Effects of Temperature and Strain Rate on the Tensile Behavior of Short Fiber Reinforced Polyamide-6

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Tensile behavior of extruded short E-glass fiber reinforced polyamide-6 composite sheet has been determined at different temperatures (21.5°C, 50°C, 75°C, 100°C) and different strain rates (0.05/min, 0.5/min, 5/min). Experimental results show that this composite is a strain rate and temperature dependent material. Both elastic modulus and tensile strength of the composite increased with strain rate and decreased with temperature. Experimental results also show that strain rate sensitivity and temperature sensitivity of this composite change at a temperature between 25°C and 50°C as a result of the glass transition of the polyamide-6 matrix. Based on the experimental stress-strain curves, a two-parameter strain rate and temperature dependent constitutive model has been established to describe the tensile behavior of short fiber reinforced polyamide-6 composite. The parameters in this model are a stress exponent n and a stress coefficient σ^*. It is shown that the stress exponent n, which controls the strain rate strengthening effect and the strain hardening effect of the composite, is not only strain rate independent but also temperature independent. The stress exponent σ^*, on the other hand, varies with both strain rate and temperature.

1. INTRODUCTION

During the past several years, increasing attention has been given to the mechanical behavior of engineering thermoplastics and thermoplastic matrix composites. One reason for this interest is that engineering thermoplastics and their composites are finding increasing applications in many structural automotive components, such as instrument panels, radiator fans, and electronic modules (1). Most of these applications require good performance over a range of temperatures and deformation rates. Hence it has become important to know the effects of temperature as well as strain rate on the mechanical behavior of engineering thermoplastics and their composites.

Polyamide-6 (nylon-6) is a semicrystalline engineering thermoplastic known for its balance of strength, modulus, and chemical resistance. Both polyamide-6 and short E-glass fiber reinforced polyamide-6 composite have many potential applications in automobiles where creep resistance, stiffness and some toughness are demanded in addition to weight savings. Two examples of its automotive applications are radiator fans and air intake manifolds. The E-glass fibers give the composite its stiffness and strength and the polyamide-6 matrix provides the means of achieving toughness and chemical resistance in addition to holding the fibers together. Several publications have considered the mechanical properties of short fiber reinforced polyamides. For example, Laura *et al.* (2) examined the effect of glass fiber content on the tensile modulus, yield strength and impact strength of a rubber-toughened polyamide-6. Darlington and Smith (3) reported the creep, creep rupture and impact strength of short fiber reinforced polyamide-6 and polyamide-6, 6. Akay and Barkley (4) examined the fiber orientation effect on the elastic modulus, tensile strength and fracture properties of injection molded polyamide composites. Ramsteiner and Theysohn (5) studied the effect of fiber/matrix interfacial strength and fiber volume fraction on the tensile and impact strengths of unidirectional, short glass fiber reinforced polyamide-6.

In this paper, the tensile behavior of a short E-glass fiber reinforced polyamide-6 composite is examined at four different temperatures and three different strain rates. Based on the experimental results, a two-parameter constitutive equation is proposed that can be used to predict the tensile stress-strain characteristics of this composite over the range of temperatures and strain rates considered. The strain rate and temperature sensitivities of tensile strength and modulus of the composite are also established.

2. EXPERIMENTS

The material used in this study was a short E-glass fiber reinforced polyamide-6 (trade name: Capron 8233). The fiber content in this composite was 33% by weight. Several extruded sheets of this material were obtained from AlliedSignal Plastics. The glass transition temperature, T_g, of polyamide-6 matrix is between 40°C and 50°C (6) and its melting point is 215°C. In a recent study (7), the glass transition temperature of polyamide-6 is reported as 40°C.

Dogbone-shaped tensile specimens were machined from one of the extruded sheets in the extrusion direction and normal to the extrusion direction of the sheet. Uniaxial tension tests were performed on an MTS servohydraulic testing machine equipped with an environmental chamber in which heating is performed by forced air convection. Axial strain was measured using a strain gauge extensometer (25 mm gauge length). The tests were conducted at three different crosshead speeds, namely 1.25, 12.5 and 125 mm/min and at four different temperatures, namely 21.5, 50, 75 and 100°C. Since the gauge length was 25 mm, the average strain rates were assumed to be 0.05, 0.5 and 5 min^{-1}. Three parameters were determined from each stress-strain curve: elastic modulus (E), tensile strength (σ_b), and failure strain (ε_b). Elastic modulus or Young's modulus is the initial slope of the stress-strain curve. Tensile strength is the stress at failure and the strain corresponding to the tensile strength is the failure strain.

3. RESULTS

Tensile stress-strain curves of the short E-glass fiber reinforced polyamide-6 composite in the extrusion direction and normal to the extrusion direction are shown in *Figs. 1–4*. The tensile stress-strain curves are mostly non-linear and do not exhibit any obvious yield point. The rate at which stress increases with strain reduces drastically after an initial rapid increase and at higher temperatures, the stress-strain curves become nearly flat as the failure strain is approached.

Figures 1 and *2* show the effect of temperature on the stress-strain curves of the polyamide-6 composite in the extrusion direction and normal to the extrusion direction, respectively. As expected, the overall stress level decreases with increasing temperature. Both modulus and tensile strength decrease with increasing temperature, while the failure strain increases as the temperature is increased up to 75°C; however, at 100°C, the failure strain is decreased. *Figure 3* shows the effect of strain rate on the stress-strain curves of the polyamide-6 composite in the extrusion direction (*Figs. 3a* and *3b*) as well as normal to the extrusion direction (*Figs. 3c* and *3d*) at 21.5 and 100°C. It is observed in these figures that the overall stress level increases with increasing strain rate; however, the effect of strain rate on the failure strain is relatively small for the three strain rates investigated.

Figures 4a and *4b* show comparisons of stress-strain curves of the composite in the extrusion direction and normal to the extrusion direction at 21.5°C and 100°C, respectively. At both temperatures, modulus and tensile strength are much higher in the extrusion direction than normal to the extrusion direction. The failure strain, on the other hand, is much higher in normal to the extrusion direction. Tensile property values at other temperatures and strain rates are given in *Tables 1* and *2*. The significant difference in properties in two mutually perpendicular directions indicates inherent anisotropy of the extruded sheets, which may arise as a result of preferential orientation of fibers in the extrusion direction. The higher modulus, higher tensile strength and lower failure strain in the extrusion direction are indications that the short fibers in the as-received extruded sheet are preferentially oriented in that direction.

From *Figs. 1–4* and *Tables 1–2*, it can be concluded that short fiber reinforced polyamide-6 is a temperature and strain rate sensitive material. Furthermore, in the as-received extruded sheet form, the material is also anisotropic. *Figure 5* shows the variation of modulus E and tensile strength σ_b with $\ln \dot{\varepsilon}$. The effect of temperature is also shown in this figure. The variation of these two properties with temperature is shown in *Fig. 6*. In general, both E and σ_b increase with increasing strain rate and decrease with increasing temperature. The following empirical relationships are found to fit the modulus and tensile strength data and represent the temperature sensitivity and strain rate sensitivity of these two properties of this composite.

$$E = E_0 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{m_1} \exp\left[-\lambda_1 (T - T_0)\right] \tag{1}$$

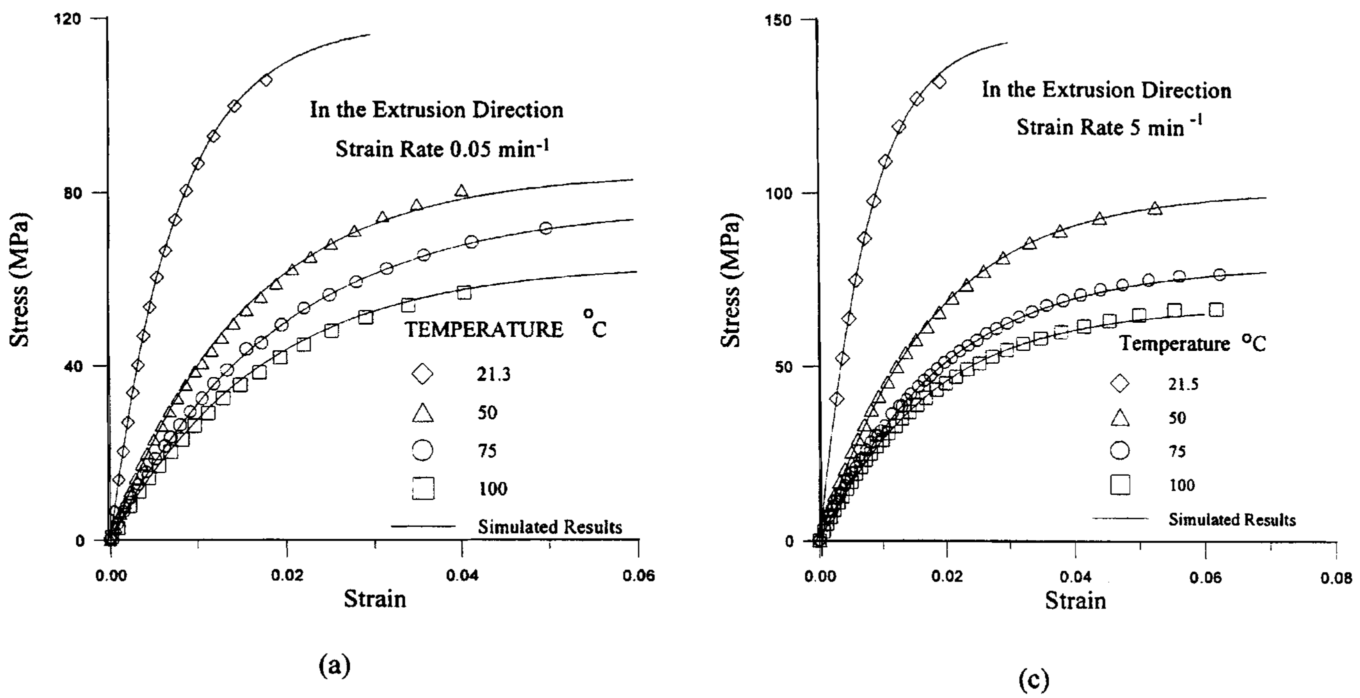
$$\sigma_b = \sigma_{b0} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{m_2} \exp\left[-\lambda_2 (T - T_0)\right] \tag{2}$$

where E_0, σ_{b0}, $\dot{\varepsilon}_0$ and T_0 are reference elastic modulus, reference tensile strength, reference strain rate and reference temperature, respectively. Two other parameters, m and λ, appearing in *Eqs 1* and *2* are defined as strain rate strengthening coefficient and thermal softening coefficient, respectively. Mathematically, they are defined as

$$m_{1,2} = \frac{\partial \ln(E, \sigma_b)}{\partial \ln \dot{\varepsilon}} \tag{3}$$

$$\lambda_{1,2} = -\frac{\partial \ln(E, \sigma_b)}{\partial T} \tag{4}$$

In *Figs. 5* and *6*, it can be observed that the strain rate and temperature sensitivities of the composite at 21.5°C



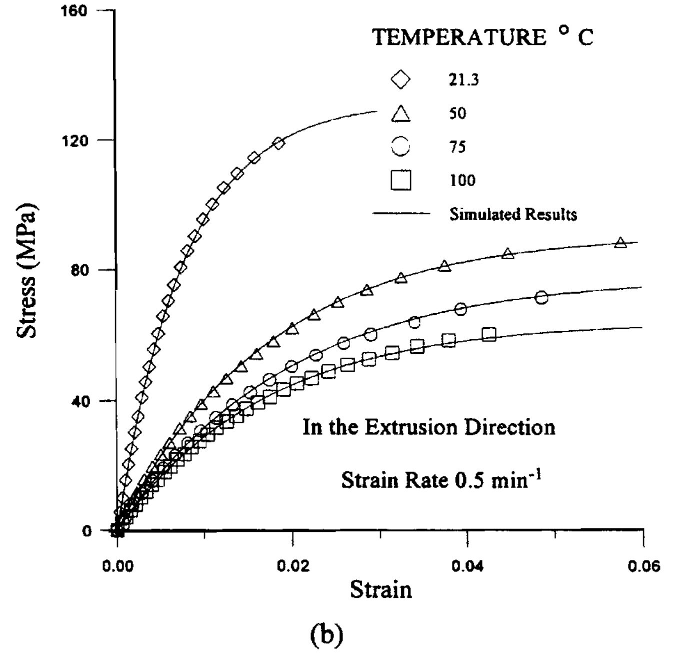
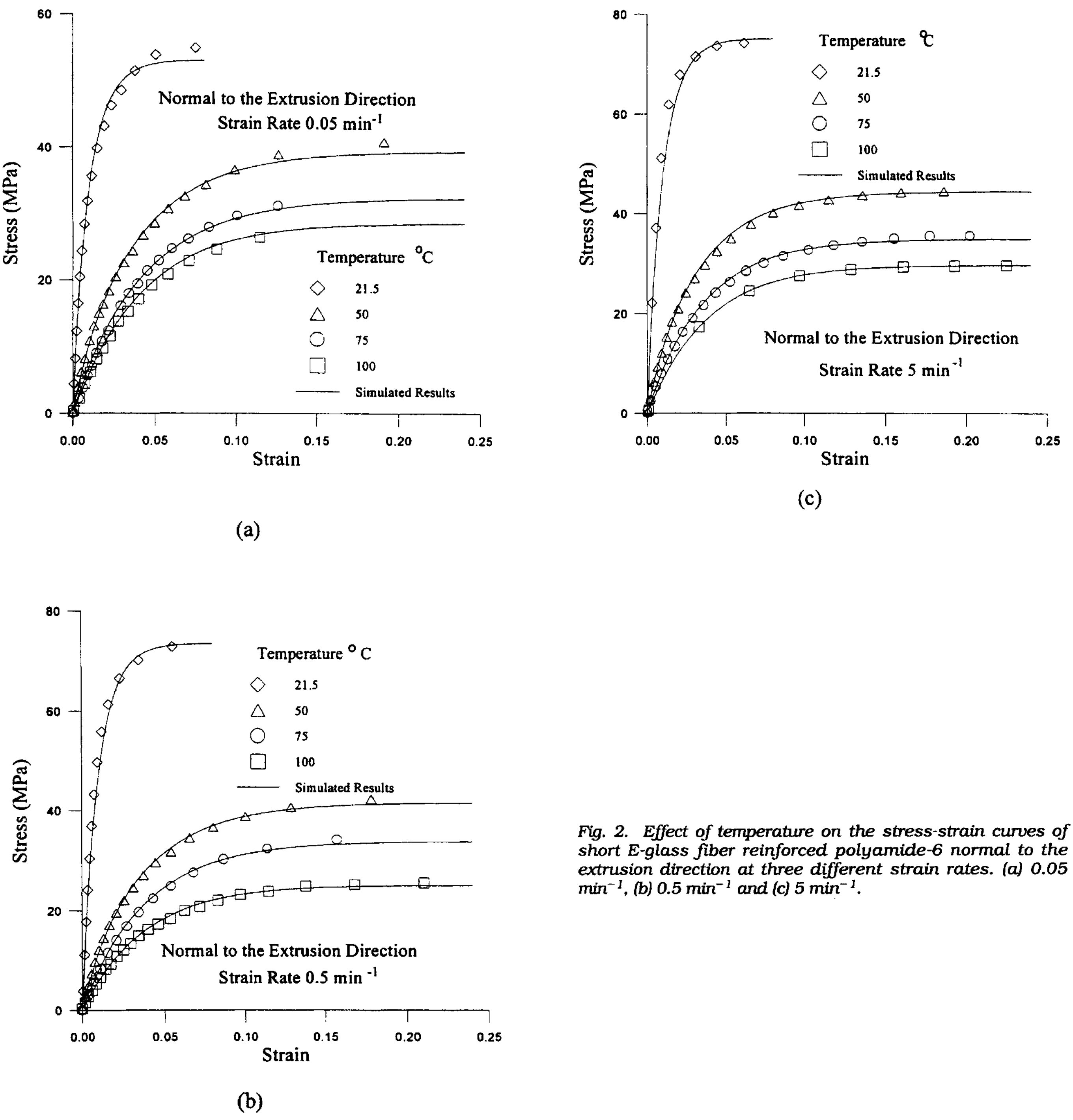


Fig. 1. Effect of temperature on the stress-strain curves of short E-glass fiber reinforced polyamide-6 in the extrusion direction at three different strain rates. (a) 0.05 min^{-1}, (b) 0.5 min^{-1} and (c) 5 min^{-1}.

are considerably different from that at the other three temperatures. This is indicated by the change in slope that occurs as the temperature is increased from 21.5°C to 50°C. Since the glass transition temperature of polyamide-6 is between 40°C and 50°C, it is assumed that the strain rate sensitivity has changed due to glass transition. Assuming $\dot{\varepsilon}_0 = 0.05$/min and $T_0 = 50$°C, m and λ values are calculated from the experimental results using the least square method (*Table 3*). The strain rate sensitivity and temperature sensitivity values are given over two temperature ranges, between 21.5°C and 50°C and between 50°C and 100°C. It can be observed that both modulus and strength are more temperature sensitive between 21.5°C and 50°C than between 50°C and 100°C. The strain rate sensitivity of modulus is also much higher between 21.5°C and 50°C. The difference in strain rate sensitivity of tensile strength is not as high as in the case of modulus. It



(a)

(c)

(b)

Fig. 2. Effect of temperature on the stress-strain curves of short E-glass fiber reinforced polyamide-6 normal to the extrusion direction at three different strain rates. (a) 0.05 min^{-1}, (b) 0.5 min^{-1} and (c) 5 min^{-1}.

can also be observed from this table that the strain rate sensitivity and temperature sensitivity of E-glass fiber reinforced polaymide-6 is much lower in the extrusion direction than normal to the extrusion direction. The difference in strain rate and temperature sensitivity in these two mutually perpendicular directions can also be explained in terms of preferential fiber orientation in the extrusion direction of the sheet. As a result of the preferential orientation, the extrusion direction is more fiber-dominated and the normal to the extrusion direction is more matrix-dominated.

4. CONSTITUTIVE EQUATION

In this section, we develop a constitutive equation that describes the tensile stress-strain behavior of short fiber reinforced polyamide-6. The total strain is assumed to be the sum of elastic strain, ε_e, and inelastic strain, ε_i, (8), so that the strain rate can be written as

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_i \qquad (5)$$

where, $\dot{\varepsilon}_e$ and $\dot{\varepsilon}_i$ represent the strain rates corresponding to the elastic and inelastic components, respectively.

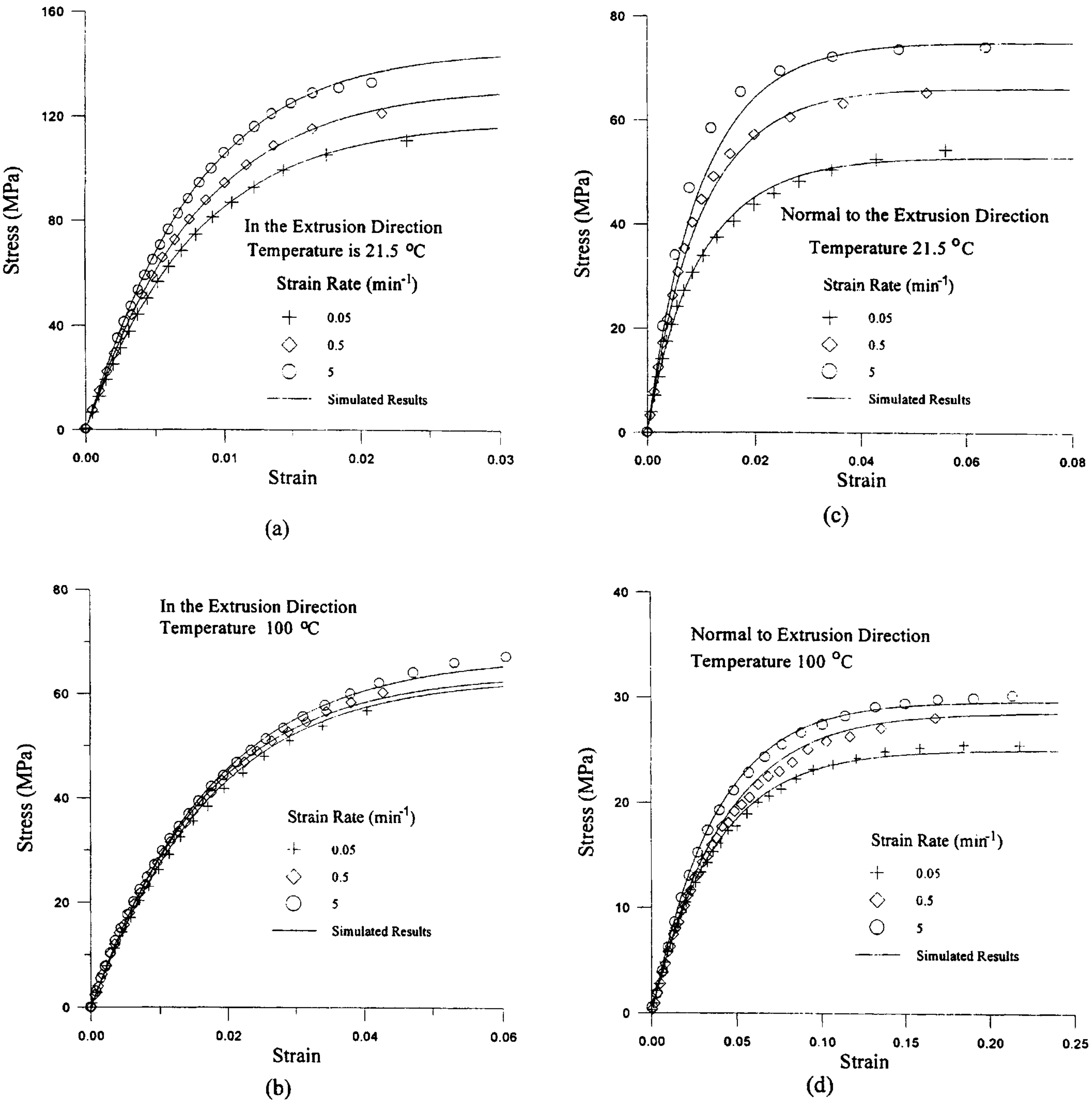


Fig. 3. Effect of strain rate on the stress-strain curves of short E-glass fiber reinforced polyamide-6 at 21.5 and 100°C. (a) and (b) in the extrusion direction, (c) and (d) normal to the extrusion direction.

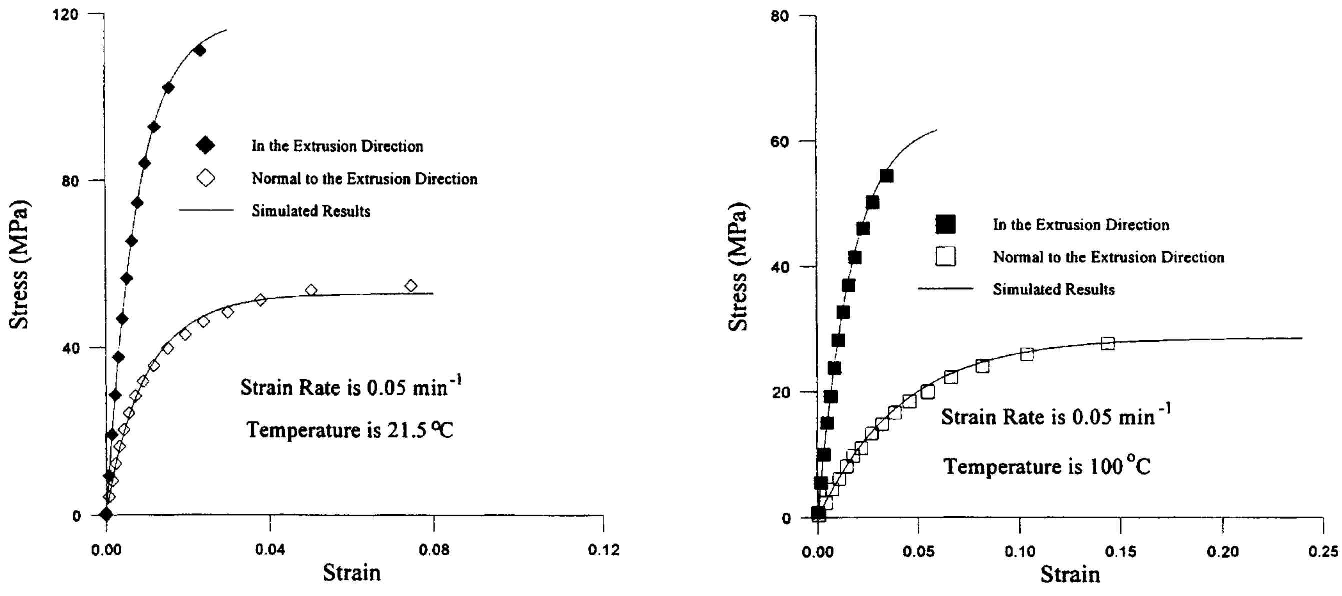
The elastic strain rate is assumed to be path-independent, such that

$$\dot{\varepsilon}_e = \frac{1}{E}\frac{d\sigma}{dt} \tag{6}$$

where E is elastic modulus of the material, and σ is the stress. The inelastic strain rate, $\dot{\varepsilon}_i$, is assumed to follow a power-law function of stress

$$\dot{\varepsilon}_i = C\left(\frac{\sigma}{\sigma_0}\right)^n \tag{7}$$

where σ_0 and n are defined as the reference stress and the stress exponent, respectively. Both the strain rate strengthening as well as the strain hardening effects of the composite are controlled by the stress exponent n. C is a material parameter. Substituting *Eqs 6* and *7* into *Eq 5*, we obtain



(a) (b)

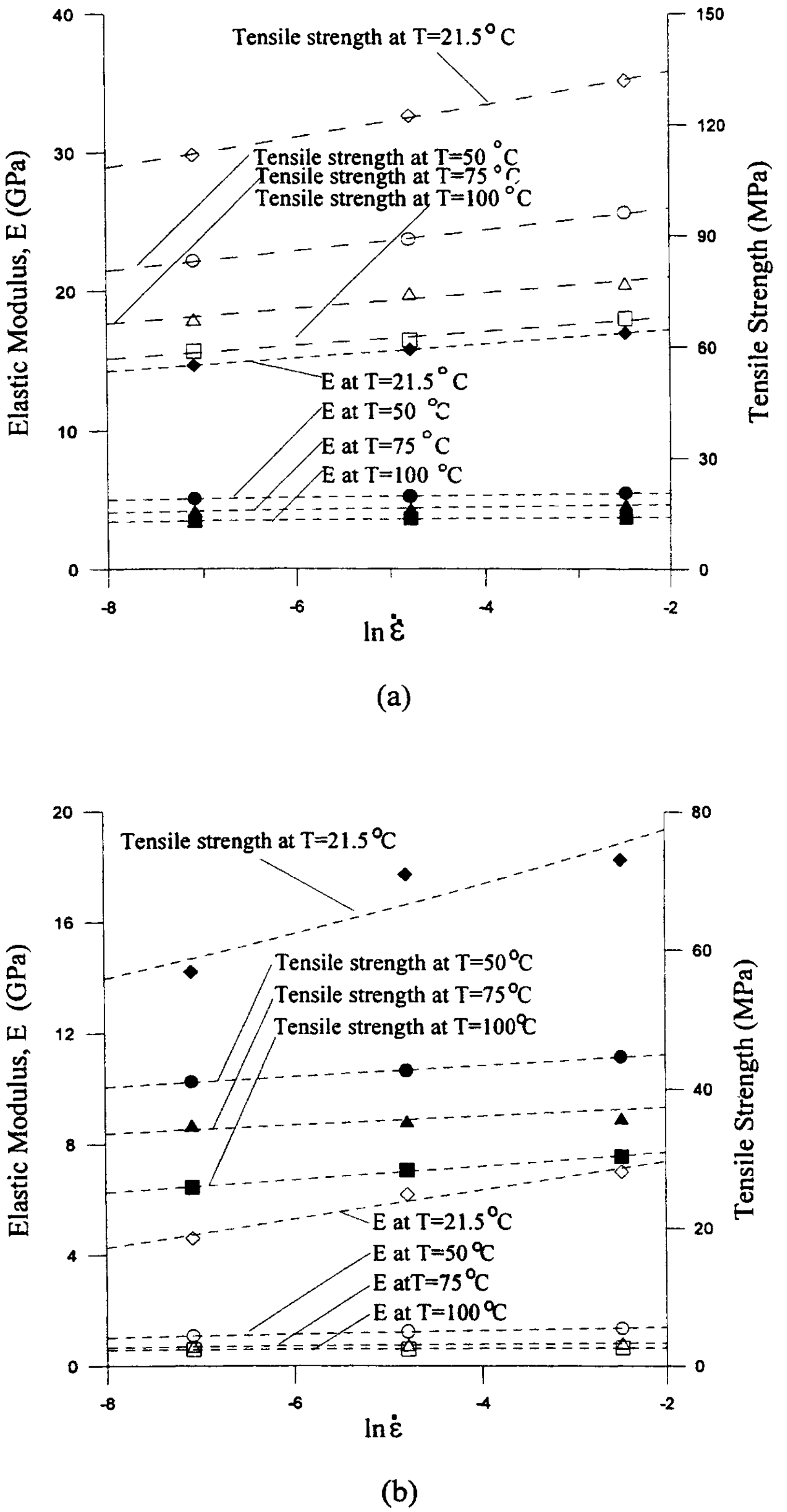
Fig. 4. Comparison of the stress-strain curves of short E-glass fiber reinforced polyamide-6 in the extrusion direction and normal to the extrusion direction at strain rate 0.05 min^{-1}. (a) at 21.5°C and (b) at 100°C.

Table 1. Tensile Properties of Short E-glass Fiber Reinforced Polyamide-6 in the Extrusion Direction.

Strain Rate (min^{-1})	Temp. (°C)	Elastic Modulus E (GPa)	Tensile Strength σ_b (MPa)	Failure Strain ε_b (%)	Stress Exponent n	Stress Coefficient σ^* (MPa)
0.05	21.5	14.68	111.8	2.330	1.022	118.8
0.5		15.79	122.3	2.222	1.056	132.0
5		16.99	132.0	2.116	1.057	138.6
0.05	50	5.067	83.68	4.664	1.094	87.11
0.5		5.226	89.65	5.717	1.049	94.31
5		5.472	98.35	6.073	1.058	101.6
0.05	75	4.175	71.92	5.526	1.067	70.60
0.5		4.340	76.38	5.977	1.068	77.20
5		4.651	78.78	6.129	1.074	79.60
0.05	100	3.441	63.44	4.675	1.085	58.71
0.5		3.631	65.97	4.758	1.025	62.90
5		3.711	71.71	6.103	1.024	64.81

Table 2. Tensile Properties of Short E-glass Fiber Reinforced Polyamide-6 Normal to the Extrusion Direction.

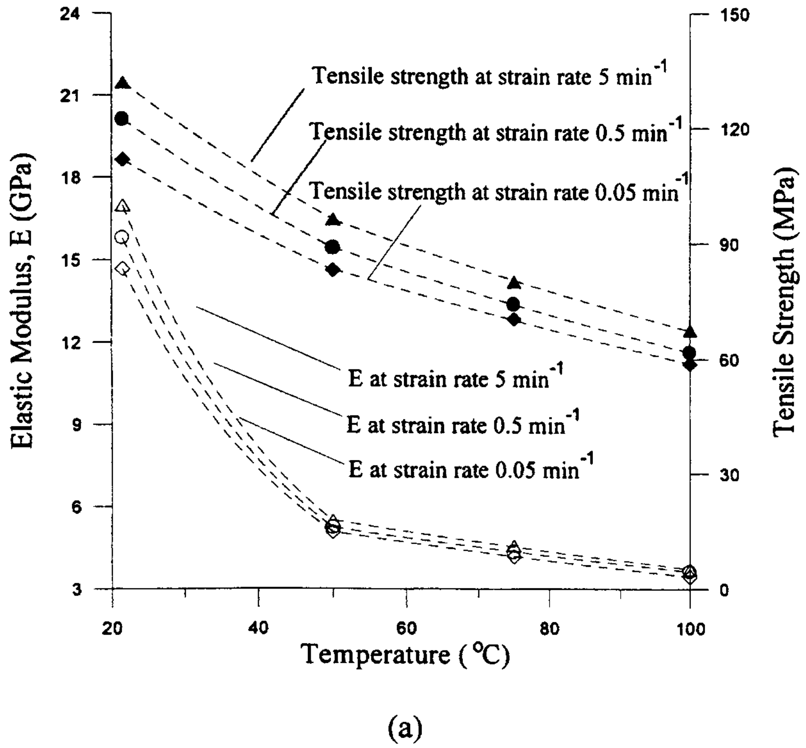
Strain Rate (min^{-1})	Temp. (°C)	Elastic Modulus E (GPa)	Tensile Strength σ_b (MPa)	Failure Strain ε_b (%)	Stress Exponent n	Stress Coefficient σ^* (MPa)
0.05	21.5	4.625	56.84	6.711	0.9658	53.01
0.5		6.191	70.90	4.804	0.9226	71.81
5		7.028	73.06	5.737	0.9531	75.38
0.05	50	1.074	40.97	18.25	0.9388	41.46
0.5		1.243	42.59	19.45	0.9341	43.66
5		1.370	44.61	18.81	0.9480	45.35
0.05	75	0.6891	35.81	15.57	0.9577	33.20
0.5		0.7501	34.73	18.23	0.9502	35.44
5		0.8279	35.43	23.63	0.9157	36.69
0.05	100	0.5912	25.79	16.21	0.9749	23.61
0.5		0.6086	28.24	19.14	0.9639	27.98
5		0.6556	30.30	22.08	0.9629	30.43



(a)

(b)

Fig. 5. Variation of elastic modulus and tensile strength of short E-glass fiber reinforced polyamide-6 as a function of ln ε̇. (a) in the extrusion direction and (b) normal to the extrusion direction.



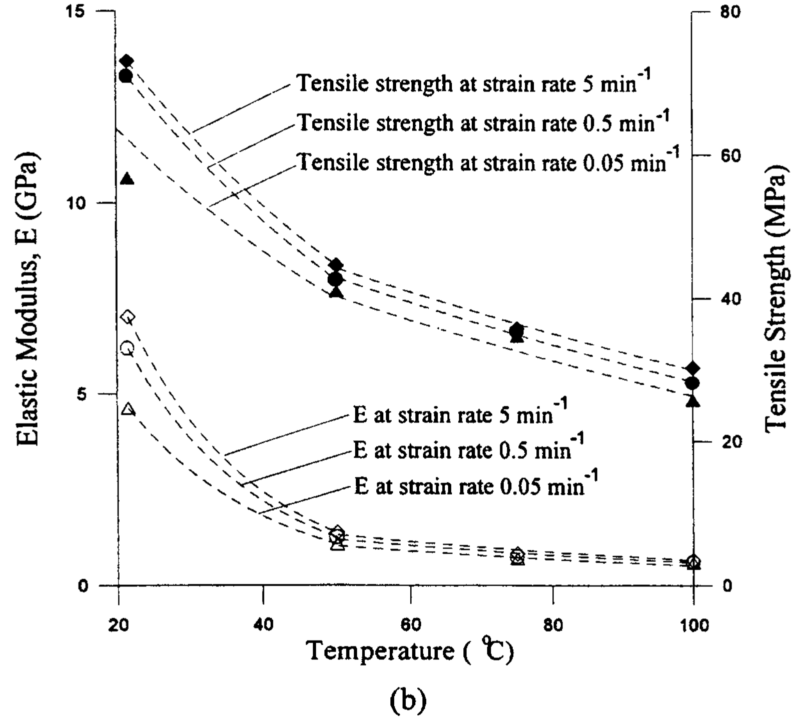


Fig. 6. Variation of elastic modulus and tensile strength as a function of temperature. (a) in the extrusion direction and (b) normal to the extrusion direction.

Table 3. Strain Rate Strengthening Coefficients and Thermal Softening Coefficients of Short E-Glass Fiber Reinforced Polyamide-6.

	In the Extrusion Direction		Normal to the Extrusion Direction	
Temperature Range (°C)	21.5–50	50–100	21.5–50	50–100
m_1 (for elastic modulus)	0.03177	0.01884	0.09085	0.03546
λ_1 (for elastic modulus)	0.03862	0.007956	0.05500	0.01366
m_2 (for tensile strength)	0.03611	0.03034	0.05451	0.03499
λ_2 (for tensile strength)	0.01094	0.007073	0.01556	0.008403

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + C\left(\frac{\sigma}{\sigma_0}\right)^n \qquad (8)$$

If we further assume that $\sigma^* = \sigma_0/\sqrt[n]{C/\varepsilon}$, *Eq 8* can be rewritten as

$$\frac{d\sigma}{d\varepsilon} = E - E\left(\frac{\sigma}{\sigma^*}\right)^n \qquad (9)$$

In *Eq 9*, the parameter σ^* is called the stress coefficient.

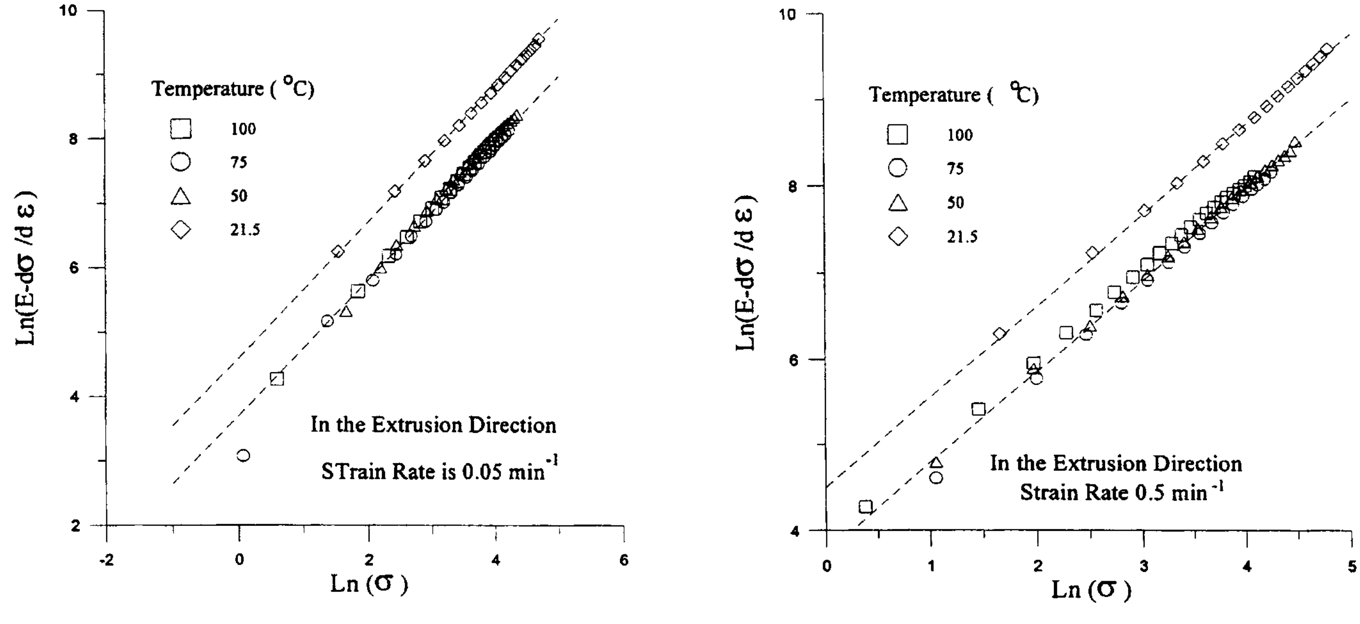
To determine the parameters n and σ^*, we take logarithms on both sides of *Eq 9* to write

$$\ln\left(E - \frac{d\sigma}{d\varepsilon}\right) = n\ln\sigma - n\ln\sigma^* + \ln E \qquad (10)$$

Equation 10 represents a linear plot of $\ln\left(E - \frac{d\sigma}{d\varepsilon}\right)$ vs. $\ln\sigma$. The slope of this linear plot is equal to the stress exponent n and the intercept on the ordinate is equal to $(\ln E - n\ln\sigma^*)$, from which the stress coefficient σ^* can be determined.

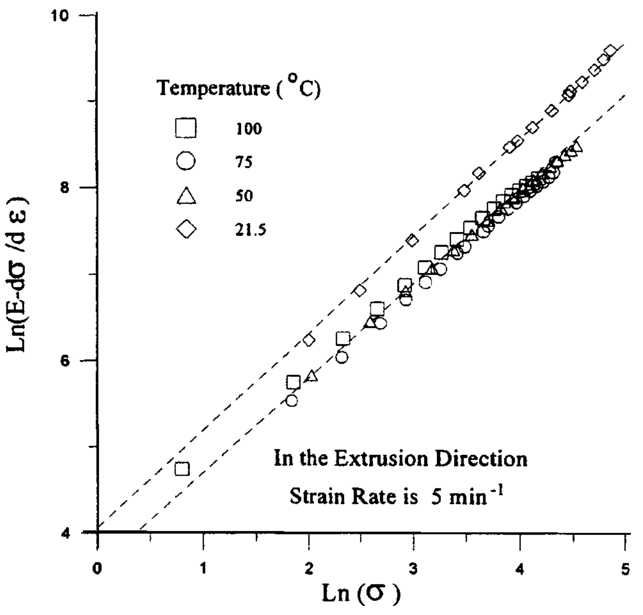
The values of $\ln\left(E - \frac{d\sigma}{d\varepsilon}\right)$ are derived from the stress-strain plots shown in *Figs. 1* and *2*. *Figures 7* and *8* show the plots $\ln(E - d\sigma/d\varepsilon)$ vs. $\ln\sigma$ at 21.5°C, 50°C, 75°C and 100°C for the extrusion direction and normal to the extrusion direction, respectively. As these figures show, these plots are linear at all four temperatures. In the extrusion direction, the derived data at 50°C, 75°C and 100°C fall on the same line, but the line representing the 21.5°C temperature is distinctly different. In the normal to the extrusion direction, the lines representing the four different temperatures are separated, although the 50°C, 75°C and 100°C-lines are much closer than the 21.5°C line.

Figure 9 shows the plots of $\ln(E - d\sigma/d\varepsilon)$ vs. $\ln\sigma$ at strain rates 0.05, 0.5 and 5 min^{-1} for the 21.5°C test



(a) (b)

Fig. 7. Plots of $\ln(E\text{-}d\sigma/d\varepsilon)$ vs. $\ln\sigma$ for short E-glass fiber reinforced polyamide-6 in the extrusion direction. (a) 0.05 min^{-1}, (b) 0.5 min^{-1} and (c) 5 min^{-1}.



(c)

Fig. 7. Continued.

temperature. In both extrusion and normal to extrusion directions, the derived data at these strain rates fall on the same line. Similar merger of data is also observed at the other three temperatures, indicating that the stress exponent n is independent of strain rate. *Figures 10* and *11* show the stress coefficient σ^* and stress exponent n plotted as a function of temperature and strain rate, respectively. It can be observed from this figure that n does not vary much with either temperature or strain rate and, therefore, we consider n to be independent of both temperature as well as strain rate. However, the stress coefficient depends on both strain rate as well as temperature. It decreases with increasing temperature (*Fig. 10*), but increases with increasing strain rate (*Fig. 11*). The stress exponent n is higher in the extrusion direction than normal to the extrusion direction. The stress coefficient σ^* in the extrusion direction is also different from that in the normal to the extrusion direction. *Tables 1* and *2* include the values of n and σ^* at various test conditions used. The average values of the stress exponent n and expressions for the stress coefficients σ^* in these two directions are as follows:

In the extrusion direction:

$n = 1.057$

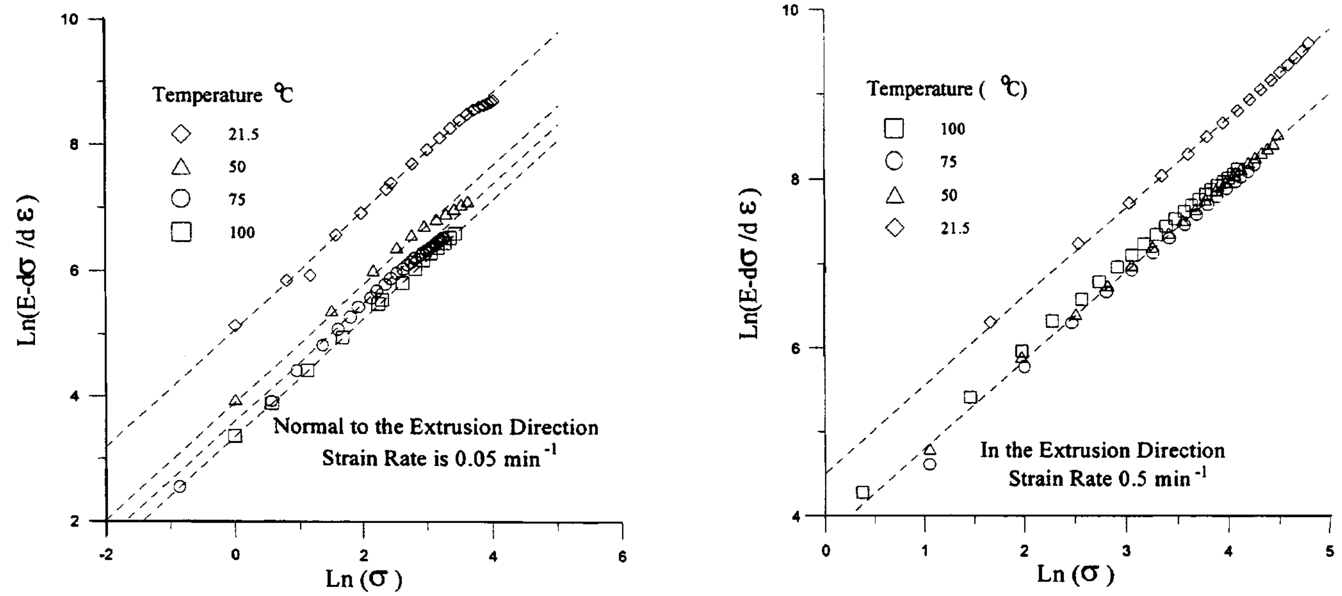
$$\sigma^* (MPa) = 58.7 \left(\frac{\dot{\varepsilon}}{0.05/min}\right)^{0.00286} \exp[-0.00895\,(T - 21.5°C)]$$

Normal to the extrusion direction:

$n = 0.9489$

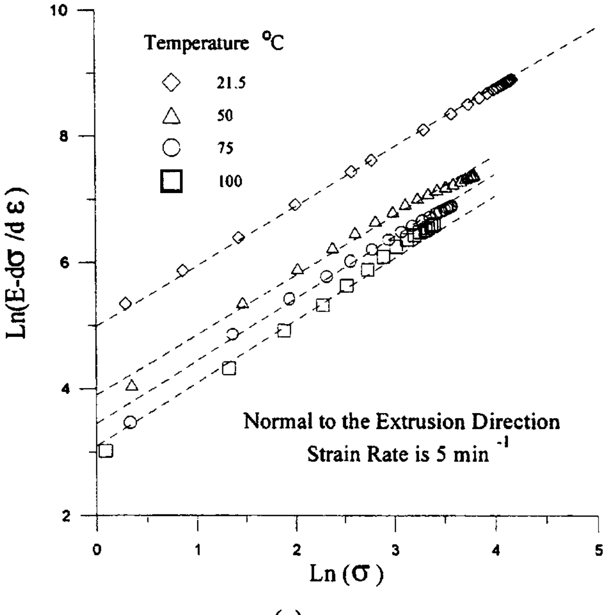
$$\sigma^* (MPa) = 23.6 \left(\frac{\dot{\varepsilon}}{0.05/min}\right)^{0.04319} \exp[-0.01107\,(T - 21.5°C)]$$

In the above equations the reference strain rate and temperature are assumed as 0.05 min^{-1} and 21.5°C, respectively. Substituting the elastic modulus E, stress



(a) (b)

Fig. 8. Plots of ln(E-dσ/dε) vs. lnσ for short E-glass fiber reinforced polyamide-6 normal to the extrusion direction. (a) 0.05 min^{-1}, (b) 0.5 min^{-1} and (c) 5 min^{-1}.



(c)

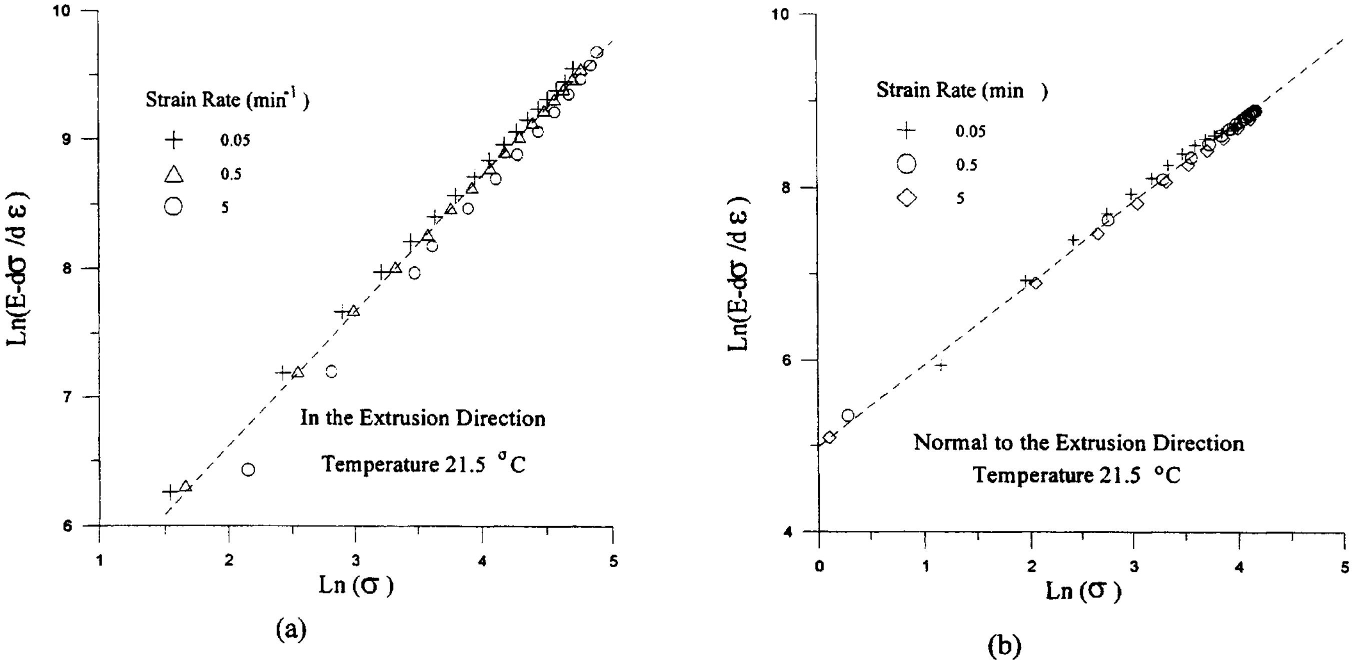
Fig. 8. Continued.

exponent n and stress coefficient σ^* into *Eq 9*, the slope of the stress-strain curve, $d\sigma/d\varepsilon$, is calculated in a step-wise fashion at a strain interval of 0.005, starting with $d\sigma/d\varepsilon = E$ at $\varepsilon = 0$ and $\sigma = 0$. The resulting stress-strain plots are shown in *Figs. 1-4* and they seem to fit the experimental data well.

5. CONCLUSIONS

Uniaxial tensile tests were conducted on an extruded polyamide-6 matrix composite sheet containing 33 weight % short E-glass fibers at four different temperatures and three different strain rates. Based on the experimental data, the following conclusions are reached:

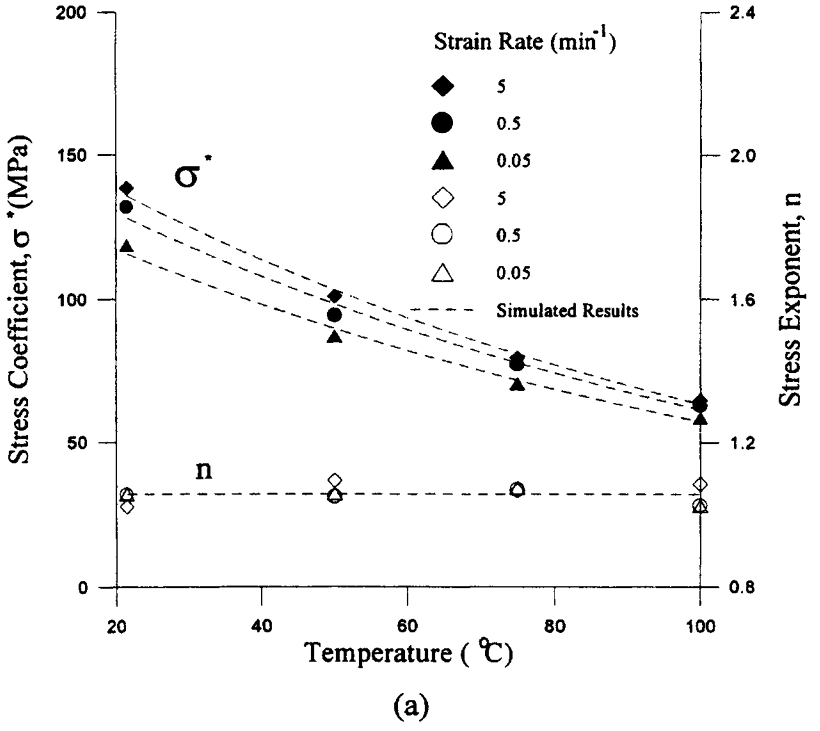
1. Short E-glass fiber reinforced polyamide-6 is a typical strain rate and temperature dependent material. Both elastic modulus and tensile strength of the composite decrease with increasing temperature and increase with increasing strain rate. There is a change in the strain rate sensitivity and the temperature sensitivity of composite between 21.5°C and 50°C, possibly as a result of the glass transition of the polyamide-6 matrix.
2. The extruded composite sheet is anisotropic in the sense that the tensile properties of the sheet in the extrusion direction are significantly different from those in the normal to the extrusion direction. The strain rate and temperature sensitivities of the composite are much lower in the extrusion direction than normal to the extrusion direction.
3. A two-parameter strain rate and temperature dependent constitutive model has been established to describe the tensile behavior of composite. The parameters in this model are called the stress exponent and the stress coefficient. The stress exponent n, which controls the strain rate strengthening effect and strain hardening



(a)

(b)

Fig. 9. Plots of ln(E-dσ/dε) vs. lnσ for short E-glass fiber reinforced polyamide-6 at 21.5°C. (a) in the extrusion direction and (b) normal to the extrusion direction.



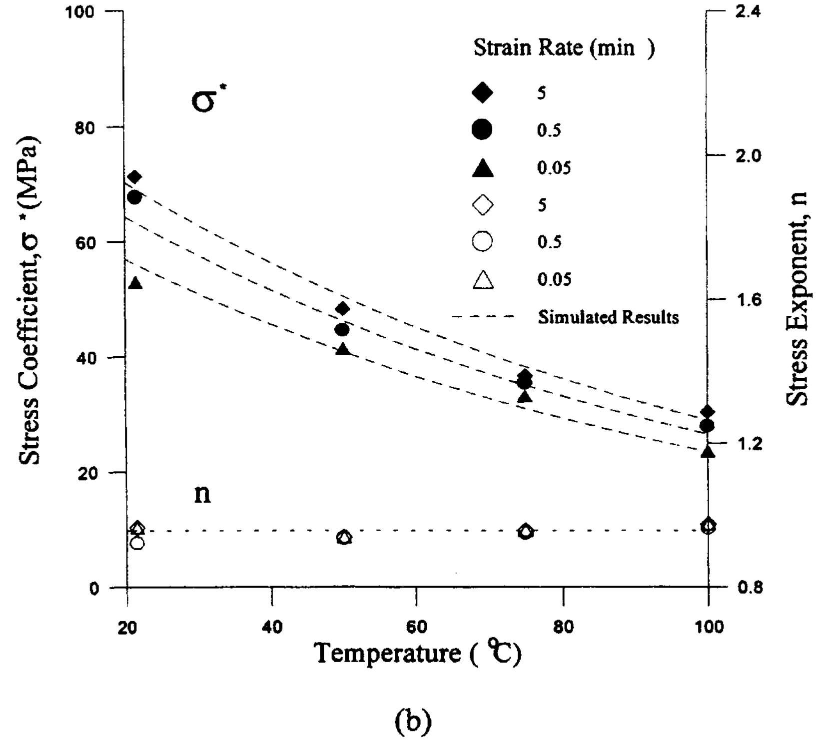
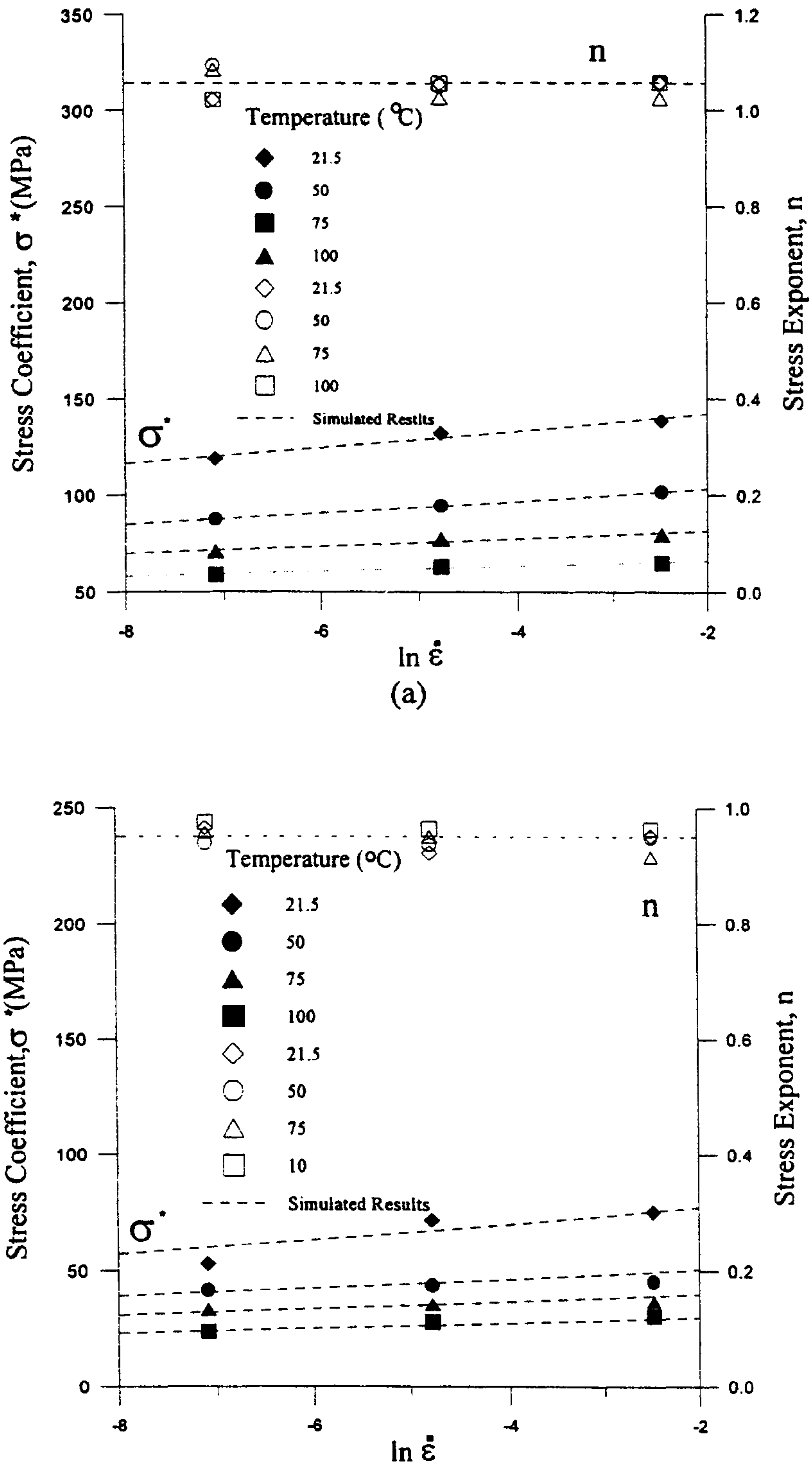


Fig. 10. Effect of temperature on stress exponent n and stress coefficient σ of short E-glass fiber reinforced polyamide-6. (a) in the extrusion direction and (b) normal to the extrusion direction.*



(a)

(b)

Fig. 11. Effect of strain rate on stress exponent n and stress coefficient σ of short E-glass fiber reinforced polyamide-6. (a) in the extrusion direction and (b) normal to the extrusion direction.*

effect of the composite, are not only strain rate independent, but also temperature independent. The stress coefficient σ^*, on the other hand, depend on both strain rate and temperature.

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