EFFECT OF MATRIX PROPERTIES ON STATISTICAL STRENGTH AND DISTRIBUTION OF SiC/Al ALLOY COMPOSITE WIRES

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This paper deals with the tensile strength of composite wires of SiC(Nicalon) fiber reinforced Al alloys, Al-5.7%Ni, Al-4.0%Cu and pure-Al matrix. The strength of matrix was changed by heat treating. Tensile test of wires and fibers extracted from the composite wires were carried out. The hardness and microstructure of matrix were examined. Effect of matrix behavior on the statistical strength of composite wires was investigated, connecting with the rule of mixture (ROM). Test results showed that strength of fibers extracted from the composite wires decreased with increase in quenching temperature if the reaction between fiber and matrix occurred. The strength of SiC/Al and SiC/Al-5.7%Ni wires also decreased by quenching. The strength of SiC/Al-4%Cu wire was enhanced by quenching. The scatter of strength of pure-Al matrix wire kept constant over the quenching temperature range, and that of Al-5.7%Ni matrix wire became large with increase in quenching temperature, whereas that of Al-4.0%Cu matrix wire was decreased by quenching.

1. INTRODUCTION

FRM (fiber reinforced metal) is noticed as a new material having high specific modulus, high specific strength and excellent thermal resistance. Composite wire is a kind of semi-finished composites developed in recent years. It can be used to produce composites components in various shape or size by secondary-fabrication. In order to utilize the excellent properties of composite wire, and to produce it into machine parts, it is necessary to understand strength change, the strength distribution, and to analyze the effecting factors. Up to now, a lot of studies on FRM about matrix alloying, high temperature strength, thermal stability and so on has been done. These studies mostly concentrated on the degradation of fiber strength due to interface reaction. However it has seldom been done about the effect of matrix properties on the strength. The strength distribution and the factors controlling FRM strength has not been fully investigated.

Here the composite wire of continuous SiC(Nicalon) fiber reinforced Al alloys was taken as a FRM. The properties of matrix were changed by a series of heat treatments. The effects of matrix properties on strength and its distribution were discussed.

2. EXPERIMENTAL METHODS

2.1 Materials and heat treatment

In the present work, composite wires (produced by Nippon Carbon Co. Ltd.) with a diameter of 0.5 mm were used as test materials, which are manufactured by infiltrating molten Al alloys to a bundle of consisting of about 500 continuous SiC filaments. Composite wires with three kinds of matrix, pure-Al, Al-5.7%Ni and Al-4.0%Cu, were employed, which were written hereinafter as SiC/pure-Al, SiC/Al-5.7Ni and SiC/Al-4.0Cu. In order to change the matrix properties, the wires were heated up to the temperature range of 200°C to 600°C for 10 min in argon atmosphere, and then quenched into water.

2.2 Tensile test and microstructure observation

Composite wire was directly clipped by the air-chuck, no using any tab for tensile test. Load was recorded by a pen-recorder connecting to a load cell via strain amplifier. Gauge length of 50 mm and cross head speed of 1.5 mm/min were used for tensile test. The composite wires were ground and polished using a series of diamond pastes with different grit size. Then they were etched in a 5%HF water solution for about 2 minutes. Vickers micro-hardness of matrix was measured. Load, loading time and test points were 10 grams, 15 seconds and 10 spots, res-
pectively. Volume fraction of fiber ($V_f$) was measured by counting the fiber number in photograph of cross section of composite wires.

2.3 Tensile test of extracted fiber

The SiC fiber in composite wires was extracted by dissolving aluminum matrix in 10% NaOH water solution. In order to investigate the strength change of fibers through different heat treatment, tensile test for SiC mono-fiber was carried out. Test conditions were: 10 mm gauge length, 0.2 mm/min. tensile speed and 80 sample number of samples.

3. RESULTS

3.1 Results of tensile test

Figure 1 shows the wire strength change quenched at different temperature. From the figure, it can be seen that strength of SiC/Al-4.0Cu wire was little lower, but that of SiC/Al-5.7Ni wire was about 125 MPa higher comparing to that of SiC/pure-Al wire for the quenching temperature below 450°C. And the average strength of these kinds of wires were almost kept a constant up to 450°C. Besides, strength of SiC/pure-Al wire quenched at 450°C was only 2.2% lower than that of the as-received wire, which means that quenching did not decrease wire strength up to 450°C. However, when quenching temperature was beyond 450°C, the strength of SiC/Al-5.7Ni wire went down seriously. For example, the strength was 37.2% lower for SiC/Al-5.7Ni wire, but only 14.1% lower for SiC/pure-Al comparing to that of as-received wire when quenched at 600°C. There is Al-Al$_3$Ni eutectic structure in matrix of SiC/Al-5.7Ni wire, but only a phase in SiC/pure-Al. So the wire strength change should be correlated with the matrix properties change and SiC fiber degradation due to interface reaction between fiber and matrix. Furthermore, it is necessary to notice that the strength of SiC/pure-Al wire at elevated temperatures was constant over the temperature range of 20°C to 400°C. And the high temperature strength of SiC/Al-5.7Ni wire was much higher than that of SiC/pure-Al wire from the work of Y. Imai et al. Here we observed, the strength of SiC/Al-5.7Ni quenched wire was decreased seriously beyond 450°C. On the contrary, the strength of SiC/Al-4.0Cu wire increased by quenching exceeding to 450°C comparing to the strength as-received. Namely, this wire was quenched at 600°C, its strength enhanced about 13.6%. The reason is to be connected with the hardening of matrix by natural aging after quenching.

3.2 Scatter of wire strength

Figure 2 shows the effect of quenching temperature on Weibull shape parameter ($m$) of SiC/Al-5.7Ni, SiC/pure-Al and SiC/Al-4.0Cu wires. Weibull shape parameter of strength decreased with quenching temperature for SiC/Al-5.7Ni wire, increased for SiC/Al-

![Figure 1](image1.png)

**FIGURE 1**

The relationship between wire strength and quenching temperature.

![Figure 2](image2.png)

**FIGURE 2**

Effect of quenching temperature on Weibull shape parameter ($m$) of the wire strength.
4.0Cu, and had almost no change for SiC/pure-Al, which was about 27. The scatter of high temperature strength increased with the test temperature for SiC/pure-Al wire\(^1\). The reason is also involved in the change of matrix properties and fiber strength degradation due to interface reaction.

3.3 Strength of extracted fiber

Figure 3 shows the strength of extracted fiber from the wire quenched at different temperatures. The strength of fiber extracted from SiC/pure-Al and SiC/Al-4.0Cu wire decreased a little when quenching at 400°C, but went down seriously when quenching at 600°C comparing with the strength of fiber extracted from the wire as-received. In the case of SiC/Al-5.7Ni wire, extracted fiber strength decreased seriously more than that of other two kinds of wires for all quenching temperature. The reason is explained that fiber was damaged due to the reaction between Ni in the matrix and SiC fiber, when heat-treating. This reaction also becomes one of reasons causing a serious strength decrease of SiC/Al-5.7Ni wire quenched beyond 450°C, as shown in Figure 2. But the wire strength with quenching temperature can not be explained only using the degradation of extracted fiber strength, since the strength of fiber extracted from SiC/Al-5.7Ni was higher than that from SiC/pure-Al for the employed quenching temperature, and that of fiber extracted from SiC/Al-4.0Cu had also degradation after quenching. So it is necessary to consider both the change of strength and the microstructure of the matrix after wires are heat-treated.

3.4 Hardness and microstructure of matrix

Figure 4 shows the microstructures of SiC/Al-5.7Ni and SiC/Al-4.0Cu wire quenched at different temperatures. Chemical composition of Al-5.7%Ni alloy is near to the eutectic point, the microstructure as-received should be an Al-Al$_3$Ni eutectic structure. But this eutectic structure disappeared gradually.
when quenching temperature exceeds 350°C, and finally the structure was not observed at the quenching temperature of 600°C. In the case of SiC/Al-4.0Cu wire, CuAl2 phase in grain boundary was gradually dissolved when quenching beyond 400°C, and could not be observed after quenched at 600°C. Figure 5 shows hardness of three kinds of the matrix in wires. It can be seen that the hardness decreased while quenching over 300°C for SiC/Al-5.7Ni wire, but for SiC/Al-4.0Cu wire the hardness increased considerably because of a natural aging when quenching over 400°C, which coincided with the microstructure change in Figure 4. The hardness almost did not change (about 31 kgf/mm²) for SiC/pure-Al because matrix can not be hardened by any heat treatment. The eutectic Al-Al3Ni would be granulated during annealing and the strength decreased by granulating. In the present work, also, the change of microstructure and hardness are considered to be related with granulating of Al-Al3Ni.

4. DISCUSSIONS

4.1 Effect of matrix strength on the strength of composite wire

We will discuss the affecting factors on wire strength from two aspects: 1) degradation of fiber strength after wire was exposed at elevated temperature, and 2) the change of matrix properties caused by heat treatment. Further, we will use rule of mixture (ROM) to analyze the effect of fiber and matrix. The wire strength was calculated by ROM equation, using extracted fiber strength. The wire strength from experiment were converted into the strength with 10 mm gauge length. The wire strength generally fits Weibull distribution, the failure probability \( P(\sigma) = 1 - \exp \left( \frac{L}{L_0} (\frac{\sigma}{\sigma_0})^n \right) \)  

Where, \( L \): gauge length, \( L_0 \): standard gauge length, \( \sigma_0 \): scale parameter. If shape parameter (\( n \)) is supposed to be independent of gauge length, the size effect can be estimated by the equation,

\[
\sigma_{18} = \left( \frac{50}{10} \right)^{1/n} \sigma_{58}
\]

Where, \( \sigma_{18} \): wire strength of 10mm gauge length, \( \sigma_{58} \): wire strength of 50mm gauge length.

Figure 6 shows the relative retention of strength \( \sigma_0/\sigma_n \) (strength after quenching/strength as-received) of three kinds of wires. The \( \sigma_0/\sigma_n \) has two values, that is, the calculated result by ROM and tensile test result. The calculation based on ROM is done as follows,

\[
\sigma_c = \sigma_f V_f + \sigma_m (1 - V_f)
\]

Where, \( \sigma_f \): strength of extracted fiber, \( V_f \): volume fraction of fiber, \( \sigma_m \): matrix strength when fiber broken. The volume fraction of fiber \( V_f \), measured from the photogroph of wire section, is about 34.9% for SiC/pure-Al, 32.7% for SiC/Al-5.7Ni and \( V_f = 30.4 \) % for SiC/Al-4.0Cu, respectively. We will discuss the matrix effect from two cases: 1) supposing matrix strength has no change, \( \sigma_m \) is 100 MPa, 200 MPa and 250 MPa for SiC/pure-Al, SiC/Al-5.7Ni and SiC/Al-4.0 Cu111, respectively; 2) matrix strength changes with increase in quenching temperature, which is correspondent with matrix hardness as shown in Figure 5.

In the first case, the relative retention of wire strength calculated by ROM is only influenced by fiber strength which decreased with quenching temperature. The calculation result is shown in the first column of Table 1. In the second case, we consider that the matrix strength changes along with

Table 1 The relative retention of strength \( \sigma_0/\sigma_n \) calculated by ROM experiment data for the composite wires in different quenching temperature

<table>
<thead>
<tr>
<th>Composite wires</th>
<th>Matrix strength no change</th>
<th>Matrix strength change</th>
<th>Experiment data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC/pure-Al</td>
<td>0.98 0.87</td>
<td>0.98 0.87</td>
<td>0.98 0.85</td>
</tr>
<tr>
<td>SiC/Al-5.7Ni</td>
<td>0.95 0.82</td>
<td>0.93 0.78</td>
<td>0.98 0.93</td>
</tr>
<tr>
<td>SiC/Al-4.0Cu</td>
<td>0.98 0.93</td>
<td>0.98 1.01</td>
<td>0.98 1.14</td>
</tr>
</tbody>
</table>

Note: \( \sigma_f \) in ROM was used the extracted fiber strength from composite wires.
quenching temperature. The calculation results are shown in the second column of Table 1. Figure 6 shows a plot between quenching temperature and the relative retention of strength, for both the experiment data and the calculation result by ROM, when not considering matrix strength change. It can be seen that the relative retention of strength of experiment data has a good agreement with that of ROM for SiC/pure-Al. The reason is that the strength of pure aluminum matrix does not change after heat treatment. That means the wire strength of SiC/pure-Al is only controlled by fiber strength. In the case of SiC/Al-5.7Ni wire, eutectic Al-Al$_3$Ni does not granulated entirely when quenching up to 400°C, matrix strength almost has no change, so the wire strength changed in the way like SiC/pure-Al wire, that is, it is only influenced by fiber strength. For SiC/Al-4.0Cu wire, the relative retention of strength by ROM is almost the same as the experiment result when quenching up to 400°C, because Al$_2$Cu phase has not been dissolved into the matrix, there is not the natural aging hardening. But when quenching at 800°C, relative retention of strength calculated by ROM has a marked difference from the experiment for SiC/Al-5.7Ni and SiC/Al-4.0Cu wires, as shown in Figure 6. In the case of SiC/Al-5.7Ni, matrix is weakened since eutectic phase of Al-Al$_3$Ni granulated entirely, and in the case of SiC/Al-4.0Cu, matrix is strengthened by a natural aging after quenching. Here is the change of matrix strength, effectively influencing composite wire strength. But even if considering the effect of matrix strength, as shown in the second column of Table 1, the relative retention of strength by ROM is still different from the experiment result. This means that it is not enough to explain the effect of matrix strength change on the wire strength change when using the rule of mixture simply. Besides the effect of matrix strength, the change of fiber strengthening behavior caused by matrix change and the disorder of fiber arrangement may affect the wire strength. The discussions as above, lead us to the following ideas. For SiC/Al-5.7Ni wire, since the strength keeps a higher level when quenching at the temperature below 350°C, the matrix is almost eutectic structure, which is favorable for stress transfer, and the fiber strength is higher too. But when quenching from the temperature over 400°C, there is a strength degradation due to interface chemical reaction, meanwhile, the eutectic begins to granulate. The eutectics granulate gradually when quenching up to 600°C. Therefore the ability to transfer the stress in matrix becomes small. This is considered to be the main reason that the strength of SiC/Al-5.7Ni wire changes with quenching temperature as shown in Figure 1. Similarly, in the case of SiC/pure-Al wire, the ability of stress transfer in the matrix is also weaker because the matrix only shows a simple α phase. And the strength of extracted fiber is lower than that from SiC/Al-5.7Ni wire. So the wire strength is lower than that of SiC/Al-5.7Ni Wire. But since the matrix strength has no change almost after quenching, and the fiber strength decreases little, the wire strength becomes higher than SiC/Al-5.7Ni wire when quenching over 500°C. Whereas, for SiC/Al-4.0Cu wire, even if there is fiber strength degradation after quenching, the matrix is strengthened by natural aging after quenching over 400°C, which enhanced the ability of stress transfer in the matrix. That is why the strength of SiC/Al-4.0Cu wire increased when quenching over 400°C.
4.2 Scatter of the wire strength

High temperature strength of FRM was calculated by Monte-Carlo simulation based on a two-dimensional model by K. Goda et al. They reported the scatter of FRM strength became large at elevated temperature. The reason was considered that the stress concentration region caused by broken fiber was enlarged, and the number of defects also increased at elevated temperature. I. Fujii et al. analyzed the effect of matrix strength on the composites strength and the strength distribution based on ROM. They had a conclusion that the coefficient variation of FRP strength would become larger with decreasing matrix strength. These are the same behavior as the experiment of results in Figure 7, that is, the scatter of strength for SiC/pure-Al wire increased at elevated temperature.

![Figure 7](image)

**FIGURE 7**

The scatter change of strength for SiC/pure-Al at elevated temperature.

Figure 2 shows a scatter of strength for three kinds of wires along with quenching temperature. In the case of SiC/Al-5.7Ni, since eutectic Al₃Ni granulates gradually with quenching temperature, which weakens the matrix, the scatter of composite wire strength increases. On the other hand, the scatter of SiC/Al-4.0Cu wire strength decreases because the matrix is strengthened by natural aging after quenching. But when SiC/pure-Al is quenched, the matrix does not change in strength, so its strength scatter has no change. From these discussions, it is concluded that the distribution of composites strength is not only depended on the distribution of fiber strength, but also on the matrix strength.

5. CONCLUSIONS

The heat treatments and tensile test were carried out for three kinds of SiC/Al alloy composite wires. Effect of the matrix strength on the strength and distribution of the wires was discussed. The results obtained are summarized as follows:

1) The strength of SiC/pure-Al, SiC/Al-5.7Ni and SiC/Al-4.0Cu composite wires decreased little when they were quenched from the temperature below 450°C. When quenched over 450°C, the strength of SiC/Al-5.7Ni wire decreased more than that of SiC/pure-Al, however, the strength of SiC/Al-4.0Cu increased.

2) The rule of mixture for composites cannot reflect sufficiently the effect of matrix strength change on strength of FRM.

3) The scatter of strength for SiC/pure-Al wire was independent of quenching temperature. The scatter of strength increased for SiC/Al-5.7Ni wire, and decreased for SiC/Al-4.0Cu wire with increase in quenching temperature. This demonstrates that the matrix strength change has a close relation to the scatter of FRM strength.

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