Mechanical Properties of Composite Materials

Mitsuhiro Okayasu
Dept. Materials Science and Engineering
Ehime University
Matsuyama, Ehime, Japan
mitsuhiro.okayasu@utoronto.ca

Abstract—An examination has been made of the mechanical and failure properties of several composite materials, such as a short and a long carbon fiber reinforced plastic (short- and long-CFRP) and metal based composite material. The short CFRP materials were used for a recycled CFRP which fabricated by the following process: the CFRP, consisting of epoxy resin with carbon fiber, is injected to a rectangular plate cavity after mixing with acrylonitrile butadiene styrene resin with different weight fractions of CFRP. The fatigue and ultimate tensile strength (UTS) increased with increasing CFRP content. These correlations, however, break down, especially for tensile strength, as the CFRP content becomes more than 70%. Influence of sample temperature on the bending strength of the long-CFRP was investigated, and it appears that the strength slightly decreases with increasing the temperature, due to the weakness in the matrix. Broken fiber and pull-out or debonding between the fiber and matrix were related to the main failure of the short- and long-CFRP samples. Mechanical properties of metal based composite materials have been also investigated, where fiber-like high hardness CuAl2 structure is formed in aluminum matrix. Excellent mechanical properties were obtained in this alloy, e.g., the higher strength and the higher ductility, compared to the same alloy without the fiber-like structure. There are strong anisotropic effects on the mechanical properties due to the fiber-like metal composite in a soft Al based matrix.

Index Terms—CFRP; Carbon fiber; Mechanical property; Crack growth; Failure mechanism

I. INTRODUCTION

In recent years, composite materials have received special attention because of the excellent mechanical properties. In particular, production amount of carbon fiber reinforced plastics (CFRP) have been increased due to their high strength and low specific weight [1]. CFRP material has come into practical use for the aerospace and automotive industries, because of their contribution to higher fuel efficiency. In fact, the demand for CFRPs has dramatically increased in recent years [2]. As aerospace and automotive parts are sometimes employed in atmosphere with high temperature, examination of mechanical properties of CFRP at high temperature would be required. In addition, development of the recycling technology for CFRP has been significantly important due to their high production amount. Indeed, post-use CFRP seems to be thrown away into landfill without any consideration of environmental problems [3]. This occurrence will be a problem in the future, because the amount of waste CFRP will increase [4]. Up to date, several researchers have investigated the mechanical properties of CFRP including recycled CFRP, the information available appears to be insufficient.

On the other hand, metal matrix composite material (FRM) is also important material as engineering material. This is because of their outstanding mechanical properties. Metal matrix composite with silicon carbide particle (SiC) are one of the widely known composites, which have high strength, high hardness, high wear resistance and high corrosion resistance [5]. Effect of clustering on mechanical properties of aluminum alloy 2024-SiC metal matrix composite has been investigated. Fracture toughness and tensile tests were carried out, and their mechanical strengths were estimated well by a model [6].

Although CFRP and FRM are excellent materials to use in various engineering application, there would have still technical issue for recycling technique and lack of information regarding their mechanical properties. In this study, our experimental results obtained previously for the material properties of long-CFRP, short-CFRP [7] and FRM [8]-[9] were summarized to consider the mechanical properties of the composite materials.

II. EXPERIMENTAL PROCEDURE

II-1. Long-CFRP and short-CFRP

The long-CFRP, consisting of epoxy resin (thermosetting high polymer) with a volume fraction of 60% carbon fiber, was used. Fig. 1 shows the photograph of the long-CFRP samples showing the carbon fibers and matrix. The short-CFRP samples were made by the following process. The long-CFRP was first crushed using a rotating blade to make small fragments for which the average length by width is 3.4 mm × 0.4 mm. The crashed long-CFRP pieces were then separated individually into fiber and epoxy resin after the ball milling process. Most part of the surface of separated carbon fibers is not already coated by epoxy resin, while some fiber bundles were present that contained epoxy resin [3]. After the grinding process, it was found that the mean length of the carbon fibers is about 200 μm. The short-CFRP samples, consisting of acrylonitrile butadiene styrene resin and CFRP pieces, were fabricated using standard mixing, grinding and injection molding procedures. In this case, the CFRP pieces were added to the ABS resin before the injection process with five
different weight fractions of 0 (i.e., pure ABS), 10, 30, 50 and 70 wt.%. The injection molding process was carried out to make the short-CFRP with simple rectangular plates 150 mm × 150 mm × 3 mm.

Dumbbell-shaped specimen and compact tension (CT) specimen were used in this test, which obtained from the center area of the rectangular plate as shown in Fig. 2. In this case, the rectangular plate cut in two different directions from the mid-section, either with the loading direction (longitudinal axis of the specimen) in the direction perpendicular (Type T) or parallel (Type L) to the flow (or carbon fiber) direction. The dimension of the parallel area in the dumbbell-shaped specimen is 7 mm (l) × 3 mm (w) × 1 mm (t), and that of CT specimen is W = 24.5 mm and B = 3 mm. The CT specimen was designed based upon the ASTM standard E399 [10]. In the mid-section of the CT specimens, a through-slit (15 mm in length with a V-notch root angle of 45 degrees) was machined.

II-2. Metal composite aluminum alloy

In the present study, an attempt was made to create FRM materials via our heated mould continuous casting technology (HMC) with a eutectic aluminum alloy. Concept of this technology is as follows: unidirectional microstructure with thin fiber-like phases was created by the unidirectional rapid solidification process. In this approach, An Al-33%Cu eutectic alloy was selected to make metal composite Al alloy. Fig. 3 gives a schematic diagram of the heated mould continuous casting apparatus, consisting of a graphite crucible with runner, a graphite mould, a cooling device and pinch rolls for withdrawal of the cast metal. The cast samples in the shape of a long round bar (ø4 mm × 1 m) was made. The casting pressure was controlled by the level of molten metal in the crucible, controlled by furnace displacer block. The temperature of the molten metal was maintained at about 843K, which is 20K above the melting point of its Al alloy. The molten metal was cast through the runner and graphite mould before the cooling process. The graphite mould was heated to approximately 853K, which is just above the liquidus of the Al-Cu alloy. For the solidification process, the aluminum alloy was cooled directly by water flowing to the exit just out of the graphite mould (see Fig. 3). Interestingly, with this casting process, a unidirectional growth microstructure was created, which could be associated with metal composite material. Fig. 4 depicts microstructure of Al-33%Cu sample with the axial and transverse directions. The primary α-Al phase is visible as a dark region. A fine fiber-like eutectic structure of CuAl₂ phases with unidirectional growth along its axial direction can be observed.

Fig. 5 displays the test specimens formed with a rectangular shape. Note, in this case, tiny special specimen was designed to examine the metal composite effect on the mechanical properties, namely anisotropic microstructural effects. The specimens are denoted as (i) axial direction (OL) and (ii) transverse direction (OT), as indicated in Fig. 5. Because of the tiny specimen, finite element analysis was conducted to verify the stress-strain distribution before the testing. Fig. 5 also indicates the FEA stress distribution on the loading direction (x-axis). From this result, it is clear that the high stress level is uniformly distributed in the sample of parallel area. Thus, the material properties can be estimated to understand their material characteristics.
III. RESULTS

III-1. Long-CFRP materials

Fig. 6 shows representative bending stress - strain curves for the long-CFRP with different fiber direction. As seen, different tensile properties are obtained depending on the fiber direction. It is clear that low bending properties are obtained as the CFRP with fiber direction of more than 45° against the loading direction, while high mechanical properties are detected for the CFRP with 0° fiber direction. Fig. 7 depicts the fracture surfaces of their specimens after the bending tests. As seen, fiber surfaces are observed for the specimens with fiber direction of 45° and 90°. Those samples would be fractured by the crack growth between the fibers, namely delamination between the fiber and matrix. On the other hand, fibers are completely fractured for 0°-CFRP sample, which makes high bending strength.

Fig. 8 presents bending stress - strain curves for the CFRP tested at different sample temperatures, e.g., 20°C, 50°C and 100°C. There is clear temperature effect on the bending properties, where the higher the mechanical properties are obtained for the specimen tested at the lower temperature. Similar trends were also seen in their fatigue properties. Fig. 9 indicates the S-N curves for their CFRP samples. It is obvious that high fatigue strength is detected for the CFRP at low temperature. Their fracture characteristics were further investigated. Fig. 10 shows the fracture surfaces of the CFRPs after the bending test at different temperatures. It is interest to mention that there are different dense of the epoxy. It is seen that low density of epoxy is obvious for the samples at the higher testing temperatures. This result infers that the epoxy may have been melted during the heating process.

Fig. 4 SEM images of the HMC Al-33%Cu alloys, showing microstructure [8].

(a) Axial direction (OL)

φ4 mm

(b) Transverse direction (OT)

φ4 mm

Fig. 5 Schematic illustration of the specimens and their position; and FEA model to determine the stress distribution in the specimen and stress distribution to loading direction [8].

Fig. 6 Stress-strain curves for the long-CFRP with different fiber direction.

Fig. 7 SEM images showing the fracture surface of the specimen.

Fig. 8 Stress-strain curves for the long-CFRP with different sample temperature.
III-2. Short-CFRP materials

Fig. 11 shows the ultimate tensile strength ($\sigma_{UTS}$) for all the short-CFRP samples. Different tensile properties are obtained depending on the CFRP content and type (fiber direction). There is no clear anisotropic effect on the tensile properties for the CFRP 0% samples: $\sigma_{UTS} = 38.8 \text{ MPa}$ for Type T and $\sigma_{UTS} = 40.2 \text{ MPa}$ for Type L. For both samples Type T and L, the tensile strength increases with increasing CFRP content, but a considerable drop in the tensile strength was detected for CFRP 70%. The overall tensile strength for Type L is higher than that for Type T, particularly CFRP 30%- and CFRP 50%-Type L, e.g., the mean $\sigma_{UTS}$ value for CFRP 50%-Type L is more than 1.6 times higher than the CFRP 50%-Type T one. This corresponds to the anisotropic effect in the sample, where the fiber direction prevails for the strength although the fiber length is as short as about 200 $\mu$m as mentioned above.

Fig. 12 shows the relationship between the stress amplitude and cycle number to failure ($S$-$N$ curve) of the short-CFRP. It should be noted first that the arrows in this figure indicate the specimens which did not fail within $10^7$ cycles. From Fig. 12(a), the $S$-$N$ relationships, including the endurance limit ($\sigma_{en}$), seem to be similar level for all Type T samples, while the slope of their $S$-$N$ relationships is slightly different depending on the CFRP content. For example, the higher the CFRP content (e.g., CFRP 70%), the lower the slope of $S$-$N$ relations, in which $S$ vs. $N$ for CFRP 70%-Type T crosses those for the other Type T samples around $10^3 \sim 10^4$ cycles as indicated in Fig. 12(a). For CFRP 70%-Type T, the lowest slope of the $S$-$N$ curve is obtained for CFRP 70%-Type L (Fig. 12(b)), which also crosses the other ones at around $10^3$ cycles but only for 0%- and 10%-Type L. Interestingly, the endurance limit for both CFRP 70% is the same level of about 15.4 MPa. The $S$-$N$ curves for CFRP 30%- and 50%-Type L are located at a higher level compared to the others, even though the endurance limits for CFRP 30%- and 50%-Type L are close to that for CFRP 70%-Type L. An important observation from Fig. 12(a)(b) is that relatively high endurance limit was obtained for both CFRP 70% in spite of the low tensile properties (Fig. 11). Such fatigue properties for CFRP 70% are associated with different
crack growth rates. For instance, a rough fracture surface makes low crack growth rate due to the low crack driving force arising from severe crack closure [11].

To understand clearly the fatigue behavior of the short-CFRP samples, the $S$-$N$ relationships were quantitatively evaluated by a power law dependence of cyclic stresses and cycles to failure:

$$\sigma_a = \sigma_f N^b, \text{ MPa}$$

where $\sigma_a$ is the stress amplitude, $N_f$ represents the cycle number to final fracture, $\sigma_f$ is the fatigue strength coefficient and $b$ is the fatigue exponent. Those values ($\sigma_f$ and $b$) were obtained by least square analysis. In this case, an increased fatigue life is expected for a decreasing fatigue strength exponent $b$ and increasing fatigue strength coefficient $\sigma_f$. In the present case, the $\sigma_f$ and $b$ for the CFRP 50%-Type L sample shows high fatigue strength, e.g., $\sigma_f = 51.3$ and $b = 0.07$. On the other hand, different fatigue properties were obtained for both CFRP 70% samples with lower $b$ and lower $\sigma_f$ values ($\sigma_f = 21.3$ and $b = 0.02$).

III-3. Metal composite materials (Al-33%Cu alloy)

Fig. 13 shows the stress-strain curves for the Al-33%Cu samples: OL and OT samples. It can be seen that the relatively linear stress vs. strain relations are obtained for the both samples. The tensile strength and elongation to failure are obviously high in the OL sample compared to the other one due to the fiber-like composite effect. The tensile properties of both Al-33%Cu alloys for OL and OT are $\sigma_{UTS} = 489.8$ MPa and $\epsilon_f = 4.9\%$ and $\sigma_{UTS} = 384.1$ MPa and $\epsilon_f = 4.2\%$, respectively. Such different tensile properties (OL vs. OT) are reflected to the reinforcement by the fibrous structure. The fine eutectic structure in the longitudinal direction can enhance the material properties (OL), and that tensile strength is much higher than that for the conventional cast Al alloys. On the other hand, the high material ductility obtained for the OL samples can be explained using the failure mechanism.

Fig. 13 Stress-strain curves for the Al-33%Cu samples, obtain from axial (OL) and transverse (OT) directions [8].

Fig. 14 shows SEM images of the microstructure of both Al-33%Cu alloys. As seen in the OL sample, elongated microstructural characteristic was obtained near the crack, which would be caused by the fibrous structure. On the contrary, the crack, created in-between the fiber and matrix, can be observed for OT samples.

Fig. 14 SEM images of the Al-33% Cu alloys showing the crack paths in the mid-section of the samples: (a) axial direction (OL) and (b) transverse direction (OT) [8].

Fig. 15 shows the relationship between the stress amplitude and fatigue life for both the OL and OT samples. It should be noted first that the arrows in the $S$-$N$ diagrams are the specimens which did not fracture within 50,000 cycles. It is clear from the $S$-$N$ diagrams that the $S$-$N$ relationship for the OL is located at higher values compared to the OT sample. The endurance limit for the OL samples is approximately 400
The tensile strength increases with increasing CF RP content, not only on the CFRP content, but also on the fiber direction. The low mechanical properties can be melted when heated to the higher temperature, leading to the low mechanical properties. The primary phases and CuAl phase are sometimes seen in relatively brittle materials, e.g., ceramics [12][13].

A clear anisotropic microstructure was obtained, namely a fine lamellar eutectic structure with unidirectional growth along its axial direction. The eutectic structure was formed by the primary α-Al phase and CuAl2 phase, i.e., fiber-like reinforcement. The tensile and fatigue properties of the samples in the longitudinal direction of the loading are more than 30% higher than those for the cast samples perpendicular to the casting direction.

IV. CONCLUSIONS

An examination has been made of the mechanical and failure properties for the composite materials. The results have yielded the following conclusions.

1. Mechanical properties (tensile strength and fatigue strength) of the CFRP samples are directly attributed to the sample temperature and fiber directions. The epoxy seems to be melted when heated to the higher temperature, leading to the low mechanical properties.

2. The tensile strength of the short-CFRP is found to depend not only on the CFRP content, but also on the fiber direction. The tensile strength increases with increasing CFRP content, but drops suddenly for short-CFRP with higher fiber content, i.e., 70%. In addition, under the same CFRP content, the higher tensile strength is detected as the fiber direction is parallel to the loading direction.

3. A clear anisotropic microstructure was obtained, namely a fine lamellar eutectic structure with unidirectional growth along its axial direction. The eutectic structure was formed by the primary α-Al phase and CuAl2 phase, i.e., fiber-like reinforcement. The tensile and fatigue properties of the samples in the longitudinal direction of the loading are more than 30% higher than those for the cast samples perpendicular to the casting direction.

REFERENCES