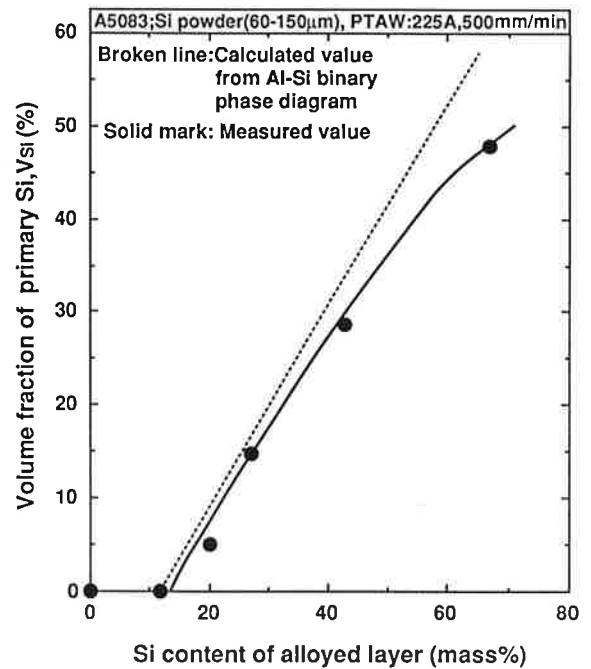


Fig. 8 Relation between Si content and volume fraction of primary Si, Vsi of alloyed layer.

Both white particle in (b) and (c) and plate-like particle in (d) were primary Si surrounded by α -Al+Si eutectic. Only a little formation of Mg_2Si was also observed due to the existence of Mg contained in base metal.

Figure 8 shows the relation between volume fraction of primary Si, Vsi and Si content in alloyed layer. Vsi increased linearly as increasing Si content. Measured value of Vsi showed good agreement with calculated value by lever law in equilibrium phase diagram, which was shown by a broken line in Fig. 8, though a little deviation between them was observed at about 70 mass% Si due to macrosegregation of primary Si. These results mean that the structure of Si alloyed layer corresponds to that predicted from Al-Si phase diagram.

Figure 9 shows the comparison of the distribution of grain size between primary Si particle in alloyed layer and Si powder used. PTA condition is 225A and 15g/min, at which condition the uniform distribution of primary Si particle was observed in alloyed layer. Grain size of Si powder scattered in the wide range from 25 to 150 μ m in diameter, but had two peaks at about 50 and 100 μ m. On the contrary, the distribution of grain size of primary Si has a sharp peak at about 30 μ m with narrow range from 20 to 50 μ m irrespective of the position of alloyed layer.

This result suggested that almost Si powders added were once melted into a molten Al pool and then newly solidified as primary Si particle.

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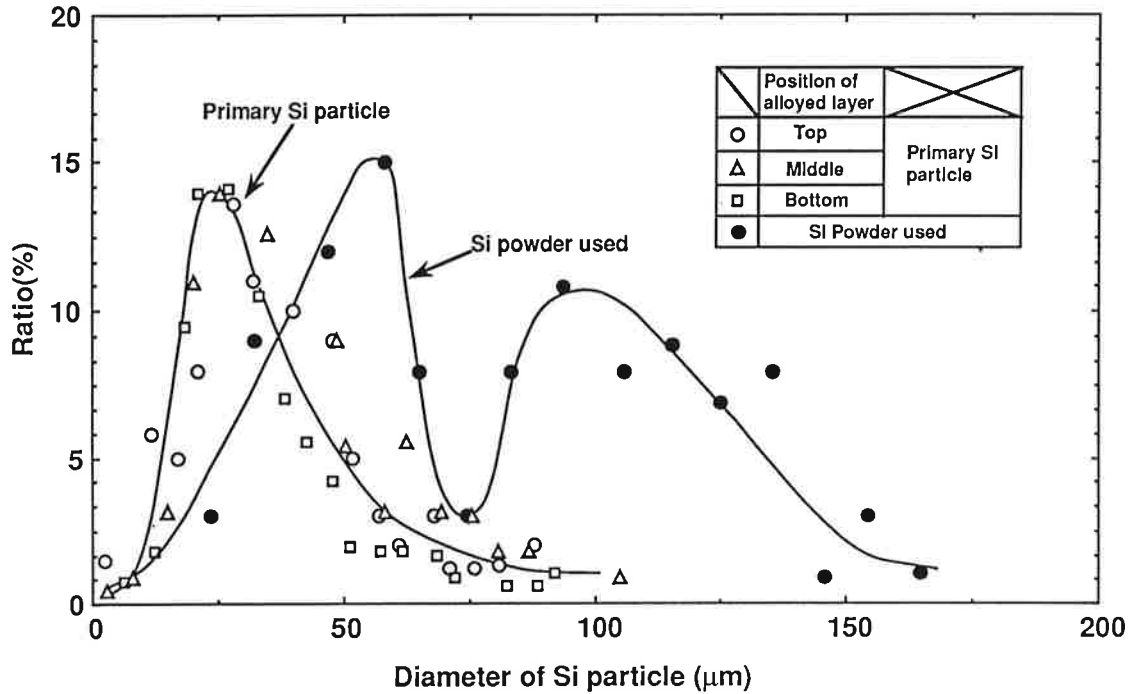


Fig. 9 Distribution of grain size of primary Si in alloyed layer and Si powder used. PTAW: 225A, 500mm/min, 15g/min.

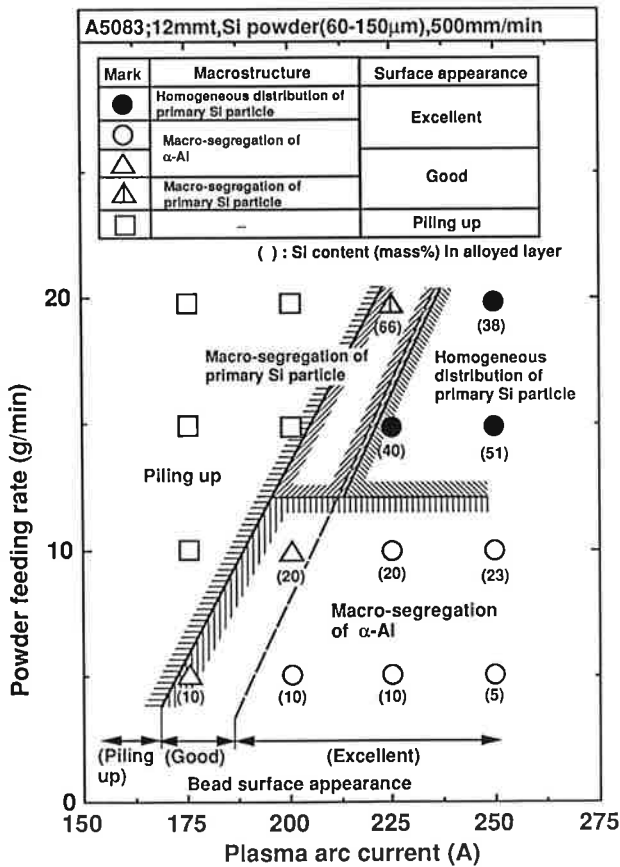


Fig. 10 Combined effect of powder feeding rate and plasma arc current on macrostructure of alloyed layers.

3.3 Formation condition of homogeneous alloyed layer

Figure 10 shows combined effect of powder feeding rate and plasma arc current on macrostructure and surface appearance of alloyed layer. Si content of alloyed layer is shown as the number in parenthesis below each mark. The condition range of a uniform dispersion of primary Si became narrower than the optimum alloying condition range for excellent surface appearance.

At constant current, macrosegregation of α -Al or primary Si were made in lower and higher powder feeding rates, respectively. Therefore, homogeneous structure was obtained at the intermediate powder feeding rate. This optimum powder feeding rate was likely to increase with increasing plasma arc current.

This result shows that the formation of homogeneous structure is related to Si content of alloyed layer. It is made clear as shown in Fig. 10 that Si content of homogeneous alloyed layer is restricted within the range from 30 to 50 mass%.

This range corresponds to the shaded zone in Al-Si phase diagram as shown in Fig. 7 and crystallization temperature of primary Si in the shaded zone ranges from 800 to 1050 °C.

Figure 11 shows a typical example of

temperature history measured near the surface of molten pool (0.5mm beneath the surface) with the optimum PTAW condition of 225A and 15g/min.

Maximum temperature reached to about 1080 °C, which was much higher temperature than the melting point of base metal (640 °C). Taking into consideration that molten pool temperature gradually decreased from the surface toward the inner of molten pool⁴⁾, this measured temperature agrees almost with the estimated liquidus temperature corresponding to the homogeneous alloyed layer (800-1050 °C).

In the case of less Si content than homogenized range, molten pool was much overheated because of decreased liquidus temperature. In this case, macrosegregation of band or island-like α -Al is easy to occur, because molten metal stream in molten pool is easy also to occur owing to decreased viscosity of molten metal by larger overheating. On the other hand, at more Si content than homogenized range, macrosegregation of primary Si is likely to occur, because effective stirring of molten pool was suppressed owing to the increasing viscosity of molten metal due to small overheating. Moreover, fluidity of molten Al-Si alloy shows the maximum value at Si content ranging 10 to 15mass%⁶⁾. This tendency may accelerate the above phenomena.

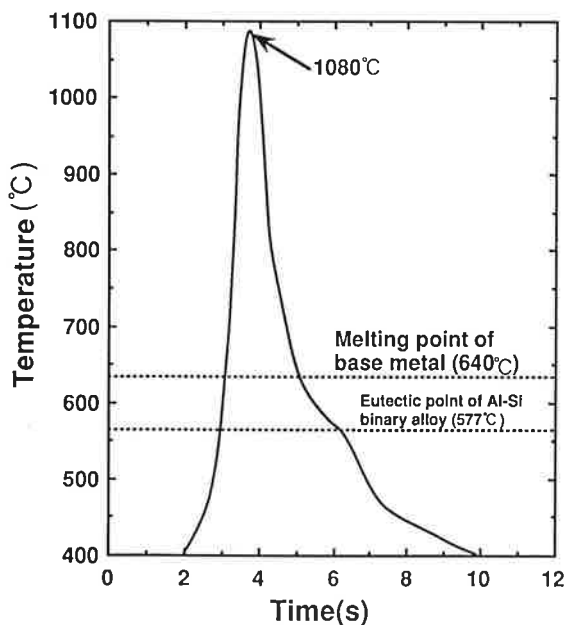


Fig. 11 Typical example of temperature cycle in alloyed layer during PTA process. PTAW:225A, 500mm/min, 15g/min.

Therefore, from these reasons Si content showing uniform distribution of primary Si was restricted in the

range of about 30 to 50 mass%.

In addition, solidification rate is about 200°C/s according to Fig. 11. This very high solidification rate in PTA process is considered to suppress the growth of primary Si particle.

Consequently, high temperature and rapid solidification rate of molten pool, which are features of PTA process, enable the formation of high Si content alloyed layer with uniform distribution of fine primary Si particle.

3.4 Hardness of alloyed layer

Figure 12 shows hardness distribution of Si alloyed layer at different powder feeding rate with 225A.

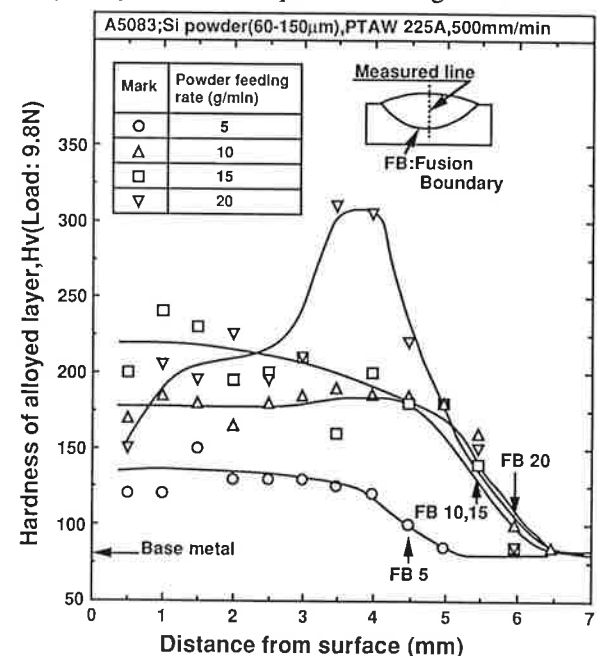


Fig. 12 Hardness distribution on crosssection of alloyed layer at different powder feeding rate in 225A.

Hardness distribution was uniform with less powder feeding rate than 20g/min. Irregular distribution in the hardness at 20g/min was due to macrosegregation of primary Si which was shown in Fig. 6 as plate-like primary Si. Relation between hardness and Si content in alloyed layer was shown in Fig. 13. Hardness increased linearly with the increase in Si content in hypo-eutectic range as the increase of eutectic Si, but increased exponentially in hyper-eutectic range according as the role of particle dispersion strengthening in metal-matrix composite^{7,8)}.

Figure 14 shows the relation between the hardness of alloyed layer and volume fraction of primary Si, V_{Si}. Primary Si scarcely influenced for hardness increase up to 30% V_{Si}, but hardness remarkably increased with more than 30% V_{Si}.

This result corresponds to hardening mechanism of particle dispersed composite material.

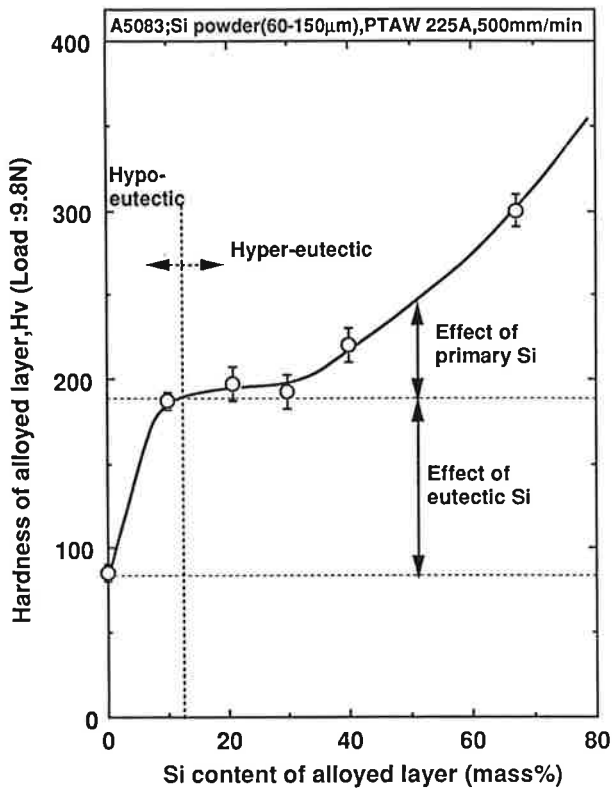


Fig. 13 Relation between hardness and Si content of alloyed layer.

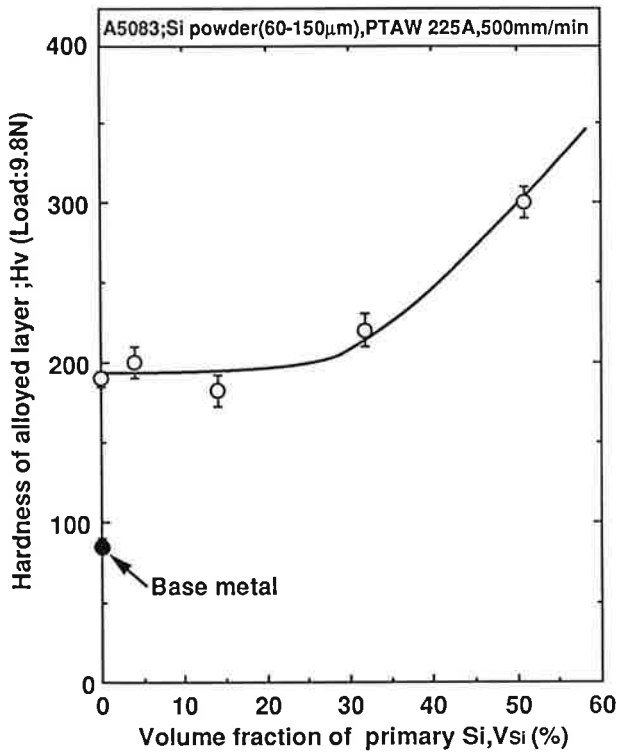


Fig. 14 Relation between hardness and volume fraction of primary Si, Vsi of alloyed layer.

3.5 Wear resistance of alloyed layer

Figure 15 shows the relation between specific wear and Si content of alloyed layer. Wear resistance was not improved in hypo-eutectic composition. On the contrary, in hyper-eutectic composition, specific wear decreased with more than 30-40mass% in Si content.

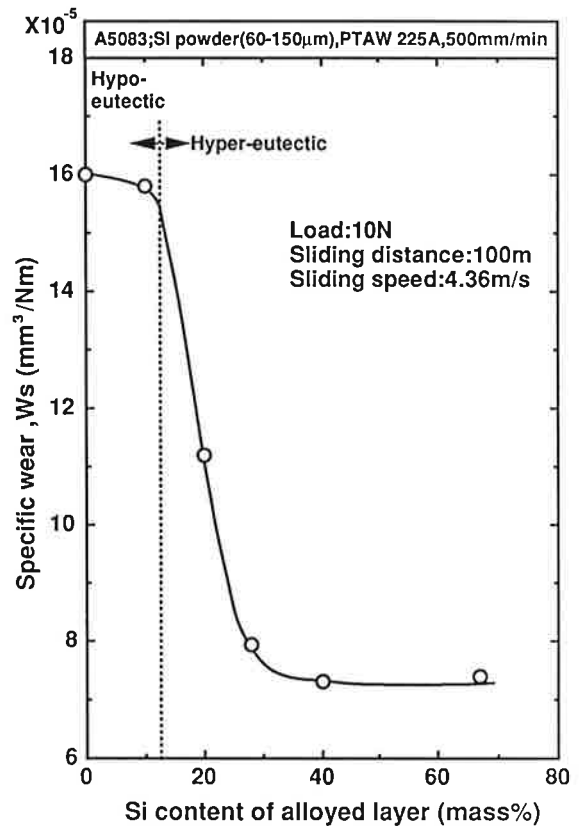


Fig. 15 Relation between specific wear and Si content of alloyed layer.

Figure 16 shows the relation between specific wear and volume fraction of primary Si, Vsi.

Specific wear decreased with increasing Vsi and converged to saturation value of about a half of base metal with more than 15% Vsi. This tendency corresponds to the feature of wear resistance of a particle dispersed composite material as similar way in hardness⁹⁾.

As shown in the previous report⁷⁾, the formation of hard intermetallic compound layer on the surface improved remarkably the wear resistance of aluminum alloy, but cracking was likely to occur in the hardened layer owing to the brittle property of intermetallic compound of aluminide.

However, it is made clear in this study, that the formation of hard particle dispersed layer can improve the anti-wear property without cracking.

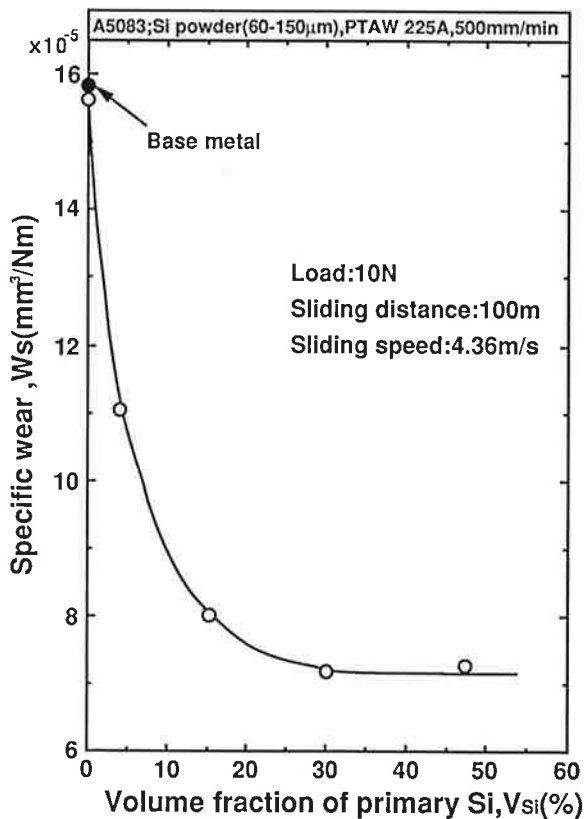


Fig. 16 Relation between specific wear and volume fraction of primary Si, V_{Si} of alloyed layer.

4. Conclusion

The formation of thick alloyed layer with high Si content have been investigated on the surface of Al alloy (A5083) plate by PTA process with Si powder. Hardening characteristics and wear resistance of alloyed layer was examined in relation to the microstructure of alloyed layer. Main results obtained were summarized as follows:

- (1) Thick hardened layer in mm-order thickness on the surface of A5083 plate can be formed by PTA process with wide range of process condition by using Si powder as alloying element because of eutectic reaction of Al-Si binary alloy.
- (2) High temperature and rapid solidification rate of molten pool, which are features of PTA process, enable the formation of high Si content alloyed layer with uniform distribution of fine primary Si particle.
- (3) Surface appearance and crosssectional shape of alloyed layer depended on both plasma arc current and powder feeding rate. High plasma arc current was beneficial to make the alloyed layer with

smooth surface appearance in wide range of powder feeding rate, because enough volume of molten pool was necessary to make alloyed layer.

- (4) Si content of alloyed layer increased linearly with increasing powder feeding rate and reached to 40-67 mass%, which was difficult to obtain by conventional cast process.
- (5) Uniform dispersion of fine primary Si particle with about $30\mu\text{m}$ in particle size can be obtained in alloyed layer with Si content ranging from 30 to 50 mass%.
- (6) Hardness of alloyed layer increased with increasing Si content, but increasing rate of hardness differed with macrostructure of alloyed layer. In hypo-eutectic range, hardness of alloyed layer increased linearly from Hv80 of base metal to Hv180 due to eutectic Si. In hyper-eutectic range, hardness of alloyed layer depended mainly on the volume fraction of primary Si, V_{Si} . Hardness increased remarkably at more than 30% V_{Si} and reached to Hv300 at about 50% V_{Si} .
- (7) Wear resistance of alloyed layer depended on V_{Si} and was remarkably improved to two times of base metal at 20-30% V_{Si} without cracking, but no more improvement was obtained at larger V_{Si} .

Acknowledgement

The authors would like to express their thanks to Showa Aluminum Co. Ltd. for offering base Al alloy and Nippon Steel Welding Product & Engineering Co. Ltd. for offering PTA overlaying apparatus.

The financial support by the Grant-In-Aids for Fundamental Scientific Research from Japan Ministry of Education Science and Culture is gratefully acknowledged.

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