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IN SITU LIQUID-CRYSTAL-POLYMER FIBER REINFORCED ALUMINUM MATRIX COMPOSITE

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<p>POLYMETS are a new class of hybrid materials composed of metals and polymers. The microstructures and properties of POLYMETS can be customized to meet a wide variety of design requirements. In this research, five to twenty volume percent of a thermotropic, wholly aromatic, liquid crystal polymer (Vectra B950) was mixed with -240/+325 mesh commercially pure aluminum powder and hot extruded at 300 °C. The tensile properties of these POLYMETS were evaluated and the results compared to a pure aluminum control specimen. Optical and electron microscopy were used to examine the microstructures of the extruded rods and fracture surfaces of the tensile specimens. It was observed that polymer fibrils aligned in the extrusion direction.</p>					
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Introduction

Recent research by Frazier, Austen, and London [1] has demonstrated the feasibility of extruding metal-polymer composites (POLYMETs) of aluminum/PEEK and aluminum/Xydar. Extrusion through a high shear, 90 ° die (as shown schematically in Figure 1) or a converging conical die, improves the properties of these aluminum-polymer composites. This is believed to be the result of texture development, that is, the bulk and molecular orientation of the polymer in the extrusion direction. The yield strengths of these metal-polymer composites were found to be 13 to 18 percent greater than that predicted by the rule-of-mixtures, and their specific yield strengths were found to be 14 to 21 percent greater than that of the aluminum control specimen.

The properties of polymers such as polyethylene (PE), polypropylene (PP), and polyetheretherketone (PEEK) have been substantially improved by extrusion and drawing through conical converging dies. Richardson, et al. [2] reports nearly a three fold increase in modulus for PEEK after drawing through a die reduction of 3:1 at 310 °C. Such an improvement has been attributed to the molecular alignment produced by the drawing operation. Several studies indicate that thermotropic, liquid-crystal copolyesters that exhibit rigid rod-like morphologies in the melt are readily drawn into fibers [3,4,5, & 6]. Sawyer and Jaffe [3] report that fibers produced from copolyesters of 2,6 Naphthyl and 1,4 phenyl exhibit a hierarchical fibril microstructure. Fibril diameters range from 5 micron macrofibrils to 0.05 micron microfibrils depending upon local shear stresses. In another study, Isayev and Modic [7] have shown that, under certain conditions, thermotropic, liquid-crystal polymers form high modulus and high strength filaments when deformed in a flexible polymer matrix at high strain rates.

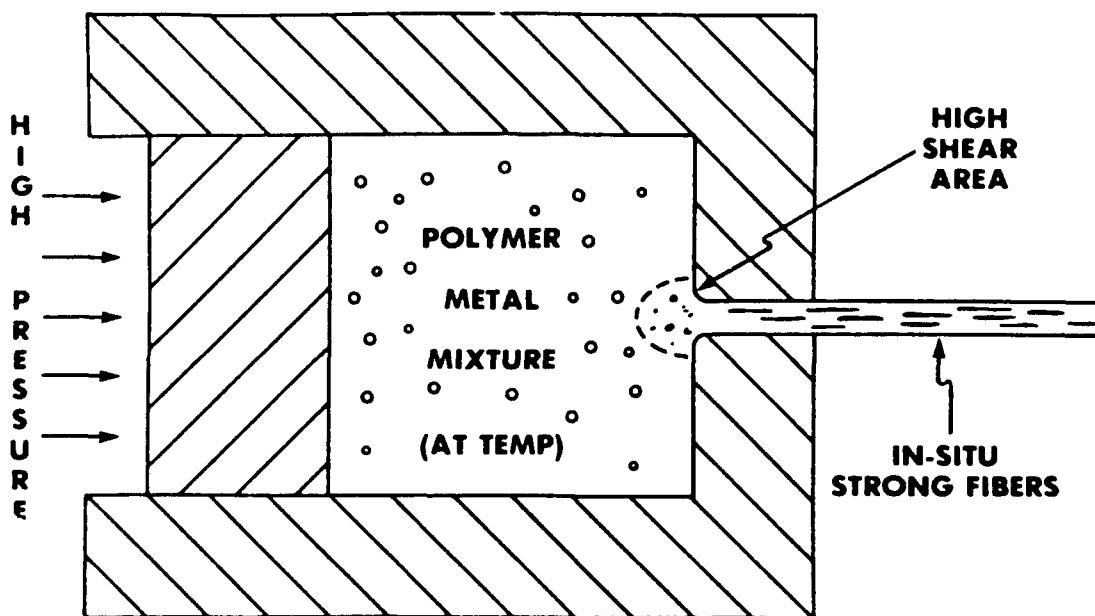


Figure 1 - The POLYMET extrusion process illustrating the formation of fibers in situ.

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The purpose of this investigation was to explore the potential of producing metal matrix composites with fiber-like structures formed in situ during extrusion. The focus of this work is on the effect of extrusion ratio on the microstructure and mechanical properties of the POLYMETS.

Experimental Work

Materials Processing

The POLYMETS examined in this research were prepared from commercially pure aluminum and Vectra, a wholly aromatic, thermotropic, liquid-crystal copolyester (LCPE). The aluminum forms the matrix; the polymer is the second phase reinforcement. Processing involved extensive extrusion deformation in order to directionally align the polymeric material. In addition, a commercially pure aluminum alloy was prepared in an identical manner to the POLYMETS and used as a control specimen. The test matrix and material designations are provided in Table I.

Table I. Test Matrix .

Material	<u>Extrusion Ratio</u>		
	10.7/1	114/1	1225/1
CP Aluminum	S_A1	D_A1	N/A
Al 5 vol.% Vectra	S_V05	D_V05	T_V05
Al 10 vol.% Vectra	S_V10	D_V10	T_V10
Al 20 vol.% Vectra	S_V20	D_V20	T_V20

The processing schedule is presented in Figure 2. Vectra pellets, three to four millimeters in diameter, (Figure 3a) were comminuted and screened to -20 mesh. The metal-polymer blends were prepared by mixing -240/+325 mesh, commercially pure, aluminum powder (Figure 3b) and Vectra powder in a rotating V-cone blender for one hour. The powder blends were sealed in a fully annealed 2024 aluminum can. The canned powders were vacuum degassed at 300 °C (572 °F) for approximately one hour. The materials were then hot extruded on a 200 ton Innovare extrusion press at 300 °C (572 °F) using an extrusion die with an angle of 45° and area reduction 10.7/1. The POLYMETS were evaluated after the can material was scalped. Portions of the materials were canned, vacuum degassed, and re-extruded for effective area reductions of 114/1 and 1225/1.

Microstructural Characterization

Samples were prepared for optical examination by mounting them in finely ground dially phthalate powder. The mounted specimens were hand polished on successively finer grades of abrasive paper, i.e., 220, 320, 500, and 1000 grit. Because the unalloyed aluminum matrix was extremely soft, the samples were lapped in a solution of suspended silica. Metallographic samples were observed in the unetched condition on a Nikon metallograph.

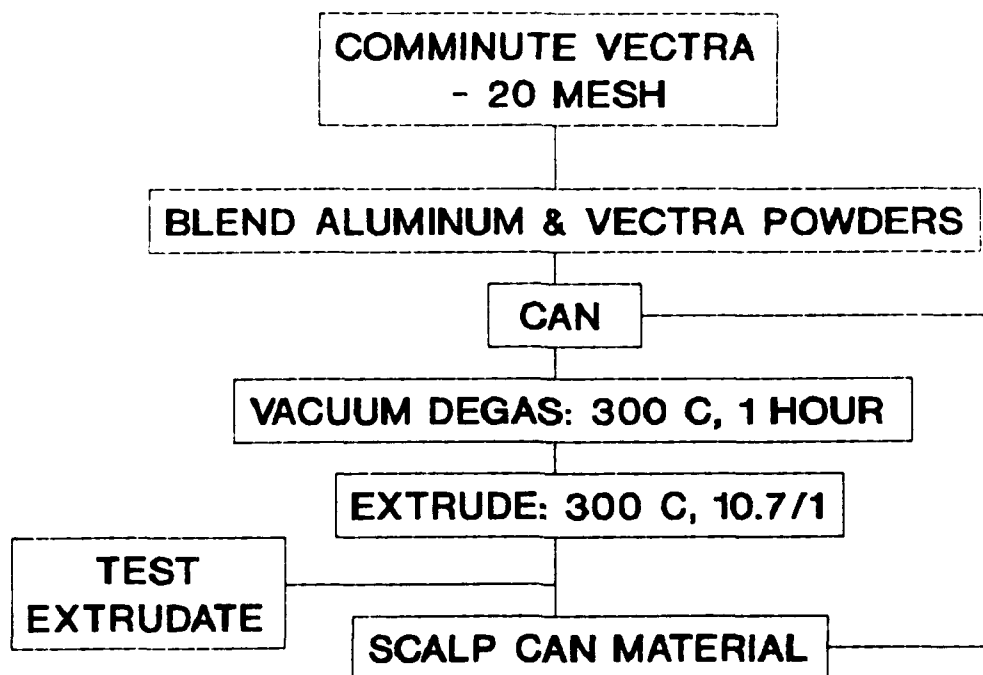


Figure 2 - POLYMET processing schedule

In order to better understand the deformation behavior of these materials, fractured tensile specimens were examined using scanning electron microscopy (SEM). The fracture surfaces of the tensile specimens were examined using an Amray scanning electron microscopy (SEM) operated at 30 kv in the secondary electron emission mode.

Mechanical Properties

Tensile tests were performed on the consolidated alloys in order to evaluate their ambient temperature response. Tensile tests were conducted in accordance with ASTM E8-81 on a instron test machine at a strain rate of 10^{-3} s^{-1} . The tensile specimens were 100 mm long and 6 mm in diameter. The reduced section was 16 mm long and 4 mm in diameter.

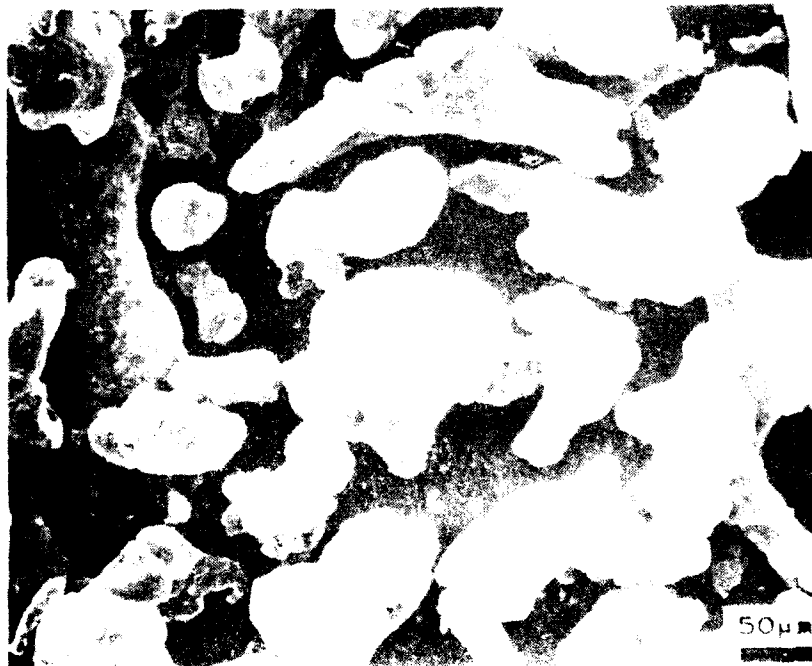
Experimental Results and Discussion

Microstructure

The microstructures observed by extruding the Al-5 vol.% vectra POLYMET at 10.7/1, 114/1, and 1225/1 are presented in Figure 4. The polymer phase is seen to elongate and thin in the extrusion direction. The observed breadth of the polymeric phase in POLYMETs extruded at 10.7/1 is between 20 and 50 microns, and the breadth of the POLYMETs extruded at 114/1 is less than 10 microns. The breadth of the polymer phase in POLYMETs extruded at area reductions of 1225/1 is between 0.5 and 3 microns.



A



B

Figure 3 - Starting POLYMET materials: (a) Vectra B950 pellets and (b) commercially pure -240/+325 mesh aluminum powder.

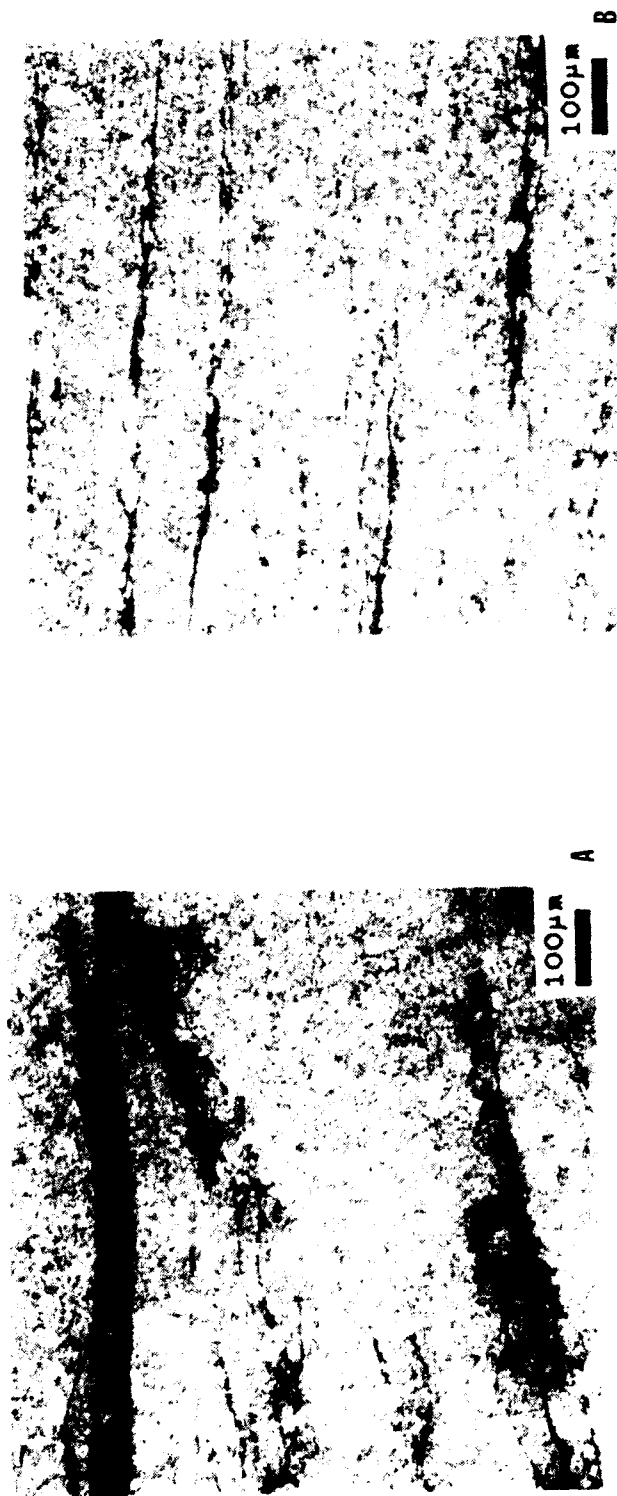
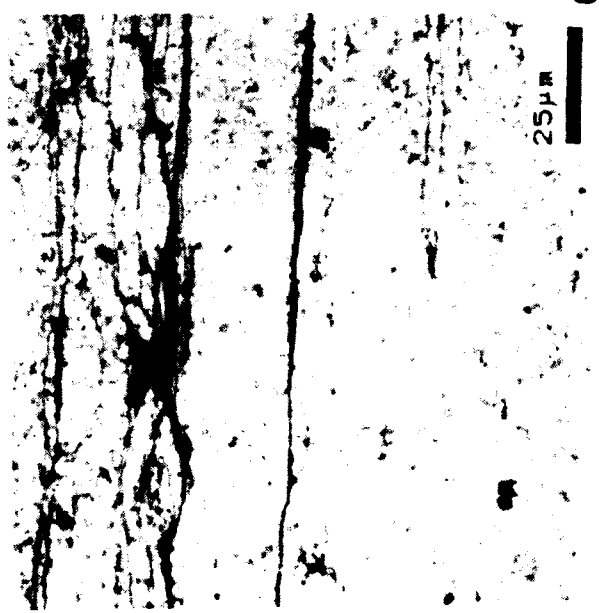


Figure 4 - Optical micrographs of Al-5 vol.% Vectra extruded at (a) 10.7/1, (b) 114/1, and (c) 1225/1.



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Similar to the Al-5 vol.% Vectra material, the polymer phase, in POLYMETS with 10 and 20 vol.% Vectra, elongates and thins in the extrusion direction. However, the higher polymer content promotes polymer segregation and isolated aluminum powder particles often appear as "islands" in a "sea" of polymer. During extrusion, the polymer inhibits and often prevents these isolated aluminum powder particles from bonding with the matrix.

Tensile Properties

The stress-strain behavior of the POLYMETS extruded at 10.7/1 and 114/1 are reported in Figures 5 and 6, and Table II. The strength and ductility of the POLYMETS decreases with increasing polymer content. For POLYMETS extruded at 10.7/1, the yield strength decreases from 100.9 MPa to 55.9 MPa as the vol.% vectra is increased from 5% to 10%. Ductility also decreases; tensile elongation declines from 1.6% to 1.2%.

Table II Tensile Properties of the Aluminum-Vectra POLYMETS.

MATERIAL	YS, MPa	UTS, MPa	% ELONG.
<u>Ext. Ratio: 10.7/1</u>			
S_Al	115.1	136	18.3
S_V05	100.9	104	1.6
S_V10	55.9	57.7	1.2
S_V20	11.2	11.2	0.5
<u>Ext. Ratio: 114/1</u>			
D_Al	83.0	138	27
D_V05	83.9	144	7.5
D_V10	53.9	72.5	1.6
D_V20	10.6	14.3	0.8

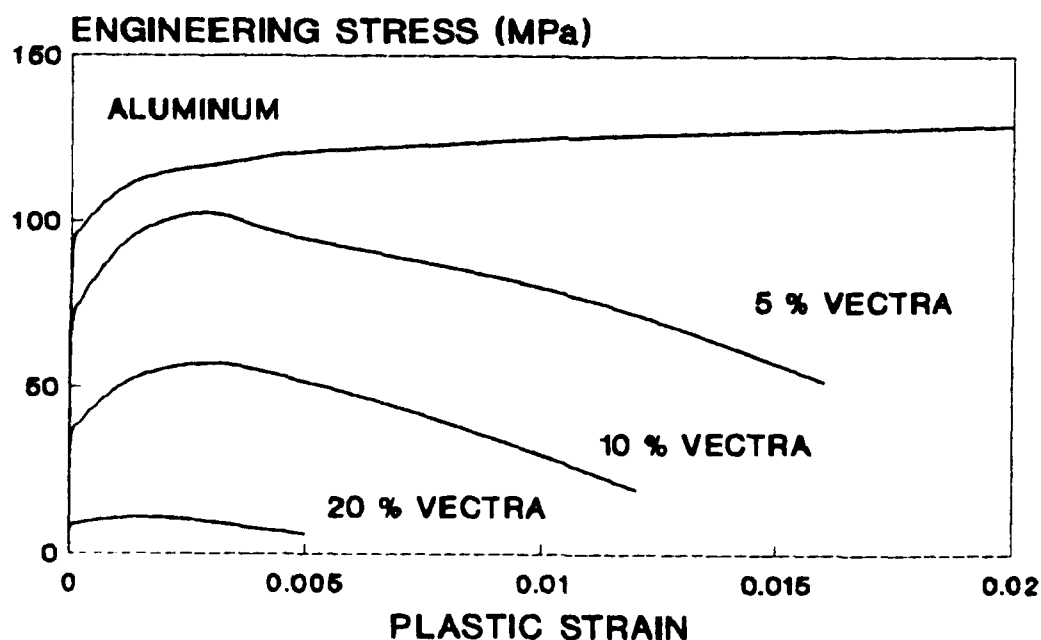


Figure 5 - Tensile stress-strain behavior of POLYMETS extruded at 10.7/1.

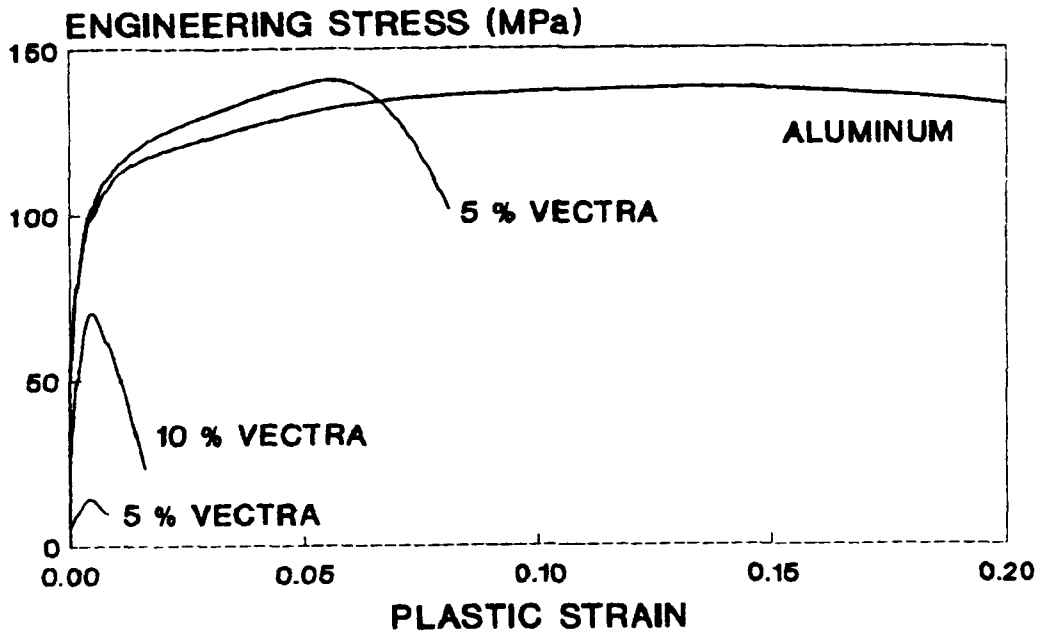


Figure 6 - Tensile stress-strain behavior of POLYMETS extruded at 114/1.

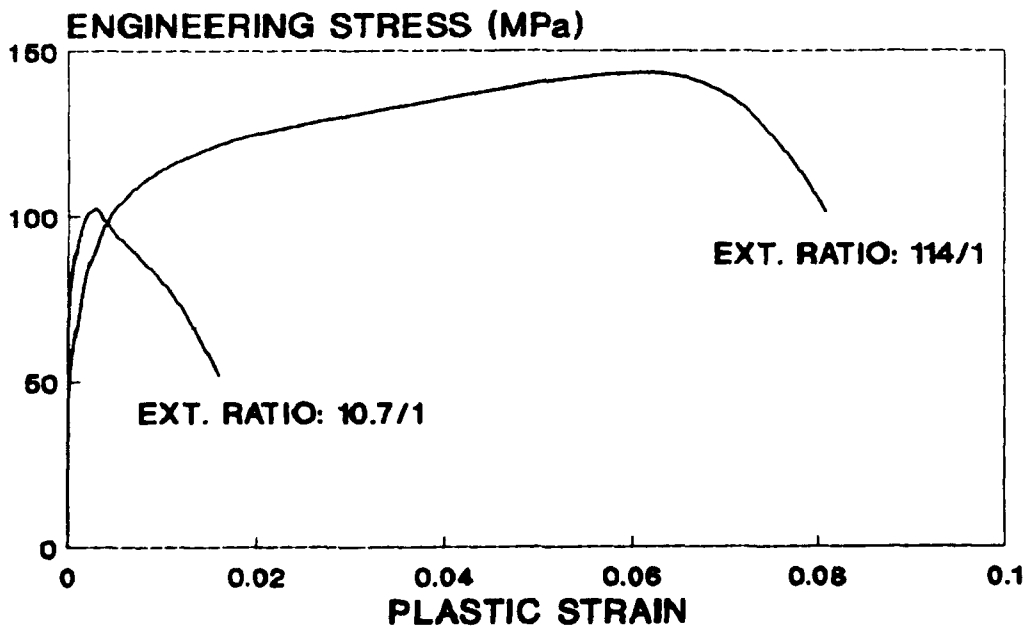


Figure 7 - Tensile stress-strain behavior of Al-5 vol.% Vectra extruded at 10.7/1 and 114/1.

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The properties of the POLYMETS are affected by the extrusion ratio: high extrusion ratios decreased yield strength, increased ultimate tensile strength, and improved ductility. The yield strength of aluminum extruded at 10.7/1 and 114/1 decreased from 115.7 MPa to 83.0 MPa. Ductility of the aluminum increased from 18.3% to 27.0%; however, the ultimate tensile strength of the aluminum remained virtually unchanged, i.e., between 136 and 138 MPa.

The stress-strain curves for Al-5 vol.% Vectra extruded at 10.7/1 and 114/1 are shown in Figure 7. The yield strength of aluminum 5% Vectra decreased from 100.9 MPa to 83.9 MPa when extruded at reduction ratios of 10.7/1 and 114/1, respectively; however, the ultimate tensile strength increased from 104 MPa to 144 MPa. The elongation of aluminum 5% Vectra increased significantly with extrusion ratio from 1.6 to 7.5.

An approximation of the energy required to cause tensile failure was obtained by measuring the area under the stress-strain curve. These data are presented in Table III. The energy expended to cause tensile failure of a POLYMETS is affected by the extrusion ratio: high extrusion ratios increase expended energy. The energy absorbed by aluminum 5% Vectra extruded at 10.7/1 and 114/1 increased from 1.3 mJ/mm³ to 10 mJ/mm³, i.e., nearly 670%.

Table III The Approximate Energy Expended During Tensile Examination.

MATERIAL	ENERGY (mJ/mm ³)	
	<u>EXTRUSION RATIO</u>	
	10.7/1	114/1
Aluminum	20	35
Al-5% Vectra	1.3	10
Al-10% Vectra	0.5	0.94
Al-20% Vectra	0.04	0.11

The yield strengths of the POLYMETS decreased with increased extrusion ratio. Interestingly, however, there was also a concomitant decrease in the yield strength of the aluminum control specimen. Further microstructural analysis is required in order to unambiguously identify the cause of this decrease. Although among the possible causes are processes involving matrix recovery, recrystallization, and grain growth.

In order to more accurately assess the effect of extrusion ratio on POLYMET yield strength, the decrease in matrix yield strength (as observed in the aluminum control sample) must be taken into account. The normalized yield strengths of the POLYMETS (based on the properties of the aluminum control samples) are presented in Table IV.

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Table IV. Normalized Yield Strength.

MATERIAL	YIELD STRENGTH (MPa)	
	<u>EXTRUSION RATIO</u>	
	10.7/1	114/1
Aluminum	115.1	115.1
Al-5% Vectra	100.9	116.3
Al-10% Vectra	55.9	74.7
Al-20% Vectra	11.2	14.7

The normalized yield strengths of the POLYMETS increase with extrusion ratio. The average normalized yield strength of the POLYMETS extruded at 114/1 is 26.7% greater than those extruded at 10.7/1. The normalized yield strength of the aluminum-5 vol.% Vectra increased 15.3%, i.e., from 100.9 MPa to 116.3 MPa. By inference, the increase in normalized yield strengths of the POLYMETS is attributable to morphological and crystallographic changes in the polymeric phase.

Fracture Behavior

Representative fractographs of POLYMETS extruded at 114/1 are presented in Figure 8. Polymer films, typically 0.5 microns thick and over 10 microns wide, are clearly visible. The polymer films appear to emanate from grain boundaries or prior particle boundaries. This type of fracture morphology may indicate poor matrix cohesion and result in lower ductility and reduced transverse strength. There was insufficient 1225/1 extruded material produced to determine tensile properties, but the very fine fibrils shown in the microstructure of the 5% Vectra material appear encouraging.

Fractographs of Al-5 vol.% Vectra clearly show fibrils emanating from matrix dimples, Figure 9a & 9b. The fibrils are approximately 1.5 microns in diameter. The dimple size and spacing is similar to that of the aluminum control specimen, Figure 9c.

Conclusions

1. In situ fibril and film formation was observed and was the result of extrusion processing.
2. The ultimate tensile strength and ductility of aluminum/Vectra POLYMETS is improved by increasing the extrusion ratio from 10.7/1 to 114/1.
3. The yield strengths of the POLYMETS declined by increasing the extrusion ratio; however, the normalized yield strengths of the POLYMETS increased an average of 26.7%.
4. Increases in the ultimate tensile strengths and normalized yield strengths of the POLYMETS with extrusion ratio are attributable to polymer fibril and film formation.
5. The energy required to produce tensile failure is significantly enhanced by increasing the extrusion ratio from 10.7/1 to 114/1.

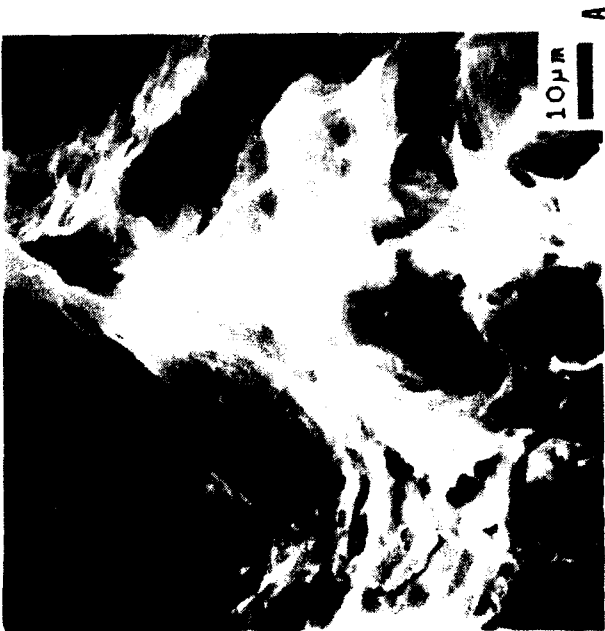


Figure 8 - SEM fractographs of POLYMETs extruded at 114/1: (a) Al-5 vol.% Vectra, (b) Al-10 vol.% Vectra, and (c) Al-20 vol.% Vectra.



Figure 9 - SEM fractograph of Al-5 vol.% Vectra extruded at 1225/1: (a) multiple polymer fibrils, (b) a single fibril in a matrix dimple, and (c) the aluminum control specimen extruded at 10.7/1.

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