Abstract
In metal matrix composites, the spacing between discontinuous reinforcements can affect strengthening by interfering with the motion of dislocations through the metal. This project looks for similar phenomena in polymer matrix composites (PMCs), since the molecular activity of the polymer chains should be altered in the vicinity of the reinforcements. Awareness of such a trend can improve the understanding of PMC mechanics, which in turn can improve PMC characterization and selection techniques. This project sought a relationship between particle spacing and overall strengthening in a discontinuously-reinforced PMC test case composed of alumina particles in a polyphenylene sulfide matrix. Tensile tests were run on hot-pressed composite samples with varying reinforcement volume fraction and particle size. Data showed that composite strength increases as particle spacing increases, except at high volume fractions where this trend reverses. These results provide preliminary data but demonstrate a need for more in-depth investigation.

Keywords: Spacing, strength, PMC

1. Introduction
As designers and engineers implement polymer matrix composites (PMCs) into an increasingly wide variety of applications, the need for accurate and detailed information about the characteristics and properties of these materials grows.[1-4] Engineers commonly use strength data as a means for comparing and selecting materials for industrial application. The amount of reinforcement by volume and its effect on composite strength is the most frequently studied relationship in most discontinuously-reinforced (DR) composites. In contrast, the effect of the reinforcement spacing, which accounts for volume fraction and size of reinforcements, on composite strength is still unclear in DR PMC systems, though there are well-understood behaviors observed in metal-matrix composites (MMCs).[5-7]

To control the spacing in these systems as an independent variable in strength tests, the particle size can be varied for a constant reinforcement volume fraction ($V_r$). Producing samples to test this effect requires a processing method that can produce high-quality specimens with minimal variation between batches. From these specimens, tensile tests provide strength values that can be statistically analyzed to identify any relationships present between particle spacing and composite strengthening.

2. Theory
Current research contains little on the particle spacing effect on strength in PMCs. Since little research was found in PMCs, the work in MMCs was consulted for a basis in forming a hypothesis. When considering the strength of a metal or MMC, the Orowan effect tells us that the presence of small, incoherent phases or particles can increase the overall strength of the material. As dislocations move past these particles, they form loops that surround the particles and interfere with subsequent dislocation motion, thus raising the strength of the material.[8,9] This phenomenon implies that a small particle spacing will provide the best composite strengthening. It is also known that if the spacing between these particles is too small, then the dislocations will not pass between the particles; in contrast, widely spaced particles affected by these loops do not typically impact the strengthening significantly. An intermediate distance
between the particles must therefore be determined to obtain the optimum strengthening.

Though this phenomenon accurately describes the behavior of MMCs, it cannot be directly applied to PMCs, since dislocations are not present within polymers. With the basic understanding that polymer deformation is achieved primarily through the motion of polymer chains, particle spacing in a DR PMC should also affect the strength of that composite material. For two PMC samples with an equal $V_R$ but different spacing between the particles, implying varied particle sizes, the specimen with larger particles having more material between them should have more space available for the polymer chains to freely move. In contrast, smaller closely-packed particles should impede the motion of those chains, thereby strengthening the composite.

3. Experimental

To test for a relationship between particle spacing and composite strengthening, techniques were developed to process a DR PMC and to obtain tensile test specimens from the processed composite.

3.1 Material Selection and Characterization

The matrix needed to be a nontoxic, semicrystalline thermoplastic with a glass transition temperature ($T_g$) above room temperature; polyphenylene sulfide (PPS) was selected based on these criteria. Alumina ($\text{Al}_2\text{O}_3$) polishing powder in 5.0-μm and 0.05-μm particle sizes was selected as the reinforcement phase. Tabulated densities of both materials and particle sizes of the reinforcement were verified through characterization prior to using these values in calculations.

3.2 Processing Options

Both $V_R$ and $L_{ee}$ were varied to observe strengthening trends with respect to the particle spacing. Volume fractions of 1%, 3%, and 10% alumina were selected. Edge-to-edge spacing $L_{ee}$ values for these conditions are reported in Table 1 according to Equation 1 below:

$$L_{ee} = 1.25 \sqrt{\frac{2p}{3V_R}} - 2r \sqrt{\frac{2}{3}}$$

\[\text{(1)}\]

Table 1. Theoretical particle spacing values in μm

| Particle Size, μm | Volume Fraction, $V_R$ |
|------------------|------------------------|
|                  | 1%         | 3%          | 10%         |
| 0.05             | 0.8229     | 0.4406      | N/A         |
| 5.00             | 82.2852    | 44.0565     | 20.4379     |

As shown in Table 1, the spacing between particles decreases with increasing volume fraction and with decreasing particle size. These values illustrate the selected conditions (5.0 and 0.05 μm particles with 1%, 3%, or 10% $V_R$) should produce significantly differing spacings.

Two techniques, injection molding and hot pressing, were considered for producing the DR PMCs for this project. Injection molding, using a Dynisco LMM injection molder, involved mixing the alumina with melted PPS; poor mixing and the settling of the alumina particles clogged the injection nozzle several times and did not produce any testable samples. Hot pressing yielded better results, producing 7.5 cm x 12.5 cm composite plates. For this method, PPS and alumina powders were mixed by ball milling. The processing method developed for this experiment entailed hot pressing under the following parameters:

- 10 minute melt time
- ~1.25 MPa applied pressure
- 275 °C top plate, 285 °C bottom plate

These conditions allowed for a sufficient amount of time to ensure a fully melted sample while minimizing porosity and particle settling.

3.3 Sample Preparation

Tensile test specimens were made from the pressed plates of composite through two steps: cutting blanks from the plates and punching dogbone specimens from each blank. Using the punch on a material as brittle as the PMC in this lab causes substantial cracking in the surrounding part; to avoid excess material waste, small rectangles were cut from the large plate using a band saw. These blanks were cut slightly larger than the dogbones. Through this technique, a dozen dogbones can be quickly made from a single hot-pressed plate.

3.4 Tensile Testing

A Texture Technologies Corp. TA-XT2i Texture Analyser was used for the tensile testing. This machine proved to be suitable to our experiment by having a small test frame with a 50 g (~500 N) load cell; difficulties with this machine included a relatively fast strain rate (0.1 mm/s) and uncertainty in the calibration of the equipment. For this reason, exact values of the data presented herein are may not be accurate, though the observed trends should still apply. Flaws produced during the processing and sample preparation stages (porosity, notches, cracks) caused an extremely large scatter among the data, which is typical of failure testing of other brittle materials.
4. Tensile Test Results and Discussion

Preliminary tensile testing was performed to try and observe any general trends present in the strengthening of the PMC. Tables 2 and 3 present data for increasing volume fraction for particle sizes of 0.05 and 5 μm, respectively.

The strength values for both particle sizes show a decrease as V_R is increased from 1% to 3%, indicating that strength decreases with particle spacing. With the 5.0 μm particles, though, strength increased from 3% to 10% V_R, meaning that strength increases as particle spacing decreases. This discrepancy could occur because 3% may correspond to V_{min} similar to that described by Agarwal; this V_{min} would represent the V_R for which the composite strength is at a minimum, even compared to the strength of the unfilled matrix.\[11\]

Tables 4 and 5 show the strength effects of increasing particle size for V_R values of 1% and 3%, respectively.

For both V_R values, increasing the particle size (thereby increasing the particle spacing) increases the strength of the composite. This matches the trend observed when increasing from 1% to 3% V_R for a constant particle size but disagrees with the trend hypothesized in Section 2 (that strength should increase with decreasing particle spacing).

5. Conclusions and Future Work

5.1 Conclusions

Hot pressing successfully produced DR PMCs. Using a punch to produce dogbones caused some imperfections that affected the tensile test results. It may be necessary to abandon punching dogbones and to cut samples (not necessarily dogbones) by some other means.

Results from tensile testing demonstrate that for lower particle volume fractions, increasing the V_R (decreasing the particle spacing) decreased the composite strength, though at higher V_R values this trend is reversed. For a constant V_R, increasing the particle size (decreasing the particle spacing) increased the strength. Overall, these results show that composite strength increases with particle spacing, though the specific strengthening mechanism cannot yet be determined. These results are only preliminary; further research is necessary to draw any definite conclusions about the effect of particle spacing on PMC strengthening.

5.2 Future Work

To continue using a PPS matrix, more tensile tests must be performed, since PPS is a brittle materials and its failure can only be properly studied through in-depth statistical analysis. Using a more ductile material like polyethylene would allow the yield strength to be measured instead of fracture strength. In this situation, fewer samples would be necessary, since the yield phenomenon is less variable than fracture. This is because yield values generally show less variation than do fracture strength measurements.

While it appears that the processing method described above is adequate for producing DR PMC samples with good particle dispersion, additional characterization can be applied to verify this. Accurate microscopy could verify the spacing values predicted or scanning electron microscopy (SEM) could be used to look for particle agglomeration and flaws on fracture surfaces. Further characterization of the polymer matrix (i.e. crystallinity, molecular weight) could also help to explain the observed results. Finally, a more accurate and easily controlled tensile tester should produce more reliable data. In particular, a test frame with a high load capacity (~500 N), slower strain rates (0.01 mm/s or less), and finer resolution for measuring extension or strain (0.005 mm or less) would be ideal.

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