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The Notch Sensitivity of Polymeric Materials

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Synopsis

Stress–strain tests were made on about five dozen polymeric materials using unnotched and notched specimens containing six different types of notches. Notches decrease the strength, but they decrease the elongation to break even more drastically in general. Notch sensitivity factors are defined for strength and for energy to fracture in such a manner that the greater the notch sensitivity factor, the greater is the effect of a notch relative to the unnotched material. The notch sensitivity factor for breaking (or yield) strength is not the same as the notch sensitivity factor for energy to fracture as measured by the area under the stress–strain curve. Brittle polymers and composites tend to have greater notch sensitivity factors for strength than ductile polymers. For brittle polymers, the notch sensitivity factor for energy to fracture tends to increase with the elongation to break of the unnotched polymer. Notches generally are more detrimental to ductile polymers than to brittle ones as far as the energy to fracture is concerned. For ductile polymers, the shape of the stress–strain curve is important in determining the sensitivity to notches. The ratio of the upper to lower yield strengths should be small for low notch sensitivity. It is desirable to have the breaking strength greater than the yield strength. Glass fibers and filler in ductile matrices increase the notch sensitivity for strength but decrease the sensitivity for energy to fracture relative to the unfilled polymer. Rubber-filled polymers have a reduced notch sensitivity for strength relative to the unfilled polymer, but the notch sensitivity for energy to fracture may be either increased or decreased, depending upon the system. The energy to fracture for notched specimens correlates better with Izod impact strength than does the energy to fracture for unnotched specimens. It is recommended that notched stress–strain specimens be routinely measured along with unnotched specimens.

INTRODUCTION

It is well known that notches, cuts, and scratches can greatly reduce the impact strength, the tensile strength, and the fatique life of polymeric materials. Notched specimens are routinely used in tests of impact strength, but notched stress–strain specimens are rarely used. Most of the literature on notches for plastic materials is for impact tests.[1–6] The effect of cracks on strength is found in the field of fracture toughness testing.[6–8] The sparsity of literature on notched stress–strain test specimens is surprising in view of the expected importance of such tests.[9,10] Comparison of stress–strain data for notched specimens with unnotched specimens should provide more information than what can be obtained from the usual notched Izod test or from the unnotched stress–strain tests alone.

Some materials are more sensitive to notches or cuts than others. A major objective of this investigation was to attempt to correlate the notch sensitivity of materials with the nature of their unnotched stress–strain curves. Five dozen kinds of polymeric materials giving a total of about 4000 specimens of

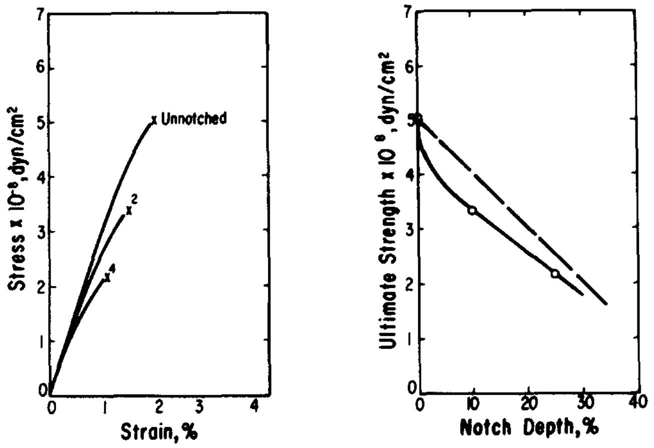

Fig. 1. Stress–strain curves and ultimate strength of polystyrene as a function of notch depth.

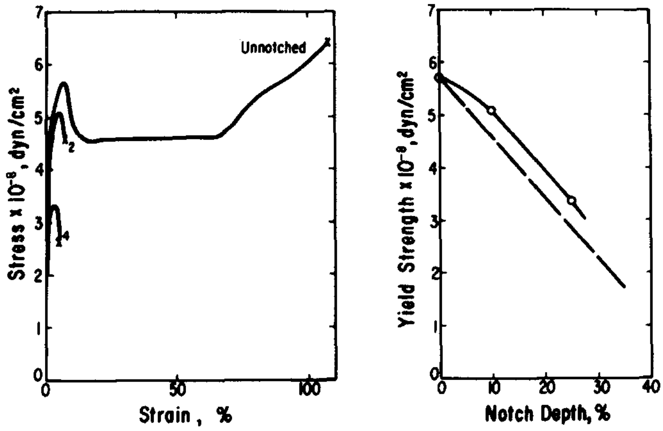

Fig. 2. Stress–strain curves and yield strength of polycarbonate as a function of notch depth.

different materials and notching conditions were tested. The results are summarized here.

MATERIALS AND TECHNIQUES

The stress–strain tests were made on $\frac{1}{8}$-in.-thick dogbone-shaped tensile bars with a $\frac{1}{2}$-in.-wide section $2\frac{1}{4}$ in. in length. Most of the bars were molded on a 1-oz Watson Stillman injection molding machine. Molding was done at the temperature recommended by the manufacturer of the resin, and an effort was made to minimize molecular orientation in the bars. For soft elastomers, dogbone-shaped tensile specimens were cut from compression-molded sheets $\frac{1}{8}$ in. thick.

After some preliminary studies, six types of notches were selected for most of the work. The standardized notches are given in Table I. The notch severity factor k is the stress concentration factor at the notch tip at the begin-

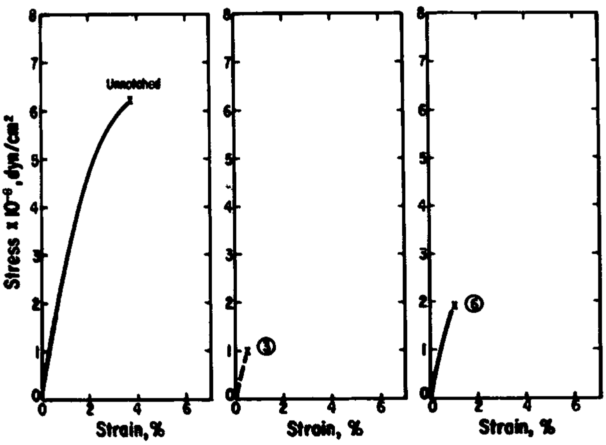

Fig. 3. Stress–strain curves of poly(methyl methacrylate): unnotched, notch #3 with a stress concentration factor of 8.08, and notch #6 with a stress concentration factor of 2.05.

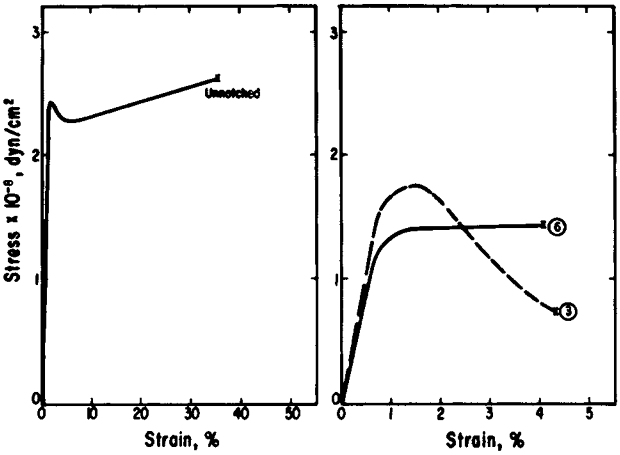

Fig. 4. Stress–strain curves of high-impact polystyrene: unnotched, notch #3, and notch #6.

ning of the stress–strain test; its calculation is described in the discussion section.

The unnotched and notched bars were conditioned at 24°C and 50% relative humidity for several days prior to testing unless they were intentionally dried or soaked in water before testing. The stress–strain tests were made on an Instron tester using an extensometer with a 1-in. span placed so that the notch came in the center of the span. When the ultimate elongation was more than 100%, the extensometer had to be reset. Resetting the extensometer was possible in general only when the specimen had uniform extension without necking. In other cases, an apparent extension was calculated from the spacing between two fiducial marks. All the stresses were calculated on the basis of the original cross-sectional area for both the notched and unnotched bars. In general, a strain rate of 0.10 in./min was used for rigid materials, and a strain rate of 1.0 in./min was used for soft elastomers. On an

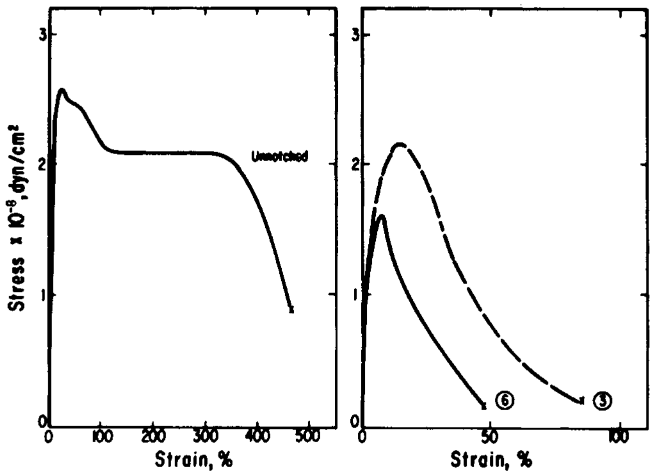

Fig. 5. Stress–strain curves of high-density polyethylene: unnotched, notch #3, and notch #6.

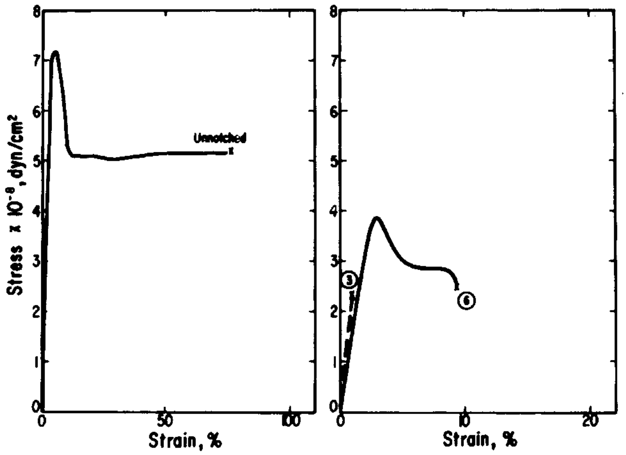

Fig. 6. Stress–strain curves of polysulfone: unnotched, notch #3, and notch #6.

average, at least four tensile bars were used for each notch condition. A "best" stress–strain curve was drawn from the average value of four good tensile tests in each case. The energies to yield and fracture were calculated from the area under the stress–strain curves.

Some of the approximately 60 materials studied are listed in Table II. Most of these materials were commercial polymers, but a few were experimental materials. These materials cover the range of rigid brittle and ductile polymers, elastomers, crystalline and amorphous polymers, and composite materials.

RESULTS AND DISCUSSION

Some of the stress–strain and notch sensitivity data are shown in Tables II–VII and in Figures 1–8.

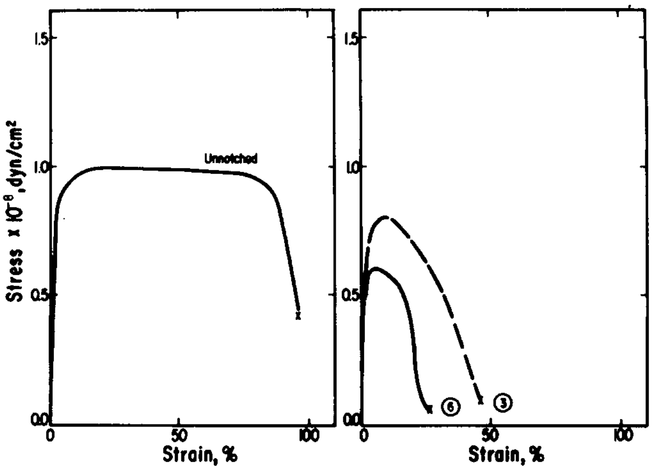

Fig. 7. Stress–strain curves of poly(tetrafluoroethylene) sheet oriented in the 0° direction: unnotched, notch #3, and notch #6.

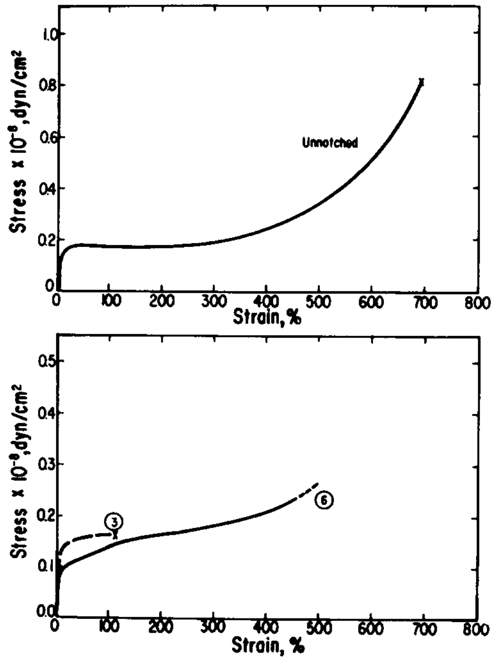

Fig. 8. Stress–strain curve of Kraton (styrene–butadiene–styrene block polymer): unnotched, notch #3, and notch #6.

The severity of the notch condition, as listed in Table I, is quantified by the stress concentration factor of the same notch cut on the edge of a purely elastic solid bar. The theoretical stress concentration factors k are calculated by using the following equations[11]:

$$k = 1 + 2\,(h/r)^{1/2} \text{ for single V-shaped notches} \qquad (1)$$

$$k = 0.37 + 0.832\,\{r/(w - 2h)\}^{-1/2} \text{ for symmetrical double V-shaped notches} \qquad (2)$$

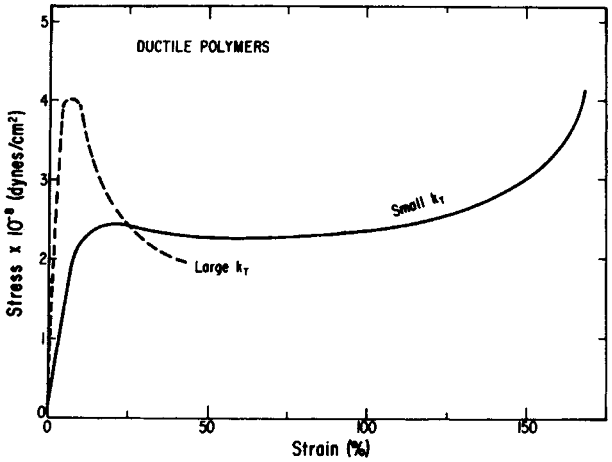

Fig. 9. Shapes of stress–strain curves of ductile polymers which tend to give large and small k_T (notch sensitivity factors for energy to break) values.

These stress concentration factors are for notches cut in the edges of the specimens with a radius of curvature r at the tip. The depth of the notch is h, and w is the width of the unnotched bar.

The notch sensitivity factors are defined by the following ratios:

$$k_S = \frac{\left\{\begin{matrix}\text{yield (or breaking) strength} \\ \text{of unnotched bar}\end{matrix}\right\} \times \left\{\begin{matrix}\text{residual cross-sectional} \\ \text{area at the notch site}\end{matrix}\right\}}{\left\{\begin{matrix}\text{yield (or breaking) strength} \\ \text{of notched bar}\end{matrix}\right\} \times \left\{\begin{matrix}\text{original cross-sectional} \\ \text{area of the unnotched bar}\end{matrix}\right\}} \tag{3}$$

$$k_T = \frac{\left\{\begin{matrix}\text{area under stress–strain} \\ \text{curve for unnotched bar}\end{matrix}\right\} \times \left\{\begin{matrix}\text{residual cross-sectional} \\ \text{area at the notch site}\end{matrix}\right\}}{\left\{\begin{matrix}\text{area under stress–strain} \\ \text{curve for notched bar}\end{matrix}\right\} \times \left\{\begin{matrix}\text{original cross-sectional} \\ \text{area of unnotched bar}\end{matrix}\right\}} \tag{4}$$

The notch sensitivity factor for strength is k_s, and the notch sensitivity factor for energy to fracture is k_T. If a notch has no effect, the notch sensitivity factors are 1.0. If a notch has a detrimental effect, the notch sensitivities are greater than 1.0. Thus, a low value for the notch sensitivities is desirable. Since the notch sensitivity factors are ratios, the absolute values are cancelled out. Thus, the notch sensitivity factors indicate the *relative* detrimental effect of a notch on the properties of a given material. In some cases, a material with a high notch sensitivity could be stronger (or tougher) in the notched state than another material with a low notch sensitivity which had a low strength to start with in the unnotched state. The two notch sensitivity factors k_S and k_T are always different. For polymers which neck, k_T may be somewhat ambiguous, especially in the case where the necked region fills only part of the specimen between the extensometer grips.

The data show a number of effects, some of which were unexpected. In addition to decreasing both the strength and the energy to fracture, notches

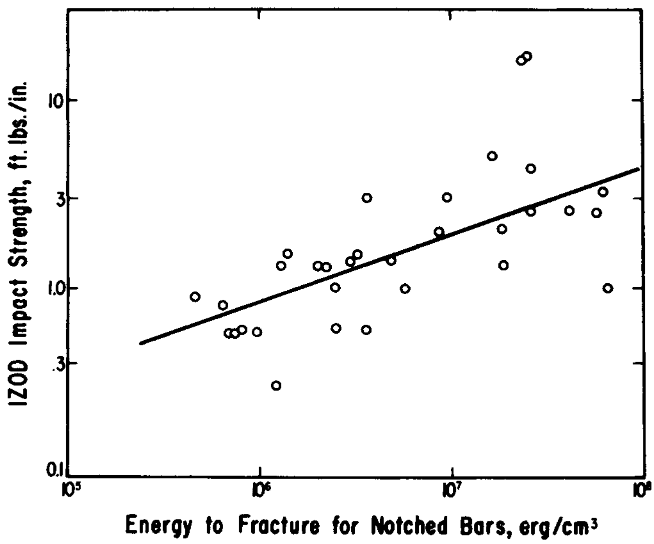

Fig. 10. Correlation of Izod impact strength with energy to fracture of notched specimens. Notch #3 with a stress concentration factor of 8.08 was used.

in many cases change the mode of fracture from ductile to brittle behavior. Some of the effects can be explained in terms of the three major effects of notches: (1) Notches act as stress concentrators so that the stress in the bar is nonuniform. (2) The strain rate at the tip of the notch is greater than the strain rate elsewhere in the bar. (3) The notches change the nature of the stress field from a uniaxial tensile stress to a triaxial stress in the region of the notch. Bars with a single notch tend to bend, so there is a tearing action not found with the symmetrical double-notched specimens.

The effect of the stress concentration due to notches is shown for a typical brittle material in Figure 1. Both the tensile strength and the elongation to break decrease as the notch severity factor increases. For such polymers, the tensile strength decreases faster than the decrease in cross-sectional area as the depth of the notches is increased. This is in sharp contrast to the effect of notches on a typical ductile polymer such as shown in Figure 2. The greatest effect of notches on ductile polymers is generally the great decrease in elongation to break and the area under the stress–strain curve. The effect on yield strength is less. Often the decrease in yield strength is less than the decrease in cross-sectional area as the depth of the notches is increased. This is illustrated in Figure 2.

For a given notch geometry, the notch sensitivity factor for strength, k_S, is greater for a single notch than for a double notch. This generally agrees with the notch severity factors. However, even at equal notch severity factors, a single notch usually gives a greater k_S than a double notch. The notch sensitivity factor for energy to fracture, k_T, generally increases also with the notch severity factor. However, sometimes there are reversals in which a dull notch (notch #6) gives a larger k_T than a sharp notch (notch #3) which has a higher notch severity factor. Teflon is an outstanding example, but other examples include such ductile polymers as the nylons, ABS, HDPE, PTMT, PET, Formvar, and the ionomer. Brittle polymers occasionally showing this be-

TABLE I
Types of Notches

Notch Number	Radius of Notch Tip	Depth of Notch	Mode	Severity of Notch, k
1	0.01"	0.05"	single	5.48
2	0.01"	0.05"	double	5.64
3	0.01"	0.125"	single	8.08
4	0.01"	0.125"	double	4.45
5	0.06"	0.125"	single	3.89
6	0.06"	0.125"	double	2.05

TABLE II
Polymers and Their Izod Impact Strengths

Polymer and Manufacturer	Impact Strength (ft lbs./in. notch)
Polystyrene, PS, Monsanto	0.3
Polymethyl methacrylate, PMMA, Rohm & Haas	0.3
Styrene-Acrylonitrile Copolymer, SAN, Monsanto	0.6
Polypropylene, PP, Diamond Shamrock	0.6
Polytetramethylene terephthalate, PTMT, Eastman	1.0
High impact polystyrene, HIPS, Monsanto	1.0
Nylon 66 (dry), Monsanto	1.0
Zytel® 408, du Pont	2.5
Nylon 6 (dry), Allied Chemical	1.2
Polysulfone, Union Carbide	1.3
Polyoxymethylene, POM, du Pont	1.4
Rigid polyvinyl chloride, PVC, Diamond Shamrock	2.6
Teflon®, du Pont	4.3
ABS, Monsanto	5.0
Polycarbonate, PC, Mobay	16.0
High density polyethylene, HDPE, Monsanto	-
Polyethylene terephthalate, PET, Goodyear	-
Polyvinyl butyral, Butrar,® Monsanto	-
Polyvinyl formal, Formvar,® Monsanto	-
Polyphenylene oxide, PPO, Gen. Elect.	-
Polyethylene ionomer, Surlyn® 1559, du Pont	-
Hytrel® 6355, du Pont	-
Thermoplastic rubber, TPR 1900, Uniroyal	-
Styrene-butadiene block polymer, Kraton, Shell	-
EPDM rubber, du Pont	-
SAN + 20% glass fibers, Fiberfil	0.8
PTMT + 20% glass fibers, Eastman	1.0
PP + 20% glass fibers, Thermofil	1.5
HDPE + 40% glass fibers, LNP Corp.	1.3
Nylon 66 + calcined clay	1.3
Nylon 66 + 33% glass fibers, du Pont	3.0

TABLE III
Mechanical Properties of Unnotched Plastic Bars

Plastics:	Strength and Elongation:				Energy:		Modulus:
	Yield $\sigma_y \times 10^{-8}$: (dyn/cm²)	ε_y: (%)	Break $\sigma_u \times 10^{-8}$: (dyn/cm²)	ε_u: (%)	Yield $E_y \times 10^{-7}$: (erg/cm³)	Break $E_u \times 10^{-7}$: (erg/cm³)	(dyn/cm²)
PMMA			6.22	3.7 ± 1.5		1.49	2.93×10^{10}
PS			5.02	1.9 ± 0.3		0.58	3.57×10^{10}
SAN			6.98	2.4 ± 0.1		0.92	3.80×10^{10}
HIPS	2.41	1.4	2.63	35.8 ± 7.0	0.29	8.26	3.06×10^{10}
ABS	4.40	2.3	2.69	32.9 ± 0.7	0.73	12.61	3.65×10^{10}
HDPE	2.57	18.6	0.89	470. ± 96.	3.89	94.77	1.48×10^{10}
-annealed at 127°C for 72 hrs.	2.52	10.8	2.07	715. ±	2.61	152.45	1.37×10^{10}
Polypropylene	3.26	4.8	2.00	64.7 ± 30.3	1.80	16.04	2.14×10^{10}
Polyoxymethylene			5.63	5.8 ± 1.2		2.34	2.82×10^{10}
Rigid PVC	4.68	4.0	3.39	88.7 ± 4.4	1.18	35.15	2.82×10^{10}
Polycarbonate M-50	5.71	6.4	6.47	108. ± 8.5	2.54	53.84	3.54×10^{10}
Polysulfone	7.20	5.6	5.14	76.2 ± 21.1	3.05	41.17	4.24×10^{10}
PTMT	4.56	16.3	4.33	267. ± 1.0	6.44	98.46	2.38×10^{10}
PET - transparent	5.04	3.4	3.87	306. ±	1.31	96.84	2.74×10^{10}
- semi-transparent	5.84	4.1	4.28	540. ±	-	225.94	3.12×10^{10}
Teflon - 0°	1.01	28.1	0.41	95.8 ± 16.0	2.58	9.28	1.07×10^{10}
- 90°	0.93	3.4	0.13	34.5 ± 2.8	0.27	2.63	1.36×10^{10}
Polyphenylene oxide	5.62	6.5	4.77	79.2 ±	2.50	36.26	2.44×10^{10}
Formvar	6.35	4.9	5.40	57.2 ± 6.1	2.29	30.96	4.91×10^{10}
Butvar	4.39	3.2	2.42	72.6 ± 4.3	0.92	25.58	3.19×10^{10}
Nylon 6 - dried	5.03	18.7	5.20	166. ± 35.	9.77	77.29	3.32×10^{10}
Nylon 6 - 1.21% H_2O	3.64	28.9	4.91	196. ± 2.8	8.78	74.98	1.52×10^{10}
-10.29% H_2O	2.08	39.2	3.50	193. ± 22.	5.86	46.00	0.44×10^{10}
Nylon 66 - 0.56% H_2O	7.30	23.5	5.72	73.1 ±	14.93	46.91	2.67×10^{10}
Nylon 66 - 2.23% H_2O	5.14	23.3	5.00	245. ± 1.	10.14	121.82	1.61×10^{10}
Nylon 66 - 0% H_2O	7.83	20.0	6.21	101. ± 33	13.2	67.8	3.25×10^{10}
Nylon 66 - 7.47% H_2O	3.37	50.0	4.65	234. ± 8.	14.1	83.2	
EPDM rubber			0.133	198 ± 18		1.55	0.14×10^{8}
Ionomer, Surlyn 1559	1.69	81	1.55	86 ± 13	10.7	11.9	0.30×10^{10}
TPR-1900	0.50	136	0.30	149 ± 39	5.8	6.4	0.13×10^{10}
Kraton 1101	0.17	42	≥ 0.81	≥ 692 ± 23	0.64	≥ 20.1	0.30×10^{9}
Hytrel 4055	0.62	51	1.69	606 ± 0	2.44	62.0	0.58×10^{9}
Hytrel 6355	1.78	29	2.82	354 ± 71	2.72	70.6	0.28×10^{10}
SAN + 20% Glass			7.47	1.18 ± 0.04		0.46	6.66×10^{10}
PP + 20% Glass	3.52	1.37	3.12	1.52 ± 0.03	0.32	0.37	4.72×10^{10}
PTMT + 20% Glass			9.33	2.07 ± 0.18		1.17	7.09×10^{10}
HDPE + 40% Glass	3.54	0.95	3.50	0.97 ± 0.20		0.23	7.65×10^{10}
Nylon 66 + Minerals			7.18	8.12 ± 1.10		4.87	5.22×10^{10}
- Vac. Dried at 71°C			8.39	4.88 ± 2.73		3.52	
- Soaked in Water (3.66 % Water)			5.21	30.9 ± -		13.98	2.64×10^{10}
Nylon 66 + 33% Glass			9.97	3.01 ± 0.24		2.10	7.52×10^{10}
(3.03% Water)			6.62	3.43 ± 0.25		1.63	8.68×10^{10}

TABLE IV
Yield or Breaking Strength of Notched Plastic Bars

	Types of Notches (Re. Table I)					
Plastics	#1	#2	#3	#4	#5	#6
PMMA	1.72*	1.90*	0.99*	1.16*	1.77*	1.90*
PS	3.40*	3.33	2.13	2.17	2.12	2.12
SAN	2.88*	3.33*	1.93	2.07	1.80	2.15
HIPS	2.35	2.23	1.78	1.43	1.95	1.45*
ABS	3.92	3.83	2.99	2.40	3.17	2.28
HDPE	2.42	2.36	2.19	1.76	2.15	1.64
- annealed at 127°C for 72 hrs.	2.56	2.49	2.12	1.64	2.31	1.57
Polypropylene	2.83*	2.85*	1.88*	1.76	2.12	1.80
Polyoxymethylene	5.09*	5.18*	3.35*	3.01*	3.57*	3.28*
Rigid PVC	4.33	4.09	3.42	2.78	3.41	2.65
Polycarbonate M-50	5.17	5.09	3.80	3.36	4.01	3.21
Polysulfone	4.02*	3.85*	2.29*	2.50*	4.70	3.89
PTMT	4.34	4.29	3.51	2.88	3.60	2.83
PET - transparent	4.46	4.46	2.99	2.97*	3.41	3.31
- semi-transparent	5.25	5.32	3.26*	3.52	3.39	3.63
Teflon - 0°	1.00	0.94	0.81	0.61	0.84	0.60
- 90°	0.88	0.86	0.75	0.59	0.73	0.56
Polyphenylene oxide				2.91		1.90
Formvar	5.83	5.91	4.46	3.91	4.85	3.67
Butvar	4.09	4.11	3.24	2.74	3.12	2.60
Nylon 6 - dried		4.36		3.23		3.13
- 1.21% H_2O	3.43	3.31	2.93	2.43	3.10	2.50
- 10.29% H_2O		1.86		1.24		1.25
Nylon 66 - 0.56% H_2O	6.34*	6.34*	3.83*	3.98*	4.46	3.22*
EPDM rubber	0.063	0.063	0.047	0.040	0.073	0.055
Ionomer, Surlyn	1.35	1.29	1.04	0.91	1.15	0.96
TPR-1900	0.45	0.42	0.38	0.32	0.42	0.34
Kraton-1101	0.25	> 0.23	0.17	0.16	> 0.26	> 0.24
Hytrel 4055	> 0.84	0.87	0.70	0.47	0.81	0.72
Hytrel 6355	1.72	1.62	1.38	1.16	1.50	1.11
SAN + 20% Glass	4.39*	4.21*	2.62*	2.67*	2.95	3.17
PP + 20% Glass	2.83	2.72	1.98	1.63	2.04	1.71
PTMT + 20% Glass	5.90	6.29	3.76	3.53	4.24	4.51
PE + 40% Glass	2.49	2.55	1.76	1.73	1.94	1.78
Nylon 66 + Mineral	5.33*	5.20*	2.96	3.05	4.45	3.92
Nylon 66 + 33% Glass (Dry)	6.92	6.85	4.44	4.33	5.03*	5.16
- Wet (3.03% Water)		4.81		3.12		3.48

*Brittle fracture was observed.

Units of strength are 10^8 dynes/cm^2.

TABLE V
Notch Sensitivity Factors for Strength

	Types of Notches (Re. Table I)					
Plastics	#1	#2	#3	#4	#5	#6
PMMA	3.26	2.62	4.71	2.68	2.64	1.64
PS	1.33	1.21	1.77	1.16	1.78	1.18
SAN	2.18	1.68	2.71	1.69	2.91	1.62
HIPS	0.92	0.87	1.01	0.84	0.93	0.83
ABS	1.01	0.92	1.10	0.92	1.04	0.96
HDPE	0.96	0.87	0.88	0.73	0.90	0.78
-annealed at 127°C for 72 hrs.	0.89	0.81	0.89	0.77	0.82	0.80
Polypropylene	1.04	0.92	1.30	0.93	1.15	0.91
Polyoxymethylene	1.00	0.87	1.26	0.94	1.18	0.86
Rigid PVC	0.97	0.92	1.03	0.84	1.03	0.88
Polycarbonate M-50	0.99	0.90	1.13	0.85	1.07	0.89
Polysulfone	1.61	1.50	2.36	1.44	1.15	0.93
PTMT	0.94	0.84	0.96	0.78	0.94	0.81
PET - transparent	1.02	0.90	1.26	0.85	1.11	0.76
- semi-transparent	1.00	0.88	1.34	0.83	1.29	0.80
Teflon - 0°	0.91	0.86	0.94	0.83	0.90	0.84
- 90°	0.95	0.87	0.93	0.79	0.96	0.83
Polyphenylene oxide				0.97		1.48
Formvar	0.98	0.86	1.07	0.81	0.98	0.87
Butvar	0.97	0.85	1.02	0.80	1.06	0.84
Nylon 6 - dried		0.92		0.78		0.80
- 1.21% H_2O	0.96	0.88	0.93	0.75	0.88	0.73
- 10.29% H_2O		0.90		0.84		0.83
Nylon 66 - 0.56% H_2O	0.96	0.86	1.33	0.85	1.14	1.05
EPDM rubber:	1.90	1.69	2.12	1.66	1.37	1.21
Ionomer Surlyn	1.13	1.05	1.22	0.93	1.10	0.88
TPR-1900	1.00	0.95	0.99	0.78	0.89	0.74
Kraton-1101	2.92	< 2.82	3.68	2.61	< 2.34	< 1.69
Hytrel 4055	< 1.90	0.64	0.71	0.99	0.57	0.43
Hytrel 6355	0.93	0.88	0.97	0.77	0.89	0.80
SAN + 20% Glass	1.53	1.42	2.14	1.40	1.91	1.20
PP + 20% Glass	1.12	1.04	1.33	1.08	1.29	1.03
PTMT + 20% Glass	1.42	1.19	1.86	1.32	1.65	1.03
PE + 40% Glass	1.28	1.11	1.51	1.02	1.37	0.99
Nylon 66 + minerals	1.21	1.10	1.82	1.18	1.21	0.92
Nylon 66 + 33% Glass (Dry)	1.30	1.16	1.68	1.15	1.49	0.97
- Wet (3.03% Water)		1.11		1.07		0.96

TABLE VI
Energy Required to Fracture Notched Plastic Bars

	Types of Notches (Re. Table I)					
Plastics	#1	#2	#3	#4	#5	#6
PMMA	0.059	0.081	0.024	0.030	0.077	0.122
PS	0.22	0.27	0.12	0.14	0.19	0.12
SAN	0.15	0.18	0.08	0.15	0.07	0.09
HIPS	0.69	0.60	0.58	0.35	0.58	0.54
ABS	2.14	1.98	1.65	0.79	1.50	1.07
HDPE	16.72	9.70	8.80	3.58	11.40	4.07
- annealed at 127°C for 72 hrs.	20.94	13.34	15.86	5.28	19.30	5.63
Polypropylene	0.54	0.67	0.2	0.23	0.42	0.43
Polyoxymethylene	1.37	1.95	0.49	0.41	0.64	0.73
Rigid PVC	6.98	3.92	4.15	1.81	4.84	3.06
Polycarbonate M-50	7.82	2.73	2.47	1.23	3.75	2.64
Polysulfone	0.36	0.33	0.13	0.17	3.51	2.44
PTMT	13.06	7.33	6.65	2.33	10.27	3.93
PET - transparent	11.89	5.91	6.48	0.34	8.89	3.49
- semi-transparent	9.73	4.69	0.27	0.60	4.85	3.87
Teflon - 0°	4.26	2.32	2.64	0.94	2.86	1.10
- 90°	1.63	1.66	1.98	0.47	1.41	0.50
Polyphenylene oxide				0.50		0.53
Formvar	5.53	3.87	2.93	1.32	4.45	2.26
Butvar	5.67	3.67	3.80	1.47	4.99	2.73
Nylon 6 - dried		7.80		2.92		3.20
- 1.21% H_2O	15.19	11.70	9.01	3.87	13.77	7.85
- 10.29% H_2O		5.41		1.97		3.61
Nylon 66 - 0.56% H_2O	1.88	0.94	0.58	0.46	1.52	0.29
EPDM rubber:	0.28	0.24	0.13	0.097	0.45	0.28
Ionomer Surlyn 1559	6.39	4.85	3.04	1.52	4.85	2.32
TPR-1900	5.68	2.79	2.43	1.02	3.80	1.84
Kraton-1101	~ 7.79	~ 6.57	1.73	1.47	> 8.32	> 8.29
Hytrel 4055	> 19.48	> 16.42	14.61	3.89	21.24	14.64
Hytrel 6355	15.06	9.14	10.04	3.20	20.84	12.69
SAN + 20% Glass	0.16	0.15	0.063	0.079	0.084	0.141
PP + 20% Glass	0.40	0.26	0.32	0.16	0.31	0.21
PTMT + 20% Glass	0.39	0.48	0.25	0.23	0.30	0.37
PE + 40% Glass	0.12	0.19	0.20	0.20	0.28	0.24
Nylon 66 + Minerals	0.60	0.63	0.22	0.20	0.56	0.59
Nylon 66 + 33% Glass: (Dry)	0.73	0.81	0.36	0.31	0.29	0.60
- Wet (3.03% Water):		0.76		0.43		0.54

Units of energy of fracture are 10^7 ergs/cm^3.

TABLE VII
Notch Sensitivity Factors for Energy to Fracture

	Types of Notches (Re. Table I)					
Plastics	#1	#2	#3	#4	#5	#6
PMMA	22.7	14.7	47.6	25.3	14.5	6.10
PS	2.38	1.71	3.65	2.13	2.37	2.37
SAN	5.63	4.02	8.50	3.15	10.12	4.88
HIPS	10.71	10.94	10.71	11.97	10.64	7.62
ABS	5.30	5.09	5.75	8.02	6.33	5.90
HDPE	5.10	7.81	8.08	13.23	6.24	11.64
-annealed at 127°C for 72 hrs.	6.55	9.14	7.21	14.44	5.93	13.55
Polypropylene	26.53	19.26	47.73	34.56	28.64	18.87
Polyoxymethylene	1.54	0.96	3.58	2.88	2.75	1.61
Rigid PVC	4.53	7.17	6.35	9.71	5.45	5.74
Polycarbonate M-50	6.20	15.77	16.37	21.83	10.76	10.18
Polysulfone	102.64	99.81	241.23	118.99	8.80	8.44
PTMT	6.79	10.75	11.10	21.13	7.19	12.53
PET - transparent	7.33	13.11	11.21	142.41	8.17	13.87
- semi-transparent	20.90	38.53	625.30	187.66	34.98	29.20
Teflon - 0°	1.96	3.20	2.64	4.93	2.44	4.22
- 90°	1.45	1.27	1.00	2.79	1.40	2.65
Polyphenylene oxide				36.19		34.40
Formvar	5.04	6.40	7.92	11.73	5.22	6.85
Butvar	4.06	5.58	5.05	8.70	3.84	4.68
Nylon 6 - *dried*		7.92		13.22		12.07
- 1.21% H_2O	4.44	5.13	6.24	9.69	4.08	4.78
- 10.29 H_2O		6.80		11.67		6.37
Nylon 66 - 0.56% H_2O	22.48	39.92	60.76	50.77	23.15	81.16
EPDM rubber	4.95	5.17	8.68	7.99	2.58	2.75
Ionomer Surlyn	1.67	1.96	2.93	3.90	1.84	2.56
TPR-1900	1.01	1.84	1.98	3.14	1.26	1.74
Kraton-1101	2.32	2.45	8.71	6.83	< 1.81	< 1.21
Hytrel 4055	< 2.86	< 3.02	3.18	7.97	2.19	2.12
Hytrel 6355	4.34	6.36	5.43	11.37	2.62	2.86
SAN + 20% Glass	2.56	2.49	5.48	2.91	4.11	1.63
PP + 20% Glass	0.85	1.16	0.87	1.15	0.92	0.89
PTMT + 20% Glass	2.67	1.94	3.55	2.57	2.92	1.56
PE + 40% Glass	1.82	0.99	0.87	0.59	0.63	0.48
Nylon 66 + minerals	7.34	6.21	16.60	12.36	6.58	4.14
Nylon 66 + 33% Glass (dry)	2.59	2.07	4.39	3.34	5.40	1.74
-Wet (3.03% Water)		1.72		1.90		1.51

havior include polystyrene and SAN. The reason for the unexpected reversals is not clear, but it may be related to the volume of polymer under stress in the notched region. A dull notch has a larger volume of material under a reduced cross-sectional area than a sharp notch, so the probability of having a flaw in the volume under stress is greater with a dull notch.

Brittle polymers and composites with rigid fillers tend to have greater notch sensitivity factors for strength, k_S, than ductile polymers, but there is only a weak correlation with the elongation to break of the unnotched specimens. For ductile polymers, k_S is generally less than 1.0 for notches which give low stress concentrations (for example, notch #6), while for brittle polymers, k_S is generally greater than 1.0, even for notch #6. However, some elastomers, such as Kraton, EPDM, and ionomer, have unusually high k_S factors for sharp notches such as notch #3.

For *brittle* polymers, the notch sensitivity factor for energy to fracture, k_T, tends to increase with the elongation to break of the unnotched polymer. Examples include PS, PMMA, SAN, and SAN + glass fibers, but there are exceptions. The notch sensitivity k_T also tends to increase with the energy to fracture of the unnotched bars, i.e., notches generally are more detrimental to ductile polymers than to brittle ones as far as the energy to fracture is concerned. Again, there are exceptions.

For *ductile* polymers, the shape of the stress–strain curve has an influence on the notch sensitivity factor for energy to fracture. The upper yield strength σ_{yu} is the maximum value of the stress corresponding to the yield point. The lower yield strength σ_{yl} is the minimum value of the stress just after the yield point. As the ratio σ_{yu}/σ_{yl} decreases, k_T also tends to decrease. If the tensile strength is greater than the yield strength, or if there is an upturn in the stress (strain hardening) at the end of the stress–strain curve, these factors also help to decrease k_T. Some rubbers and elastomeric block polymers have all these characteristics, so they have very low k_T values. Figure 9 illustrates the characteristics of the stress–strain curve of ductile polymers which generally lead to high and low k_T values.

Chopped glass fibers and rigid fillers increase the notch sensitivity factor for strength compared to the value for the unfilled matrix for ductile matrices. However, the addition of glass fibers or fillers to either a brittle or ductile matrix greatly reduces the notch sensitivity factor for energy to fracture compared to the unfilled matrix. The reason appears to be that there are so many stress concentrators resulting from the filler particles that the extra stress concentration from the notch is of less importance than normal. Also, in the case of fibers, the pulling out of the fibers from the matrix enables the composite to have extra energy-absorbing capacity.

Adding a rubber phase to either a brittle or ductile matrix, as in polyblends, reduces k_S in nearly all cases when compared to the unfilled matrix. Examples include PS versus HIPS, SAN versus ABS, and nylon polyblends. The situation is more complex in regard to k_T. The addition of rubber may either increase or decrease the notch sensitivity factor for energy to fracture.

Notch sensitivity is an extremely complex property which is influenced by many factors in addition to the chemical structure of the polymers. These factors include the method of fabrication and the molecular orientation, the moisture content, the thermal history, and the crystallinity of the specimens. Because of the practical importance of notch sensitivity and our lack of knowledge to accurately predict k_S and k_T, we strongly recommend that notched stress–strain specimens be routinely measured along with unnotched specimens. The results presented here indicate that some very tough engineering plastics have a very high notch sensitivity and may become brittle under the influence of a sharp notch or cut. Design engineers and others should have such information available.

Impact strength of plastics is another very complex property. There is no correlation of notched Izod impact strength with the energy to fracture (area under stress–strain curve) for unnotched bars. However, Figure 10 shows that there is a general trend for the Izod impact strength to increase with an increase in the energy to fracture of notched bars. The correlation is not very good, even with notched bars. The correlation might not be expected to be too good because of the low strain rate of the stress–strain tests compared to impact tests.

Jerry Sugerman molded most of the test bars. R. J. Tetreault, J. C. Woodbrey, and C. W. Bulkley also prepared some of the specimens.

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