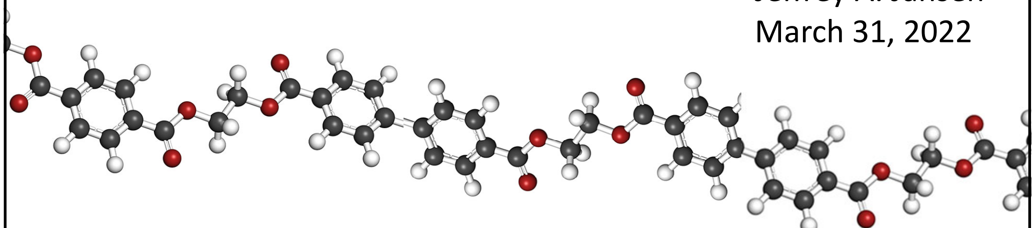
Polymer Molecular Weight:
A Key Factor in Plastic Performance

Jeffrey A. Jansen
March 31, 2022



1

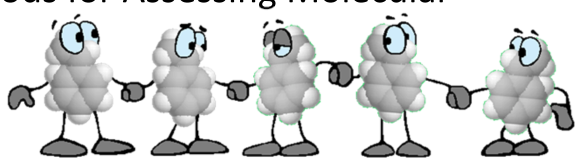
Goals

- Gain an appreciation of the criticality of Molecular Weight on the performance of polymeric materials
- Get insight as to how Molecular Weight can be altered during life cycle of the polymer
- Identify different analytical tools to measure Molecular Weight, and recognize which is best in different circumstances

2

Agenda

- Polymerization
- Molecular Weight and Its Relationship with Plastic Properties
- Chain Entanglement
- Molecular Weight Distribution
- Molecular Weight Measurement
- Molecular Degradation
- Complementary Methods for Assessing Molecular Degradation



3

POLYMERIZATION

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4

Plastic Properties

Molecular Structure

- Average Molecular Weight
- Molecular Weight Distribution
- Branching
- Tacticity
- Crystallinity
  - Amorphous
  - Semi-crystalline
- Polarity
- Crosslinking
  - Thermoplastic
  - Thermoset

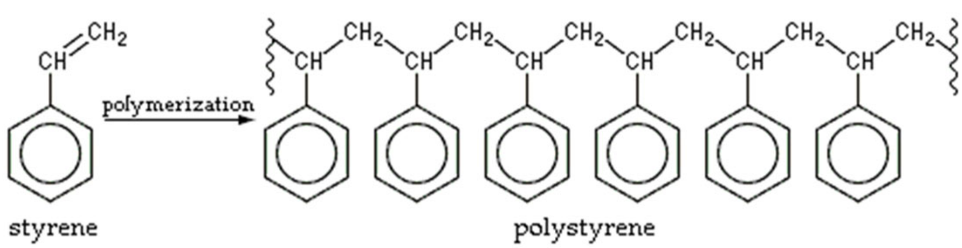
Material Composition

- Base Polymer
  - Functional Groups
  - Homopolymer / Copolymer
  - Blends / Alloys
- Additives
  - Modifiers
  - Anti-degradants
  - Colorants
  - Fillers

Polymerization

Addition Polymerization

Many monomers bond together via rearrangement without the loss of any atom or molecule.

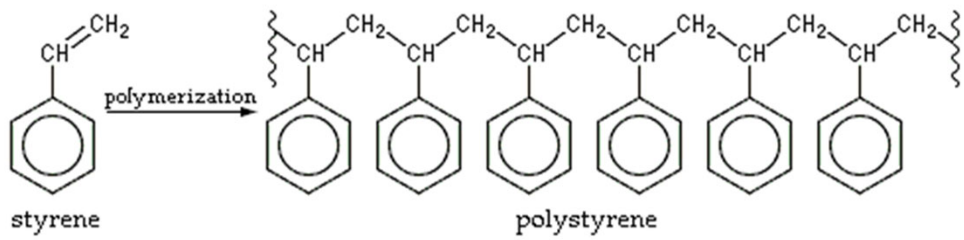


Exothermic Reaction

Polymerization

Addition Polymerization

Formation of polymers from monomers containing a C=C bond through an addition reaction.



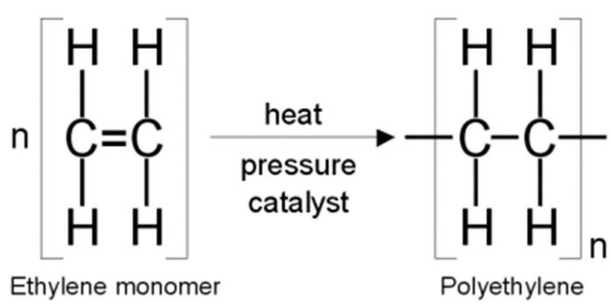
Exothermic Reaction

7

Polymerization

Addition Polymerization

Many monomers bond together via rearrangement without the loss of any atom or molecule.



Exothermic Reaction

8

Polymerization

Addition Polymerization

Polyethylene:

Free radical addition reaction

Chain initiation

The chain is initiated by free radicals, Ra•, produced by reaction between some of the ethene and the oxygen initiator.

Chain propagation

Each time a free radical hits an ethene molecule a new longer free radical is formed.

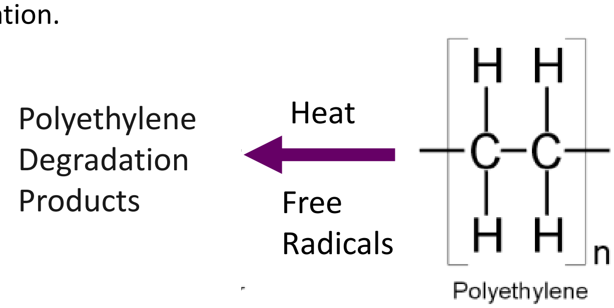
$$Ra\bullet + CH_2{=}CH_2 \longrightarrow RaCH_2CH_2\bullet$$

$$RaCH_2CH_2\bullet + CH_2{=}CH_2 \longrightarrow \underline{RaCH_2CH_2CH_2CH_2\bullet}$$

Polymerization

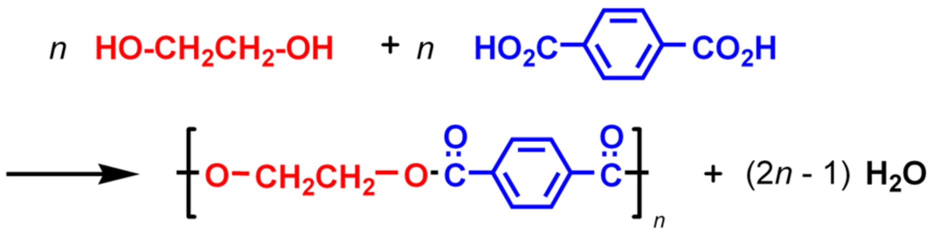
Addition Polymerization

- Free radicals are used in extending the polymerization reaction.
- Because of that, addition polymers are highly susceptible to degradation mechanisms initiated by free radicals – oxidation, UV degradation.



Polymerization

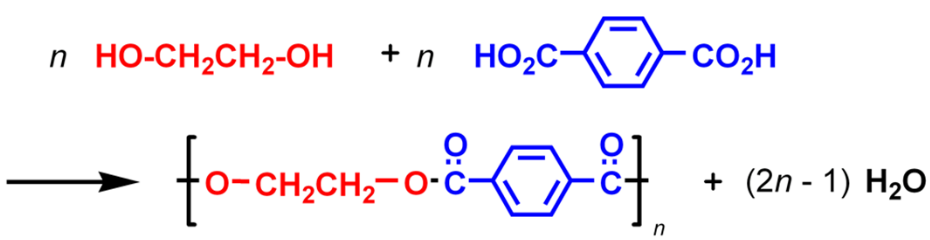
Condensation Polymerization
Condensation polymers are formed by the reaction of molecules with **two functional groups** and produces water as a by-product.



Endothermic Reaction

Polymerization

Condensation Polymerization
Produced from monomers that contain at least two functional groups – or the same functional group twice.

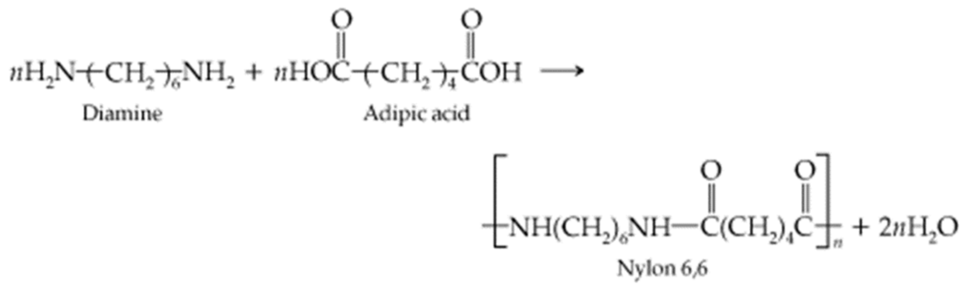


Endothermic Reaction

Polymerization

Condensation Polymerization

Condensation polymers are formed by the reaction of molecules with **two functional groups** and produces water as a by-product.



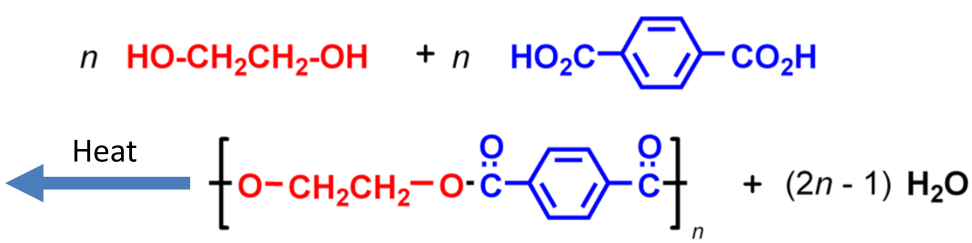
Endothermic Reaction

13

Polymerization

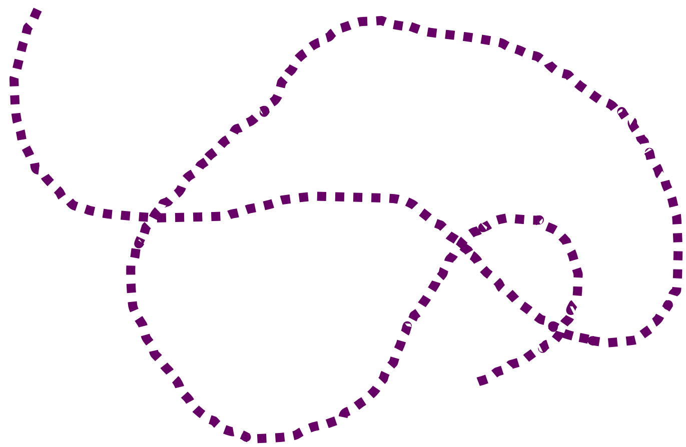
Condensation Polymerization

- Water is produced as a byproduct of polymerization.
- Because of that, condensation polymers are highly susceptible to hydrolysis.



14

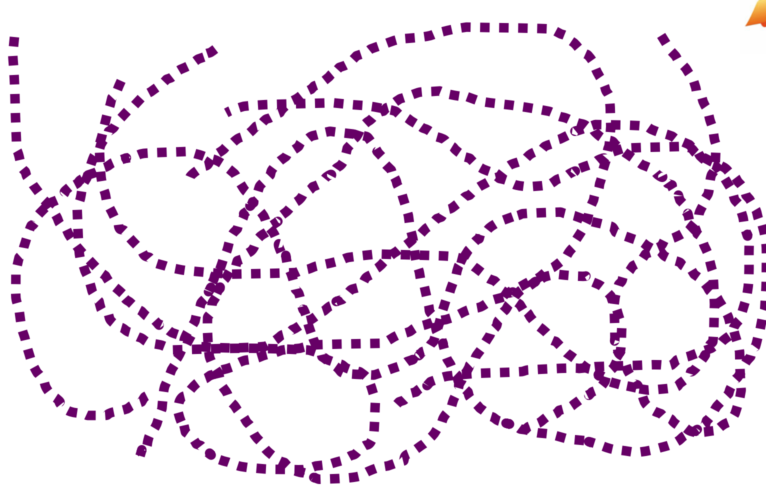
Polymerization



Polymer chain made up of repeating units

15

Polymerization



Multiple entangled chains made up of repeating units

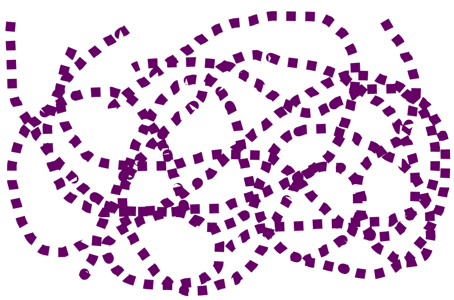
16

MOLECULAR WEIGHT / PROPERTIES

17

Molecular Weight

The collection of **entangled** polymer chains is like a bowl of spaghetti noodles.

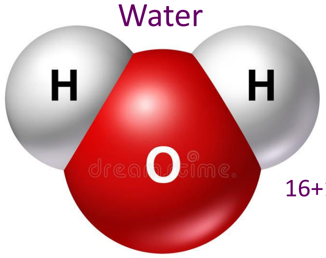


18

Molecular Weight

Molecular Weight: The sum of the atomic weights of the atoms in a molecule.

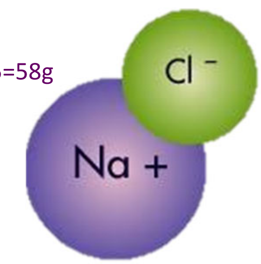
Water



16+1+1=18g

Sodium Chloride

23+35=58g

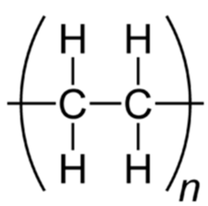


6.02 X10^{23} molecules / mole (molecular weight mass in grams)

Molecular Weight

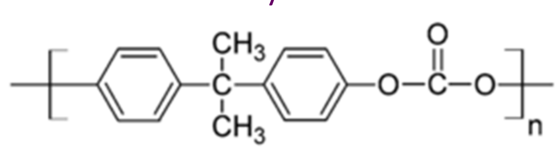
Molecular Weight: The sum of the atomic weights of the atoms in a molecule.

Polyethylene



(12x2 + 1x4) x n

Polycarbonate



(12x16 + 1x14 + 16x3) x n

6.02 X10^{23} molecules / mole (molecular weight mass in grams)

Molecular Weight

Water	1 mole = 18 grams
Sodium Chloride	1 mole = 58 grams
Polyethylene	1 mole = ~500 lbs.
Polycarbonate	1 mole = ~50 lbs.

Most commercial polymers have an average molecular weight between 10,000 and 500,000

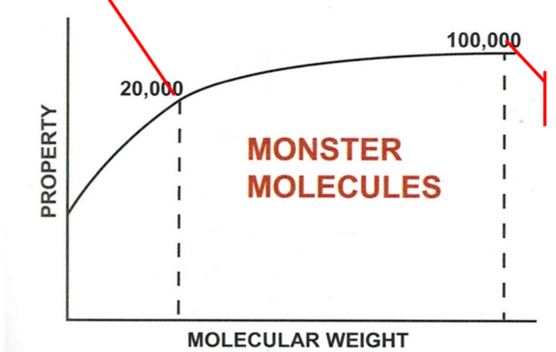
6.02 X10^{23} molecules / mole (molecular weight mass in grams)

21

Molecular Weight

Change of slope around 20K

Condensation polymers: like PC & Nylon
PC Standard Grades @ 20K-35K
PA Standard Grades @10K-40K

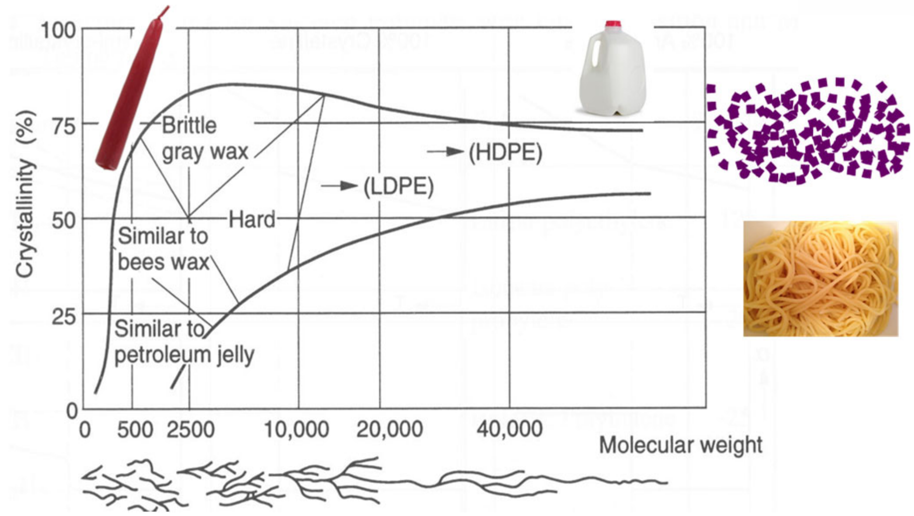


Addition polymers like PS and PMMA

Ref: Ezrin, Plastics Failure Guide

22

Molecular Weight



23

Molecular Weight

Result of Increasing Molecular Weight

Increasing MW Improves

Tensile Strength
Elongation at Break
Impact Resistance
Fatigue Resistance
Creep Resistance
Hardness
Abrasion Resistance
Softening Temperature
Chemical Resistance

Longer molecular chains produce a higher level of entanglement

24

Molecular Weight

Effects of Molecular Weight on Polycarbonate - Ductility

Increasing MW →

MECHANICAL	Unit	Method	Lexan 121R	Lexan 141R	Lexan 201R
Tensile Stress, yld, Type I, 50 mm/min	kgf/cm^2	ASTM D 638	630	630	630
Tensile Stress, brk, Type I, 50 mm/min	kgf/cm^2	ASTM D 638	700	700	700
Tensile Strain, yld, Type I, 50 mm/min	%	ASTM D 638	7	7	7
Tensile Strain, brk, Type I, 50 mm/min	%	ASTM D 638	125	130	135
Flexural Stress, yld, 1.3 mm/min, 50 mm span	kgf/cm^2	ASTM D 790	[illegible]	[illegible]	[illegible]
Flexural Modulus, 1.3 mm/min, 50 mm span	kgf/cm^2	ASTM D 790	23900	23900	23900
Hardness, Rockwell M	-	ASTM D 785	70	70	70
Hardness, Rockwell R	-	ASTM D 785	118	118	118
Taber Abrasion, CS-17, 1 kg	mg/1000cy	ASTM D 1044	10	10	10
IMPACT	**Unit**	**Method**	**Lexan 121R**	**Lexan 141R**	**Lexan 201R**
Izod Impact, unnotched, 23°C	cm-kgf/cm	ASTM D 4812	326	326	326
Izod Impact, notched, 23°C	cm-kgf/cm	ASTM D 256	70	81	92
Tensile Impact, Type S	cm-kgf/cm^2	ASTM D 1822	557	589	642
Falling Dart Impact (D 3029), 23°C	cm-kgf	ASTM D 3029	1728	1728	1728
Instrumented Impact Energy @ peak, 23°C	cm-kgf	ASTM D 3763	633	-	662
Instrumented Impact Total Energy, 23°C	cm-kgf	ASTM D 3763	-	650	-
PHYSICAL	**Unit**	**Method**	**Lexan 121R**	**Lexan 141R**	**Lexan 201R**
Specific Gravity	-	ASTM D 792	1.2	1.2	1.2
Specific Volume	cm^3/g	ASTM D 792	0.83	0.83	0.83
Density	g/cm^3	ASTM D 792	1.19	1.19	1.19
Water Absorption, 24 hours	%	ASTM D 570	0.15	0.15	0.15
Water Absorption, equilibrium, 23C	%	ASTM D 570	0.35	0.35	0.35
Water Absorption, equilibrium, 100°C	%	ASTM D 570	0.58	0.58	0.58
Mold Shrinkage, flow, 3.2 mm (5)	%	SABIC Method	0.5 - 0.7	0.5 - 0.7	0.5 - 0.7
Melt Flow Rate, 300°C/1.2 kgf	g/10 min	ASTM D 1238	17.5	10.5	7

Longer molecular chains produce a higher level of entanglement

25

Molecular Weight

Effects of Molecular Weight on the Impact Properties of Acetal Copolymer

MFR (g/10min)	Notched Izod (ft-lb/in)	Un-notched Izod (ft-lb/in)	Strain @ Break (%)
2.5	1.5	25.0	75
9.0	1.3	20.0	60
27.0	1.0	17.0	40

Ref: Mike Sepe

Longer molecular chains produce a higher level of entanglement

26

Molecular Weight

Effects of Molecular Weight on the Fatigue Properties of Acetal Copolymer

MFR (g/10min)	Fatigue Strength @ 10^7 Cycles (psi)
2.5	4000
9.0	3300
27.0	3000

Ref: Mike Sepe

Longer molecular chains produce a higher level of entanglement

27

Molecular Weight

Effects of Molecular Weight on the ESCR of HDPE

MFR (g/10min)	Time to ESC failure (hours)
2	>1000
4	375
6	60
8	10
10	3

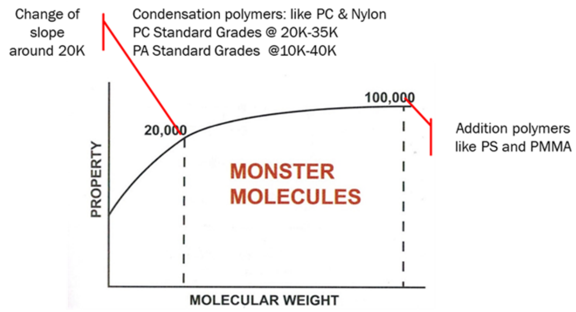
Ref: Mike Sepe

Longer molecular chains produce a higher level of entanglement

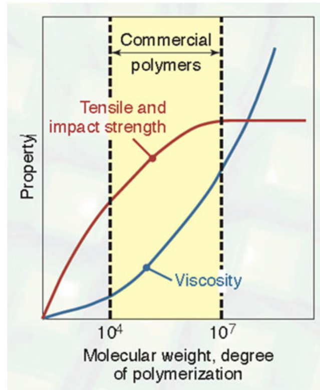
28

Molecular Weight

Effects of Increasing Molecular Weight



Ref: Ezrin, Plastics Failure Guide



Longer molecular chains produce a higher level of entanglement

Molecular Weight

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29

CHAIN ENTANGLEMENT

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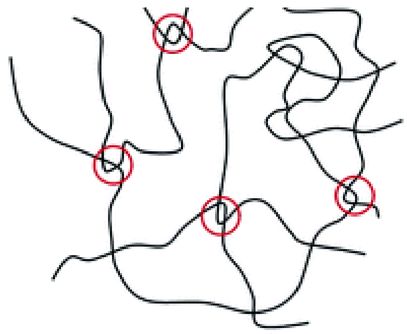
Chain Entanglement

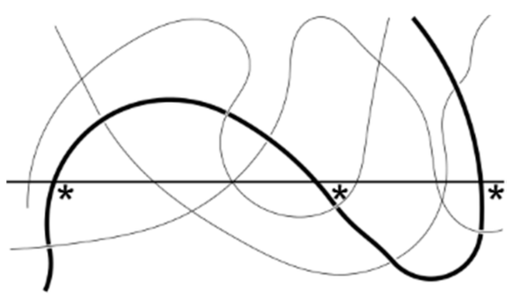
Entanglement refers to the looping points produced in the polymer chain, or in between polymer chains, making the polymer chains unable to move normally and thus affecting the nature of the polymer.



Topological entanglement

The definition of entanglement is simple: if the chain crosses an arbitrary plane 3 times, then it is entangled.

This is real polymer physics, not just a simplistic guide.



https://www.stevenabbott.co.uk/practical-solubility/polymer-entanglement.php

Chain Entanglement

Entanglement of polymers is an important aspect to many of the properties of plastics.

If polymer chains are simply "intermingled" nothing much happens.

However, if the chains entangle, there alterations to the structure that influence mechanical and physical properties.

Chain Entanglement

The level of entanglement is based on two primary factors

- The Stiffness of the polymer chain
- The Length of the polymer chain

Chain Entanglement

This is the same for polymer chains. A short and/or stiff polymer chain hardly tangles so it is easy to pull the chains. But long and/or flexible, they tangle and pulling them apart is difficult, giving high strength and ductility.



35

Chain Entanglement

Mw is the weight average molecular weight of the polymer

Me is the average molecular weight between chain entanglements

Mc is the critical molecular weight – above this entanglements occur

The mechanical properties and the predominant mode of failure and the energy required to cause a specimen to fail, depend on the ratio Mw/Me.

36

Chain Entanglement

Polymer	Critical MWt
PE	4,000
PP	7,000
PS	32,000
PVOH	7,000
PVA	25,000
PMMA	18,000
PC	4,500

PMMA and PS have a high Mc. Both known for not being tough.

PC and PE have low Mc and are known for good ductility.

https://www.stevenabbott.co.uk/practical-solubility/polymer-entanglement.php

37

Chain Entanglement

Processability is also dependent on the frequency of entanglements.

The more entangles the higher the melt viscosity – the more difficult to process.

Good Melt Processability, Poor Mechanical Properties	Optimum M_w Range	Good Mechanical Properties, Poor Melt Processability
$M_w<10M_e$	$10M_e \leq M_w \leq 15M_e$	$15M_e<M_w$
$M_w<5M_e$	$5M_e \leq M_w \leq 7.5M_e$	$7.5M_e<M_w$

https://www.polymerexpert.biz/blog/131-optimum-molecular-weight-range-for-thermoplastics

38

MOLECULAR WEIGHT DISTRIBUTION

Molecular Weight

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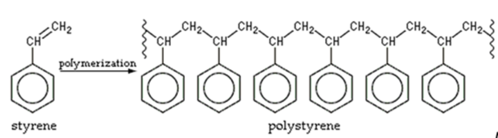
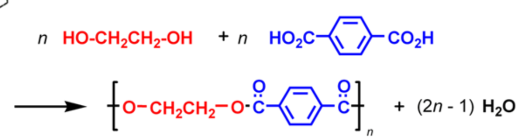
39

Molecular Weight Distribution

- Molecular Weight Distribution: The relative amounts of polymers of different molecular weights that comprise a given specimen of a polymer.
- Polymers are polydisperse – they contain chains of unequal length.
- Polymers exist as a distribution of chain lengths and molecular weights.





Molecular Weight

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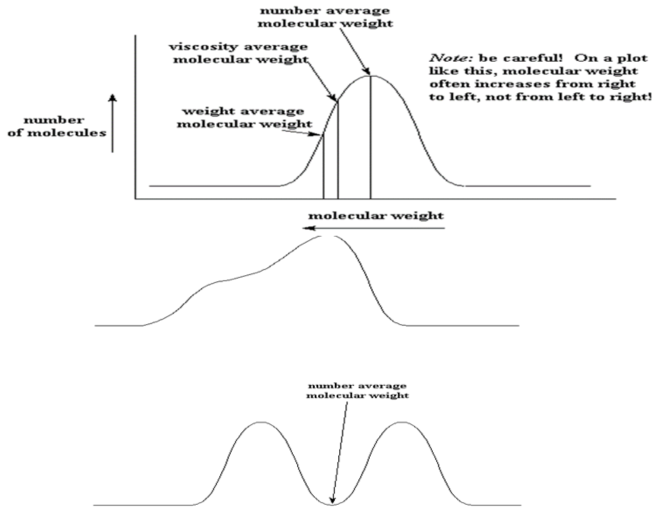
Molecular Weight Distribution



Normal

Skewed

Bimodal

41

Molecular Weight

Result of Increasing Molecular Weight Distribution

	Increasing MW Distribution
Tensile Strength	Decreases
Elongation at Break	Increases
Impact Resistance	Increases
Fatigue Resistance	Decreases
Creep Resistance	Decreases
Hardness	Nominal
Abrasion Resistance	Nominal
Softening Temperature	Decreases
Chemical Resistance	Decreases

42

MEASURING MOLECULAR WEIGHT

43

Measuring Molecular Weight

Reasons to measure molecular weight

- Quality control of polymerized polymer to verify it meets specifications (Resin manufacturer)
- Quality control to verify compounding has not excessively degraded the plastic (Compounder)
- Incoming inspection to verify resin meets specifications (Molder)
- Quality control to verify molding process has not excessively degraded the plastic (Molder)
- To assess the potential for using regrind - identify potential molecular weight reduction (Molder)
- Incoming inspection to verify molded part specifications (OEM)
- As part of a failure analysis (All)

44

Measuring Molecular Weight

Molecular Weight Determination

Three Key Methods:

- Gel Permeation Chromatography (GPC)
- Intrinsic Viscosity (IV)
- Melt Flow Rate (MFR)

45

Measuring Molecular Weight - GPC

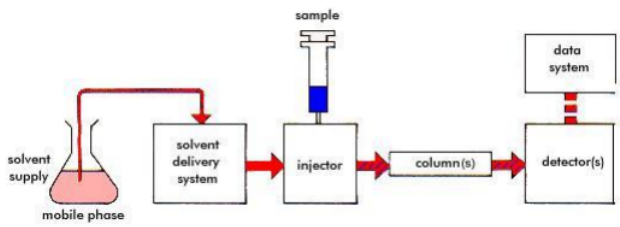
Gel Permeation Chromatography (GPC)

- GPC is a type of size exclusion chromatography based on liquid chromatography
- Separates analytes based on size - smaller molecules are retained in the packed column
- Plastic sample is dissolved in an appropriate solvent
- Various detectors including: infrared absorption, light scattering, differential refractive index, ultraviolet absorption
- Produces a “bell-shaped” distribution of molecular weight

46

Measuring Molecular Weight - GPC

Gel Permeation Chromatography (GPC)

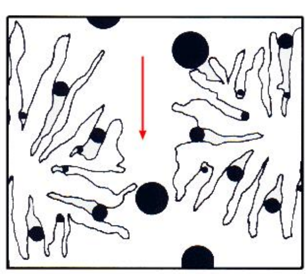


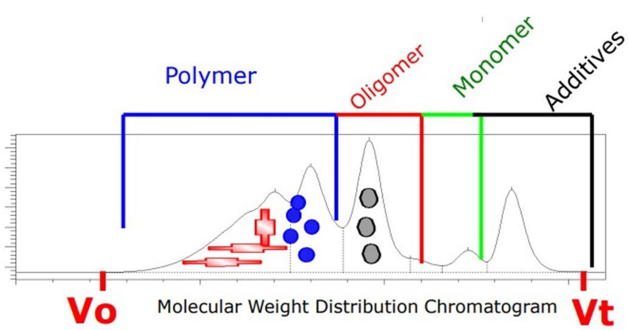
Concentration detectors
- Differential refractometer (RI)
- Ultraviolet absorbance (UV)
- Evaporative light scattering or mass detector (ELS, EMD)
- Infra-red (IR)

Molecular weight sensitive detectors
- Viscometry
- Light scattering

Measuring Molecular Weight - GPC

Gel Permeation Chromatography (GPC)

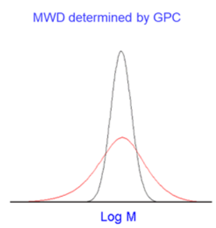




Measuring Molecular Weight - GPC

Gel Permeation Chromatography (GPC)

- **GPC is the only technique for characterizing polymer molecular weight distribution**
- As molecular weight increases the strength and toughness of the polymer increases
- However as molecular weight increases the polymer becomes more difficult to process
- GPC provides key information to predict the processability and material properties of a polymer



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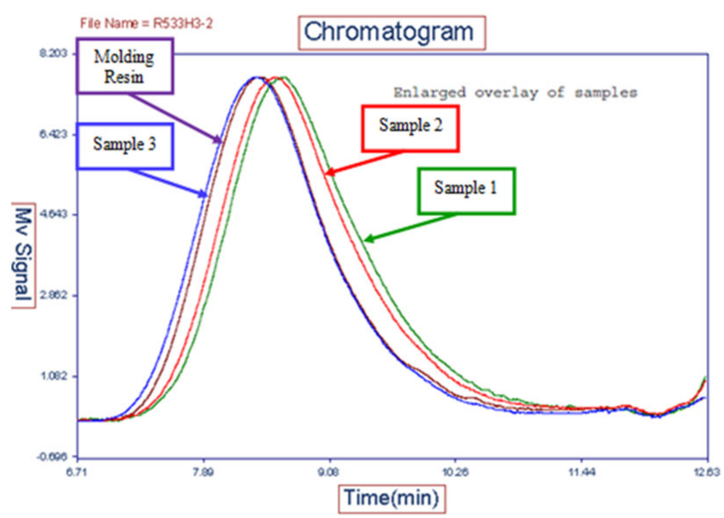
49

Measuring Molecular Weight - GPC

Gel Permeation Chromatography (GPC)



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50

Measuring Molecular Weight - GPC

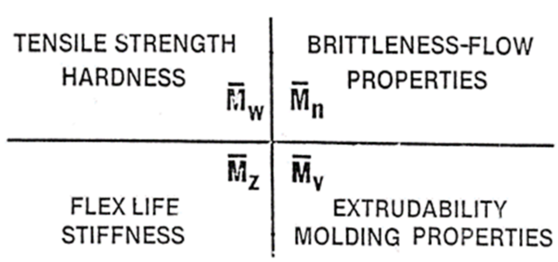
Gel Permeation Chromatography (GPC)

Gel Permeation Chromatography Results
(Average Molecular Weight)

Sample	Run	M_n		M_w		M_z		M_w/M_n	
Molding Resin	1	9,702	9,759	46,512	46,556	84,961	85,207	4.79	4.77
	2	9,816		46,601		85,093		4.75	
Sample 1	1	9,003	9,085	33,926	33,881	64,318	64,261	3.77	3.73
	2	9,167		33,835		64,204		3.69	
Sample 2	1	8,416	8,443	37,439	37,407	71,367	71,136	4.45	4.43
	2	8,470		37,375		70,905		4.41	

Measuring Molecular Weight - GPC

Mn - number average molecular weight
Mw - weight average molecular weight
Mv - viscosity average molecular weight
Mp - peak molecular weight
Mw/Mn - polydispersity by GPC



Measuring Molecular Weight - GPC

Number average $M_n = \frac{\Sigma N_i M_i}{\Sigma N_i}$

Mn can be correlative with polymer colligative properties, e.g. freezing point depression

Weight average $M_w = \frac{\Sigma N_i M_i^2}{\Sigma N_i M_i}$

Mw may be correlated with properties such as melt viscosity

Z average $M_z = \frac{\Sigma N_i M_i^3}{\Sigma N_i M_i^2}$

Mz may be correlated with properties such as toughness

Polydispersity, $d = \frac{M_w}{M_n}$

Polydispersity characterises the shape of the distribution

Molecular Weight

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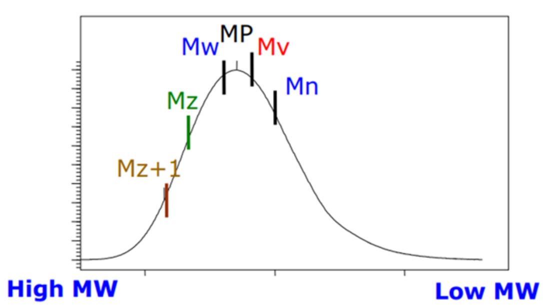
Measuring Molecular Weight - GPC



Number average molecular weight: Mn
The number average molecular weight is the statistical average molecular weight of all the polymer chains in the sample.

Molecular Weight

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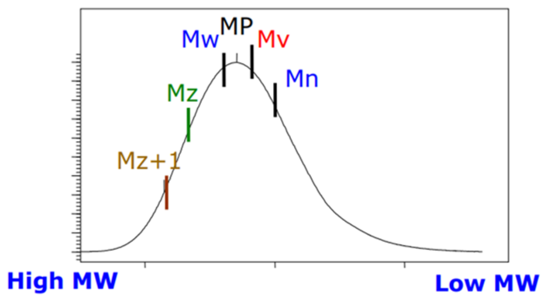
Measuring Molecular Weight - GPC



Molecular weight of the highest peak: Mp
Therefore, Mp is the mode of the molecular weight distribution.

Molecular Weight

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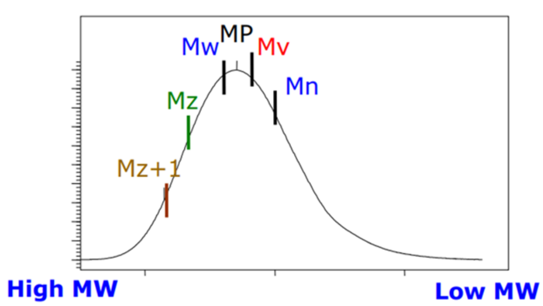
Measuring Molecular Weight - GPC



Weight average molecular weight: Mw

Compared to Mn, Mw takes into account the molecular weight of a chain in determining contributions to the molecular weight average. The more massive the chain, the more the chain contributes to Mw.

Molecular Weight

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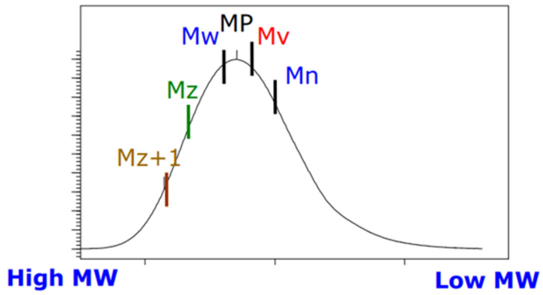
Measuring Molecular Weight - GPC



Higher average molecular weights: Mz, Mz+1
The higher averages are increasingly more sensitive to high molecular weight polymers and accordingly are increasingly more difficult to measure with precision.

Molecular Weight

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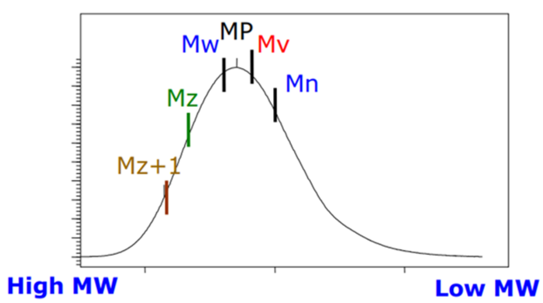
Measuring Molecular Weight - GPC



The polydispersity index is used as a measure of the broadness of a molecular weight distribution of a polymer, and is defined by:
Polydispersity index = Mw/Mn
The larger the polydispersity index, the broader the molecular weight.

Molecular Weight

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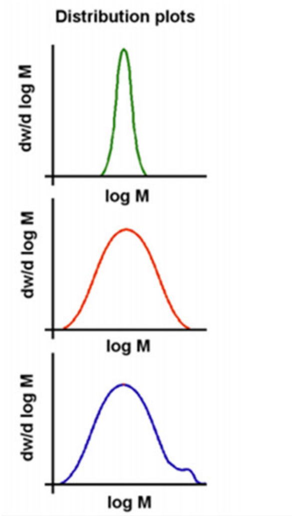
58

Measuring Molecular Weight - GPC



The polydispersity index is used as a measure of the broadness of a molecular weight distribution of a polymer, and is defined by:
Polydispersity index = Mw/Mn
The larger the polydispersity index, the broader the molecular weight.

59

Measuring Molecular Weight - IV

Intrinsic Viscosity (IV)

- IV is a measure of the capability of a polymer in solution to enhance the viscosity of the solution
- Indirect measurement of the average molecular weight:

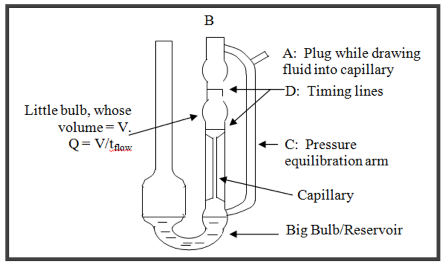
↑ Average Molecular Weight - ↑ IV

60

Measuring Molecular Weight - IV

Intrinsic Viscosity (IV)

- ASTM D 2857
- The polymer is dissolved in an appropriate solvent
- Sample size: 40-50 mg
- Measure the flow time of a solution through a glass capillary – Ubbelohde viscometer
- Testing is conducted to find the viscosity at different concentrations and then extrapolate to zero concentration



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61

Measuring Molecular Weight - MFR

Melt Flow Rate (MFR)

- Most common measure of molecular weight
- Test method: ASTM D 1238
- Measures the flow of a thermoplastic material through a specified orifice under unique conditions of temperature and load
- Units: g/10 min.

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62

Measuring Molecular Weight - MFR

Melt Flow Rate (MFR)

- MFR is an indirect measure of average molecular weight
- MFR is inversely proportional to the average molecular weight:

↑ Average Molecular Weight – ↑ Melt Viscosity – ↓ Melt Flow Rate

- MFR testing does not generate a direct measure of the average molecular weight, however:

$$MFR \approx M_w^{3.4}$$
$$M_w \approx MFR^{0.238}$$

- The standard MFR test does not provide information regarding the molecular weight distribution
- Testing can be conducted at two conditions representing different shear rates (capillary rheology)
- Experiments can be run to assess thermal stability

Molecular Weight

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PICKING THE RIGHT TEST

Molecular Weight

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64

Measuring Molecular Weight - MFR

Approx. 16,500 resins with MFR data in SpecialChem Material Database

ABS HI100 Properties

Physical	Value & Unit	Test Condition	Test Method
Melt Mass-Flow Rate (MFR or MFI = Melt Flow Index or MI = Melt Index)	12 g/10 min	220°C/ 10 kg	ASTM D1238
Specific Gravity	1.02		ASTM D792

Molecular Weight

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65

Measuring Molecular Weight - IV

Approx. 400 resins with IV data in SpecialChem Material Database

Laser+® W (P41A) Properties

Physical	Value & Unit	Test Condition	Test Method
Intrinsic Viscosity	0.70 - 0.74 dL/g		DAK-QAR-SOP-0012
Color L	76 - 80 CIE		DAK-QAR-SOP-0011
Color B	-2 - -6 CIE		DAK-QAR-SOP-0011
Acetaldehyde Content	< 1 ppm		DAK-QAR-SOP-0010

Molecular Weight

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Measuring Molecular Weight - GPC

0 resins with GPC or molecular weight data in SpecialChem Material Database

Molecular Weight

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67

Measuring Molecular Weight

In order to identify molecular degradation, a resin sample or previous data is required for GPC, and in most cases IV.

It is possible to compare MFR results with nominal datasheet value – not ideal

Molecular Weight

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68

Measuring Molecular Weight

MFR

Advantages
- Data availability
- Ease of testing
- Low cost of contract testing
- Relatively low cost of equipment

Disadvantages
- Indirect measure of average molecular weight
- No molecular weigh distribution information
- Glass fiber reinforced results – confounded
- Nylon – moisture content
- 15 g required
- Sample drying
- Sample cutting

IV

Advantages
- No interference from glass fibers
- Small sample size
- Moderate cost of contract testing
- Relatively low cost of equipment

Disadvantages
- Lack of available data
- Resin required for comparisons
- Need accurate filler content
- Solvents used in testing
- Need to dissolve sample

GPC

Advantages
- Absolute molecular weight values
- Molecular weight distribution results
- Small sample size

Disadvantages
- Sophistication of test procedure
- Solvents used in testing
- Need to dissolve sample
- High cost of contract testing
- High cost of equipment

Molecular Weight

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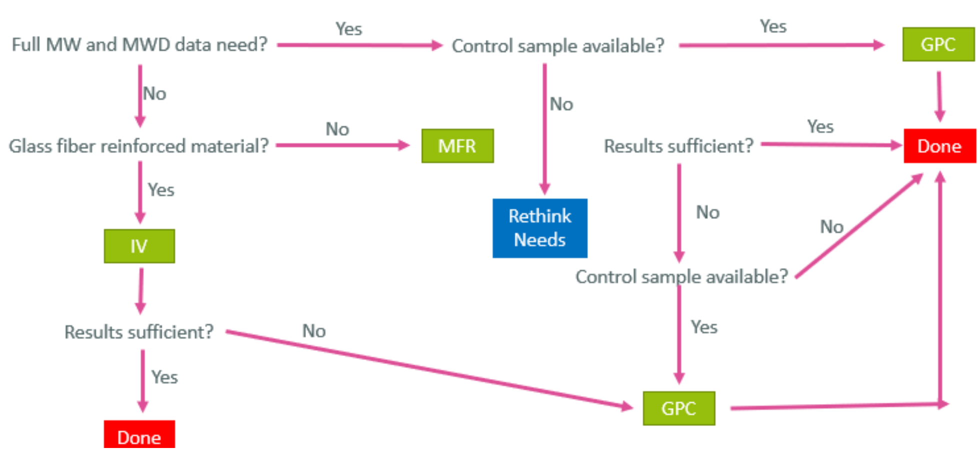
69

Measuring Molecular Weight



Molecular Weight

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70

MOLECULAR DEGRADATION

71

Molecular Degradation

Molecular Degradation is...

deleterious alteration of the molecular structure within a polymeric material as the result of a chemical reaction

72

Molecular Degradation

Molecular Degradation Mechanisms

- Oxidation
- Ultraviolet Radiation (UV)
- Hydrolysis
- Chain Scission
- Side Chain Alteration
- Destructive Crosslinking

Any point in the material life cycle

Molecular Weight Changes Permanently Through Chemical Reactions

Molecular Degradation

Molecular Degradation Mechanisms

- Compounding
  - Exposure to elevated shear induced heating while additive are incorporated into compound
- Drying
  - Exposure to extreme time/temperature profile in drying hopper
- Processing
  - Insufficient drying of resin prior to injection molding
- Storage
  - Exposure of polymeric tubing to sunlight prior to installation
- Installation
  - Elevated temperature use for welding operation
- Service
  - Contact with aggressive acid or alkaline cleaning chemical agents

Molecular Degradation

Molecular Degradation Mechanisms

Decreasing MW Reduces

- Tensile Strength
- Elongation at Break
- Impact Resistance
- Fatigue Resistance
- Creep Resistance
- Hardness
- Abrasion Resistance
- Softening Temperature
- Chemical Resistance

75

Molecular Degradation

Molecular Degradation Mechanisms

- Reduction in molecular weight → lower ductility
- Loss of entanglement associated with shortening of polymer chains
- Reduces the energy required for disentanglement/slippage to occur and shifts the preferred mechanism from yielding

76

Molecular Degradation

Thermal Oxidation

- Resin Drying
- Storage
- Service

$$2ROOH \longrightarrow RO^{\cdot} + ROO + H_2O$$

$$ROO^{\cdot} + \underset{\text{Polymer}}{RH} \longrightarrow ROOH + R^{\cdot}$$

$$R^{\cdot} + O_2 \longrightarrow ROO^{\cdot}$$

$$ROO^{\cdot} \longrightarrow \underset{\text{Ketone}}{R\text{-}\overset{O}{\overset{\|}{C}}\text{-}R'}, \underset{\text{Aldehyde}}{R\text{-}\overset{O}{\overset{\|}{C}}\text{-}H}, \underset{\text{Ester}}{R\text{-}\overset{O}{\overset{\|}{C}}\text{-}OR'}, \underset{\text{Organic Acid}}{R\text{-}\overset{O}{\overset{\|}{C}}\text{-}OH}$$

Catalyzed by metals, particularly Cu

Molecular Weight Changes Permanently Through Chemical Reactions

Molecular Degradation

Chain Scission

- Compounding
- Molding

$$\mathbf{R - R} \xrightarrow{\text{Heat}} \mathbf{R1 + R2}$$

Molecular Weight Changes Permanently Through Chemical Reactions

Molecular Degradation

Hydrolysis

- Compounding
- Molding
- Storage
- Service

$$R-\overset{\displaystyle O}{\overset{\|}{C}}-O-R1 + H_2O \longrightarrow R-\overset{\displaystyle O}{\overset{\|}{C}}-OH + R1-OH$$

Molecular Weight Changes Permanently Through Chemical Reactions

Molecular Weight

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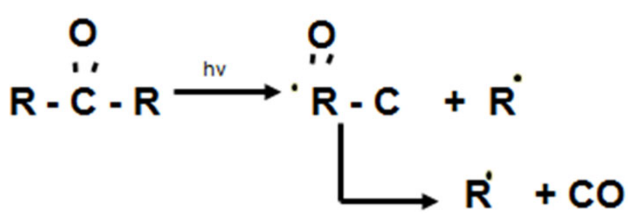
79

Molecular Degradation

UV Degradation

- Service



Molecular Weight Changes Permanently Through Chemical Reactions

Molecular Weight

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80

Molecular Degradation

Effects of Molecular Degradation

- Loss of Molecular Weight
  - Embrittlement
  - Loss of Mechanical Integrity
  - Cracking
  - Catastrophic Failure
- Conjugation
  - Discoloration
  - Loss of Gloss
  - Loss of Transparency
- Evolution of Volatiles
  - Foul Odor Generation
- Carbonyl Formation
  - Loss of Dielectric Properties

Molecular Weight

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81

COMPLEMENTARY TESTS

82

82

Complementary Tests

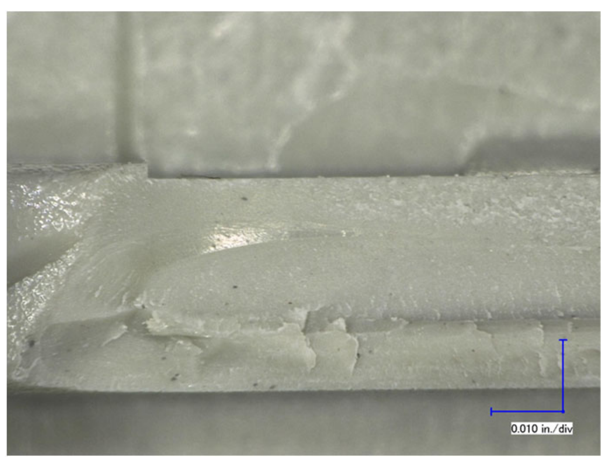
There are tests that provide clues that a plastic material may have undergone *molecular degradation*.

These results suggest molecular weight testing.

Complementary Tests

Visual

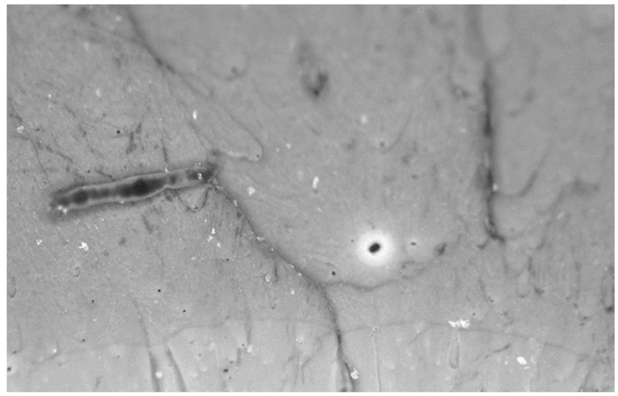
- Included black specs in part of on fracture surface



Complementary Tests

Visual

- Included black specs in part of on fracture surface

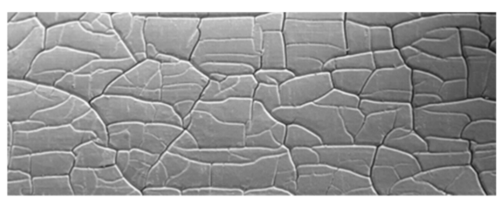


85

Complementary Tests

Visual

- Mud-cracked appearance on the surface

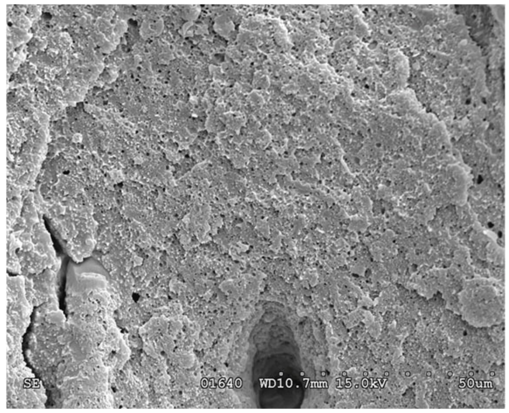


86

Complementary Tests

SEM

- Coarse fracture surface morphology
- Brittle fracture
- Micro-porosity

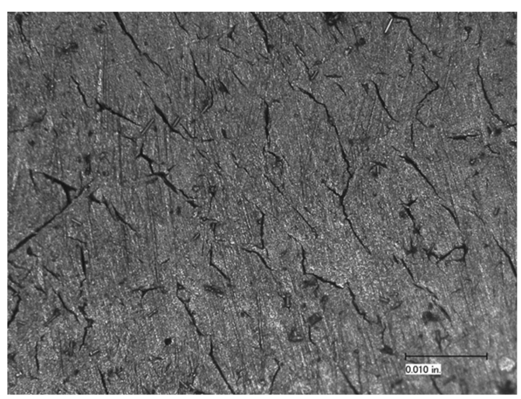


87

Complementary Tests

SEM

- Microscopic surface cracking

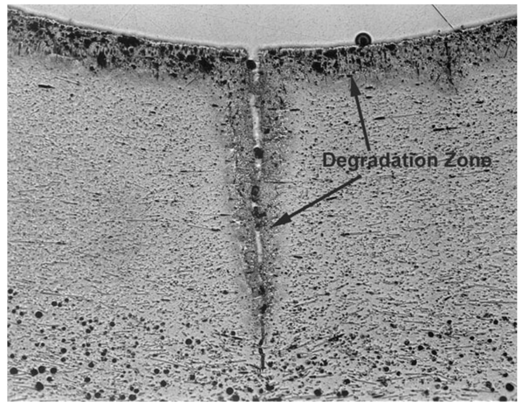


88

Complementary Tests

Cross-section

- Coarse Texture
- Darkened Color

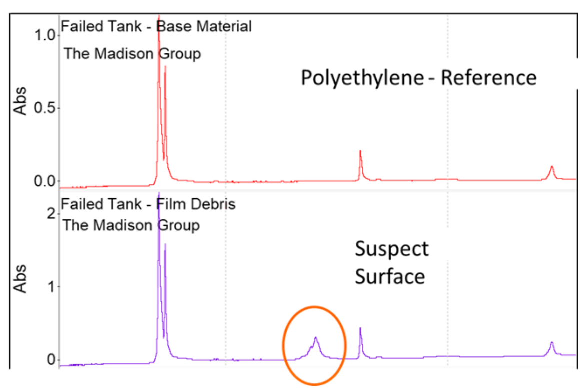


89

Complementary Tests

FTIR

- Analysis of suspect surface material indicative of oxidized polyolefin
- Spectral bands ranging 1750 cm-1 to 1710 cm-1 - broad

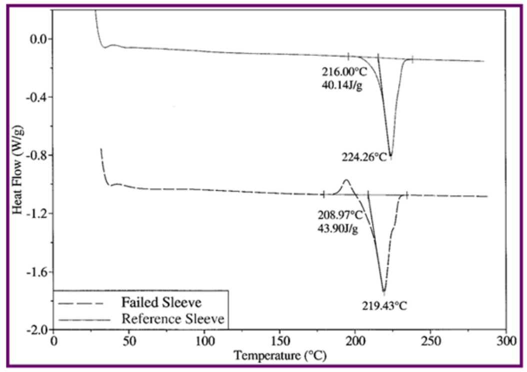


90

Complementary Tests

DSC

- Reduction in melting point or glass transition temperature

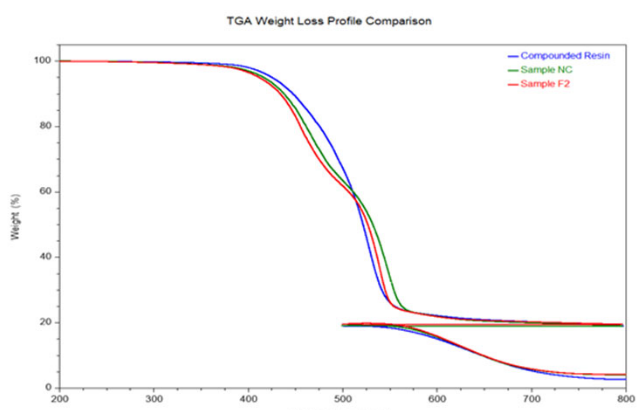


91

Complementary Tests

TGA

- Variation in weight loss temperature profile



92

Plastic Properties

Remember:
The properties of a plastic material are the direct result of the *Polymer Structure* and *Plastic Composition*

93

Questions?

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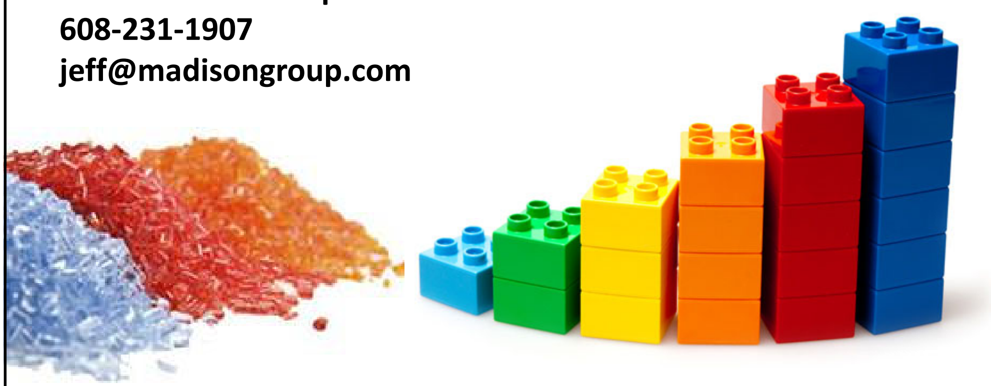
jeff@madisongroup.com



94