Effect of Cu-Additions on the Hard-Over Layer of an Aluminum Alloy

- Hardening for the Top Ring Groove of Automotive Piston by the Plasma Transferred Arc Welding Process -

J. H. Moon, C. J. Seo and S. H. Hwang

Abstract

The surface of AC8A Al alloy was modified by adding the Cu powder using a Plasma Transferred Arc (PTA) welding process. Under the optimum fabricating conditions, the modified surface of AC8A Al alloy was observed to possess the sound microstructure with a minimum porosity. Hardness and wear resistance properties of the as-fabricated alloy were compared with those of the T6 heat-treated one. In case of the as-fabricated alloy, the hardness of the modified layer was twice that of the matrix region. Although significant increase in the hardness of the matrix region was observed after T6 heat treatment, the hardness of the modified layer was not observed to change. The wear resistance of the modified layer was significantly increased compared to that of the matrix region. The microstructure of a weld zone and the matrix region were investigated using the optical microscope, scanning electron microscope (SEM), electron probe microanalysis (EPMA), and transmission electron microscope (TEM). The primary and eutectic silicon in the weld zone were finer and more curved than in the matrix region, while some precipitates has had been found therein. According to the TEM observation, the predominant precipitate present in the weld zone was the θ' phase, which is precipitated during cooling by rapid solidification in PTA welding process. Improvement of hardness and wear properties in the weld zone in the as-fabricated condition can be explained based on the presence of θ' precipitates and fine primary and eutectic silicon distribution.

Key Words : Cu-additions, Plasma transferred arc welding

1. Introduction

The plasma transferred arc (PTA) welding process is an attractive methods for surface modification, in which some and/or all of the material surface can be alloyed by using the additives of the metal powders and/or ceramics in the molten pool (refer to Fig.1). In general, such a modified layer produced by the PTA process is few millimeters thick, and has good quality without delimitation from the matrix alloy. Various additives can be easily chosen in order to achieve the desired properties of the modified surface. Another advantage of this process is its economical efficiency compared to other process, such as chemical vapor deposition, physical vapor deposition, thermal spray, and etc. As a result, this process can be suitable for the potential application in the automotive industries, industrial robots, molds, and the office machines requiring a surface modification. Within recent years, to reduce the weight of the automotive engine, the AC8A Al alloy was used for the piston material. In case of using the AC8A Al alloy, some

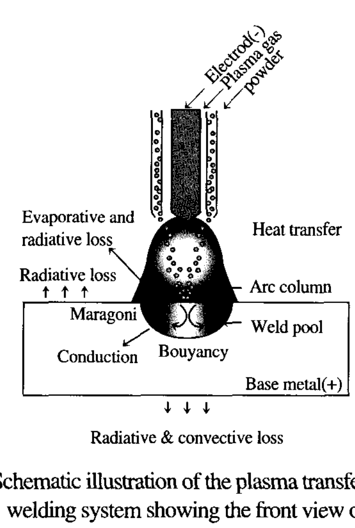

Fig. 1 Schematic illustration of the plasma transferred arc welding system showing the front view of the arc and weld pool with filler.

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problems could occur in the corner parts and top ring groove of the piston as such as the cracking and abrasion, respectively. This can be caused by the high pressures and temperatures in the combustion chamber for the Al alloy has lower abrasion resistance compared to cast iron. To solve the above-mentioned problems, inserts with Ni-Resist and reinforcement of the top ring groove of the piston are used. Some drawbacks of using the Ni-Resist are the weight increase of the piston as well as the poor thermal conductivity, causing piston ring to burnout. In addition, the position of the top ring groove cannot be raised due to the weakness of the normal aluminum alloy, and this increases crevice volume of the combustion chamber. One way to solve the problem is to use of ceramic performs which locally reinforce the piston using a high-pressure squeeze casting process. However, due to the expensive ceramic performs, such a method is not yet applied in practical applications.

The purposes of this study are to introduce the PTA process, which provides improved structure of the top ring groove of the piston by reinforcing with Cu powder and to suggest the possibility of industrial applications (refer to Fig.2). Microstructure study, hardness and wear properties of this surface modified alloy are also reported.

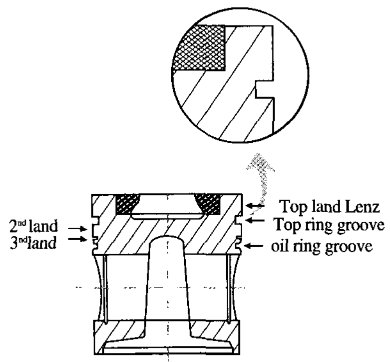

Fig. 2 Schematic illustration of the piston appearance showing the position of the top modification on the ring groove.

2. Experimental procedure

Fig. 3 shows the PTA equipment for surface modification of the automotive piston used in this study. Cu powders were used as an additional metal for modification because Cu forms a precipitates with the Al alloy and it is expected to improve the mechanical properties of the modified layer. Helium was used as the shielding gas for protection atmosphere of the molten pool and as the powder feeding gas.

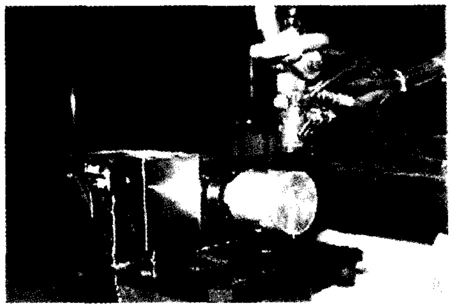

Fig. 3 Photograph showing the plasma arc transferred welding equipment used in this study.

Table 1 Formation condition of alloyed layer.

Addition powder	Cu powder
Powder feeding rate	100 g/min
Current	100-160 Amp.
Welding velocity	250 mm/min

Table 2 Condition of heat treatment.

Heat treatment temperature.	510℃ 3 hr.
Quenching	70-80℃ water
Aging temperature.	220℃ × 1-5 hr.

Ar was the pilot gas for the plasma arc. Detailed welding conditions in this study are illustrated in Table 1. Through preliminary experimentation, the width and depth of the modified layer were wider and deeper at the same welding current and application velocity.

This may be due to the increase of latent heat capacity of the matrix alloy. Constant welding velocity and/or current change gradually during processing must be considered. In this study, the welding current was changed gradually under constant welding velocity to control the layer uniformity. Heat treatment conditions for these experiments are revealed in Table 2. Various aging times are considered to optimize properties.

To observe defects, such as porosity, cracks etc., the piston was cut into quarters, and the width and depth of the modified layer are measured. The microstructure of the modified layer is investigated using optical microscope, SEM, EPMA and TEM. Variations in Cu concentration across the modified layer were measured by using JEOL JXA-8600 EPMA operated at an acceleration voltage of 20 kV, probe current of 1 × 10-8 Amp, and probe size of 2㎛. In order to observe a microstructure of the modified layer, as-fabricated alloys were cut into thin slices using a diamond cutter followed by the mechanical grinding as into 60μm thickness. The discs were punched out from the ground specimens from both the weld zone and matrix regions. Perforations of the discs were carried out on both sides of the discs by sputtering Argon ions at 6 kV as in an incident angle of 10-15°. The specimen was observed by using a Philips CM30 TEM operated at 200 kV. Selected area diffraction (SAD) patterns were recorded to identify the fine precipitates. Hardness of the modified alloy before and after T6 heat treatment was measured by using a Rockwell hardness tester (HRB). Major wear test conditions in this study were test load of 6.3 kgf, wear distance of 100 m, abrasion speed of 0.94, 1.98, 2.88 m/sec at room temperature. The specific wear was calculated using the following equation.

$$Ws = \frac{Bb^3}{8rpl} \quad (mm^3/Nm)$$

B : thickness of counter (mm) r : radius of counter (mm)
b : worn out length (mm) p : test load (N)
l : abrasion test length (m)

3. Results and discussion

Figs. 4(a)-(d) reveals the shape of piston appearance and the cross sectional view after the PTA process with Cu powder additionally thereof. The smooth beads in the modified layer are illustrated in Fig. 4(a). Some porosity, which formed in the upper side in the cross-section of the modified layer, could be removed during rough machining as shown in the Fig. 4(b). The cross sectional view of the modified piston as shown in Fig. 4(c) reveals of the sound microstructure. The piston was fabricated with Cu reinforcing on the top ring groove as shown in Fig. 4(d) using without problems in the course of final machining. A current of 150 Amp and powder feed rate of 10 g/min, show the weld zone, the fusion boundaries and matrix region as illustrated in Figs. 5(a)-(c). Fig. 5(a) shows the typical microstructure of the surface modified region with Cu powder. The primary and eutectic silicon as shown in Fig. 5(a) have crystallized with finer and more curved shapes than in the matrix region as shown in Fig. 5(c). As can be seen in Fig. 5(b), the fusion boundaries that are formed between the weld zone and matrix region, show a typical heat affected zone. In order

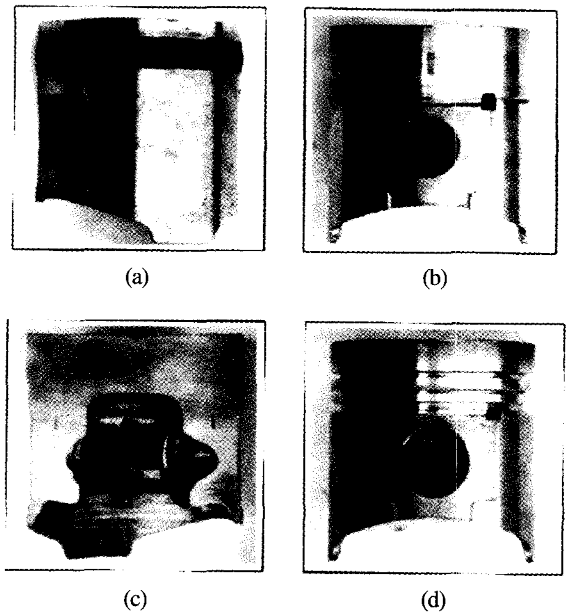

Fig. 4 Photographs showing (a) bead appearance of the piston in as-fabricated condition, (b)after rough machining, (c)macrostructure of the cross-section, and (d) piston appearance of final machining

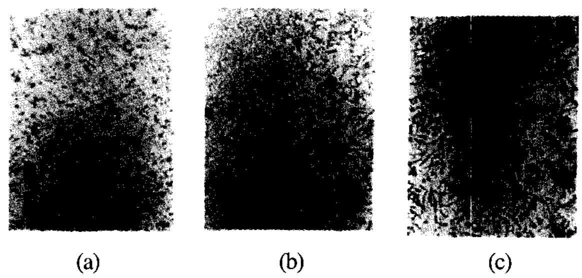

Fig. 5 Optical micrographs of the AC8A Al alloy modified with Cu element showing (a) weld zone, (b) fusion boundaries, and (c) matrix region.

to analyze the effect of additives, Al, Cu and Si concentration profiles within the modified layer were measured by using EPMA. The EPMA back-scattered electron image (BEI) and dot maps obtained from the modified layer are illustrated in Figs. 6(a)-(d). Shown in Fig. 6(a) is the BEI, revealing the distribution of Cu, Al and Si elements in the modified layer. As presented in Fig. 6(b)-(d), Al and Cu concentrations within the BEI as shown in Fig. 6(a) were measured to be approximately 70 and 30 wt%, respectively, which may be considered the eutectic composition in Al-Cu alloy. These are considered to be due to the re-melting between additive and matrix alloy to form Cu compounds in the weld zone and rapid solidification followed by cooling. Formation of the fine primary silicon, round eutectic silicon and Cu compounds provided strong evidence that in the course

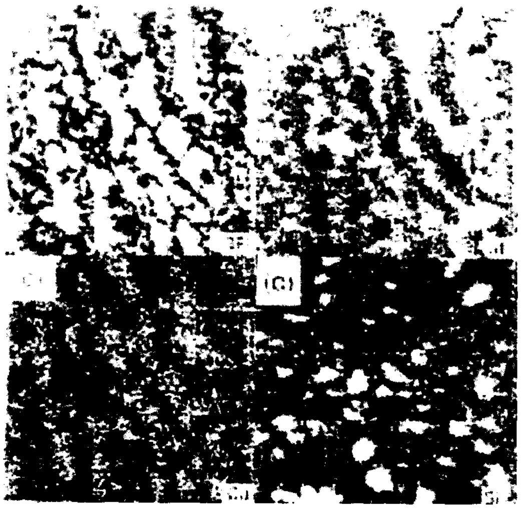

Fig. 6 EPMA micrographs in the weld zone showing the distribution of the Al, Cu and Si elements. : (a) backscattered electron image, (b) concentration profile of Al, (c) concentration profile of Cu, and (d) concentration profile of Si.

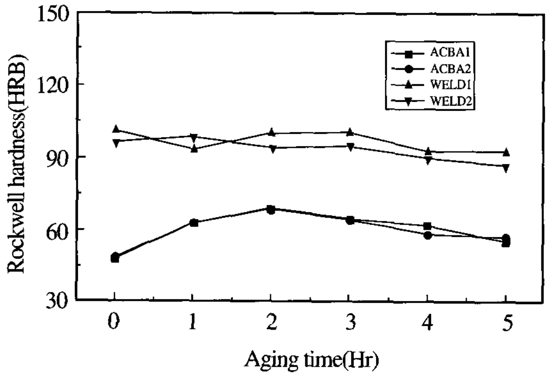

Fig. 7 Hardness distribution with aging time.

of processing, re-melting and rapid solidificat.

Fig. 7 illustrates Rockwell hardness change with aging time. In the case of the as-fabricated alloy, the hardness of the modified layer was twice that of the matrix region. Hardness of the modified layer was slightly decreased with aging time and no significant change was found before and after T6 heat treatment. The increase in the hardness of the matrix region observed after T6 heat treatment may be due to the fine, well-distributed precipitates.

TEM micrographs obtained from the matrix region and weld zone of the AC8A Al alloy are illustrated in Figs. 8(a)-(c). Bright field image taken from the matrix region in Fig. 8(a) shows typical cast microstructure of the AC8A Al alloy. Bright field image in Fig. 8(b) taken from the weld zone shows the cellular structure of α–aluminum and large crystallized Cu compounds.

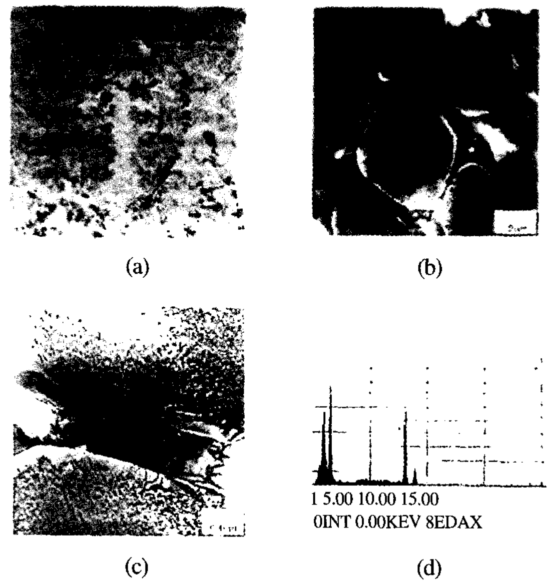

Fig. 8 TEM micrographs of the AC8A Al alloy modified with Cu element showing (a) BF image obtained from matrix region, (b) BF image obtained from weld zone, (c) enlarged view of (b) showing Cu compounds (arrow A) and fine precipitates in the α-Al region, (d),EDS spectra corresponding to area A as shown in Fig, 8(c)

Enlarged view Fig. 8(c) of Fig. 8(b) shows fine precipitates in theα -Al and large crystallized Cu compounds (arrow A) which areθ phase analyzed by energy disperse X-ray spectra (EDS) in Fig. 8(d). A TEM bright field image shown in Fig. 9(a) shows fine distributed precipitates in the weld zone. Corresponding dark field image is shown in Fig. 9(b), SAD pattern taken from precipitates in [001]Al zone axis is shown in Fig. 9(c) and a schematic drawing of (c) is shown in Fig. 9(d). These indicate that fine precipitates are θ' phase. Compared to the matrix region, fine θ' precipitates in weld zone indicated that Cu powders are re-melted during processing by the plasma heat source and rapidly solidified from supersaturated to metastable phase. The presence of θ' precipitates shows that rapid solidification occurs during cooling even though the estimated cooling rate is not too fast.

Fig. 10 shows the amounts of specific wear with variation of the abrasion speed of 0.94, 1.98 and 2.88 m/sec. As the abrasion speed increases, the amounts of specific wear of AC8A Al alloy increased compared to other specimens. In case of the modified layer, there was no difference in the amount of specific wear before and after T6 heat treatment of modified layer. The Ni-Resist ring, however, shows better wear resistance than that of

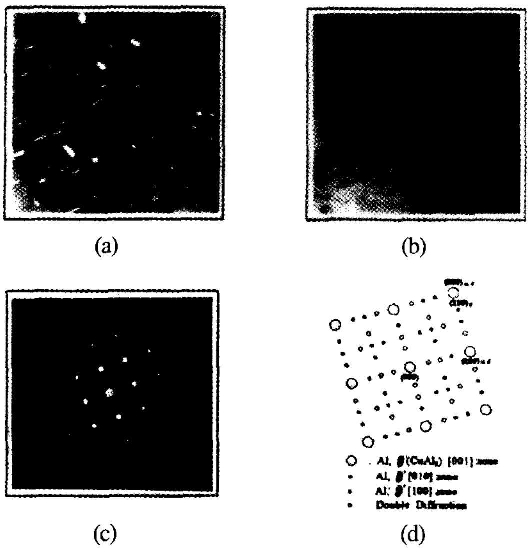

Fig. 9 TEM micrographs showing (a) DF image obtained from weld zone showing fine distributed precipitates, (b) corresponding to BF image of (a), (c) SAD pattern taken from the fine precipitates showing θ' phase in [001] zone axis, (d) schematic illustration of (c).

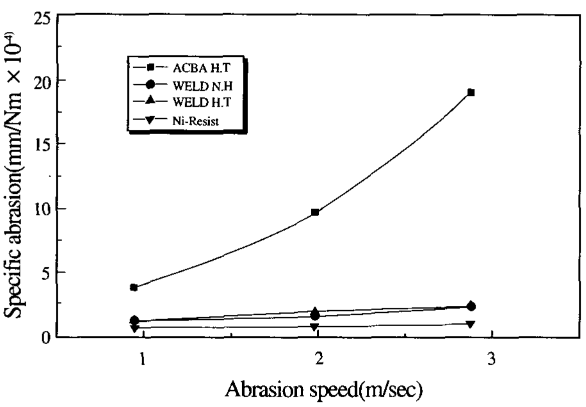

Fig. 10 Specific wear according to variation of the abrasion speed.

the modified layer. It may be considered that Cu powder addition is a favorable method to get the wear resistance equivalent to that of the Ni-Resist ring.

3. Conclusion

A smooth bead with Cu powder added on the AC8A Al alloy could be fabricated at the welding current of 150 Amp. Moreover, the powder feed rate is of 10 g/min as by using the PTA welding process. The welding current and velocity used during processing were important parameters to control the width and depth of the modified layer. The hardness and wear resistance of the modified layer were higher thereof as compared to the matrix alloy. A formation of the fine primary silicon and round eutectic silicon in the modified layer provided the strong evidence which is favored as during processing re-melting and rapid solidification. The microstructure of the modified layer reveals the uniformly distributed fine θ'precipitates, although the modified layer is not heat-treated. The presence of θ' precipitates is considered to improve the hardness and wear properties.

Based upon these observations, this process may be useful in the industrial applications that require a surface hardening of the Al alloys.

References

1. A. T. Alps and J. Zhang: Wear Rate Transitions in Cast Aluminum Silicon Alloys Reinforced with SiC Particles, *Scripta Metallurgy Material*, Vol. 26 (1992), pp.505-509
2. M. K. Surappa, S. V. Prasad and P. K. Rohatgi: Wear and Abrasion of Cast Al-Alumina Particle Composites, *Wear*, Vol. 77 (1982), pp.295-302
3. A. G. Wang and I. M. Hutchings: Wear of Alumina-Fiber Aluminum Composites by Two-Body Abrasion, *Material Science and Technology*, Vol. 5 (1989), pp.71-76
4. B. S. Lim, S. H. Hwang and C. J. Shur: A Study on the Formation of Functionally Composite Layer on Al Alloy Surface by Plasma Transferred Arc Overlaying Process, *Journal of the Korean Welding Society*, Vol. 17, No. 5 (1999), pp.371-379
5. B. S. Rheem, B. S. Kim, S. H. Oh, S. H. Hwang, C. J, Suhr: A Study on Formation of Thick Hardened Layer on Al Alloy Surface by PTAW Process, *Journal of the Korean Welding Society*, Vol. 15, No. 5 (1997), pp.467-477
6. N. Saka and D. P. Karalekas: Friction and Abrasion of Cast-Aluminum Particle Composites in K. C. Ludema(eds), *Wear of Materials, ASME, New York*, (1985), pp.784-793
7. J. H. Moon: Computer Simulation and Characteristic Evaluation of Surface Modified Layer by PTAW Process on Aluminum Alloy. *Ph. D. Thesis, School of Metallurgical & Materials Engineering, Univ of Sung Kyun Kwan, Suwon Korea*, (1995)
8. F. Matsuda: The State of the Art on the Development of Hard Surface Modification with Thick Layer for Aluminum and its Alloys, *IIW-IX-1732-94*