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The Effect of Particle Reinforcement on the Dynamic Deformation of Epoxy-Matrix Composites

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14. ABSTRACT

Multiphase composite materials consisting of one or more types of particle reinforcement in an epoxy matrix are being studied to determine the effect of reinforcement on the dynamic yield strength and critical impact velocity for plastic deformation. Casting was used to prepare epoxymatrix composites with varying particle loading fractions (20 - 50 Vol%), size (5 and 50 |im), and type (Al or Ni+Al). The cast samples were tested at strain rates in the range of 10^ to 10" s"', using a 7.62 mm gas gun with a rod-on-anvil (Taylor) impact experiment setup. The recovered impacted specimens were analyzed to determine the dimensions of their deformed and undeformed regions. The yield strength and critical velocity for plastic deformation were evaluated using Hutching's analysis and correlated with quantitative characteristics of the size and distribution of the reinforcement phases.

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THE EFFECT OF PARTICLE REINFORCEMENT ON THE DYNAMIC DEFORMATION OF EPOXY-MATRIX COMPOSITES

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Abstract. Multiphase composite materials consisting of one or more types of particle reinforcement in an epoxy matrix are being studied to determine the effect of reinforcement on the dynamic yield strength and critical impact velocity for plastic deformation. Casting was used to prepare epoxy-matrix composites with varying particle loading fractions (20 – 50 Vol%), size (5 and 50 μm), and type (Al or Ni+Al). The cast samples were tested at strain rates in the range of 10^3 to 10^4 s^{-1}, using a 7.62 mm gas gun with a rod-on-anvil (Taylor) impact experiment setup. The recovered impacted specimens were analyzed to determine the dimensions of their deformed and undeformed regions. The yield strength and critical velocity for plastic deformation were evaluated using Hutching's analysis and correlated with quantitative characteristics of the size and distribution of the reinforcement phases [1, 2].

Keywords: Particulate composites, Taylor rod-on-anvil impact, dynamic mechanical behavior
PACS: 81.70.Bt, 81.05.Qk

INTRODUCTION

By carefully choosing the types of particles used in particulate reinforced polymer-based composites, materials with multifunctional characteristics can often be achieved. For example, Teflon (PTFE) can be reinforced with Al and W particles [3], or epoxy with Ni and Al particles [4] to produce structural materials with exothermic reactive properties. The properties of the particulate composites are often modified by varying particle size, loading fractions, and particle type [4-8].

While most studies only change one factor at a time and examine the effect on the behavior of the material property, interaction effects between variables need to be taken into account. A 2^k factorial design of experiments is an efficient technique that can be used to determine appropriate material compositions for testing and analyzing effects of multiple factors. For this type of design, each factor *k* has two possible states, either a low or high state, giving a total number of 2^k material configurations for a particular design space. After material testing, analysis of variance (ANOVA) is often used to determine the significance of each main factor and interactions between them.

In this study a two factorial design of experiments is used to examine the interaction effects of particle size and loading fractions of two particle types on the dynamic mechanical behavior of epoxy cast particulate composites.

EXPERIMENTAL PROCEDURE

In order to determine the effects of aluminum particle size, and volume fractions of aluminum, and nickel on the dynamic mechanical behavior of epoxy-matrix based composites, materials were prepared according to a 2^3 factorial design of experiments. The average aluminum particle size was varied between 5 μm and 50 μm, the volume fraction of aluminum varied between 0.20 and 0.40, and the volume fraction of nickel varied from 0.00 to 0.10. The resultant material combinations from the factorial design are shown in Table 1. Polymer-matrix composites of aluminum and nickel powders within an epoxy (EPON-826/DEA) binder were prepared by casting, and machined down to 7.62 mm dia. by 38.1 mm length specimens (diameter: length , 1:5).

Table 1. Material configurations determined from a two-factorial design of experiments

Material	Al Particle Size (μm)	Al Volume Fraction (%)	Ni Volume Fraction (%)
MNML-1	50	40	10
MNML-2	5	40	10
MNML-3	50	20	10
MNML-4	5	20	10
MNML-5	50	40	0
MNML-6	5	40	0
MNML-7	50	20	0
MNML-8	5	20	0

Dynamic Impact Experiments

Taylor rod-on-anvil impact experiments were conducted on a 7.62 mm gas gun with a laser interrupted velocity measurement system, as shown in Fig 1. An IMACON 200 high-speed camera was used to capture transient dynamic deformation states as the specimens impacted a rigid anvil. Specimens were propelled between 75 m/s and 200 m/s to produce strain rates between 10^3 to 10^4 s^{-1}. Impacted specimens were then recovered from the soft catch tank and post impact geometry measurements were taken.

The final strains were calculated from impacted specimen geometry and used in Hutchings analysis to extrapolate the critical velocity (V_c), for plastic deformation by conducting a linear fit of strain-velocity data (see Fig. 2). From these values the dynamic yield stress (Y) and strain (ε_y) are solved iteratively using the following equations:

$$Y = \frac{\rho V_C^2 \overline{C}_p^2}{\varepsilon_y - \varepsilon_y^2}\left(\frac{1}{1-\varepsilon} - \frac{1-\overline{C}_p^2}{1-\varepsilon_y}\right)^2, \quad (1)$$

$$Y = \frac{\rho V_C^2}{\varepsilon_y}\left(1-\varepsilon_y\right), \quad (2)$$

where, C_p is the ratio of elastic and plastic wave speeds and ρ the density. Average values and standard deviations for Y and ε_y were taken from at least 5 impact experiments. These results are shown in Fig. 4 and 5 respectively with error bars representing one standard deviation.

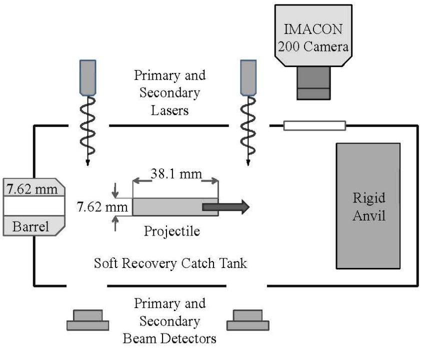

Figure 1. Schematic diagram of Taylor impact experiments.

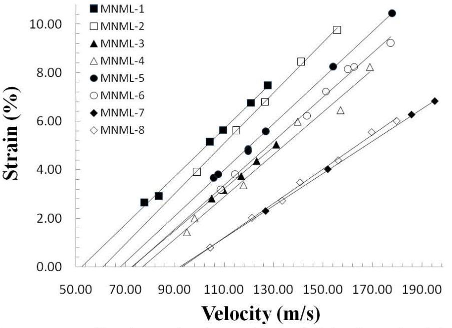

Figure 2. Strain-velocity plot. Critical velocities are based on intercepts of linear-fits (R^2=.981-999) with the velocity axis.

RESULTS AND DISCUSSION

The minimum velocity necessary to generate plastic deformation in the material during Taylor impact experiments, considered the critical velocity, was obtained by taking the x-axis intercept of a line fitted to the respective data points. The critical velocity was found to be highly dependent on the total volume fraction of particles present (Fig. 3). As the volume fraction is increased from 0.20 to 0.50 the critical velocity decreased from 93 to 52 m/s. Also, the composites containing smaller Al particles (5 µm) required a higher velocity for onset of plastic deformation (7% higher on average) than those with larger particles (50 µm) of the same volume fraction.

The trends associated with each factor for yield stress are not as clear as they are for the critical velocity (Fig. 4). The most recognizable feature in the data is a sharp decrease (~100 MPa) in yield strength between 30 and 40% particle concentration. This indicates the possibility of a percolation threshold existing within this particle concentration range. At high enough concentrations of reinforcement the probability of particles touching or within close proximity increases, creating a threshold where the transfer of stress becomes inefficient and stress concentrations become more prevalent due to particle-particle interactions resulting in a decrease of the overall strength for the material. This is consistent with other theories [9-11]. Below this threshold, materials with larger aluminum particles have higher yield strengths than their counterparts with smaller aluminum particles. The opposite is true for particle concentrations above the percolation threshold indicating strong interaction effects. Also, upon increasing the particle concentration from 40 to 50% there is a small increase in yield strength. This increase is most likely due to the introduction of stiffer nickel particles.

The yield strains for the composites range from 3.1 to 4.1% (Fig. 5). While this is a fairly narrow range, trends exist for the different factors within the factorial design. The yield strain values increase with increasing volume fraction up to ~40% particle concentration and then decrease at levels beyond this concentration for materials with large aluminum particles and decrease slightly before this concentration for materials with small aluminum particles. This again may be due to a percolation threshold. Additionally, the composites with smaller aluminum particles had a higher yield strain than those with same the particle concentration but larger aluminum particles.

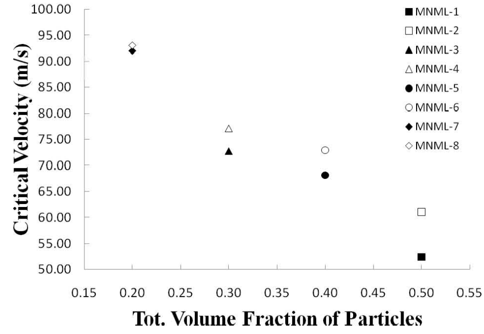

Figure 3. Critical velocity vs. particle concentration (50µm Al = closed data points, 5µm Al = open data points).

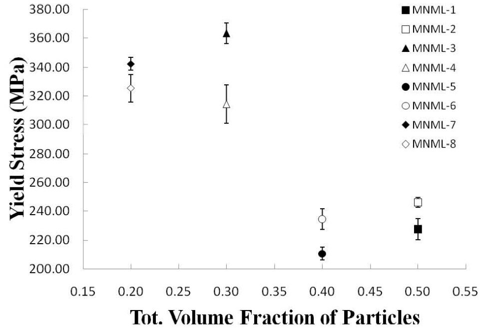

Figure 4. Yield stress vs. particle concentration (50µm Al = closed data points, 5µm Al = open data points).

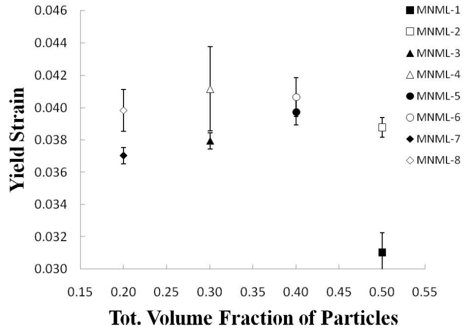

Figure 5. Yield strain vs. particle concentration (50µm Al = closed data points, 5µm Al = open data points).

In cases where the smaller particles influence the mechanical behavior, the particles are distributed more uniformly throughout the matrix. This may help distribute the stress, deterring local stress concentrations that can promote early onset of damage and yielding. The composite with smaller Al particles can thus, accept higher impact velocities and reach higher elastic strains before bulk material yielding becomes measureable. This also explains the increase in the yield stress for materials MNML-2 and MNML-6 with high particle concentrations.

For materials containing nickel, there were slightly lower critical velocity values. In this case, the stiffer nickel particles deform less, which may increase the stress within the surrounding matrix and aluminum particles. If this effect is present at large enough length scales, then the overall stress for the composite can be higher than a composite without nickel that deforms more readily. The effect of nickel on the trends for the yield stress and strain are not as distinguishable and will not be addressed here.

Analysis of variance (ANOVA) was used to quantify and more clearly resolve any trends associated with the changes in aluminum particle size, volume fraction of aluminum, and the volume fraction of nickel, on the dynamic yield stress, strain, and critical velocities for plastic deformation. From ANOVA, the equation modeling the effects of these variables is given below with the coefficients for each mechanical response listed in table 2. Each factor was determined to be significant from the determined ANOVA F- and p-values.

$$\begin{aligned} response &= a + b(Al_{size}) + c(Al_{vol}) + d(Ni_{vol}) \\ &+ e(Al_{size} * Al_{vol}) + f(Al_{size} * Ni_{vol}) + \\ &g(Al_{vol} * Ni_{vol}) + h(Al_{size} * Al_{vol} * Ni_{vol}) \end{aligned} \quad , \qquad (3)$$

The equations were optimized for maximum yield stress and strain resulting in the composite with $Al_{size} \sim 34\mu m$, $Al_{vol.} = 20\%$ and $Ni_{vol.} = 10\%$, and predicted to have $\sigma_{yield} = 345$ MPa and $\varepsilon_{yield} = 0.04$. However, since the predicted volume fractions for aluminum and nickel are both at the limits of the factorial design space composite compositions lying outside this space may have higher optimized yield stress and strain properties for the imposed loading conditions.

Table 2. Coefficient values corresponding to equation 3 for each mechanical response.

Coefficients	σ_{yield}	ε_{yield}	V_{crit}
a	407.777	3.99E-02	112.8378
b	1.326	-1.11E-04	0.0604
c	-4.269	2.22E-05	-0.9847
d	-4.979	5.36E-04	-1.9644
e	-0.046	2.25E-06	-0.0042
f	0.150	1.03E-05	-0.0063
g	0.152	-1.62E-05	0.0205
h	-0.003	-6.38E-07	-0.0001

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