"Mechanical testing may give insights into the behavior of polymers during forming processes or in service."

Mechanical Testing of Solid Polymers*

by

Dr. –Ing. Adolfo Jesus R. Gopez

ABSTRACT

Standard tests for polymer mechanical properties are designed for use with easily available or easily constructed apparatus to allow widespread use of such tests. Properties measured are often used for design purposes and these properties are threshold or extremal values. No real effort is made to compare materials at intermediate testing stages. Non-standard tests such as the tensile test at constant true strain rate and the plane simple shear test are therefore used to explore the plastic deformation behavior of solid polymers. Strain rate and temperature effects have been explored to establish constitutive equations of flow for some polymers while the mechanism of plastic deformation in glassy polymers has been explored. A comparison between amorphous and semi-crystalline polymers from the point of view of mechanical properties is made. Some aspects of plastic instability in polymers are also discussed.

INTRODUCTION

Objectives

This paper has three principal objectives:

a) to describe the major testing methods used to determine the mechanical properties of solid polymers;

b) to describe some of the methods used in studying the plastic deformation behavior of solid polymers; and

c) to discuss some aspects of research in plastic deformation of solid polymers.

Background Information

Some information on the nature of polymers and the associated nomenclature is provided in this section.

Polymers may be classified with respect to their microstructure as amorphous or semi crystalline (Van Vlack, 1975). Due to the long molecules found in polymers, it is practically impossible to have a completely crystalline polymer. Crystallization takes place by the folding and rearrangement of molecular chains (Kovacs, 1982). The longer the molecular chain, the slower this process is. The

---

*Paper delivered at the ASEAN-EEC Seminar-Workshop on Materials Science, "Ceramics and Polymers Research and Development," February 9-13, 1987, Cebu Plaza Hotel, Cebu City, Philippines. Cooperating Agencies: N.S.T.A., P.C.I.E.R.D. and M.S.R.I.

highest degree of crystallinity obtained so far is 98 percent for high density polyethylene (HDPE). Due to the higher packing factors of crystallized structures, it may be said that the density of polymers increases as crystallinity of the structure increases.

The crystallinity of a polymer depends on the cooling rate or the time given to the molecular chains for folding and rearrangement. For some polymers, even very slow cooling fails to produce crystallization. These polymers are classified as amorphous. One notable example is polycarbonate.

Polymer microstructures are usually determined by microscopic inspection and x-ray diffraction. Microscopic examination of thin polymer films with a polarizing microscope reveals spherulites in semi-crystalline polymers. Spherulites are spherical groups of radially-oriented crystallites tied together by amorphous arrangements of molecular chains. They are the rough equivalents of grains in metals (see Figure 1). Amorphous polymers have no spherulites.

X-ray diffraction confirms whether polymers are amorphous or not. Wide angle diffraction by amorphous polymers yields two halos on the resulting pattern (Kakudo and Kasai, 1972).

Polymer mechanical properties are strongly time and temperature dependent. Consequently, polymers are often referred to as viscoelastic (Ferry, 1970). They have a viscous (time dependent) response and an elastic (instantaneous) response, with the amount of viscous response decreasing with temperature. At low temperatures, polymers are described as glassy (the amorphous phase has the characteristics of a hard solid) while at intermediate temperatures, they may be described as rubbery. At high temperatures, they behave rather like viscous liquids.

Polymer testing is very often done at or close to room temperature where most of the applications are made. At this temperature, the polymer is considered to be a solid in the same category as a metal in the solid state. This is is not entirely true since polymers do have some viscoelastic response at this temperature range. This response may in many cases be considered to be negligible. For the sake of accuracy, tests can be done to determine the viscoelastic properties of polymers even at relatively low temperatures (see for example, Ferry, 1970). These tests, however, are not within the scope of this paper.

In the succeeding discussion, polymers at low temperatures will be considered to be solids with negligible viscoelasticity. As such, the deformation resulting from stress application may be defined as elastic or plastic depending on whether there is residual strain or not. Elastic deformation may be defined as strain, which, upon the removal of the applied stress is recovered instantaneously or shortly thereafter. A rule of thumb is 1,000 seconds or 15 minutes after stress removal (see for example, Boni, 1981 and Gopez, 1983). If more than 15 minutes after the removal of stress the specimen still displays some residual strain, this is referred to as plastic strain.

Definition of Terms

For purposes of standardization terms pertaining to polymers have been defined by ASTM D883 while terms pertaining to mechanical testing are defined by Annex Al of ASTM D638. Some of the terms are repeated here for clarity.

polymer, n——a substance consisting of molecules characterized by the repetition (neglecting ends, branch junctions and other minor irregularities) of one or more types of monomeric units. (IUPAC) (1971)

plastic, n——a material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or processing into finished articles, can be shaped by flow.

Note 1——Rubber, textiles, adhesives and paint, which may in some cases meet this definition, are not considered plastics. See ASTM definitions of these terms.

thermoplastic, n——a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion, (1969)

thermoset, n——a plastic that, after having been cured by heat or other means, is substantially infusible and insoluble. (1973)

viscosity——the property of resistance of flow exhibited within the body of a material.

creep, n——the time-dependent part of strain resulting from stress.

glass transition——the reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.

glass transition temperature (Tg)——the approximate midpoint of the temperature range over which the glass transition takes place.

tensile strength (nominal)——the maximum tensile stress (nominal) sustained by the specimen during a tension test. When the maximum stress occurs at the yield point, it shall be designated Tensile Strength at Yield. When the maximum stress occurs at break, it shall be designated Tensile Strength at Break.

gage length——the original length of that portion of the specimen over which strain or change in length is determined.

elongation——the increase in length produced in the gage length of the test specimen by a tensile load. It is expressed in units of length, usually millimeters (or inches). (Also known as extension).

modulus of elasticity——the ratio of stress (nominal) to corresponding strain below the proportional limit of a material. It is expressed in force per unit area, usually megapascals (or pounds-force per square inch) (Also known as elastic modulus or Young's modulus).

necking——the localized reduction in cross-section which may occur in a material under tensile stress.

strain——the ratio of the elongation to the gage length of the test specimen, that is, the change in length per unit of original length. It is expressed as a dimensionless ratio.

yield point——the first point on the stress-strain curve at which an increase in strain occurs without an increase in stress.

yield strength——the stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. Unless otherwise specified, this stress will be the stress at the yield point and when expressed in relation to the Tensile Strength shall be designated either Tensile Strength at Yield or Tensile Stress at Yield.

offset yield strength——the stress at which the strain exceeds by a specified amount (the offset) an extension of the initial proportional portion of the stress-strain curve. It is expressed in force per unit area, usually megapascals (or pounds-force per square inch). (See Figure 2)

Table 1.
Standard ASTM tests for determining strength of plastics and composites
(*Guide to Engineered Materials*. 1986)

Properties	Test	Description
Compressive	D 695	To determine compressive strength and modulus (most common), deformation, strain, slenderness ratio, crushing load, etc. of rigid plastics.
Creep	D2990	Tensile, compressive and flexural creep; creep rupture of plastics for determination of creep modulus, strain, and creep rupture strength.
Flexural	D 790	To determine how a material resists bending (a combination of compression and tension). Flex strength and modulus used to indicate the stiffness of rigid/ semirigid plastics. For advanced composites, 3-point method recommended for ultimate flex strength and flex modulus. At elevated temperatures, 4-point method minimizes specimen crushing.
Flexural	D 229	To determine the flexural properties of electrical insulating materials (rigid sheet and plate) at and above room temperature.
Interlaminar shear strength	D2344	To determine short-beam shear strength (interlaminar shear strength) at failure of reinforced plastics. Variety of failure modes possible.
Interlaminar shear strength	D2733	To determine ILSS of structural reinforced plastics at elevated temperatures.
Shear	D 732	To determine shear strength of a material. Most applicable to film and sheet.
Shear	D3518	For unidirectional reinforced plastics, details methods for determining ultimate shear strength and stress-strain properties of in-plane shear.
Stiffness	D1043	Torsion test determines stiffness properties of plastics as a function of temperature. Measures apparent modulus of rigidity (apparent shear modulus of elasticity).
Stress relaxation	D2991	To determine time-dependent stress reduction at constant deformation.
Tensile	D 638	To determine tensile strength at yield or break, modulus of elasticity, and per cent elongation at yield or break.
Tensile	D3039	To determine tensile properties of oriented fiber composites. Includes procedure for determining Poisson's ration.
Tensile	D2585	Preparation and tensile testing of filament-wound pressure vessels.
Tensile	D2290	To determine apparent tensile strength of ring or tubular high-modulus composites (extruded or molded) by the split disk method.

Table 2.
Tests for fatigue resistance of plastics/composites
(*Guide to Engineered Materials*, 1986)

Test	Designation	Description
Flexural fatigue	ASTM D 671	Fatigue strength of plastics is determined by testing specimens on a fixed-cantilever machine that provides a constant amplitude of force each cyle. Frequency of testing is typically 30 Hz. Tests are run at various loads (stress amplitudes) to produce failure (at log of cycles=4, 5, 6, and 7). S-N curve is plotted from resulting data.
Tension-tension fatigue	ASTM D3479	Test for oriented high-modulus composites to determine constant-amplitude tension-tension fatigue properties. Testing is recommended at a minimum of 5 stress or strain levels to plot stress or strain vs. log of cycles to failure. In Method A, test specimen is cycled between two tensile loads; Method B, between two tensile strain limits. Cyclic rates from 900 to 3600 cpm are typical. Max stress (or strain) vs. log of cycles to failure.

ASTM designations refer to standard test methods developed by the American Society for Testing and Materials.

STANDARD TESTS FOR DETERMINING STRENGTH OF POLYMERS

Mechanical Properties Determined Through Standard Tests

Tables 1, 2 and 3 provide a summary of the mechanical properties of polymers which are determined through standard (ASTM) tests. Typical data sheets on polymers are given by Tables 4A & 4B. In many cases when industrial polymers are furnished, a table of properties is also given by the manufacturer. These other properties may strongly affect polymer mechanical properties. Environmental conditions such as moisture, humidity, ultraviolet rays and/or chemicals and solvents may drastically affect the performance of a polymer. Additives for flame retardancy, for easier processing, for color or other purposes, usually decrease the strength of polymers. On the other hand, reinforcements such as glass fiber or carbon fiber may improve strength. Temperature effects as discussed in the Introduction affect strength greatly. Amorphous polymers cannot be used above the glass transition temperature T_g while semi-crystalline polymers can be used close to melting temperature, T_m. For many applications under load, however, the deflection temperature under load (DTUL) may be the service limit. Standard tests to account for many of the aforementioned factors have also been developed. However, they are not within the scope of this paper.

In general, it may be stated that standard tests:

a) are designed to make use of easily available (or easily constructed) equipment so the tests can be as widespread as possible;
b) are used to measure properties which are threshold or extremal values and therefore easily

measured (there is no real effort to compare materials at intermediate stages in the testing);

c) are used in order to obtain design data.

In designing with polymers it must be kept in mind that some other information aside from what is available may be needed. For instance polymers have higher creep than metals so for applications at constant load, creep data may be required. For applications with imposed strain, stress relaxation data will be needed. For fatigue applications, polymers have no endurance limit, while in some cases, such as weight saving, specific properties may even give polymers an advantage. For stiffness requirements, the flexural (bending) modulus is usually taken instead of the Young's modulus.

Table 3.
Standard tests for measuring
toughness of plastics/composites
(*Guide to Engineered Materials*, 1986)

Test	Designation	Description
Brittleness temperature	ASTM D 746	Test used to determine temperature at which plastics and elastomers exhibit brittle failure under impact.
Falling weight	ASTM D3029	Impact resistance indicated by energy to break or crack rigid plastics by means of a falling weight (tup). Procedure recommends constant height, variable weight.
Falling weight	ASTM D1709	Similar to D 3029 but for measuring impact resistance of polyethylene film by free falling dart.
Falling weight	ASTM D2444	Test for impact resistance or thermoplastic pipe and fittings by falling weight (tup).
Fracture toughness	ASTM E 399	Covers test method to determine plane strain fracture toughness.
High-rate/stress strain (tension)	ASTM D2289	Area under stress-strain curve corresponds to measure of impact resistance at testing speeds up to 10,000 in./min.
Izod impact	ASTM D 256	Energy to break a notched (cantilever beam) specimen upon impact by a pendulum. Notch tends to promote brittle failure. "Unnotched" impact strength is obtained by reversing the notched specimen in the vise. Notch sensitivity can be determined by using Method D. (Charpy impact testing is also covered in this test method).
Tensile impact	ASTM D1822	Recommended for plastic materials that are too flexible, too thin or too rigid to be tested by ASTM D 256. Measures energy to break by "shock in tension" imparted by a swinging pendulum.

Table 4A. Sample property table for LEXAN. (Plastics Properties Guide, GE Plastics).

General Purpose Grades LEXAN® resin

Typical Property Values – English Units (SI Units)

PROPERTY	ASTM TEST METHOD	LEXAN 121 resin	LEXAN 1411 resin	LEXAN 141 resin	LEXAN 161 resin	LEXAN 101 resin	LEXAN 181 resin
PHYSICAL							
Specific Gravity	D792	1.20	1.20	1.20	1.20	1.20	1.20
Specific Volume, in^3/lb (cm^3/g)	–	23.1 (0.83)	23.1 (0.83)	23.1 (0.83)	23.1 (0.83)	23.1 (0.83)	23.1 (0.83)
Weight/Volume, lbs/in^3 (g/cm^3)	–	0.043 (1.20)	0.043 (1.20)	0.043 (1.20)	0.043 (1.20)	0 043 (1.20)	0.043 (1.20)
Water Absorption, %	D570						
24 hrs @ 73°F (23°C)		0.15	0.15	0.15	0.15	0.15	0.15
Equilibrium, 73°F (23°C)		0.35	0.35	0.35	0.35	0.35	0.35
Equilibrium, 212°F (100°C)		0.58	0.58	0.58	0.58	0.58	0.58
Mold Shrinkage, in/in (mm/mm)	D955	0.005-0.007	0.005-0.007	0.005-0.007	0.005-0.007	0.005-0.007	0.005-0.007
Light Transmittance, % at 0.125"	D1003	89	89	89	89	89	89
Haze, % @ 0.125"	D1003	1	1	1	1	1	1
Refractive Index	–	1.586	1.586	1.586	1.586	1.586	1.586
THERMAL							
Deflection Temperature °F (°C)	D648						
@ 66 psi (0.46 MPa)							
@ 264 psi (1.82 MPa)		265 ( )	270 ( )	270 ( )	270 ( )	270 ( )	275 ( )
Specific Heat, Btu/lb/°F (kJ/kg/°K)	–	0.30 (1.25)	0.30 (1.25)	0.30 (1.25)	0.30 (1.25)	0.30 (1.25)	0.30 (1.25)
Thermal Conductivity Btu-in/h-ft^2 °F(W/Km)	–	1.35 (.19)	1.35 (.19)	1.35 (.19)	1.35 (.19)	1.35 (.19)	1.35 (.19)
Coefficient of Thermal Expansion, in/in/°F (m/m/°C)	– D696	3.75×10^{-5} (6.75×10^{-5})	3.75×10^{-5} (6.75×10^{-5})	3.75×10^{-5} (6.75×10^{-5})	3.75×10^{-5} (6.75×10^{-5})	3.75×10^{-5} (6.75×10^{-5})	3.75×10^{-5} (6.75×10^{-5})
Vicat Softening Temperature, °F (°C)	D1525	305-315 (152-157)	305-315 (152-157)	305-315 (152-157)	305-315 (152-157)	305-315 (152-157)	305-315 (152-157)
Viscosity Midpoint (Melt Flow Rate) g/10 mm	D1238 Condition O	16.5	11.5	9.5	8.0	6.5	5.3
Brittleness Temperature, °F (°C)	D746	<-200 (<-129)	<-200 (<-129)	<-200 (<-129)	<-200 (<-129)	<-200 (<-129)	<-200 (<-129)
Flammability Ratings							
ASTM D635*	D635	AEB <1"	AEB <1"	AEB <1"	AEB <1"	AEB <1"	AEB <1"
UL Standard 94* 1/16" (1.6 mm)	UL94	V-2	V-2	V-2	V-2	V-2	V-2
UL Standard 94* 1/8" (3.2 mm)	UL94	V-2	V-2	V-2	V-2	V-2	V-2
Oxygen Index	D2863	25.0	25.0	25.0	25.0	25.0	25.0
ELECTRICAL							
Dielectric Strength, volts/ml (kV/mm) Short time, 125 mils (3.2 mm)	D149	380 (15.0)	380 (15.0)	380 (15.0	380 (15.0)	380 (15.0)	380 (15.0)
Dielectric Constant	D150						
60Hz		3.17	3.17	3.17	3.17	3.17	3.17
10°Hz		2.96	2.96	2.96	2.96	2.96	2.96
Power Factor	D150						
60Hz		0.0009	0.0009	0.0009	0.0009	0.0009	0.0009
10°Hz		0.010	0.010	0.010	0.010	0.010	0.010
Volume Resistivity, ohm-cm @ 73°F, dry (23°C)	D257	$>10^{16}$	$>10^{16}$	$>10^{16}$	$>10^{16}$	$>10^{16}$	$>10^{16}$
Arc Resistance, sec	D495						
Stainless Steel Electrodes		10-11	10-11	10-11	10-11	10-11	10-11
Tungsten Electrodes		120	120	120	120	120	120
MECHANICAL							
Tensile Strength, psi (MPa)	D638						
Yield		9.000 (62)	9.000 (62)	9.000 (62)	9.000 (62)	9.000 (62)	9.000 (62)
Ultimate		10.000 (69)	10.000 (69)	10.000 (69)	10.000 (69)	10.000 (69)	10.000 (69)
Elongation, %	D638						
Rupture		125	130	130	130	135	135
Flexural Strength, psi (MPa)	D790	14.000 (97)	14.000 (97)	14.000 (97)	14.000 (98)	14.000 (98)	14.000 (98)
Flexural Modulus, 10^5 psi (MPa)	D790	3.40 (2.300)	3.40 (2.300)	3.40 (2.300)	3.40 (2.300)	3.40 (2.300)	3.40 (2.300)
Compressive Strength, psi (MPa)	D695	12.500 (86)	12.500 (86)	12.500 (86)	12.500 (86)	12.600 (86)	12.500 (86)
Compressive Modulus, 10^5 psi (MPa)	D695	3.45 (2.400)	3.45 (2.400)	3.45 (2.400)	3.45 (2.400)	3.45 (2.400)	3.45 (2.400)
Shear Strength psi (MPa)	D732						
Yield		6.000 (40)	6.000 (40)	6.000 (40)	6.000 (40)	6.000 (40)	6.000 (40)
Ultimate		10.000 (70)	10.000 (70)	10.000 (70)	10.000 (70)	10.000 (70)	10.000 (70)
Shear Modulus, 10^5 psi (MPa)	–	1.14 (790)	1.14 (790)	1.14 (790)	1.14 (790)	1.14 (790)	1;14 (790)
Izod Impact Strength, ft-lbs/in (J/m)	D256						
Notched, ⅛" thick (3.2 mm)		13 (694)	14 (748)	15 (801)	16 (854)	17 (908)	18 (961)
Tensile Impact Strength, ft-lbs/m^2 (kJ/m^2)	D1822						
S type		225 (470)	250 (525)	275 (578)	290 (610)	300 (630)	320 (673)
Dynatop Impact Strength	D3763						
ft-lbs (J)		46 (62)	47 (64)	47 (64)	47 (64)	48 (65)	48 (65)
Fatigue Strength, psi @ 2.5 mm cycles (MPa)	D671	1.000 (7.0)	1.000 (7.0)	1.000 (7.0)	1.000 (7.0)	1.000 (7.0)	1.000 (7.0)
Rockwell Hardness	D785						
M		70	70	70	70	70	70
R		118	118	118	118	118	118
Deformation Under, Load %	D621						
4000 psi @ 73°F (27 MPa @ 23°C)		0.2	0.2	0.2	0.2	0.2	0.2
4000 psi @ 158°F (27 Mpa @ 70°C)		0.5	0.5	0.5	0.5	0.5	0.5
Taber Abrasion Resistance, weight loss, mg/1000 cycles	D1044	10	10	10	10	10	10

*This rating is not intended to reflect hazards of this or any other material under actual fire conditions.

TABLE OF PROPERTIES FOR SHEET MATERIALS

Table 4B. Sample property table for sheet products. (Cadillac Plastic)

These values are representative of those obtained under standard ASTM conditions and should not be used to design parts which function under different condition. Since they are average values, they should not be used as minimums for material specifications.

Property	Property Factor	Text Standard ASTM	Teflon PTFE Virgin	UHMW Virgin	Polypropylene Natural	Acrylic P Mid Cast	Lexan Polycarbonate Extruded	Polystyrene Hi-Impact	PVC Rigid	Polyurethane Thermoplastic	ABS Natural
Specific Gravity	1 = Water	D792	2.1-2.3	94	90-91	1.18-1.2	1.21	1.03-1.06	1.38	1.03-1.26	1.02-1.06
Density	lb/in^3	D792	.08	034	.033	.043	.044	.038	.05	.037-046	.038
Tensile Strength	PSI	D638 †	2000-5000	4000-6300	4000-6000	9000	8900-10500	2700-620	6000-6500	2000-8000	2500-8000
Elongation	%	D638 †	75-350	200-450	100-700	2-10	8-125	8-125	80-100	100-800	20-100
Compressive Strength 1%	PSI	D695	1700	–	3500-8000	14000-18000	10500-12500	10500-12500	8000-13000	20000	5200-10000
Flexural Strength	PSI	D790	No Break	–	5000-8000	12000-14000	13500	4500-8300	10000-16000	700-1000	4000-14000
Impact Strength, Izod	ft/lb/in of notch	D256A	3.0	No Break	4.10	3-5	14-17	.95-3.5	1.75-2	No Break	2.5-12
Hardness	Rockwell	D785	R10-20	R50-64	R80-100	M80-100	M62-R118	R50-100	R90-113	Share 70A-87A	R75-115
Thermal Conductivity	BTU in/hr/ft2°F	C177	1.73	–	1.22-2.8	1.30	1.34	3.0	4.0	–	–
Thermal Expansion	10-4 in/in °F	D696	5.5-7.5	7.2	5.8	4.5	3.75	–	–	–	–
Resistance To Heat °F	Continuous	–	500	180	200	160	200	140-175	160	180-200	140-160
Melt Point °F	°F	D1525	> 600	> 250	> 275	–	> 300	210-225	> 300	–	200
Brittleness Temp. °F ‡	°F	D748	< 400	< -250	-20 to 32	–	< -200	–	< -40	< -60	–
Deflection Temp. 284 psi	°F	D648	100-140	110-120	115-140	165-210	260-280	170-205	163	–	Anneal 170-220
Deflection Temp. 88 psi	°F	D648	–	155-180	185-250	175-225	280	165-200	169	–	Anneal 170-235
Volume Resistivity	ohm/cm	D257	> 1 x 10^{18}	1 x 10^{18}	65 x 10^{15}	> 1 x 10^{15}	> 1 x 10^{15}	1 x 10^{17}	7.1 x 10^{19}	2.1 x 10^{11}-4.7 x 10^{13}	10^{14} - 10^{14}
Dielectric Strength ‡	V/10^3 in	D149	400-500	450-500 (.080)	600-650 (.125)	330 (.125)	< 400 (.125)	250-550	350-500 (.125)	450-500 (.125)	350-500 (.125)
Dielectric Constant	50-100 Hz	D150	2.1-2.2	2.3-2.35	2.1-2.3	3.5-4.5	2.99	2.5	–	6.7-7.5	283
Dielectric Constant	10^3 Hz	D150	2.1-2.2	–	2.1-2.3	3.0-3.5	2.99	2.5	–	6.7-7.5	--
Dielectric Constant	10^6 Hz	D150	2.1-2.2	–	2.1-2.3	3.0	2.93	2.5	–	6.5-71	2 77
Dissipation Factor	50-100 Hz	D150	.0003	–	.0003	.05-.06	.0006	.0001-.0004	–	.015-.017	.005
Dissipation Factor	10^3 Hz	D150	.0003	–	.0003	.04-.06	.009	.0001-.0004	–	.050-.060	–
Dissipation Factor	10^4 Hz	D150	.0003	–	.0003	.025	.010	.0001-.0004	–	–	007
Water Absorption 24 Hr.	%	D570	< .01	< .01	.01-.03	.3-.4	.010	.05-.07	.04	.08-1	.2-.45
Water Absorption Saturation	%	–	–	< .01	.01-.03	–	.12	–	–	–	–
Burn Rate	Description	D635	No Burn	Burns	Burns	Slightly Affected	.34	Burns	Slightly Affected	Burns	Burns
Effect of Sunlight	Description	D543	No Effect	Affected	Affected	Slightly Affected	Slightly Affected	Affected	Affected	No Effect	–
Wear Factor (k)	K x 10^{10}	–	–	251	–	–	Slightly Affected	–	–	–	–
Coefficient of Friction	Dynamic	–	.04-.10	.09-.12	–	–		–	–	–	–

o Property values shown as a blank — independent tests must be conducted.

† Test standard for tensile strengths at yield and breakage as follows. D638 for thermoplastics. D651 for thermoset. D412 elastometers and D882 for thin sheet.

‡ Sizes in parenthesis are thicknesses of specimen tested.

The ASTM is not the only organization to have standard tests for polymers. Other offices are the Association Francaise des Normes et Standards (AFNOR), Deutsche Industrie Normen (DIN) and the Japan Institute of Standards (JIS) among others.

Tensile Test: A Typical Curve

Standard specimen shapes and dimensions for tensile testing have been defined (ASTM D638) as shown by Figure 3. Thin specimens (Types I, II, IV, V) with thickness of 3.2 ± 0.4 mm (0.13 ± .02 in) are usually obtained by molding while thicker specimens are cut out of plates. The specimen shapes are chosen to avoid any parasite effects originating from the grips such as stress concentration. (See also G'sell, 1982A). Rod specimens are also allowed by the test. These specimens have a shape similar to that for Types I, II, III, V but have a circular cross-section. Diameter of rod specimens range from 3.2 mm (1/8 in) to 50.8 mm (2 in). ASTM D882 describes a tensile test for thin plastic sheeting.

Figure 4 shows possible shapes of the stress-strain curve with corresponding designations of measurable properties. Figure 5 (G'sell 1982B) shows a typical tensile stress-strain curve with corresponding observations at the different stages of the curve. This serves to illustrate the complexity of the plastic deformation response of a polymer. Some other tests used to study plastic deformation will be discussed later in this paper.

Compression Test

ASTM D 695 specifies the necessary elements to conduct a compression test. Information which may be obtained include modulus of elasticity, yield stress, deformation beyond yield point and compressive strength. In certain cases, however, some plastic materials deform continuously until a flat disk is obtained. No real value of compressive strength can then be obtained.

A compression test is usually more difficult to carry out due to possible problems in alignment of specimen grips, buckling of specimens and the effects of friction at end plates. In some cases, deformation beyond yield point is accompanied by crazing or the formation of shear bands, thus rendering the interpretation of these data difficult.

Torsion Test

ASTM D1043 makes use of a standardized torsion test to obtain the value of the apparent shear modulus of elasticity G. With a properly equipped machine, values of G at different temperatures can also be determined. This test is therefore essentially a single property test and totally ignores any possibility of studying plastic deformation. This test is mentioned in particular because it cannot be performed with a universal testing machine. In contrast, most of the other tests (i.e., tensile, compressive, bending) mentioned in Table 1 can be done with a properly equipped universal testing machine.

SOME TESTS USED TO STUDY THE PLASTIC DEFORMATION OF POLYMERS

In order to better explore the plastic deformation response of polymers, researchers have developed non-standard tests. Some of these tests are often referred to in the literature on mechanical testing. A study of the results obtained from these tests may give insights into the behavior of polymers during forming processes or in service. For instance, standard tests often give *nominal stress* and *nominal strain* data whereas many of the other tests give *true stress* and *true strain.* Very often strain rate (the rate at which specimen deformation is induced), is not precisely defined in standard tests. In some processes involving polymers, the strain rate may be an important parameter.

Non-standard tests are then used to determine strain rate effects.

In this section, the discussion will be limited to three types of tests with which the author has had some direct or indirect experience.

Tensile Testing at Constant True Strain Rate

In a conventional tensile test, stabilized necking is very often observed. Observations indicate that at some point in the test, a portion of the gage length of the specimen will have undergone necking while other portions are still undeformed (See Figure 5). This condition indicates that the actual strain values and the local strain rate will vary from point to point in the specimen (Brown and Ward, 1968).

To obtain an intrinsic true stress-true strain curve at constant true strain rate, G'sell (G'sell and Jonas, 1979) modified an extensometer and constructed an exponential operational amplifier for use with an LVDT (linear variable differential transducer) – equipped testing machine (MTS closed-loop tensile testing machine). Figure 6A shows a schematic diagram of circumference gauge (modified extensometer) while Figure 6B shows an equivalent electrical diagram of the control system.

The system increased the strain at a constant rate in the area at which the extensometer was in contact with the specimen. Some of the resulting curves are shown in Figures 7A and 7B (G'sell and Jonas 1979; G'sell, 1982B).

For the polymers tested, these curves show that the actual local strain does not exceed 2. For PVC the true strain at rupture is only around 0.8 while the apparent nominal strain at rupture has been reported to be around 2 or 200 percent (Bauwens, 1982). These curves also show that some polymers (PC, PVC) actually exhibit a strain softening response with a stress drop at yield. Stress drops are not observed in the true-stress-strain curves of the other polymers, even though conventional tensile testing shows apparent stress drops at yield.

Torsion Test

This test is carried out by getting a cylindrical specimen, fixing one of its ends and applying a couple to twist the other end. A square or rectangular element drawn on the surface of the specimen such that a set of its sides is parallel to the cylinder's geometric axis will be transformed into a parallellogram under the action of the applied stress. As can be seen from Figure 8, the deformation produced is equivalent to simple shear. By some calculations it is therefore possible to convert the torque-angle of twist data obtained in this test into a shear stress-shear strain curve and obtain the material response to simple shear (Canova, et. al., 1982). The data obtained may then be considered to complement tensile or compressive test data.

In this type of test, however, inhomogeneous stress and strain patterns result from the combination of specimen geometry and the applied couple. The applied couple will be zero and have no effect at the specimen center but it will have a maximum value and maximum effect at the surface of the specimen. The strain (angle of twist) will vary in a similar fashion, from zero at the specimen center to a maximum value at the surface. The use of specimens in the form of hollow cylinders, as reported by Wu and Turner (1973) reduces the effects of this inhomogenous specimen deformation but does not totally remove them. Shear bands have been observed in this type of test (Bauwens, 1970; Wu and Turner, 1973).

To obtain better data in simple shear, a test with uniform shear stress throughout the specimen was therefore developed.

Shear Test

Film Shear Test

In an initial attempt to obtain simple shear test data, rectangular polymer films were clamped at two parallel edges and stress was applied by moving one edge to produce the simple shear geometry, see Figure 9. This test was applied to various polymers (Robertson and Joynson, 1966, 1968; Brown and Ward, 1968; Brown, et al., 1968) and the corresponding shear stress-shear strain curves were obtained. However, by a geometrical analysis of isolated large sherulites, Boni, et al. (1982) demonstrated that due to the wide spacing between grips and the thinness of the specimens, this test produced more of a tensile stress field than a simple shear stress field. Figure 10 shows an isolated spherulite in a film of polybutene 1 undergoing the film shear test.

A circle drawn on the surface of a material would be transformed to an ellipse with inclined axes due to the application of a simple shear stress (see Figure 11). By observing the change in the shape of an isolated large spherulite in polybutene-1 sheet subjected to film shearing, it was demonstrated that the resulting elliptical shape of the spherulite was due to the application of a tensile stress rather than a simple shear stress (combination of tensile and compressive stresses).

The formation of folds in the film sample (see Figure 9) as shearing proceeded was also observed. By a stress analysis, it was shown (Boni, et al., 1982) that these folds were actually a buckling response to the compressive stress component of the applied simple shear stress. In the same way that a slender column buckles under compressive stress, formation of folds is observed in the film specimens in the direction of the compressive stress. This response also contributes to an increase in the effect of the tensile stress as previously mentioned.

The shear stress-shear strain data obtained by film shearing are therefore affected by the formation of folds in the specimens and the accuracy of the stress-strain curves in the plastic range may be questioned (Boni, et al., 1982).

Plane Simple Shear Test

Figure 12 shows a schematic diagram of the simple shear testing machine designed by G'sell and Boni (Boni, 1981; G'sell et al., 1983). The specimen geometry and dimensions shown on Figure 13 were chosen to avoid buckling of specimens and to reduce the magnitude of possible end effects.

The "useful" part (equivalent to the gauge length of tensile test specimens) is the thin, slender portion with the given dimensions while the other portions serve to grip the specimen in the shear testing apparatus.

The test data are recorded in the form of shear stress vs. shear strain curves with the tests usually carried out at constant shear strain rate. The shear stress is obtained using the ratio F/S with F being the applied force (in Newtons, N) measured by the load cell of the testing machine and S (=L.e) being the area (in mm^2) of the specimen on which the force acts. Shear stress is expressed in megapascals, MPa (1MPa=1N/mm^2).

Figure 14 shows an element undergoing plane simple shear. The shear strain γ is the ratio x/h, with x being the relative displacement in the specimen and h being the sheared width at the point at which x is measured.

One of the ways by which shear strain is measured is with the use of a shear transducer (Figure 15) developed for use with rigid polymers such as polycarbonate (Gopez, 1983; G'sell and Gopez, 1985). With the transducer, the actual displacement x is measured in the specimen by means of a modified strain gauge with needles at both arms. The sheared width h is the point-to-point distance between the two needles at zero strain position (Gopez, 1983, G'sell and Gopez, 1985).

Recently, a method involving the use of a video camera and direct data acquisition by means of a microcomputer was developed. The author had the occasion to observe a test carried out with the said measuring aids and equipment in April 1985.

The shear stress-shear strain curves obtained for the different polymers are given in Figure 16 (G'sell, et al. 1983; Gopez, 1981 as cited by Boni, 1981). Large shear strains were attained with very little or no crazing and no necking behavior. A notable case is polymethyl methacrylate (PMMA), for which rupture takes place at about 200 percent. In tension at room temperature, PMMA ruptures after only a few percent strain.

Table 5, taken from Boni (1981) gives the parameters which were determined from the shear stress-shear strain curves presented in Figure 16.

Table 5. Data obtained from stress-strain curves.
(Boni, 1981)

Polymer DATA	POM	PMMA	PA66	PC*	PVC	PB-1	PP	HDPE
Curve No.	1	2	3	4	5	6	7	8
Apparent modulus (E, MPa)	400	385	220	420	380	70	130	100
Yield stress (τ_e, MPa)	56	48	40	38.5	42	11.5	18	12
Yield strain (γ_e)	0.4	0.3	0.8	0.2	0.17	0.18	0.2	0.3
Stress drop at yield (MPa)	–	4.4	–	3.0	7.5	–	–	1.2
Plastic strain hardening rate ($d\tau/d\gamma$, MPa)	0	13	5.8	21	4	4.9	1.75	1.3
Stress at rupture (τ , MPa)	59	53	75	54	45	31.6	28	22
Strain at rupture (γ_r)	1.6	1.8	4.5	1.8	4	4	7	11
Type of fracture	B**	B	D**	B	B	D	D	D

* Corrected data, source: Gopez 1983.
** B=brittle; D=ductile

SELECTED TOPICS IN POLYMER TESTING

Effects of Strain Rate and Temperature

Figure 17. shows the effects of strain rate on the tensile true stress-strain curves of polyvinyl chloride (PVC) and high density polyethylene (HDPE) (G'sell and Jonas, 1979). In general, higher

strain rates mean higher flow stresses. The stress-strain curves are shifted vertically upwards by an increase in the strain rate. Similar observations have been noted in the case of simple shear testing of polyethylene (HDPE) (Boni, 1981; G'sell et al., 1983) and polycarbonate (PC) (Gopez, 1983; G'sell and Gopez, 1985). Figures 18 and 20 show the shear stress-shear strain curves obtained for these polymers at different strain rates. Curves at very high strain rates (curve 1 in Figure 18 and all curves marked "a" in Figure 20) are not shifted vertically with respect to the others due to a possible self heating effect caused by the rapid straining.

Figure 19 shows tests done on polyethylene at different temperatures from –37 to 120°C using a strain rate of $3\ 10^{-3}\ s^{-1}$ (below the self heating strain rate). The stress drop at yield decreases as the temperature is decreased from 23 to –37°C. It is suppressed completely as the temperature is increased from 23 to 120°C. The strain hardening rate shows a consistent decrease as the temperature is increased and it may be said that increasing temperature has a weakening effect on the material. The viscous flow response at 120°C may be contrasted with the "glassy" response at –37°C

For polycarbonate, the curves obtained at different temperatures from –100 to 150°C at a strain rate of $3\ 10^{-3}\ s^{-1}$ are shown on Figure 21. The upper yield stress decreases gradually as the temperature increases and drops to zero at the glass transition temperature. At high temperatures (150°C) the curve is almost linear indicating viscous flow.

Testing of polymers at various temperatures and strain rates is usually done to obtain constitutive equations of flow. G'sell (G'sell and Jonas, 1979) formulated constitutive equations for HDPE and PVC in tension of the following form:

$$\sigma(\varepsilon, \dot{\varepsilon}) = k \exp\left(\frac{\gamma_\varepsilon}{2}\varepsilon^2\right) \cdot \varepsilon^m$$

where $\gamma = \left[\frac{d\ 1n\sigma}{d\varepsilon}\right]_{\dot{\varepsilon}}$ is the relative strain hardening coefficient.

$m = \left[\frac{d\ 1n\sigma}{d\ 1n\dot{\varepsilon}}\right]_{\varepsilon}$ is the strain rate sensitivity coefficient.

and $\gamma = \gamma_\varepsilon \cdot \varepsilon$

From the test data, G'sell proposed:

For HDPE: $\sigma_{MPa} = 46.1 \exp(0.43\varepsilon^2) \quad \varepsilon^{0.06}$

For PVC : $\sigma_{MPa} = 62.2 \exp(1.18\varepsilon^2) \quad \varepsilon^{0.025}$

In the case of simple shear, Boni (1981) proposed a constitutive equation of flow based on Argon's (1973) additive form:

$$\tau(\gamma, \dot{\gamma}, T) = \tau_i(\gamma, T) + \tau^*(\gamma, T)$$

where τ_i = "internal stress" reflect the strain hardening effects.

τ^* = "effective stress" reflects the strain rate effects.

Boni's equation is:

$$\tau(\gamma, \dot{\gamma}, T) = \tau_{io}\left((1-AT)(\gamma + B\gamma^2)^{-} + \tau_o^*\ 1n\left(\frac{\dot{\gamma}}{\gamma}\right)\exp\left(-\frac{T}{T_o}\right)\right.$$

where $\tau_{io} = 2.8$ MPa

$A = 2.35\ 10^{-3}$ MPA/°K

$B = 1.5\ 10^{-2}$

T is in Kelvin

$\tau_o{}^{*} = 62\ \text{MPa}$

$\dot{\gamma}_o = 2.10^{-10}\ 5^{1}$

$T_o = 65\ \text{K}$

For polycarbonate in simple shear, Gopez (1983, 1984) proposed a different multiplicative form:

$$\tau(\gamma, \dot{\gamma}, T) = f_1\ (\gamma) \cdot f_2\ (\dot{\gamma}) \cdot f_3\ (T)$$

From experimental data, he obtained:

$$\tau(\gamma, \dot{\gamma}, T) = K \exp\ (h\gamma) \cdot \dot{\gamma}^{m} \cdot \exp\ (\theta T)$$

where $K = 32\ \text{MPa}$

$h = 0.50$

$m = 0.03$

$\theta = -6.0.10^{-3}\ C^{-1}$

T is in Centigrade.

Comparison of Amorphous and Semi-Crystalline Polymers

Based on the results obtained in tensile and simple shear testing, the yield behavior appears to be different for glassy amorphous polymers and semi-crystalline polymers. Well-pronounced stress drops at yield have been observed for the glassy polymers: PMMA, PC and PVC; while for the semi-crystalline polymers, a gradual decrease in the slope of the stress-strain curve is observed at yield. A slight drop in stress has been observed after yield for high density polyethylene and polypropylene. Apparently the viscoelastic to plastic transition behavior is more gradual for semi-crystalline polymers.

The strain hardening rate of glassy polymers appears to be higher than that of semi-crystalline polymers; exceptions being PA66 which has a high strain hardening rate and PVC which has a low strain hardening rate. The strain hardening rate is indicated by the slope of the stress-strain curve after yield.

The fracture behavior is also different for the two types of polymers. For glassy polymers, brittle fracture occurs, while for semi-crystalline polymers, fracture occurs at much larger strains along the specimen edges with fracture surfaces being fibrous and exhibiting striations.

Investigation of the Mechanism of Plastic Deformation

Simple shear test results indicate that glassy polymers do exhibit a relatively large amount of plastic deformation before rupture. This was not previously apparent from results obtained in uniaxial tension. The study of the mechanism of plastic deformation in the glassy state is one of the aspects in which the plane simple shear test may be used to obtain more information. The absence of any crazing or reduction in the specimen cross-sectional area greatly enhances the utility of the test in this field of study.

Results obtained in low cycle simple shear fatigue tests by Gopez (1983) taken together with those of other investigators (Rabinowitz and Beardmore, 1974; G'sell and Jonas, 1979) seem to indicate a defect-based mechanism whose kinetics are similar to those proposed by Gilman and Johnston (1962; Gilman, 1973) for dislocations in metals. Due to the amorphous nature of the glassy polymers, the nature of the elementary defect has not yet been postulated. There is, however, no lack of theories available. Argon (1973) describes the defect as a kink in a molecular chain while Bowden and Raha (1974) view it as analogous to a dislocation loop. Vitek (1982) describes it as shear or density defect. Available experimental results have not shed much light on this issue.

Density measurements shown by Tables 6 and 7 (Brady and Yeh, 1971; Wu and Turner, 1973;

Rabinowitz and Beardmore, 1974; Gopez, 1983) seem to indicate that the presence of these defects causes an increase in the density of the deformed material. It cannot therefore be claimed that these defects are due to an increase in free volume and that plastic deformation of glassy polymers is due to an increase in free volume. It may however be argued that the *initiation* of plastic deformation may be due to an initial increase in free volume but when deformation takes place this free volume is lost due to a resulting heavier packing of molecular chains in deformed glassy polymers.

More work needs to be done to determine the exact nature of the plastic deformation mechanism in glassy polymers and the plane simple shear test may be useful in this field of study.

Plastic Instability: Necking and Shear Band Formation

In tensile testing, necking at yield is very often observed for polymers (Bauwens, 1967 and 1970; Brown and Ward, 1968; Brady and Yeh, 1971; G'sell, 1982B). This necking does not immediately lead to failure. In fact, the "neck" stabilizes and then propagates. In contrast metals fail soon after necking. In some cases, necking has also been associated with the formation of shear bands (Bauwens, 1967 and 1970; Brady and Yeh, 1971). G'sell and Aly-Helal (Aly-Helal, 1982) studied the necking phenomenon in HDPE. By selection of the appropriate parameters they were able to make a computer simulation of polymer cold drawing which predicted the tensile test curve and the specimen profile to within 15 percent.

Shear bands were first observed in amorphous polymers by Whitney (1963), but it was Aragon et al. (1968) who first studied them in detail in polystyrene deformed by compression. Li and his co-workers (Li and Wu, 1976; Chau and Li, 1979, 1980, 1981, 1982A, 1982B) did more studies on shear bands in polystyrene. Eventually, it was found that shear bands also formed in polycarbonate. Wu and Turner (1973) used a torsion test while G'sell and Gopez (1985) used the plane simple shear test.

Table 6. Density Measurements at 23 ± 1°C (Gopez, 1981; Gopez, 1984)

Sample	Mechanical History	Density, g/cm^3
PCN	Undeformed polycarbonate	1.1974 ± 0.0013
PCNT	Undeformed polycarbonate Annealed 3 hours at 150°C Quenched in ice water	1.1970 ± 0.0013
PCE3	Tensile test specimen $\gamma pl = 0.57\ \varepsilon_{nom} = 10^{-3}\,s^{-1}$ T = 23°C	1.2050 ± 0.0017
PC207	Shear test specimen $\gamma pl = 0.77$ ($\varepsilon pl, eq = 0.37$) $\dot{\gamma} = 3\ 10^{-3}\,s^{-1}$, T = 23°C	1.2033 ± 0.0017
PC208	Shear test specimen Deformed to $\gamma pl = 0.80$ and brought back to $\gamma = 0$ $\dot{\gamma} = 3\ 10^{-3}\,s^{-1}$, T = 23°C	1.1997 ± 0.0017
PC215	Shear test specimen Deformed to $\gamma pl = 0.80$ and brought back to $\gamma = 0$: Annealed 3 hours at 150°C Cooled slowly to room temperature	1.1972 ± 0.0017

It appears that, in general, glassy amorphous polymers are more prone to shear band formation than semi-crystalline polymers. Formation of shear bands in torsion and simple shear was also shown to be accompanied by a stress drop in the corresponding stress-strain curve. Band initiation also appears to take place at points of stress concentration. Bowden (1970) formulated a criterion of non-homogeneous plastic deformation, while Argon (1973; Argon and Bessonov, 1977) proposed a mathematical treatment of shear band kinetics.

Table 7. **Increase in specific gravity due to plastic deformation (Gopez, 1981; Gopez, 1984)**

Polymer Tested*	Type of Test	Increase in Specific Gravity	Reference
PC	Tensile Test 25°C	0.20%	Brady and Yeh, 1971
PMMA	Tensile Test 25°C	0.50%	Brady and Yeh, 1971
PS, atactic	Tensile and Compression 25°C	0.25%	Brady and Yeh, 1971
PC	Fatigue 25°C	1%	Rabinowitz and Beardmore, 1974
PC	Torsion 21°C	0.1%	Wu and Turner, 1973
PMMA	———	0.5%	Enders, 1969 cited by Brady and Yeh, 1971

* PC = polycarbonate; PMMA = polymethylmethacrylate; PS = polystyrene.

CONCLUSION

In this paper different types of testing methods used for polymers have been discussed. Aside from the standard tests which are used to determine properties which may be needed for design or service considerations, some tests used to explore plastic deformation behavior were also considered. Selected topics in polymer testing were also discussed.

REFERENCES

ALY-HELAL N.A. (1982), 'Etude et Simulation du Developpement de la Striction dans le Polyethylene a Haute Densite", These de Docteur-Ingenieur, I.N.P.L., NANCY.

Annual Book of ASTM Standards (1980), Part 35 "Plastics-General Test Methods, Nomenclature," American Society for Testing and Materials, Philadelphia, Pa.

ARGON A.S., ANDREWS R.D., GODRICK, J.A. and WHITNEY W. (1968), *J. Appl. Phys., 39,* 1899.

ARGON A.S. (1973), *Phil. Mag., 28,* 839.

ARGON A.S. and BESSONOV M.I. (1977), *Polym. Eng'g. Sci., 17.*

BAUWENS J.-C. (1967), *J. Polym. Sci.* A-2, *5,* 1145.

BAUWENS J.-C. (1970), *J. Polym. Sci.* A-2, *8,* 893.

BAUWENS, J.-C. (1982) "Plastic Deformation: Experimental Data and Constitutive Equations" in

Plastic Deformation of Amorphous and Semi-Crystalline Materials, B. ESCAIG and C. G 'SELL ed., Editions de Physiques, p. 175.

BONI S. (1981), "Conception d'une Machine de Cisaillement Plan pour la Determination du Comportement Plastique de Materiaux Polymeres", These d' Ingenieur C.N.A.M., NANCY.

BONI S., G'SELL C., WEYNANT T.E. and HAUDIN J. M. (1982), *Polymer Testing, 3,* 3.

BOWDEN P. B. (1970), *Phil. Mag., 22,* 455.

BOWDEN P. B. and RAHA S. (1970), *Phil. Mag., 22,* 463.

BOWDEN P. B. and RAHA S. (1974) *Phil. Mag., 29,* 149.

BRADY T. E. and YEH G.S.Y. (1971) *J. Appl. Phys., 42,* 4622.

BROWN N., DUCKETT R.A. and WARD I.M. (1968), *Phil. Mag., 18,* 483.

BROWN N. and WARD I.M. (1968), *J. Polym. Sci.* A-2, *6,* 607.

CADILLAC PLASTIC, "Global Source for Sheet, Rod, Tube and Film", p. 50.

CANOVA G. R., SHRIVASTAVA S., JONAS J.J. and G'SELL C. (1982), "The Use of Torsion Testing to Assess Material Formability", Formability of Metallic Materials – 2000 A.D., ASTM STP 753, J. R. NEWBY AND B. A. NIEMEIER, eds., American Society for Testing and Materials, pp. 189-210.

CHAU C. C. and LI J.C.M. (1979), *J. Mater. Sci., 14,* 1593.

CHAU C.C. and LI J.C.M. (1980), *J. Mater. Sci., 15,* 1898.

CHAU C.C. and LI J.C.M. (1981), *J. Mater. Sci., 16,* 1858.

CHAU C.C. and LI J.C.M. (1982) A, *J. Mater. Sci., 17,* 652.

CHAU C.C. and LI J.C.M. (1982) B, *J. Mater. Sci., 17,* 3445.

FERRY J.D. (1970), *Viscoelastic Properties of Polymers,* 2nd ed., John Wiley and Sons, Inc., New York.

GILMAN J.J. and JOHNSTON W.G. (1962), in "Solid State Physics, Advances in Research and Applications", F. SEITZ and D. TURNBULL ed., *13,* 147, Academic Press, New York.

GILMAN J.J. (1973), *J. Appl. Phys., 44,* 675.

GOPEZ A.J.R. (1981), unpublished work for a D.E.A. in Materials Science, Lab. Phys. du Solide-E.N.S.M.I.M. NANCY as cited by Boni, 1981.

GOPEZ, A.J.R. (1983), "Etude de la Deformation du Polycarbonate en Cisaillement Simple", Thesis for "Docteur-Ingenieur", Lab. Phys. du Solide-E.N.S.M.I.M. NANCY, 27 June 1983.

GOPEZ A.J.R. (1984), *Phil. Engineering Journal,* Vol. V, No. 1, 127.

G'SELL, C. (1982A) "Mechanical Testing Techniques of the Plastic Behavior of Amorphous and Semi-Crystalline Materials", in *Plastic Deformation of Amorphous and Semi-Crystalline Materials,* B. ESCAIG and C. G'SELL ed., Editions de Physique, p. 13.

G'SELL, C. (1982B) "Plastic Necking in Solid Polymers", *Ibid.,* p. 375.

G'SELL C. and GOPEZ A.J.R. (1985), *J. Mat'ls. Sci., 20,* 3462-3478.

G'SELL C. and JONAS J. J. (1979), *J. Mater. Sci., 14,* 583.

G'SELL C. and JONAS J. J. (1981), *J. Mater. Sci., 16,* 1956.

G'SELL C. BONI S. and SHRIVASTAVA S. (1983), *J. Mater. Sci., 18,* 903.

Guide to Engineerd Materials (1986), J. BITTENCE, ed., Vol. 1 No. 1, Mid June.

KAKUDO M. and KASAI N. (1972), *X-Ray Diffraction by Polymers,* Kodansha Ltd., Tokyo.

KOVACS A.J. (1982), "Structure and Morphology of Polymer Crystals" in *Plastic Deformation of Amorphous and Semi-Crystalline Materials,* B. ESCAIG AND C. G. 'SELL ed., Editions de Physique, p. 289.

LI J.C.M. and WU J. B. C. (1976), *J. Mater. Sci., 11,* 446.

Plastics Properties Guide, GE Plastics, One Plastics Ave., Pitsfield, Ma.

RABINOWITZ S. and BEARDMORE P. (1974), *J. Mater. Sci., 9,* 81.

ROBERTSON R. E. and JOYNSON C. W. (1966), *J. Appl. Phys., 37,* 3969.

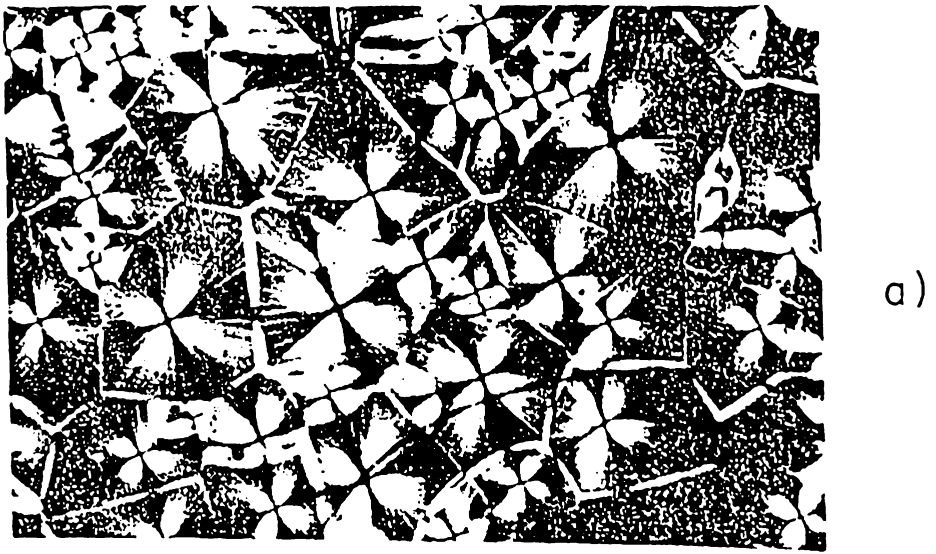
ROBERTSON R. E. and JOYNSON C. W. (1968), *J. Polym. Sci., A-2, 6,* 607.

VAN VLACK L. N. (1975), *Elements of Materials Science and Engineering,* Addison-Wesley Publishing Company, Reading, Massachusetts.

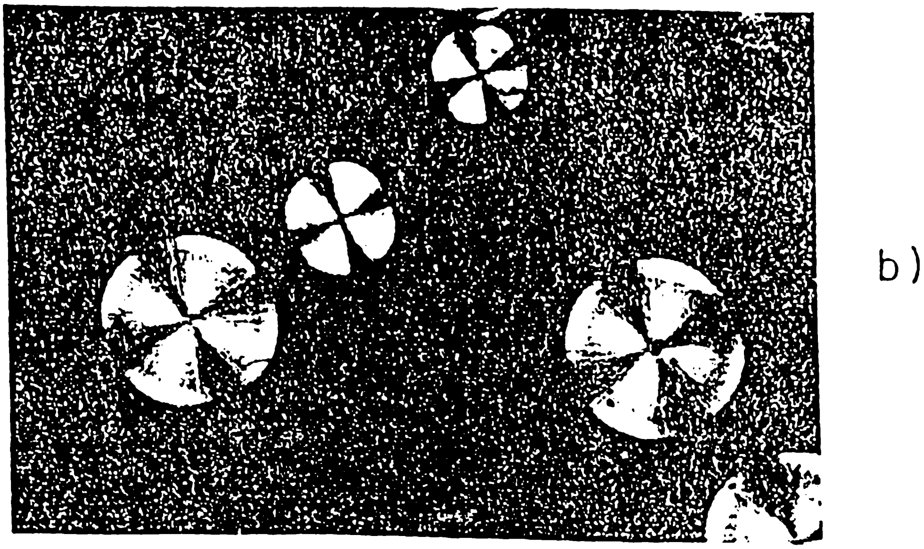
VITEK V. (1982), "Atomic Structure and Defect in Metallic Glasses" in *Plastic Deformation of Amorphous and Semi-Crystalline Materials,* B. ESCAIG and C. G'SELL ed., Editions de Physique, p. 143.

WHITNEY W. (1963), *J. Appl. Phys., 34,* 3633.

WU W. and TURNER A.P.L. (1973), *J. Polym. Sci., 11,* 2199. (1973).



a) Spherulites in a thin film of polybutene crystallized at 80°C.



b) Microstructure of a thin film whose crystallization was interrupted by quenching. Large spherulites are actually surrounded by very fine spherulites.

0,5 mm

Figure 1. (Boni, 1981)

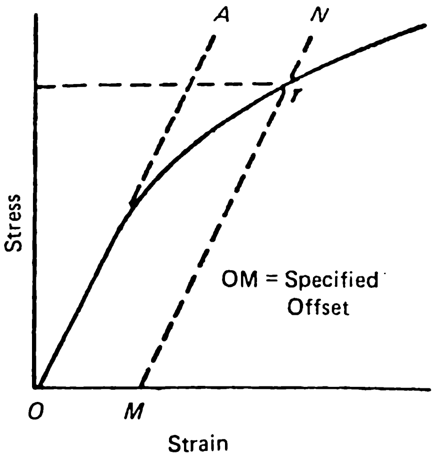
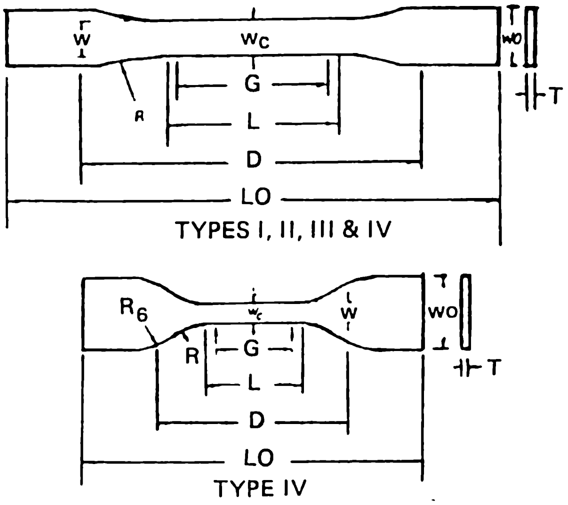


Figure 2. Offset yield strength (ASTM Part 35, 1980; p. 240).



Specimen Dimensions for Thickness, T, mm[D]

Dimensions (see drawings)	7 or under		Over 7 to 14 incl.	4 or under		Tolerances
	Type I	Type II	Type III	Type IV[C]	Type V[I]	
W – Width of narrow section[A,B]	13	6	19	6	3.18	± 0.5[C,I]
L – Length of narrow section	57	57	57	33	9.53	± 0.5[I]
WO – Width over-all, min[A]	19	19	29	19	9.53	± 6
LO – Length over-all, min[B]	165	183	246	115	63.5	no max.
G – Gage length[C]	50	50	50	...	7.62	± 0.25[I]
G – Gage length[C]	...	...	...	25	...	± 0.13
D – Distance between grips	115	135	115	64	25.4	± 5
R – Radius of fillet	76	76	76	14	12.7	±1[I]
RO – Outer radius (Type IV)	...	...	...	25	...	± 1

Figure 3. Tension test specimens for Sheet, Plate, and Molded Plastics (ASTM D638; Part 35, 1980).

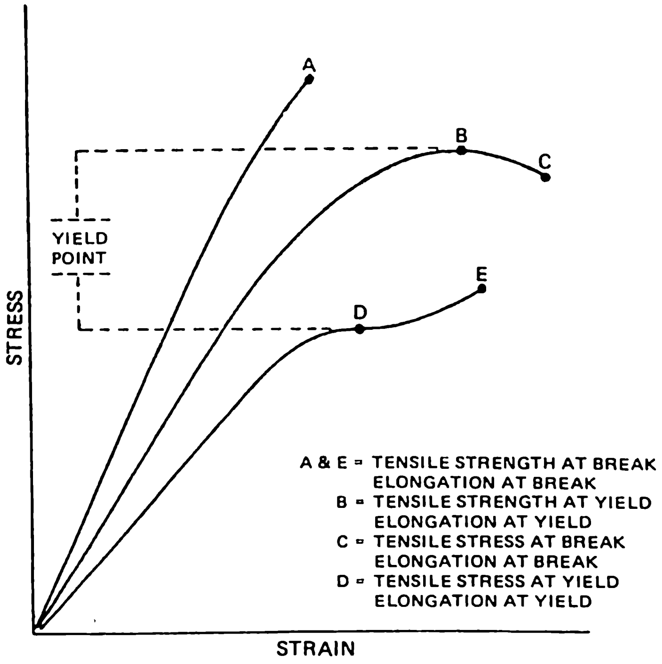


Figure 4. Some possible shapes of the stress-strain curve (ASTM Part 35, p. 239).

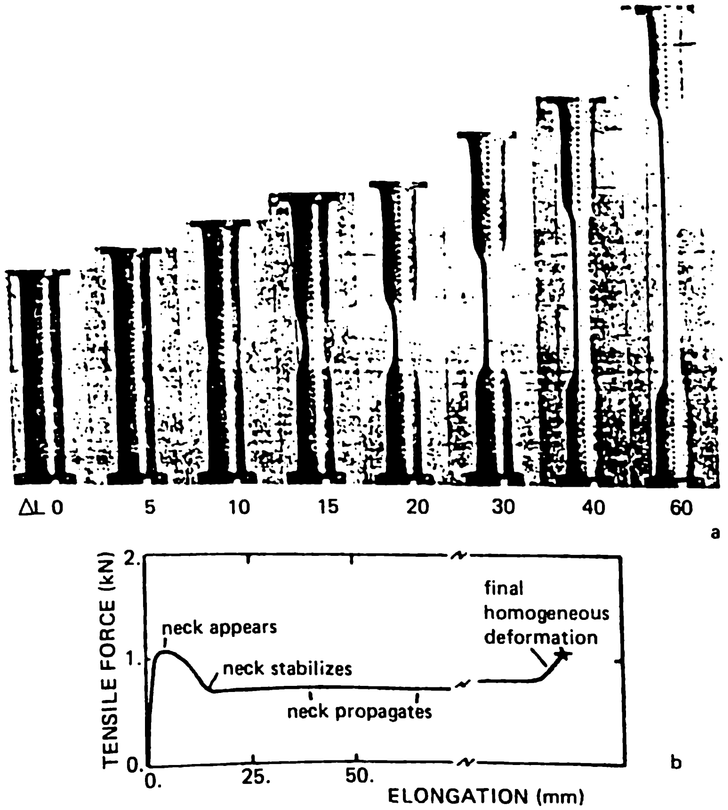


Figure 5. Experimental in-situ observation of necking in a High Density Polyethylene sample stretched at a constant elongation rate $L/L_0 = 4.10^{-4} s^{-1}$ (G'sell, 1982).

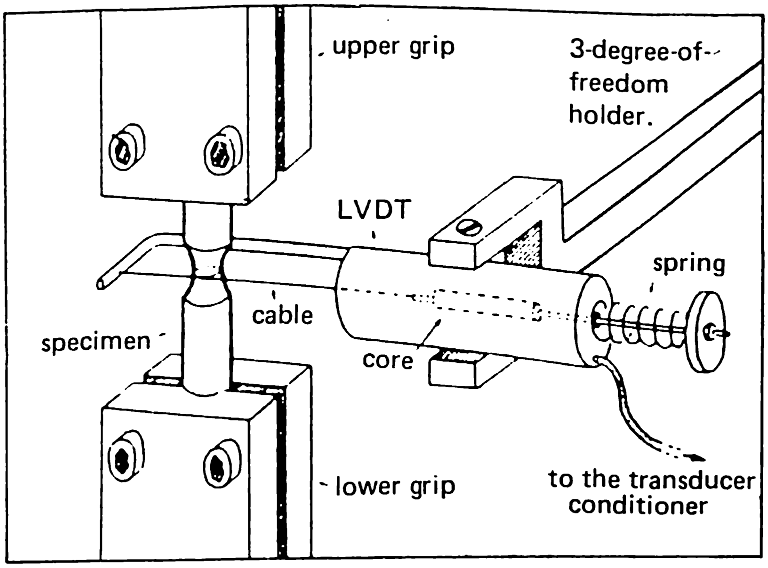


Figure 6A. Schematic diagram of the circumference gauge used for continuously monitoring the diameter of the specimens (G'sell and Jonas, 1979).

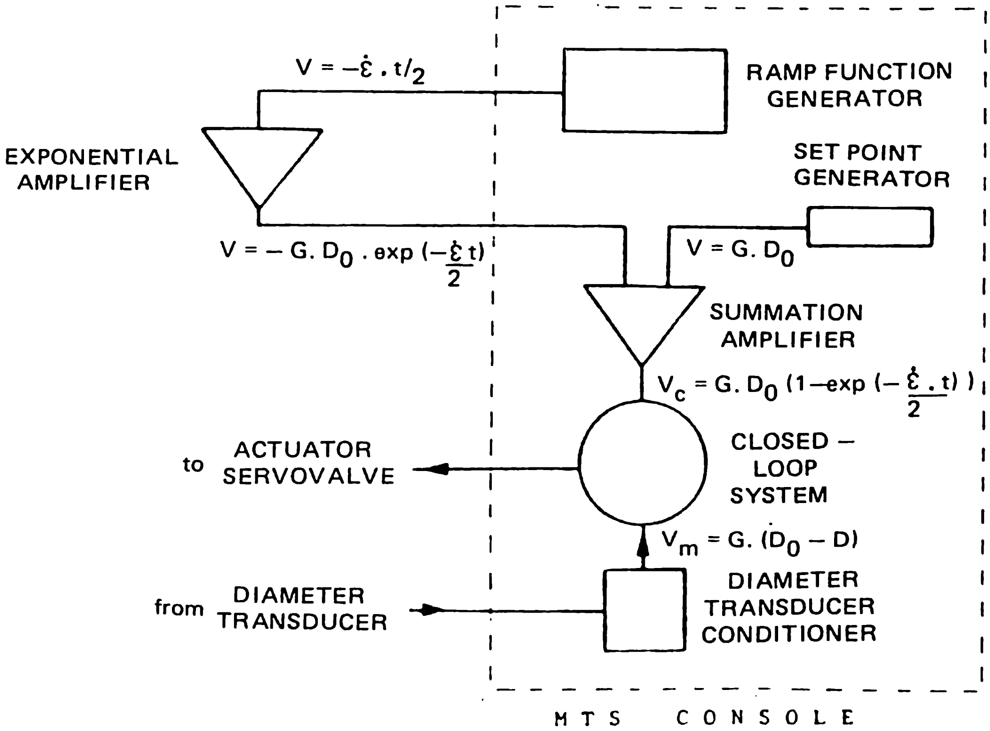


Figure 6B. Equivalent electrical diagram of the exponential control voltage generator diameter transducer and closed loop system (G'sell and Jonas, 1979).

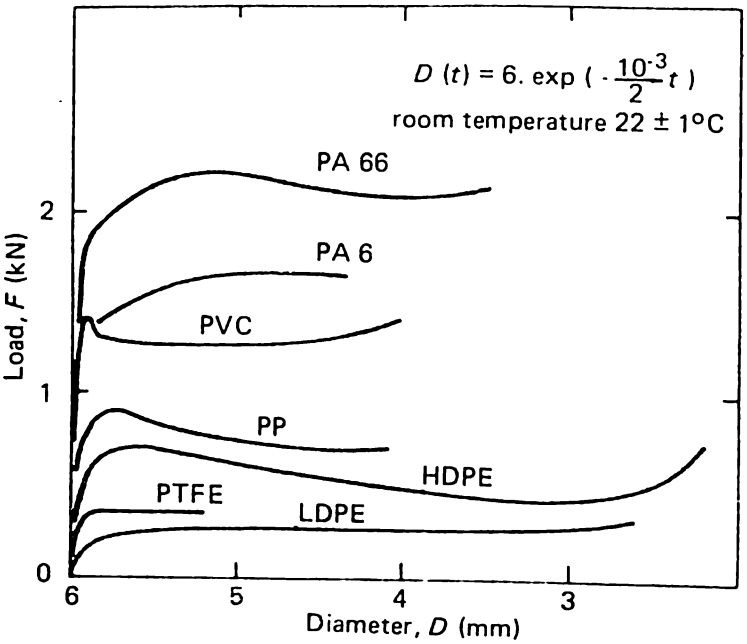


Figure 7A. Experimental load against diameter curves recorded during the testing of seven polymers at a constant true strain rate e = 10^{-3} sec^{-1} (LDPE and HDPE: low and high density polyenthylene, PTFE: polytetrafluoro-ethylene, PP: polypropylene, PVC: polyvinyl chloride, PA 6 and PA 66: polyamide 6 and 66) (G'sell and Jonas, 1981).

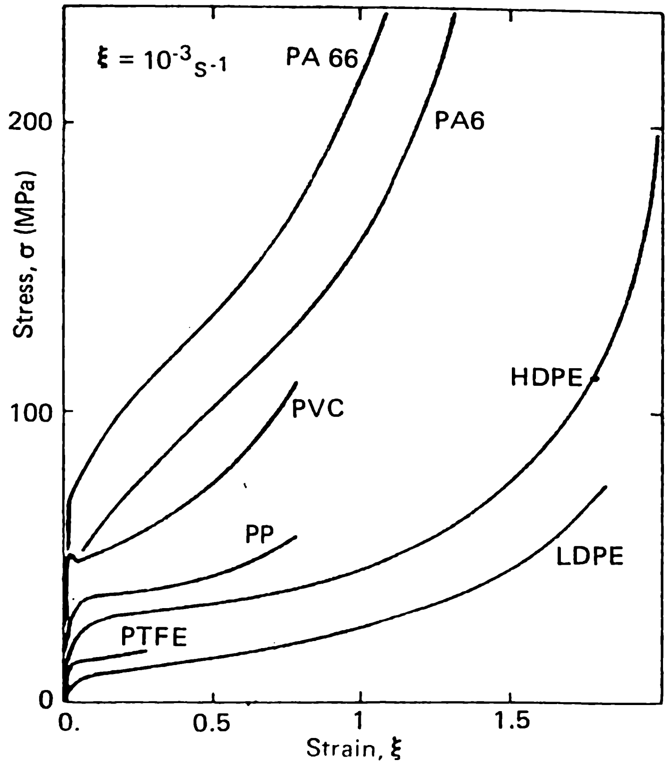


Figure 7B. True stress against true strain curves obtained from the data of Figure 7A (G'sell and Jonas, 1981).

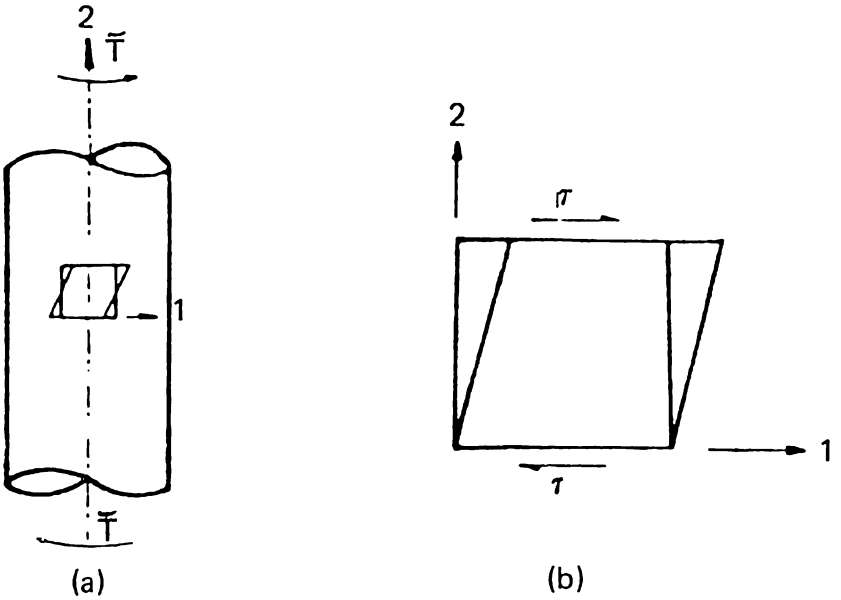
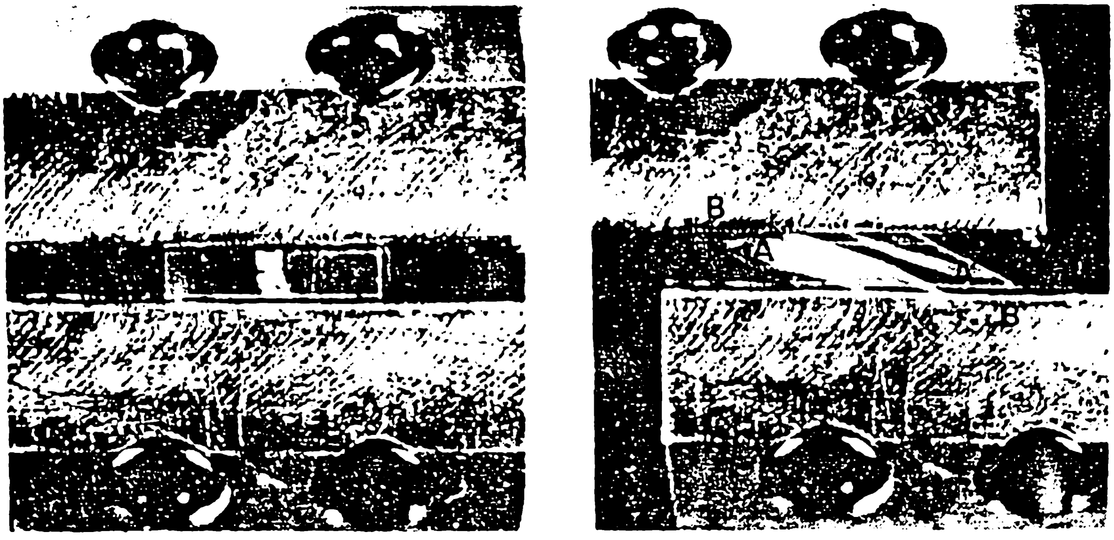


Figure 8. (a) Deformation, during twisting, of an elementary square imprinted on the surface of a torsion sample. (b) The deformation of the elementary square (a) is equivalent to simple shear (Canova et al., 1982).



$\gamma = 0$ $\gamma = 3$

Figure 9. Film shearing test. Note formation of folds at larger strains (Boni, 1981).

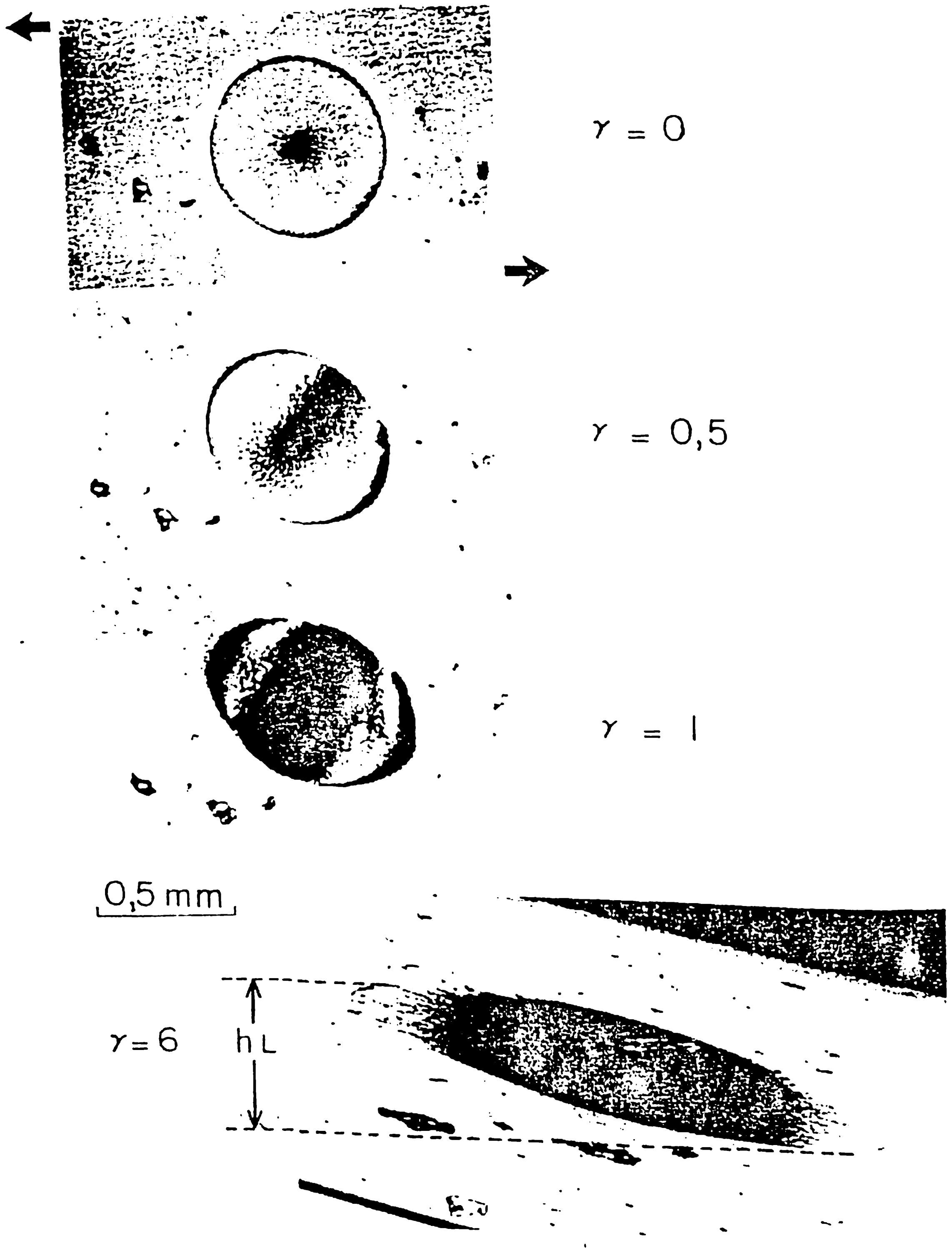


Figure 10. In-situ observation of the deformation of an isolated spherulite in a thin film of polybutene-1 undergoing film shearing (Boni, 1981).

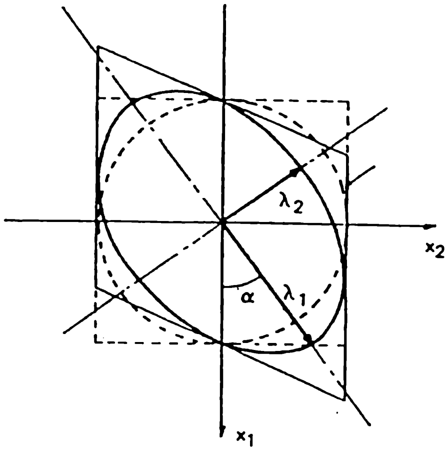


Figure 11. A circle inscribed on an element undergoing simple shear is transformed into an ellipse with inclined axes (Gopez, 1983).

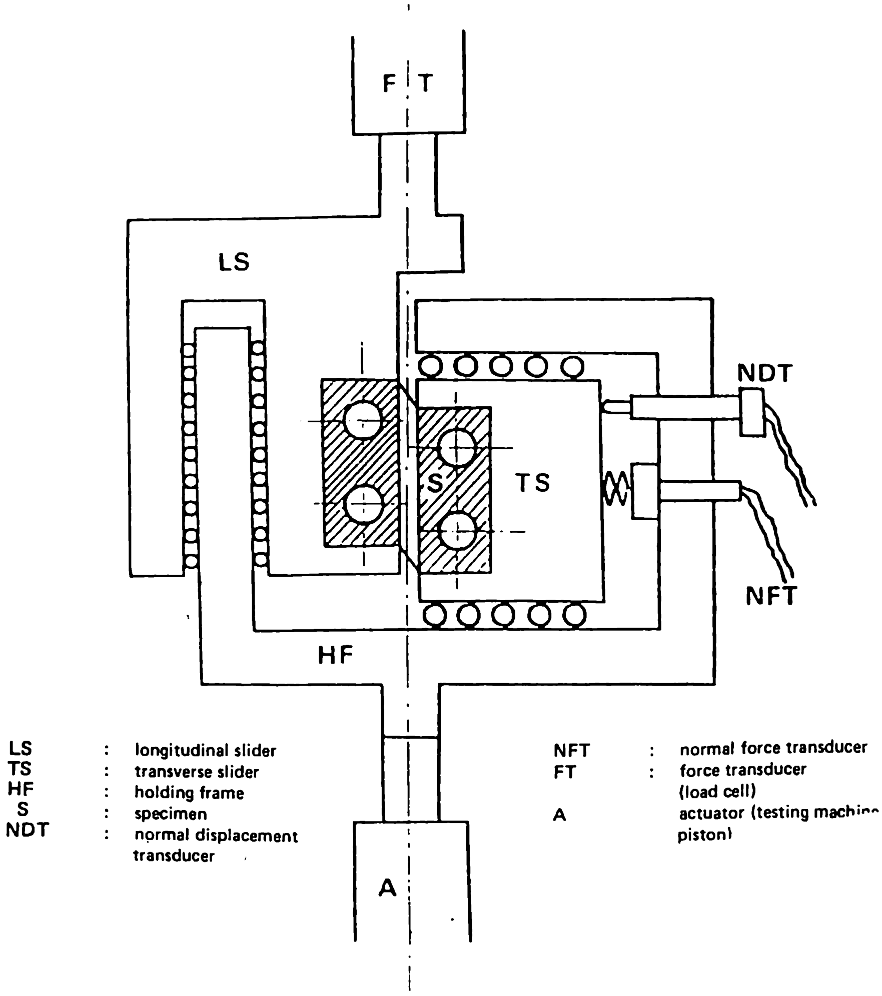


Figure 12. Diagram of the simple shear testing apparatus designed by Boni (Boni, 1981).

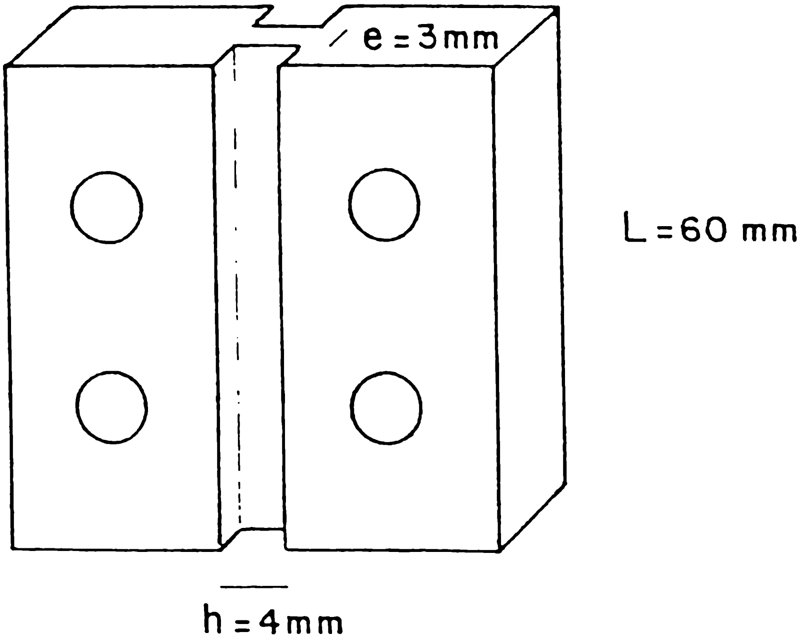


Figure 13. Simple shear test specimen (G'sell et al., 1983).

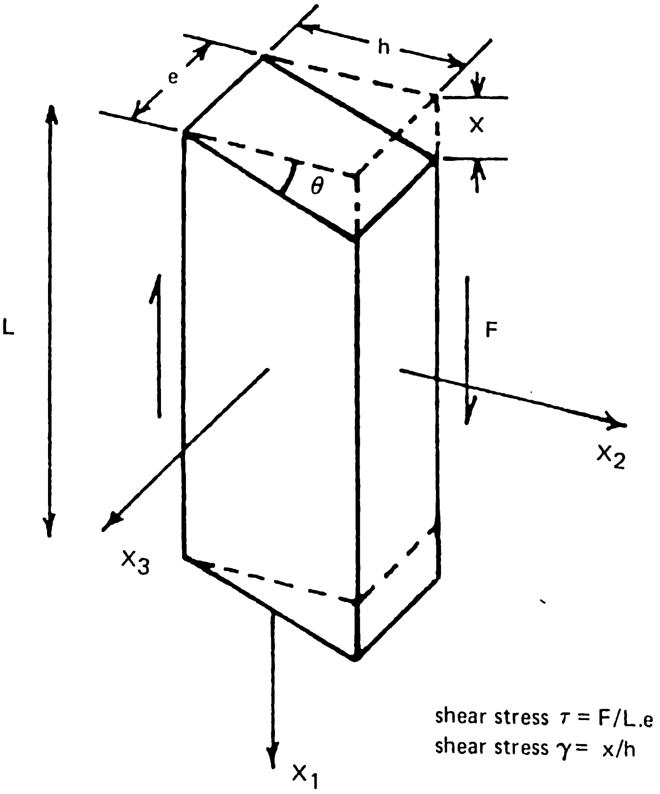


Figure 14. Element undergoing plane simple shear (Gopez, 1981).

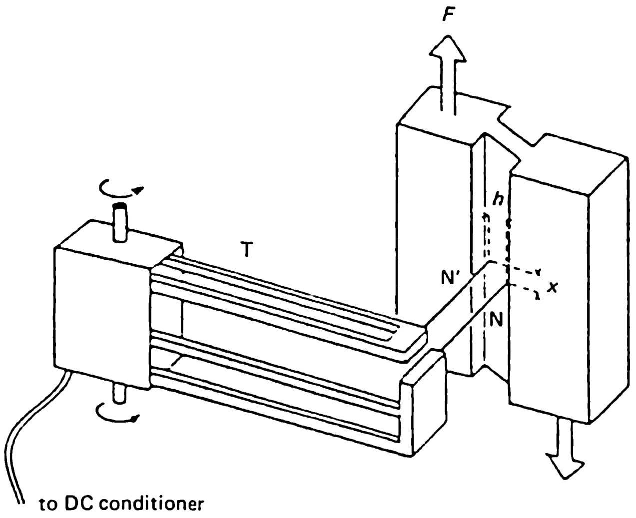


Figure 15. Shear transducer designed for the determination of the overall shear in the calibrated part of the specimens. (T, transducer; N and N' needles in contact with the specimen) (G'sell and Gopez, 1985).

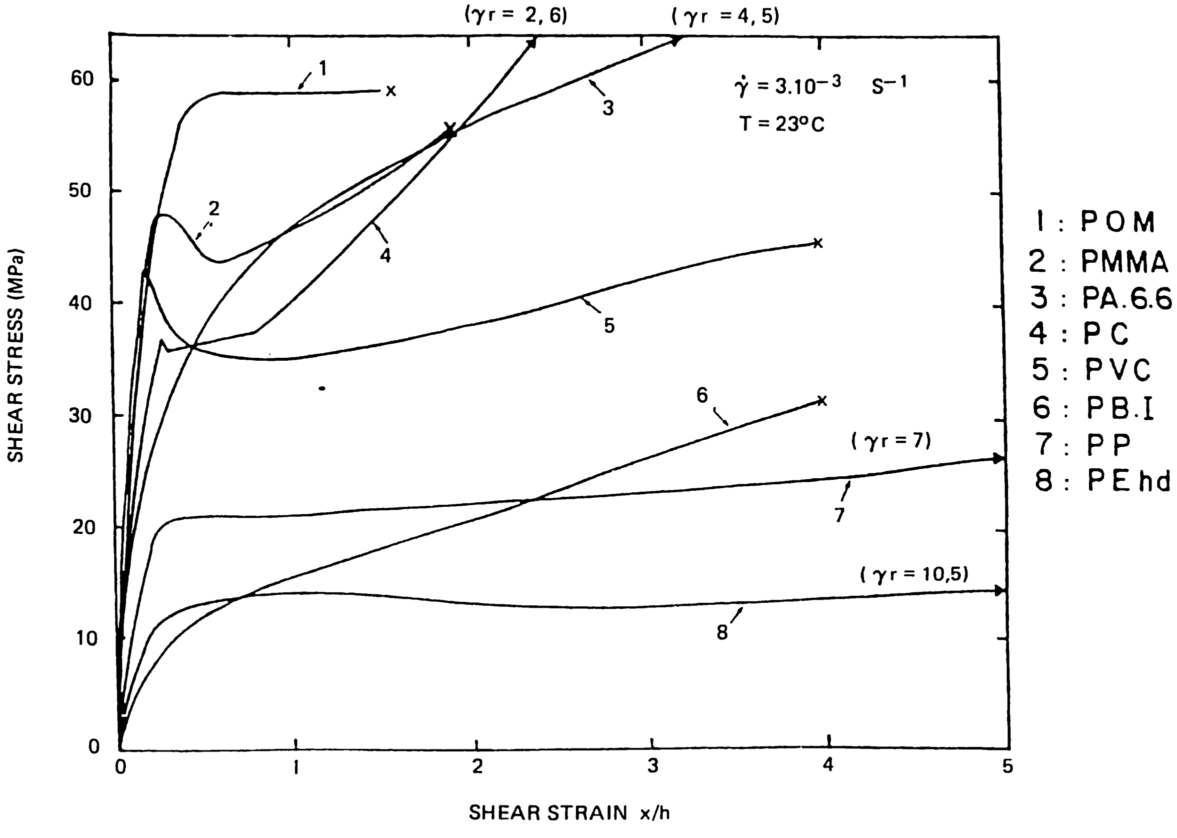


Figure 16. Shear stress-shear strain curves for different polymers (Gopez. 1981 as shown by Boni, 1981).

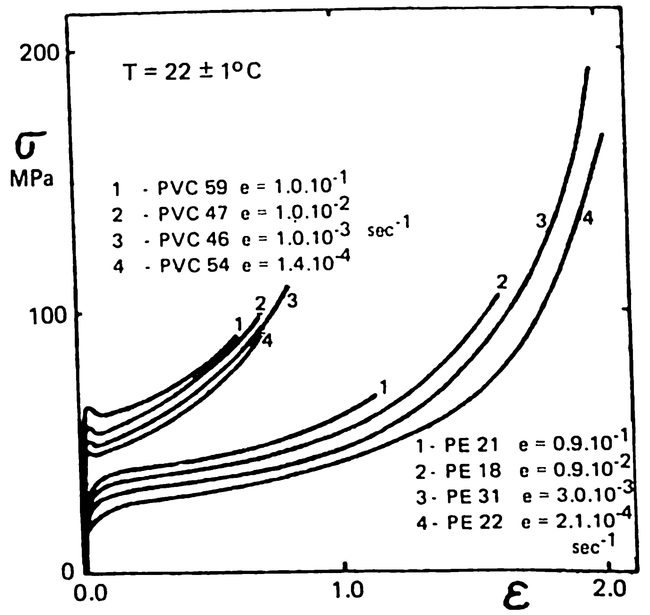


Figure 17. Typical true stress versus true strain curves obtained with hour-glass shaped specimens of PVC and HDPE tested at constant local true strain rate (G'sell and Jonas, 1979).

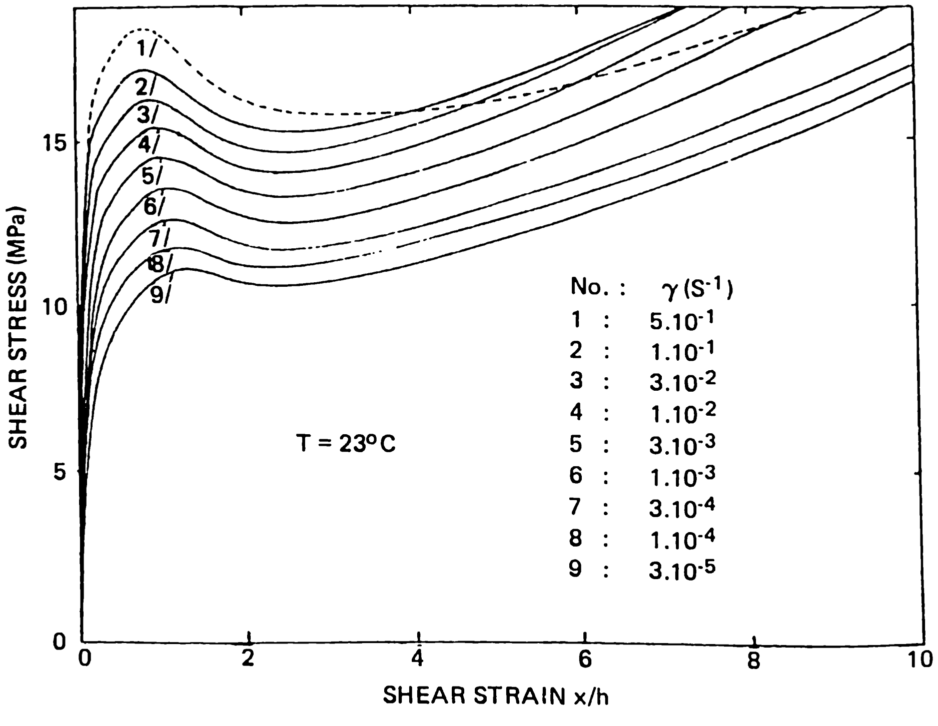


Figure 18. Shear strain rate effects on high density polyethylene (Boni, 1981 and G'sell et al., 1983).

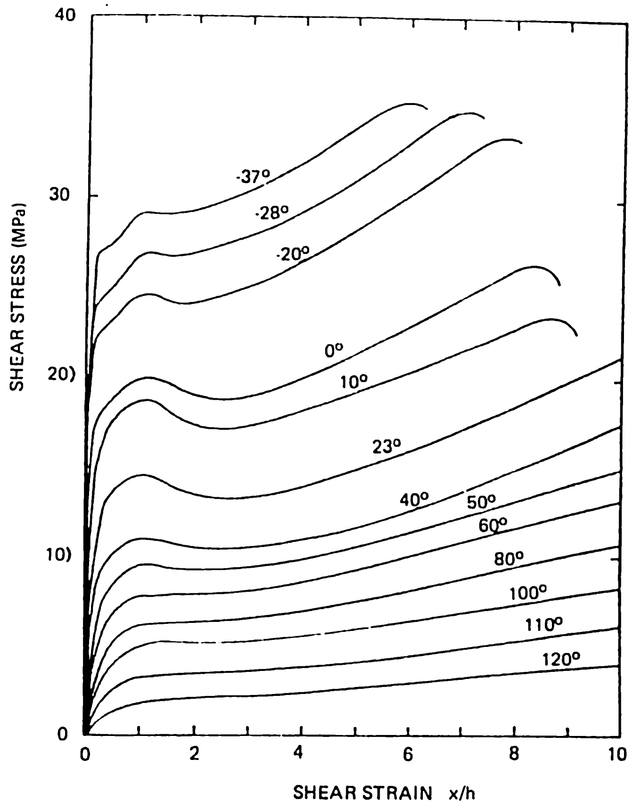


Figure 19. Temperature effects on the shear stress-shear strain curve of high density polyethylene (Boni, 1981 and G'sell et al., 1983).

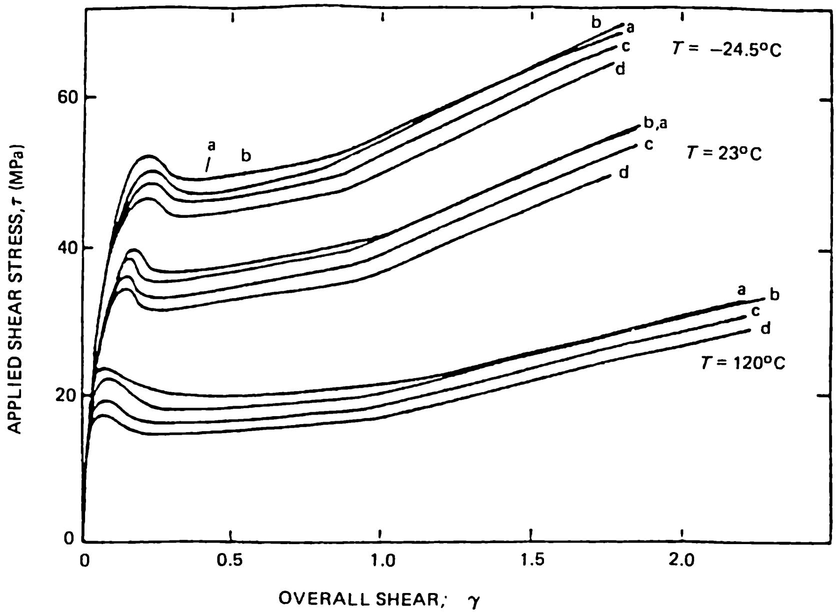


Figure 20. Shear strain rate effects on polycarbonate (Gopez, 1983, G'sell and Gopez, 1985).

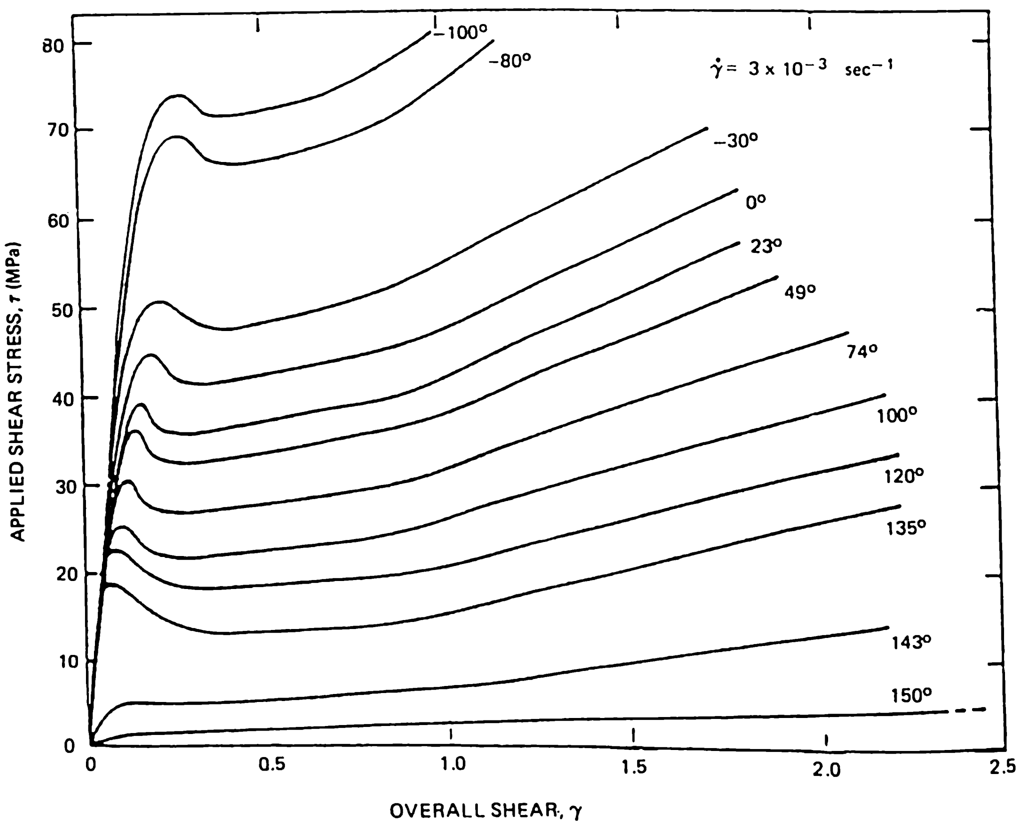


Figure 21. Temperature effects on polycarbonate (Gopez, 1983, G'sell and Gopez, 1985).