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ARTICLE

Effects of Si Content and Aging Temperature on Wear Resistance of Surfacing Layers Welded with 4043 Aluminum Welding Wires

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Abstract: 4043 aluminum welding wires are extensively used for welding 6000 series aluminum alloys due to the good flow ability of the fusion state and the low cracking tendency during welding process. Some scratches and wear on the surfaces of aluminum structural components can be repaired by surface welding with 4043 aluminum welding wires. In the present study, the influences of Si content and aging temperature on the wear resistance property of the surfacing layers welded by tungsten inert gas (TIG) welding using 4043 aluminum welding wires have been analyzed by optical microscopy, scanning electron microscopy, hardness testing and abrasive wear testing. The results show that the increase in Si content can increase the fraction of eutectic Si particles, and the heat treatment can spheroidize eutectic Si particles, resulting in further improving the wear resistance property of the surfacing layers.

Key words: surfacing weld; wear resistance; microstructure; property; heat treatment

Al-Si series alloys have been widely used in aerospace and automotive industries, owing to their exceptional characteristics including high strength, excellent wear resistance, low coefficient of thermal expansion and good casting ability [1-7]. 4043 aluminum welding wires have been extensively used for welding 6000 series aluminum alloys due to the good flow ability of the fusion state and the low cracking tendency during welding process [8]. Some scratches and wear on the surfaces of aluminum structural components can be repaired by surface welding using 4043 aluminum welding wires. In addition, the eutectic Si particles in the surfacing layers can protect the α(Al) matrix against wearing and improve the wear resistance of the alloys. Previous studies[9-14] reported that heat treatment plays an important role in the improvement of the wear resistance of Al-Si alloys owing to spheroidizing the eutectic Si particles.

In the present investigation, we have analyzed the influence of Si content and aging temperature on the wear resistance property of the surfacing layers welded with 4043 aluminum welding wires based on the systematic analyses.

1 Experiment

6061 aluminum alloy sheets with 4 mm in thickness were surfacing welded with 4043 welding wires of 3.1 mm in diameter. The chemical compositions of 6061 aluminum alloy and 4043 welding wires are summarized in Table 1. Al-Si ingots were prepared by controlled melting of commercially pure aluminum and Al-26% Si master alloy in a graphite crucible using a medium frequency induction furnace and casting in a metallic mould. Al-Si welding wires with smooth surface were prepared by extrusion and drawing processes, subsequently cleaned by sulfuric acid, phosphoric acid and so on.

Surfacing welded samples with a size of 25 mm × 25 mm × 25 mm were prepared by TIG welding. Prior to the welding process, the oxide film on the surface of the base metal was eradicated by mechanical polishing, and then the surface was cleaned with organic solvent. The TIG welding conditions adopted during the welding process were 180 A welding

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current, 20 V welding voltage, 0.1 m/min welding speed and being shielded by pure argon (99.99%). The surfacing welded samples for investigation were subjected to a solution treatment at 540 ℃ for 4 h, followed by water quenching and artificial aging at 140, 170 and 210 ℃ for 12 h. The specimens of 4.8 mm gauge diameter and 12.7 mm length for wear testing were cut from the surfacing welded samples. The wear resistance of the surfacing layers was evaluated using a MMW-1 universal wear testing machine, and the wear loss was measured by electronic weight balance. The value for each condition is the average value of three specimens. The test conditions were 100 N applied load, 100 r/min rotational speed, 15 min sliding time and 25 ℃ ambient temperature. The schematic diagram of wear testing is shown in Fig.1. The specimens for microstructural observations were cut from the surfacing layers, followed by mechanical polishing. The microstructures were observed by optical microscope (OM, DMI5000M). The wear surfaces of the surfacing layers after wear testing were observed by scanning electron microscopy (SEM, SHIMADZU SSX-550). The hardness was measured by the 452-SVD Vickers hardness tester at the load of 5 N and a loading time of 15 s.

2 Results

2.1 Wear resistance property and hardness

Generally speaking, wear rate is calculated using wear loss per unit sliding time. Wear rate and friction coefficient are always used as an evaluation of wear. Fig.2 shows the wear rates and the friction coefficients of the surfacing layers welded with 4043 welding wires. It is observed that the wear rate and friction coefficient decrease with the increase in Si content of 4043 welding wires.

The wear rates of the surfacing layers welded by 4043 welding wires after different heat treatments are shown in Fig.3. As is seen, the wear rate varies evidently with the increase in aging temperature, and the lowest wear rate (0.0283 g/h) can be obtained by aging at 170 ℃.

Fig.4 shows the friction coefficients of the surfacing layers welded with Al-5.9% Si welding wire before and after heat treatment. Compared with that before heat treatment, it is clear that the friction coefficient decreases obviously, and the wear on the surfacing layers after heat treatment is carried on more steadily in the whole wear process, while the surfacing layers before heat treatment are worn seriously in the late stage of abrasive wear.

Table 1 Chemical composition of 6061 aluminum alloy and 4043 welding wires used in the experiment (wt%)

Sample	Si	Mg	Cu	Cr	Al
Base metal	0.5	0.9	0.15	0.1	Bal.
Wire-a	5.0	—	—	—	Bal.
Wire-b	5.5	—	—	—	Bal.
Wire-c	5.9	—	—	—	Bal.

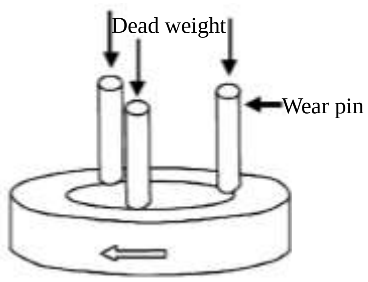

Fig.1 Schematic diagram of wear testing

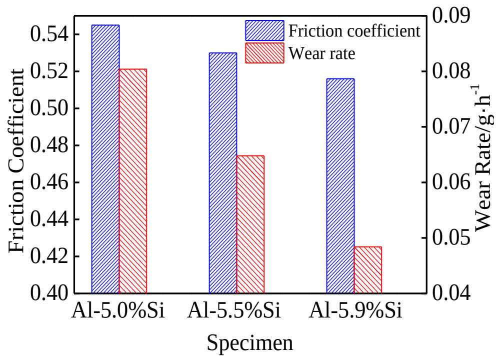

Fig.2 Wear rates and friction coefficients of the surfacing layers

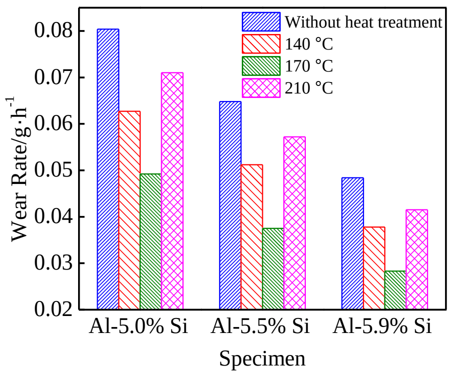

Fig.3 Wear rate of the surfacing layers welded by 4043 welding wires after different heat treatments

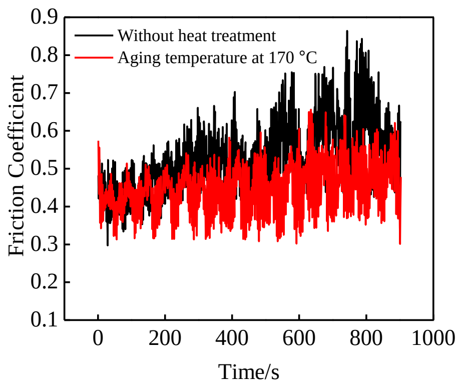

Fig.4 Friction coefficients of the surfacing layers welded with Al-5.9% Si welding wire before and after heat treatments

The hardness of the surfacing layers welded with 4043 welding wires before and after heat treatment is shown in Fig.5. With the increase in Si content, the hardness increases obviously and reaches its maximum value (660 MPa) at 5.9% Si before heat treatment. The trend of hardness after heat treatment in the range of aging temperature is contrary to that of friction coefficient. The highest hardness (779 MPa) can be obtained by aging at 170 ℃.

2.2 Microstructure observation

Fig.6 shows the microstructure of the surfacing layers welded with 4043 welding wires. As seen from the figure, the typical hypoeutectic Al-Si microstructure consisting of α(Al) with an interdendritic region of eutectic Si phase is observed. The eutectic mixture of α(Al) and Si is distributed along the grain boundaries as a non-equilibrium eutectic phase. The morphology of these eutectic Si particles mainly presents a coarse and acicular microstructure, which determines the mechanical properties. In addition, the raise of Si content increases the fraction of eutectic Si particles while decreases that of α(Al).

Optical micrographs of the microstructure of surfacing layers welded with the Al-5.9% Si welding wire after different heat treatments are shown in Fig.7. The graphs indicate the eutectic structures subjected to a heat treatment are modified, and the eutectic Si particles are initially broken down into small fragments and spheroidized gradually with the increase of aging temperature.

2.3 SEM observation

SEM images of the wear surfaces of the surfacing layers welded by welding wires of different Si contents without heat treatment are shown in Fig.8. As is seen, micro-groove and micro-cutting can be found on the wear surface. Besides, it can be also observed that shallower and narrower grooves are produced with the increase in Si content. In general, shallow and narrow groove means good wear resistance property.

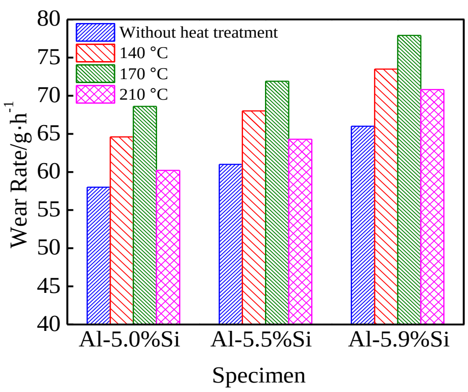

Fig.5 Hardness of the surfacing layers after different heat treatments

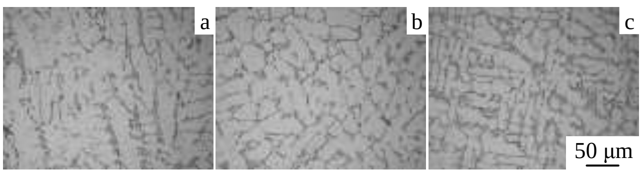

Fig.6 Optical micrographs of the microstructures of surfacing layers welded with wires of different Si contents: (a) 5.0% Si, (b) 5.5% Si, and (c) 5.9% Si

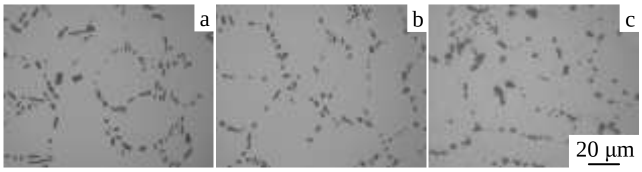

Fig.7 Optical micrographs of the microstructures of surfacing layers welded with the Al-5.9% Si welding wire after different heat treatments: (a) 140 ℃, (b) 170 ℃, and (c) 210 ℃

Fig.8 SEM images of the wear surface of the surfacing layers welded by 4043 welding wires of different Si contents without heat treatment: (a) 5.0% Si, (b) 5.5% Si, and (c) 5.9% Si

3 Discussion

Hardness is considered as an important influence on materials wear resistance. Generally speaking, material loss in abrasive wear mainly goes though micro-cutting and ploughing mechanisms. High hardness of materials can weaken the micro-cutting and ploughing in the abrasive wear process and improve the wear resistance as a conclusion. Al-Si alloys are considered as an excellent wear resistance due to the eutectic Si particles which can protect the α(Al) matrix in the abrasive wear process. Therefore, more eutectic Si particles and their uniform distribution will achieve smaller wear rate and friction coefficient, meaning better wear resistance property.

In the abrasive wear process, the crack nucleation mostly takes place at the Al/Si interface because high stress concentration is produced at the interface between acicular eutectic Si particles and α(Al) matrix, which will weaken the protective effect of eutectic Si particles on the α(Al) matrix. In addition, the bonding between acicular eutectic Si particles and α(Al) matrix is so poor that it may result in eutectic Si particles dropping from α(Al) matrix.

After the heat treatment, the coarse and acicular eutectic Si particles are initially broken down into small fragments and spheroidized. The change of the eutectic Si particles morphology will reduce the stress concentration at Al/Si interface and contribute to enhancing wear resistance of the surfacing layers. Besides, the improvement of wear resistance can be acquired due to better distribution of spheroidized eutectic Si particles and the stronger bonding between spheroidized eutectic Si particles and *α*(Al) matrix. There are evident differences on the microstructure and the wear resistance property of the surfacing layers at different aging temperatures. Fig.5 shows that the best wear resistance can be obtained by aging at 170 ℃. At low aging temperature (140 ℃), some of the acicular eutectic Si particles would not be spheroidized completely as shown in Fig.7a, and the improvement of wear resistance property can not achieve the maximum as a result. However, the spheroidized eutectic Si particles will gather and coarsen at exorbitant aging temperature (210 ℃) as shown in Fig.7c, meanwhile the fine distribution of eutectic Si particles would be damaged. These factors will cause the decrease of wear resistance property.

4 Conclusions

1) Eutectic Si particles can protect the *α*(Al) matrix in the abrasive wear process and improve the wear resistance property of surfacing layers. Increasing of Si content reduces the friction coefficient and wear rate.

2) Acicular eutectic Si particles are initially broken down into small fragments and spheroidized by a proper heat treatment. These spheroidized and uniformly distributed eutectic Si particles can strengthen the *α*(Al) matrix and increase the wear resistance. The best aging temperature is 170 ℃.

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Si 含量及热处理对 4043 铝合金焊丝堆焊层耐磨性的影响

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摘 要：4043 铝合金焊丝熔化后流动性良好，焊后不易产生结晶裂纹，广泛适用于 6000 系铝合金的焊接。利用 4043 铝合金焊丝在材料表面堆焊，可以修复部分材料表面出现的划伤与磨损。本研究使用 4043 铝合金焊丝，配合钨极惰性气体保护焊进行表面堆焊实验，采用金相显微镜，扫描电镜，硬度测试及耐磨性测试等分析检测手段研究了 Si 含量及热处理工艺对焊后堆焊层耐磨性的影响。结果表明，提高焊丝中 Si 含量可以增加共晶硅颗粒的数量。而热处理可以有效球化共晶硅颗粒，显著提高堆焊层的耐磨性。

关键词：表面堆焊；耐磨性；显微组织；性能；热处理

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