Strain rate behavior of magnetorheological materials

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Abstract. Strain rate response of two Hydroxyl-terminated Polybutadiene/Iron (HTPB/Fe) compositions under electromagnetic fields has been investigated using a Split Hopkinson Pressure bar arrangement equipped with aluminum bars. Two HTPB/Fe compositions were developed, the first without plasticizer and the second containing plasticizer. Samples were tested with and without the application of a 0.01 Tesla magnetic field. Strain gauge data taken from the Split Hopkinson Pressure Bar has been used to determine the extent of change in mechanical properties by inducing a mild electromagnetic field onto each sample. Raw data from strain gages was processed using commercial software (Signo) and Excel spreadsheet. It is of particular interest to determine whether the mechanical properties of binder systems can be manipulated by adding ferrous or Magnetostrictive particulates. Data collected from the Split Hopkinson Pressure Bar indicate changes in the Mechanical Stress-Strain curves and suggest that the impedance of a binder system can be altered by means of a magnetic field.

1. Introduction

A Smart Material is a designed material with one or more properties that can be altered by means of controlled, external stimuli such as an electronic or magnetic field. Magnetostriction is the property of a ferromagnetic material to change its shape or dimensions under magnetic field. Magnetostriction occurs once a sample has reached its saturation state by means of an applied magnetic field. At the saturation point [1], the field placed on the ferromagnetic materials exceeds the necessary amount required to change the boundaries between the domains.

The shape change that occurs during Magnetostriction can alter the mechanical properties of the material, such that the material responds differently under applied stress or strain. Research in the area of magneto rheological fluids and ferro fluids provide us with useful information in characterizing these new materials. The majority of work done with smart materials is focused on applications and yield strength under magnetic field in order to properly formulate newer, stronger materials. Most of the mechanical data in existence is from MR fluids which consist of particles primarily on the micrometer scale, making it difficult to suspend in a rigid material. Smaller nanoparticles are needed to provide a well distributed loading in the analysis of solids.

In order to resolve the problem of suspension, we synthesized a well-known binder HTPB with iron nanoparticles. The behavior of the ferromagnetic suspensions under magnetic field was investigated. We believe that modification of mechanical property at high strain rate may be useful in tailoring the sensitivity of energetic materials. The stress-strain curves were attained through experiments using the Split Hopkinson Pressure Bar (SHPB).
2. Experimental Procedure

The first set of samples consisted of a conventional plasticizer based composition with 88.25% iron powder, 5.6% R45 gum stock resin, 5.6% Isodecyl Pelargonate (IDP) plasticizer, 0.5% Isophorone diisocyanate (IPDI) curative and 0.05% Dibutyltin Dilaurate (DBTDL) catalyst. Second set of samples had no plasticizer, and contained 88% iron powder, 10.96% R45 gum stock resin, 1.02% IPDI curative and 0.02% DBTDL catalyst. Both sample sets contained high purity iron powder from Sigma Aldrich, which appeared to have uniform spherical particles, 90% of particles were between 0.25µm and 0.75µm, with average size of 0.45µm, as seen in the scanning electron micrograph in figure 1.

![Scanning electron micrograph of the iron powder used in the two compositions.](image)

Compositions were mixed at ambient temperature and atmospheric pressure. Upon completion of mixing, mixtures were placed in a vacuum desiccator in order to remove any air pockets that may have been created during the mixing process. Since material test data can be very sensitive to sample processing and preparation, machining of these soft materials was avoided by using multi-cavity molds to cast and cure samples for final size. Direct pouring of mixtures into molds generated samples with varying thickness having diameters from 9.52 mm to 12.74 mm. On an average, HTPB samples took approximately 48 hours to fully cure and were removed from molds using a die press. Cylindrical samples were polished to desired height and at each end to allow the surface areas to make full contact with the Split Hopkinson Pressure Bar. Sample densities were measured with a digital balance and vernier callipers. Densities of two compositions measured 3.8 g/cm³ and 3.9 g/cm³, respectively. The consistency of the measured densities leads us to believe that the mixing process chosen was successful, to within ±0.05 g/cm³.

The application of an electromagnetic field requires a solenoid coil, which was made of 405 turns of 20 gauge solid copper wire on a radius of 0.6785 inches and driven by 12 volt battery at one ampere direct current to induce the field. A grounded faraday cage made of aluminum mesh was used to shield the strain gauges from any unwanted interference from the field. Measurements made using a gauss meter, confirmed that the coil did in fact produce a 0.01 Tesla electromagnetic field at the center of the magnetic field.

The SHPB was used to obtain stress-strain data for various strain rates on the order of 10³/s. The SHPB system used in our research was originally configured for 15.8 mm diameter high-strength aluminum-alloy pressure bars to test explosives. The lengths of the incident and transmitter pressure bars were 1.22-m and the striker bar was 0.51 m. Pairs of 350Ω strain gages were mounted on the incident and transmitted pressure bars 0.61 m away from the specimen/bar interfaces [2]. The solid transmitter bar was replaced with a hollow bar, with a front end adapter to allow proper transition of the wave’s solid section to the tubular section without unwanted reflections of waves [3].
3. Results and Discussion

Several samples from each of the two configurations were tested in the SHPB to obtain the strain rate. Each of the data sets were dispersion corrected and processed through a data reduction scheme developed in-house. Stress-strain curves were plotted for each of the two compositions under normal conditions and with the addition of a 0.01 Tesla magnetic field. In order to ensure that the presented data was in fact accurate, an additional test was performed under the same conditions. Two additional batches of HTPB/Fe, with and without plasticizer, were mixed according to the previous recipe. Samples were cured and polished prior to testing. Stress-strain curves were plotted for each of the two compositions under normal conditions and with the addition of a 0.01 Tesla magnetic field. These plots are shown in figure 2 and 3 for compositions without and with plasticizer respectively. Corresponding strain rate vs. strain plots are shown in figure 4 and 5 respectively.

**Figure 2.** True stress vs. true strain for HTPB/Fe without Plasticizer, with and without the addition of a magnetic field.

**Figure 3.** True stress vs. true strain for HTPB/Fe with Plasticizer, with and without the addition of a magnetic field.
Figure 4. Comparison of strain rates of HTPB/Fe without Plasticizer, with and without the addition of a magnetic field.

Figure 5. Comparison of strain rates of HTPB/Fe with Plasticizer, with and without the addition of a magnetic field.

Analysis of the presented data indicates that changes in the stress-strain curve, although subtle, are in fact present. The stress values obtained indicate about ~4-5% higher values from samples tested under a field than from samples tested under normal conditions for HTPB/Fe without plasticizer. The stress values obtained indicate about ~10-11% higher values from samples tested under a field than from samples tested under normal conditions for HTPB/Fe with plasticizer. Repeatability of stresses at 0.1 strain are 7.3 ± 0.2 and 6.5 ± 0.2 for samples without plasticizer and 3.1 ± 0.15 and 2.7 ± 0.15 for samples with plasticizer for with and without field. These values allows us to conclude that the data collected is consistent with prior tests.

The stress-strain curve for HTPB/Fe without plasticizer indicates a small but apparent change in the response of the material due to the induced magnetic field. The stress-strain curve for HTPB/Fe with plasticizer indicates an impedance mismatch causing ringing in the data. This type of ringing has
been previously observed in samples with very low sound speeds. It remains to be seen whether this behavior continues when samples are tested at higher field values and higher strain rates, which is beyond the scope of the current investigation. Additional energetic compositions with large strength response due to magnetic field will be investigated in future studies.

4. Discussions
The current investigation was focused on providing groundwork for processing compositions with maximum solids packing in the material systems with single ingredient in the solids composition. One of the challenges is to physically obtain consistent composition during formulation containing uncoated or pure material. Since initial compositions had problems during processing, samples with different thicknesses were used to adjust strain rates to produce comparative results for two compositions.

Samples without plasticizer are observed to be stiffer than those with plasticizer, as indicated by stress values (without magnetic field in each case), whereas strain rates for samples without plasticizer are lower than those with plasticizer under magnetic field, indicating further stiffening of the sample. If strain rates are matched by altering the thickness of the samples, it is likely to indicate still higher difference in stresses due to magnetic field. A decrease in strain rate or an increase in stress level is indication that the material stiffening has occurred, which is important for sensitivity of energetic materials.

A model for thermoplastic failure and ignition [4] has shown that a reduction in yield strength lowers the ignition stress for an explosive. This follows because more $Pdv$ work is being done on the less compressible material. Work is underway to formulate sensitive compositions for fully utilizing the magnetically induced changes in the mechanical properties of compositions especially the strength of the compositions.

5. Conclusions
The two HTPB/Fe compositions under investigation responded to the magnetic field by displaying a subtle but notable change in strain rate and stress response to the external stimuli. The samples without plasticizer responded the most in terms of percentage change of stress at any given strain. As the stress response of the material increased, the strain hardening behavior seems to increase with strain rate. As a result, at higher strains and strain rates, material under magnetic field could offer more resistance to deformation, thereby alter sensitivity in energetic materials.

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