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The Plastics Show
Produced by PLASTICS INDUSTRY ASSOCIATION

THE MADISON GROUP
PLASTIC CONSULTING ENGINEERS

Pushing the Limits of Plastic Materials for Automotive Applications

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Senior Managing Engineer
The Madison Group

About me…

THE MADISON GROUP
PLASTIC CONSULTING ENGINEERS

- 20 years in the plastics industry
- Chemical Engineering and Materials Science Degrees
- 15+ years of failure analysis, materials analysis and testing, materials selection, and manufacturing support with The Madison Group.
- What we do at TMG: 30+ years providing consulting and engineering services for clients to successfully make polymer parts.

Design Review

Material Support

Product Testing

Manufacturing Support

Failure Analysis

Customized Training

Introduction

Understanding material performance and limitations coupled with proper design and manufacturing provides the best chance of a successful product.

Introduction

- Performance and Reliability are what customers expect.
  - Durable, reliable, environment (temperature, chemicals, etc.) resistant.
- The right material can provide significant energy and cost savings.
- Plastics have lower density, thus can be light weight and affordable.

Manifold for carbureted small block Chevy

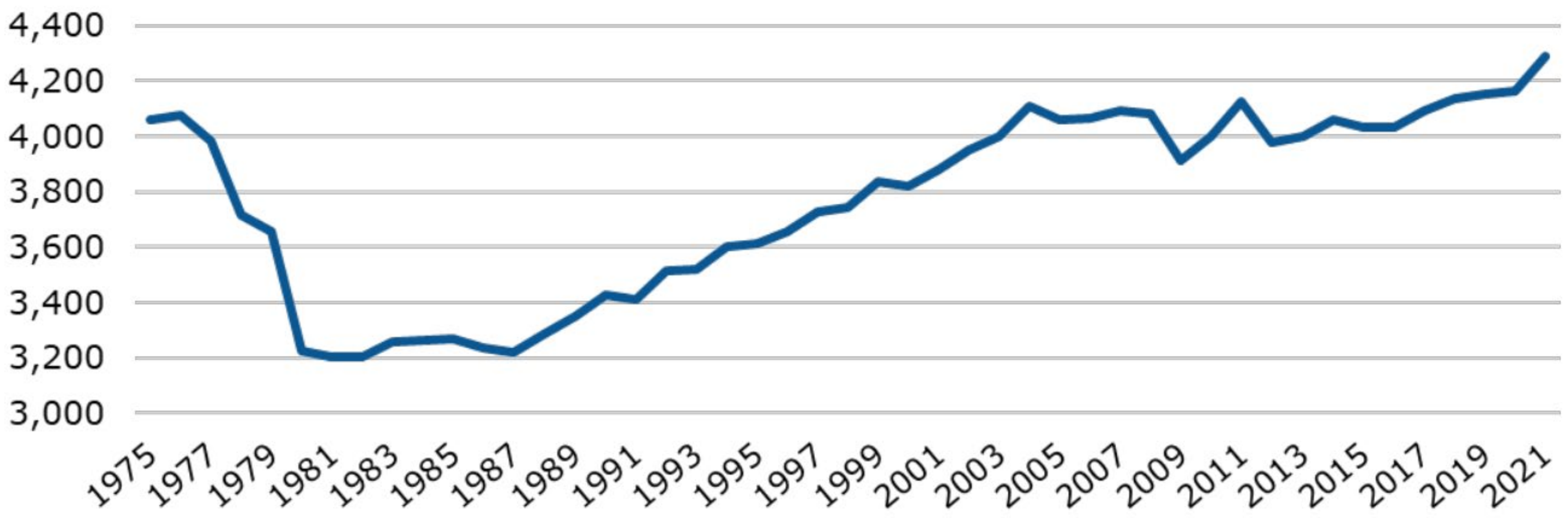
Intake manifold for Chrysler 5.7 L. Integrated with throttle body, EGR, accessory mounts, connectors, etc.

Honda Civic thermostat housing

Introduction

- Today, proper use of plastics and lightweighting is even more critical as the average vehicle weight over time has increased since it is greatly influenced by consumer preferences, comfort, safety and added technologies.

Average vehicle weight (lbs)



Source: EPA

Introduction

- The most common plastics used in car manufacturing today:

Plastics & Polymer Composites in an Average Automobile (lbs/vehicle)

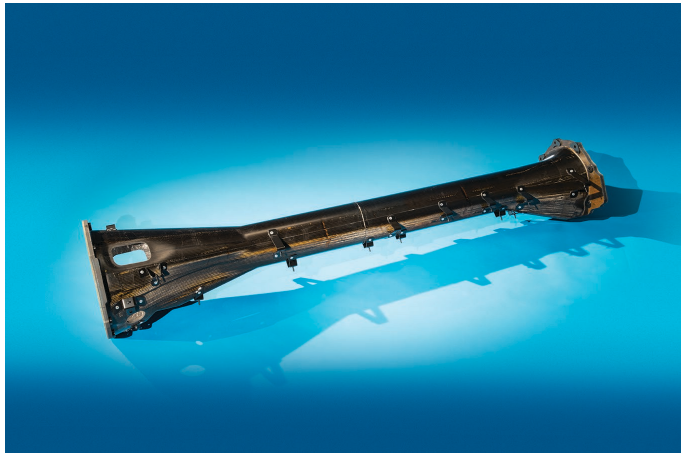
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Polypropylene	81	83	84	84	85	88	91	93	93	97
Polyurethane Foam	73	74	76	76	76	78	80	81	82	84
Nylon	37	38	38	38	38	39	39	39	39	41
High-Density Polyethylene (HDPE)	28	28	27	27	28	29	31	31	32	34
Polyvinyl Chloride (PVC)	25	26	27	27	27	28	29	30	30	31
Acrylonitrile Butadiene Styrene (ABS)	23	23	22	22	22	24	22	21	21	21
Polycarbonate	18	18	18	17	17	18	18	18	19	20
Phenolic Resins	12	11	11	11	11	12	12	13	13	15
Polyacetal Resin	8	8	8	8	8	9	9	9	9	10
Polyvinyl Butyral	6	6	6	6	6	6	6	6	6	7
Polybutylene Terephthalate (PBT)	5	5	5	5	5	5	5	5	5	6
Polymethyl Methacrylate (PMMA)	4	4	4	4	4	5	5	5	5	5
Other Plastics*	34	36	36	36	36	36	37	38	38	40
Plastics & Polymer Composites Total	**354**	**360**	**362**	**361**	**363**	**377**	**384**	**389**	**392**	**411**

*Other Plastics includes liquid crystal polymers, high-performance polyamides, polyphenylene ether, unsaturated polyester, and polyphenylene sulfide resins, among other small-volume plastics.

ACC 3-2023 Report, Chemistry and Automobiles

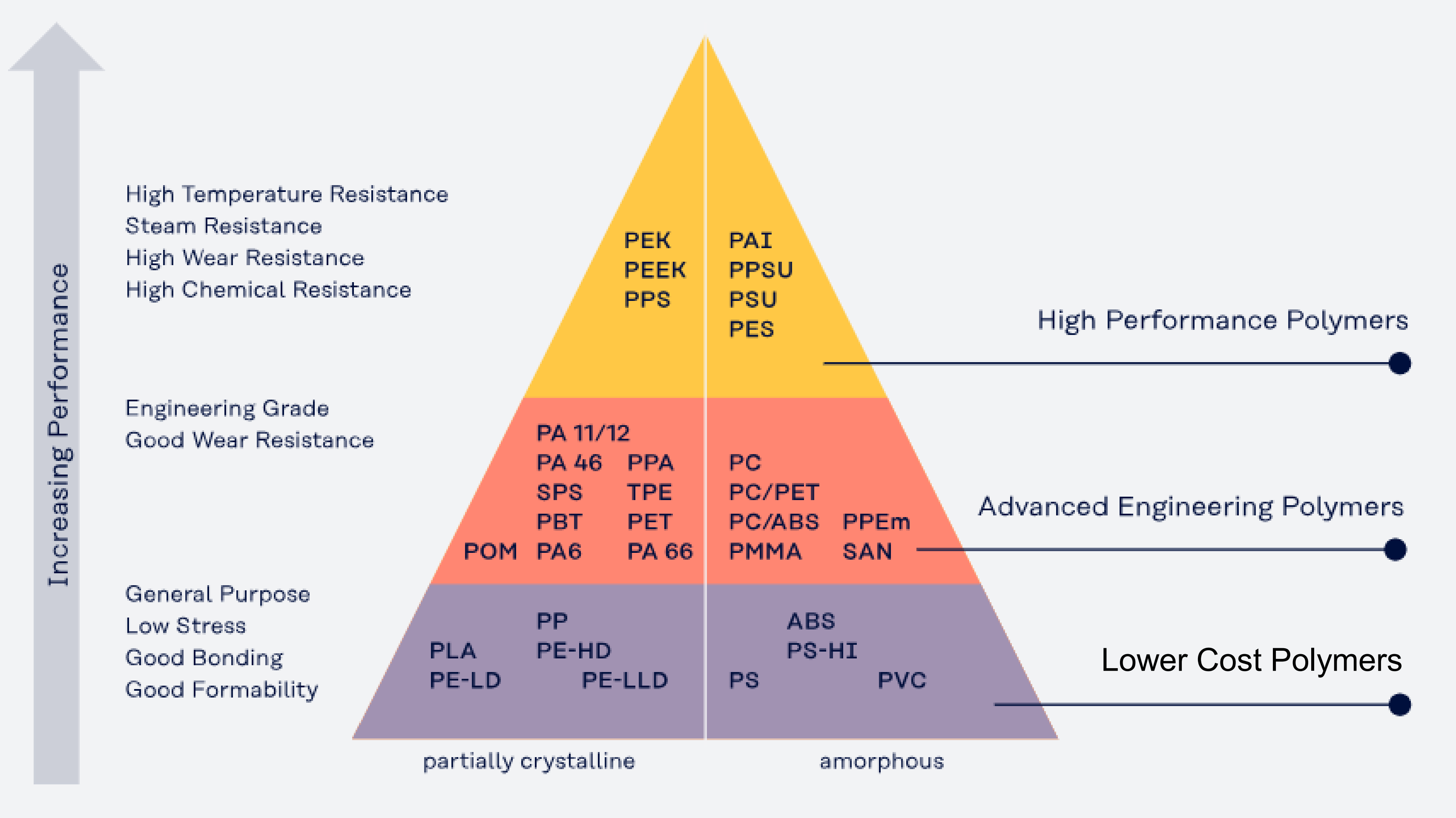
Introduction

- Common Underhood/Structural Materials
  - Polyamides (PA)
  - Polyphthalamide (PPA)
  - Polyetherimides (PEI)
  - Polybutylene Terephthalate (PBT)
  - Polypropylene GF
  - Co-polyester TPEs



https://www.automotiveplastics.com/automotive-plastics-today/under-the-hood/

Plastic Materials



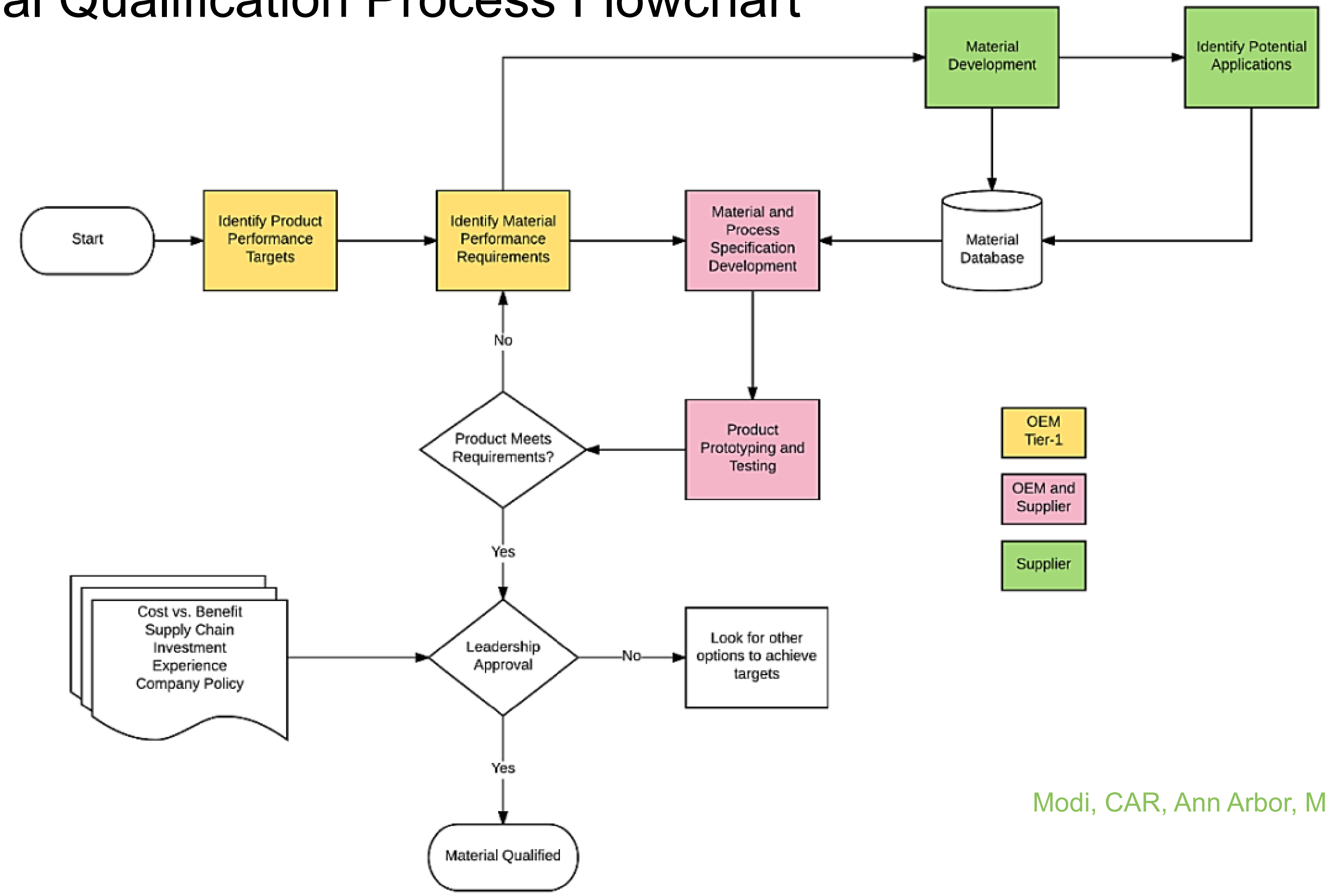
Kuraray/automotive polymers

Material Qualification Process

- A critical step for material selection and acceptance in the automotive world.
- The qualification process involves a series of iterative steps until the customer approves the supplier’s material to be considered in its future products.

Material Qualification Process

- Generic Material Qualification Process Flowchart



Modi, CAR, Ann Arbor, MI. November 2016.

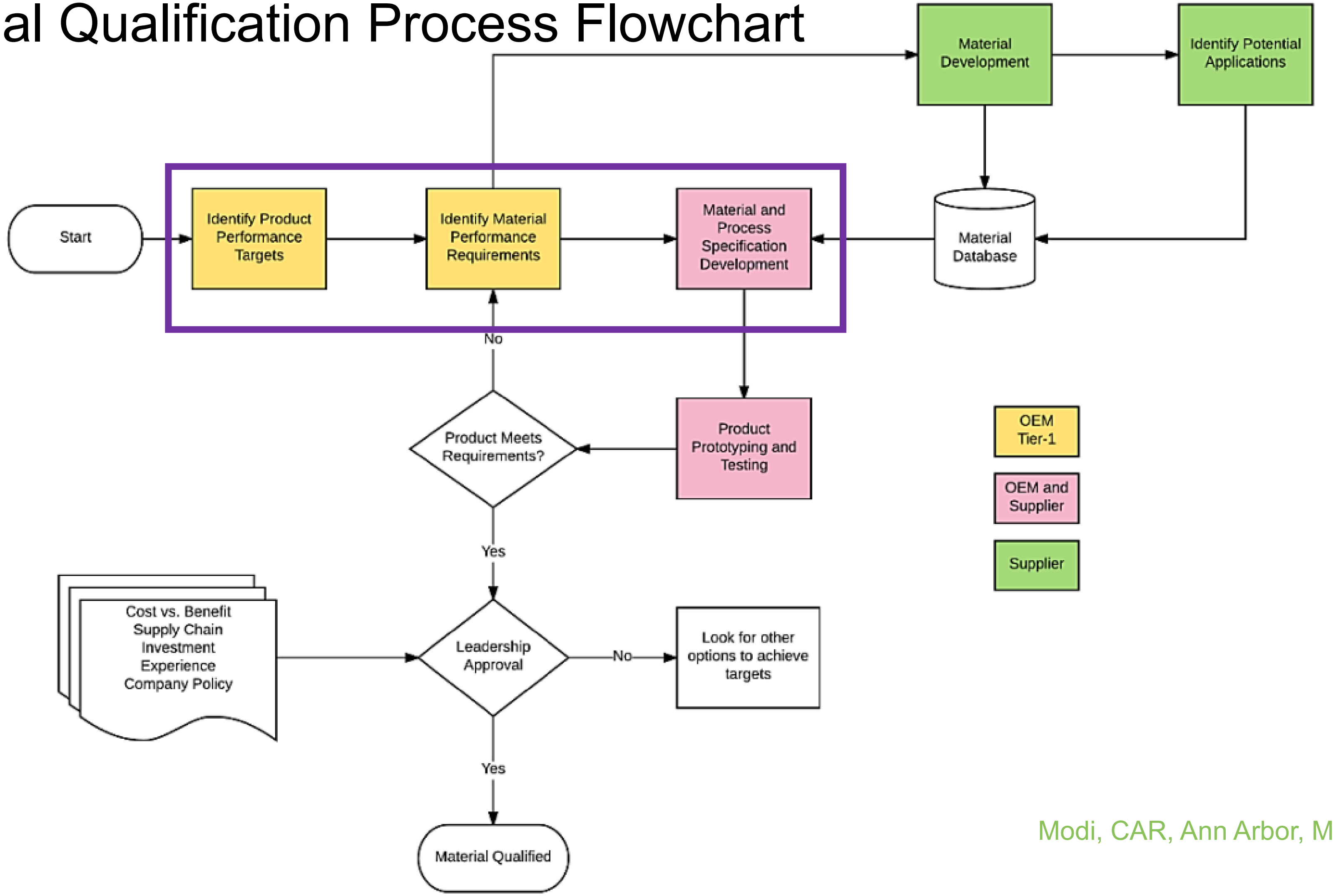
Material Qualification Process

- Flowchart summarized as three major processes:

- This presentation touches on topics related to the material development and qualification, in order to help us better comprehend critical material variables.
- Other very important factors that cannot be covered today include supply chain, manufacturing capability, and capital investment.

Material Qualification Process

- Generic Material Qualification Process Flowchart



Modi, CAR, Ann Arbor, MI. November 2016.

Qualification Properties

- Below is a table of the typical properties that are requested during qualification of plastics with additional important properties that should be requested in Bold. Only the more basic are included in datasheets.

Physical	Short-term Mechanical	Long-term Mechanical	Environmental Effects	Manufacturing Process	Certification and other
Thermal **- Tg** **- Tm** - Heat Capacity	Flex/Tension -Modulus -Strength -Elongation	**Design Factors/Notch Sensitivity**	Chemical Resistance **(Degradation and ESC)**	Recommended processing parameters	Sustainability, Life-cycle data
Density	Impact Strength	**Fatigue Life vs. Stress, T, Freq.**	**Hydrolysis vs. Temperature**	Drying requirements	Reparability
CLTE	HDT/DTUL	**Stress Relaxation**	Friction/Wear		Recyclability
Melt Flow	**DMA Modulus vs. Temp**	**Creep Rupture Curves**	**Oxidation Resistance**	Joining Requirements	Flammability and Smoke
Decomposition Temp. (TGA)	**T - Ductile to Brittle Fracture**	**Continuous Use Temperature (CUT)**	Moisture property effects	Wall-thickness limitations	Short/Long-Term Electrical
Reinforcement **Type and %**		Relative Thermal Index (RTI)			

The Fundamentals

- Polypropylene is not just Polypropylene.

Plastic: Think of a recipe

POLYMER 1, POLYMER 2, PROCESSING AIDS, ANTIOXIDANTS, UV STABILIZERS, NUCLEATING AGENTS, SLIP AGENTS, COLORANTS, PIGMENTS, FILLERS, STRENGTHENING FILLERS, BLOWING AGENTS, IMPACT MODIFIERS, ANTI-STATIC AGENTS, PLASTICIZERS FLAME RETARDANTS…

The Fundamentals -Composition

- Material Structure and Composition

Base Polymer

- Structure/Functional Groups
- Homopolymer/Copolymer
- Tacticity
- Polarity
- Amorphous/Semi-crystalline
- Crosslinking
- Blends/Alloys

Additives

- Anti-oxidants and UV
- Flame Retardants
- Colorants
- Fillers and Reinforcements
- Impact Modifiers

Molecular Weight

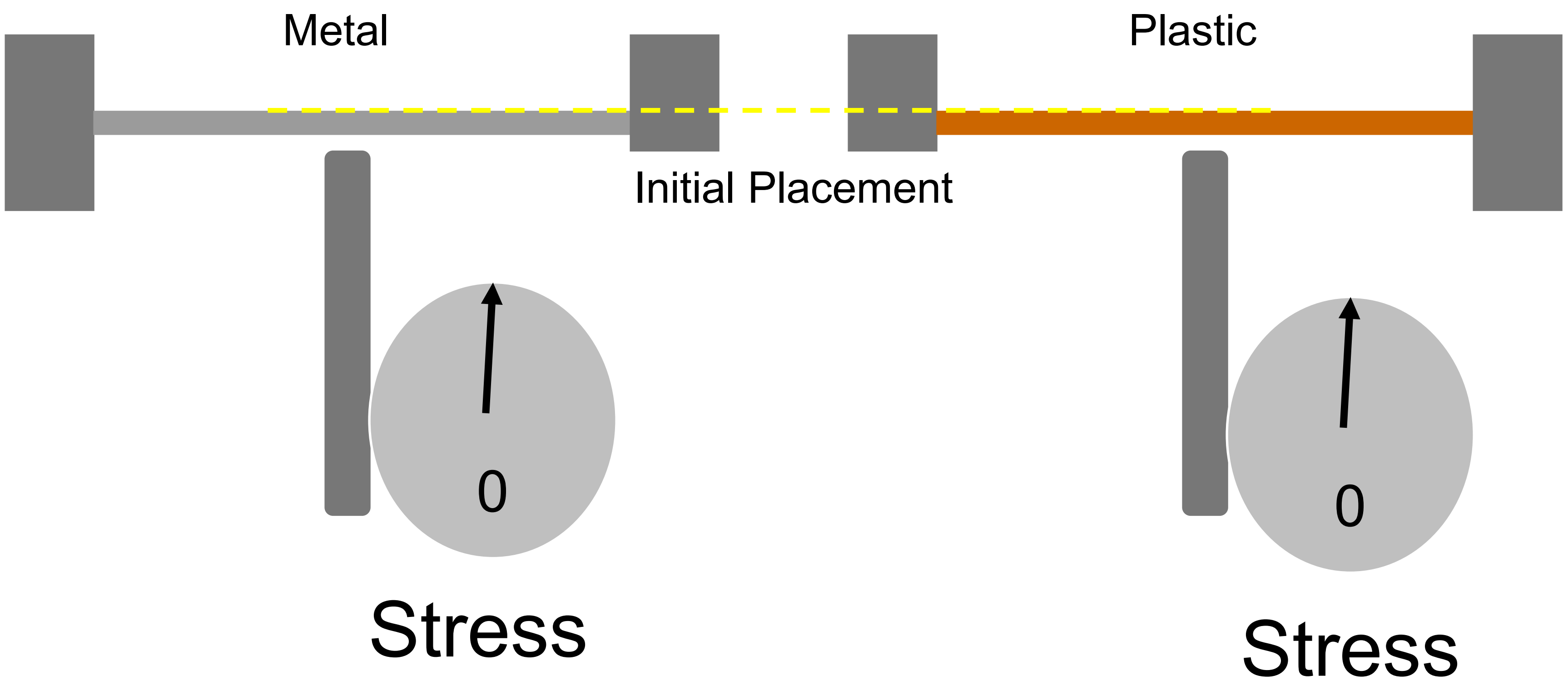
- Average Molecular Weight
- Molecular Weight Distribution

The Fundamentals - Mechanical

- Plastics are viscoelastic.
- Viscous materials, like honey, resist shear flow and strain with time when a stress is applied permanently changing shape due to stress.
- Elastic materials, like a ~~rubber band~~ **steel rod**, when stressed will strain but quickly return to their original state once the stress is removed.
- Polymers under low loads will permanently deform.
- This disentanglement mechanism is the most important material behavior to remember when pushing plastics to their limits.

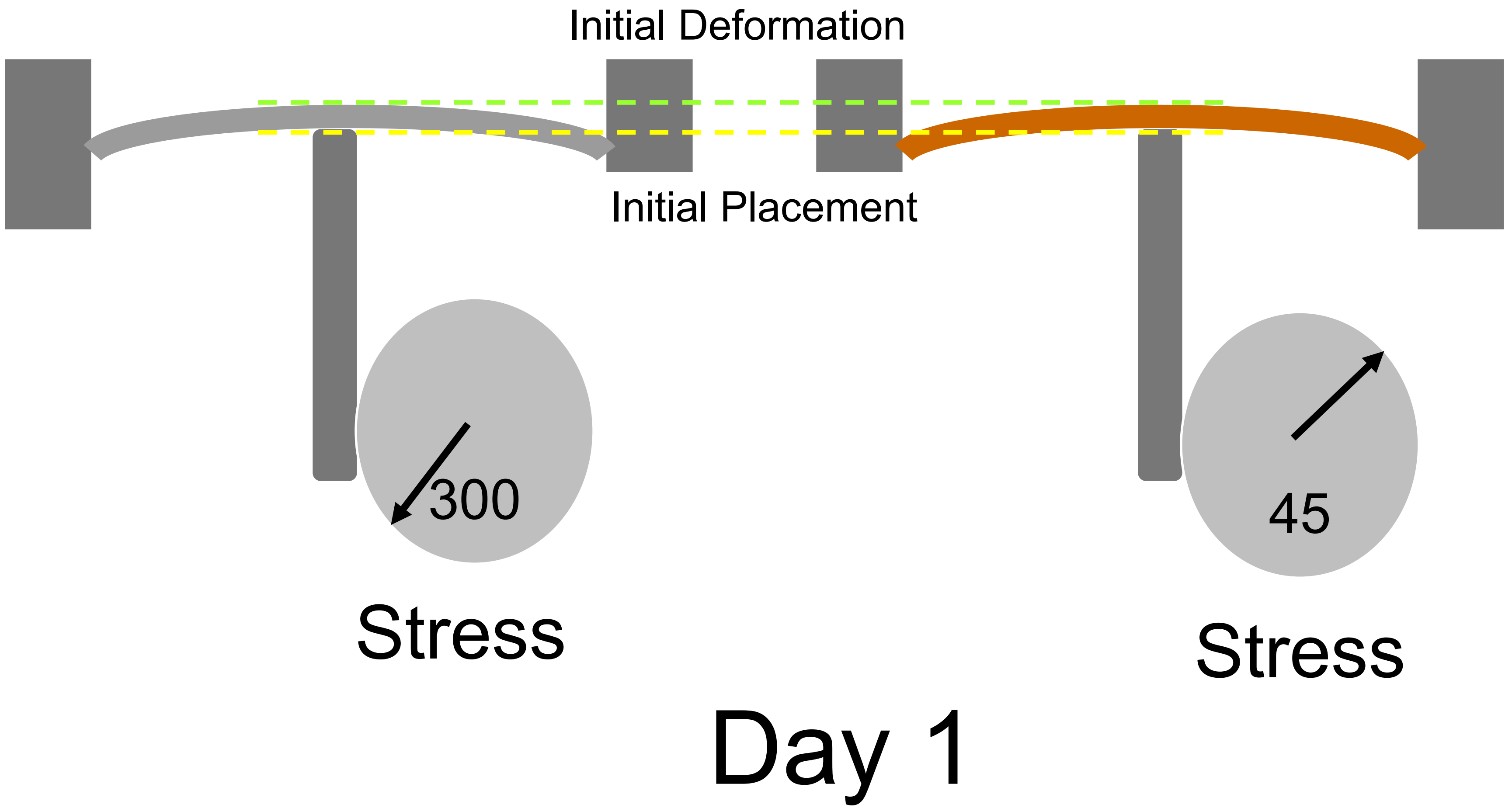
The Fundamentals

- Metal loaded overtime vs. Plastic loaded overtime.



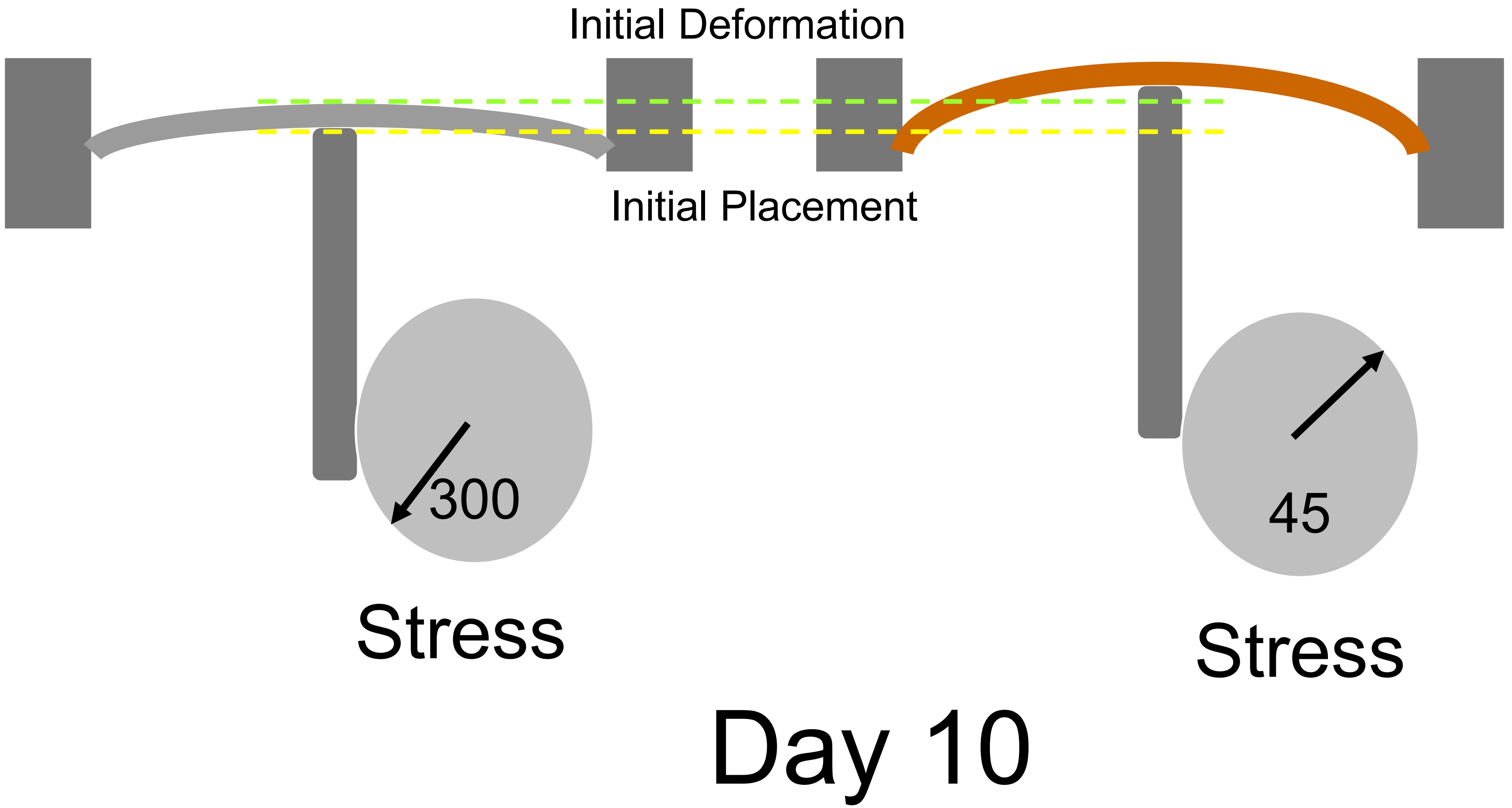
The Fundamentals

- Load applied



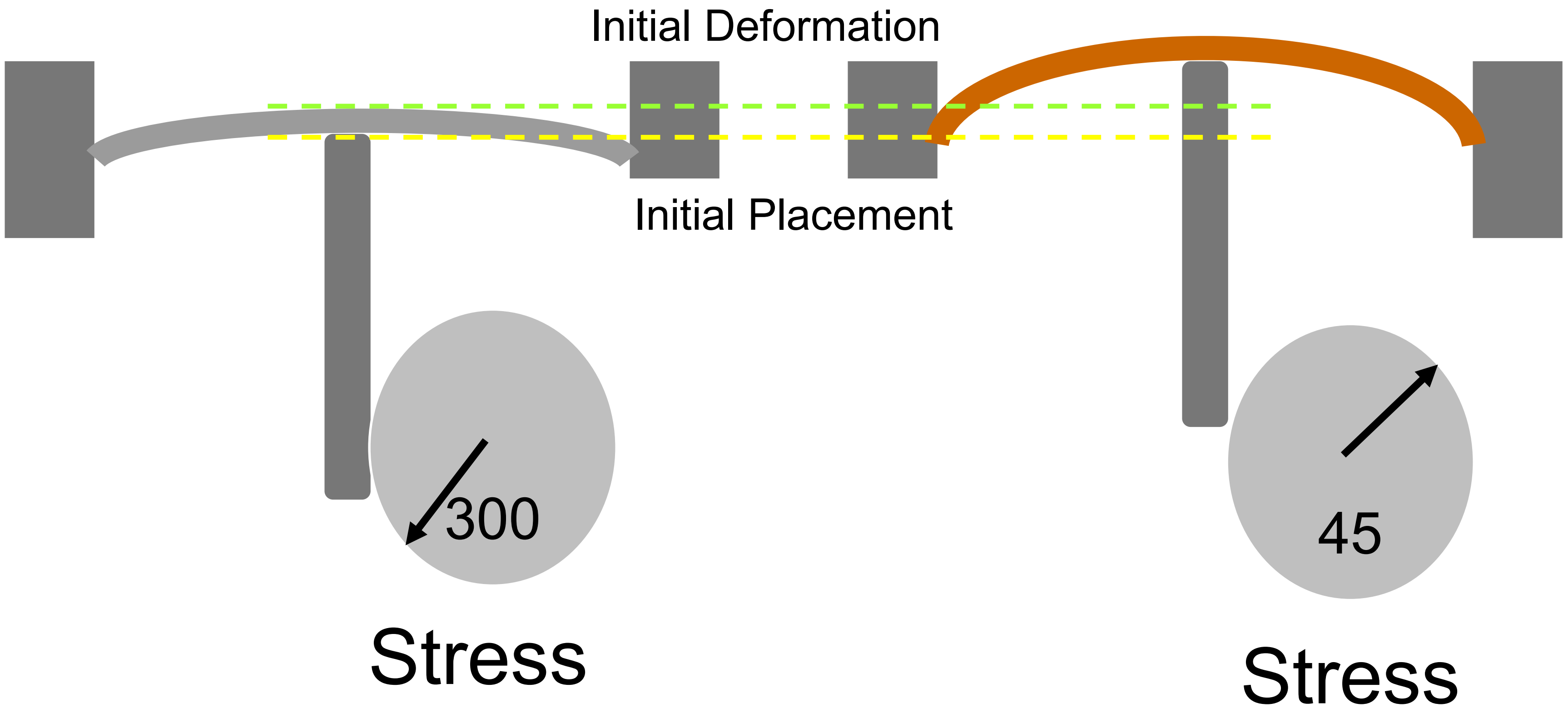
The Fundamentals

- Load applied



The Fundamentals

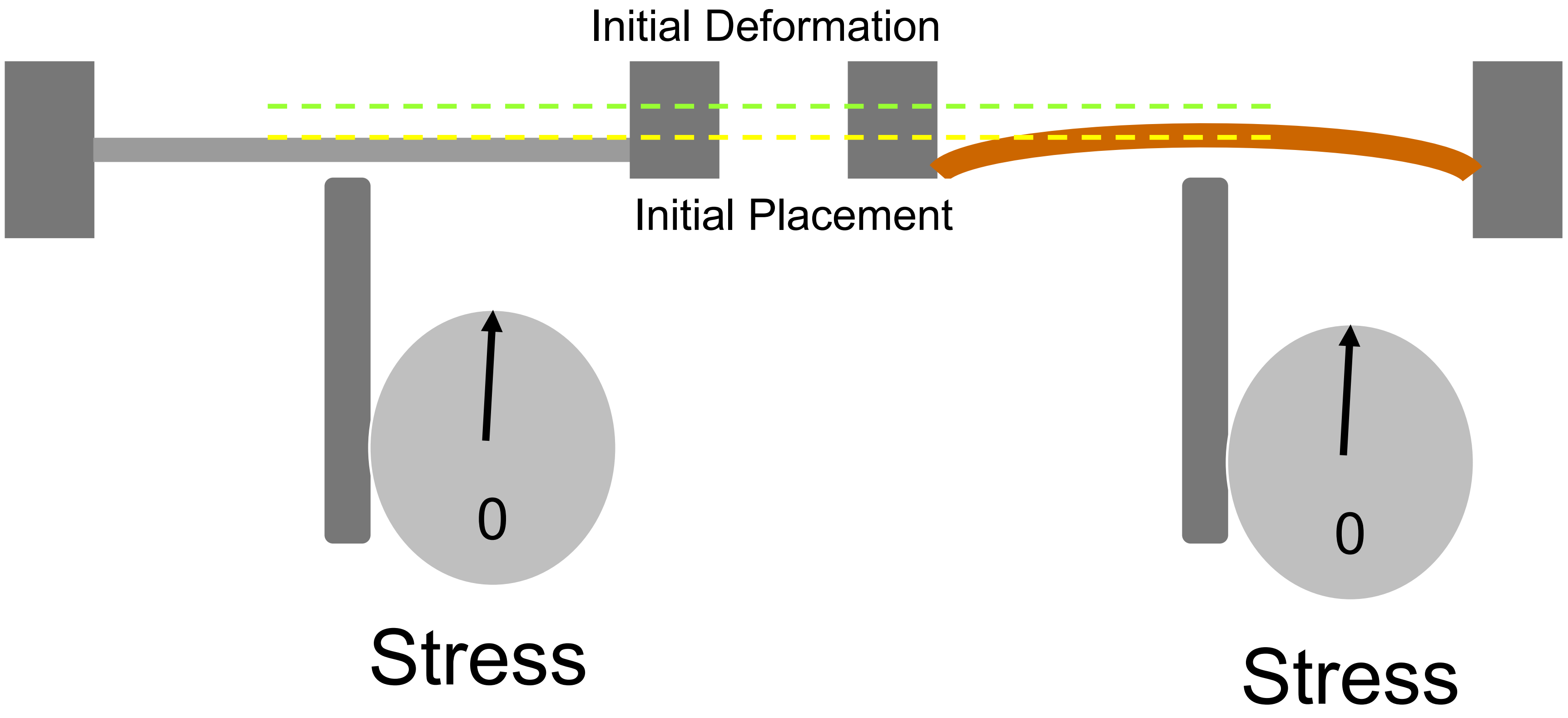
- Load applied



Day 100

The Fundamentals

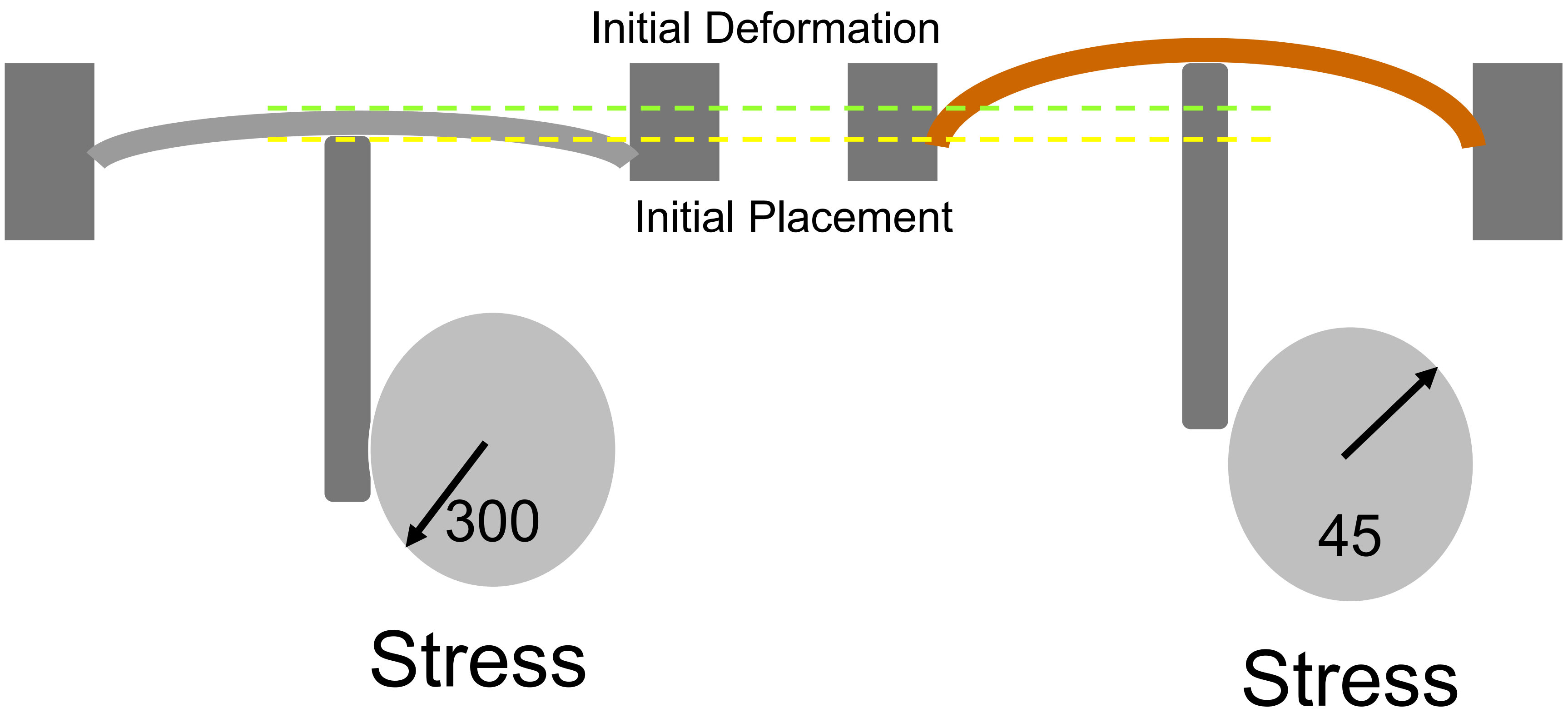
- Load released



Day 100

The Fundamentals

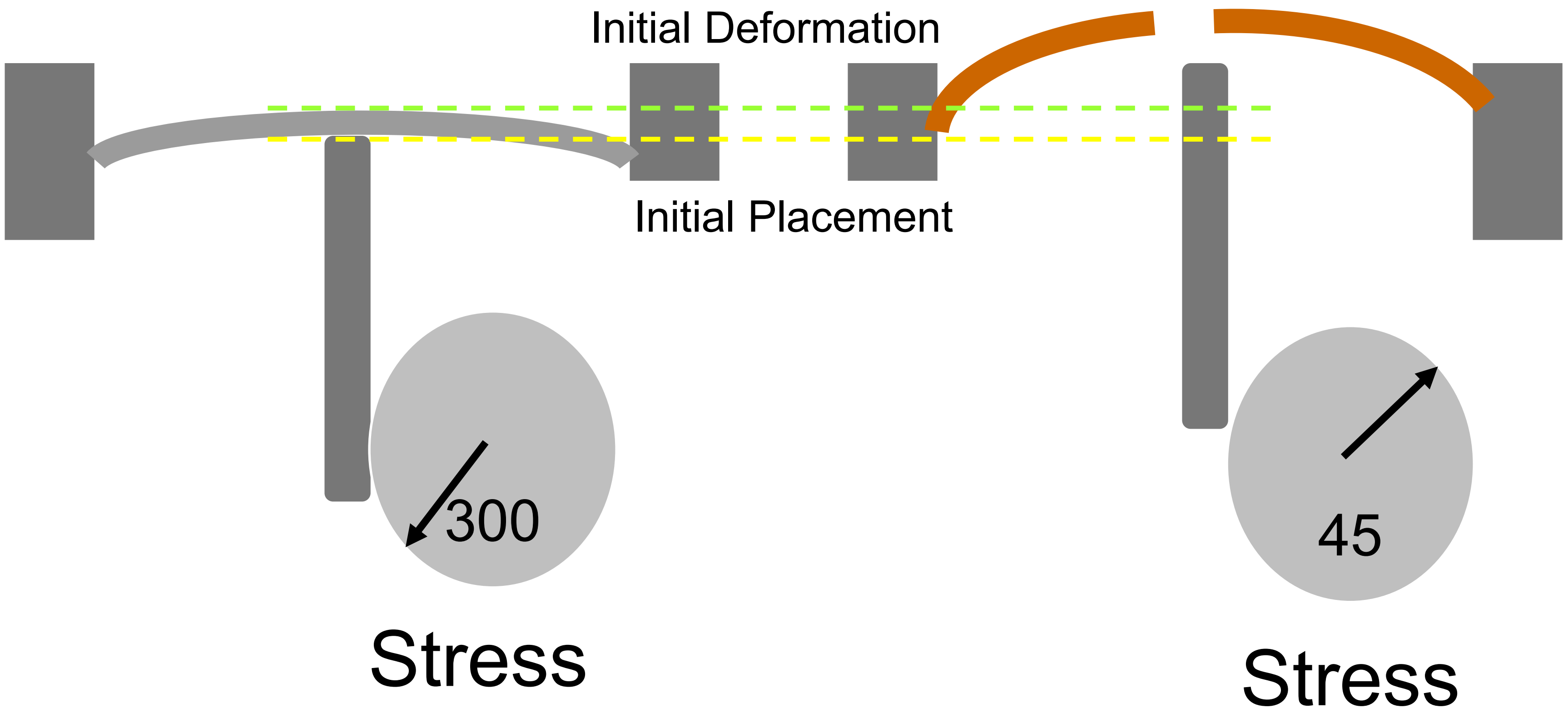
- Load applied



Day 100

The Fundamentals

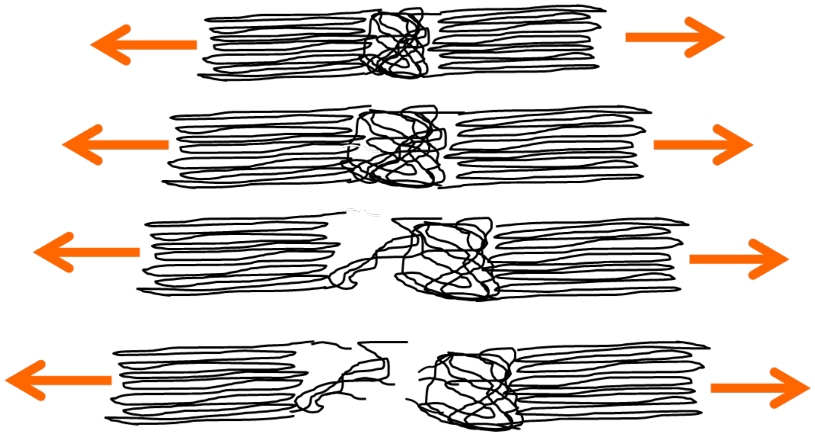
• Load applied

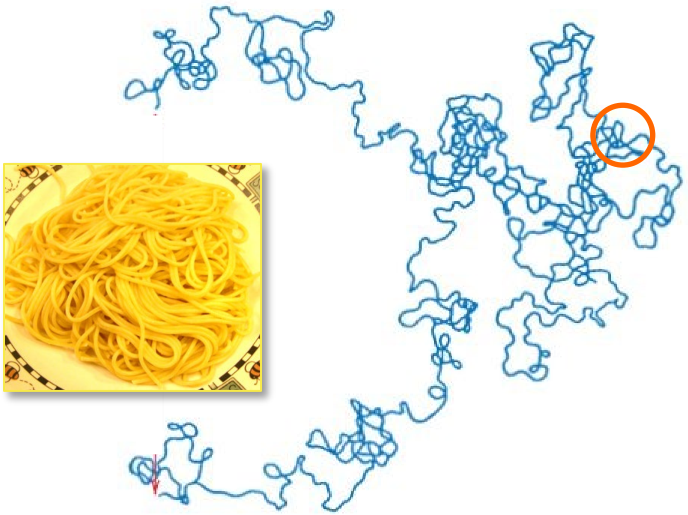


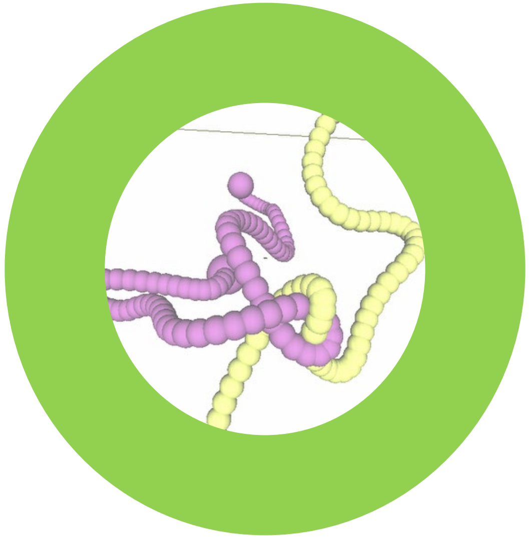
Day 1000 ??

The Fundamentals

- Disentanglement mechanism in which polymer chains slide past each other

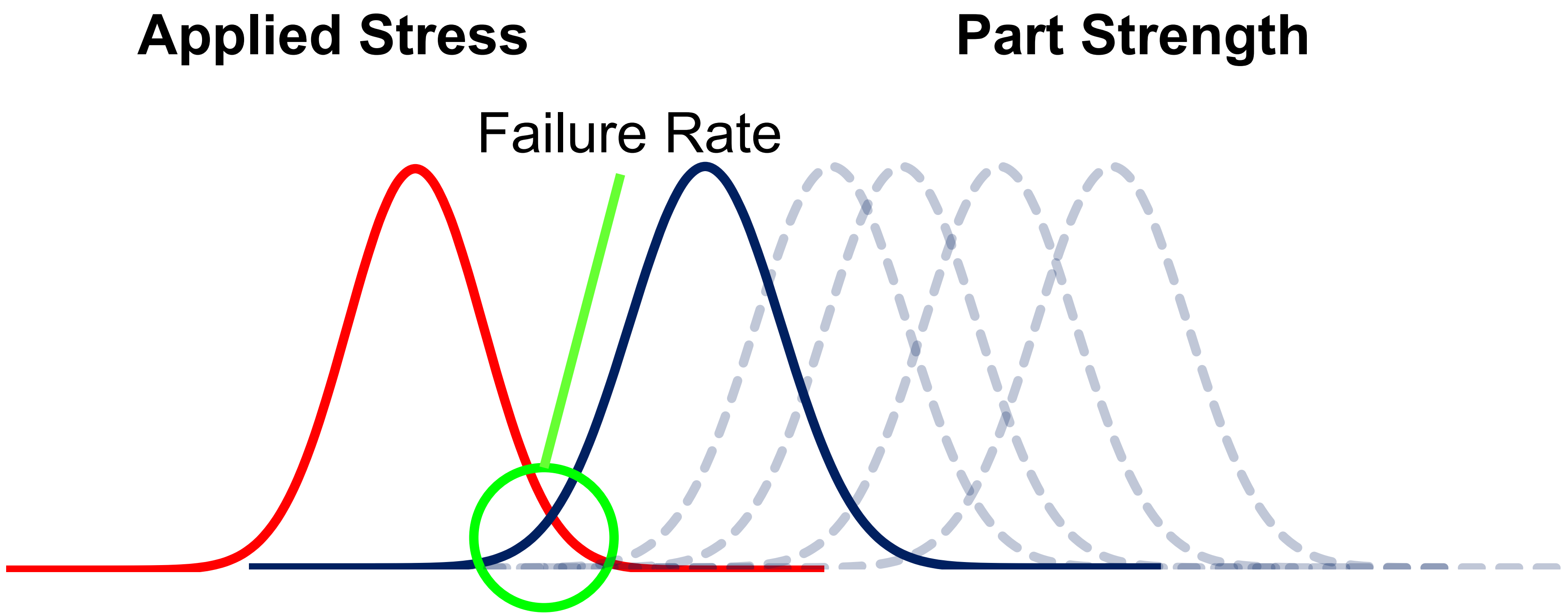






Time reduces the apparent strength of the plastic material.

The Fundamentals

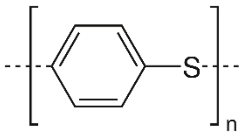


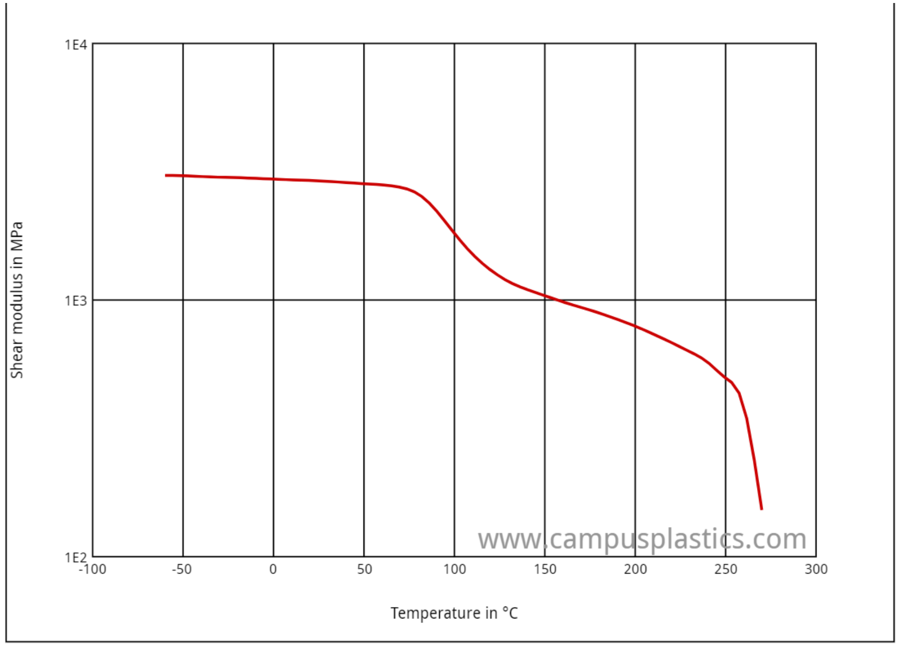
Time reduces the apparent strength of the plastic material.

Accounting for Creep

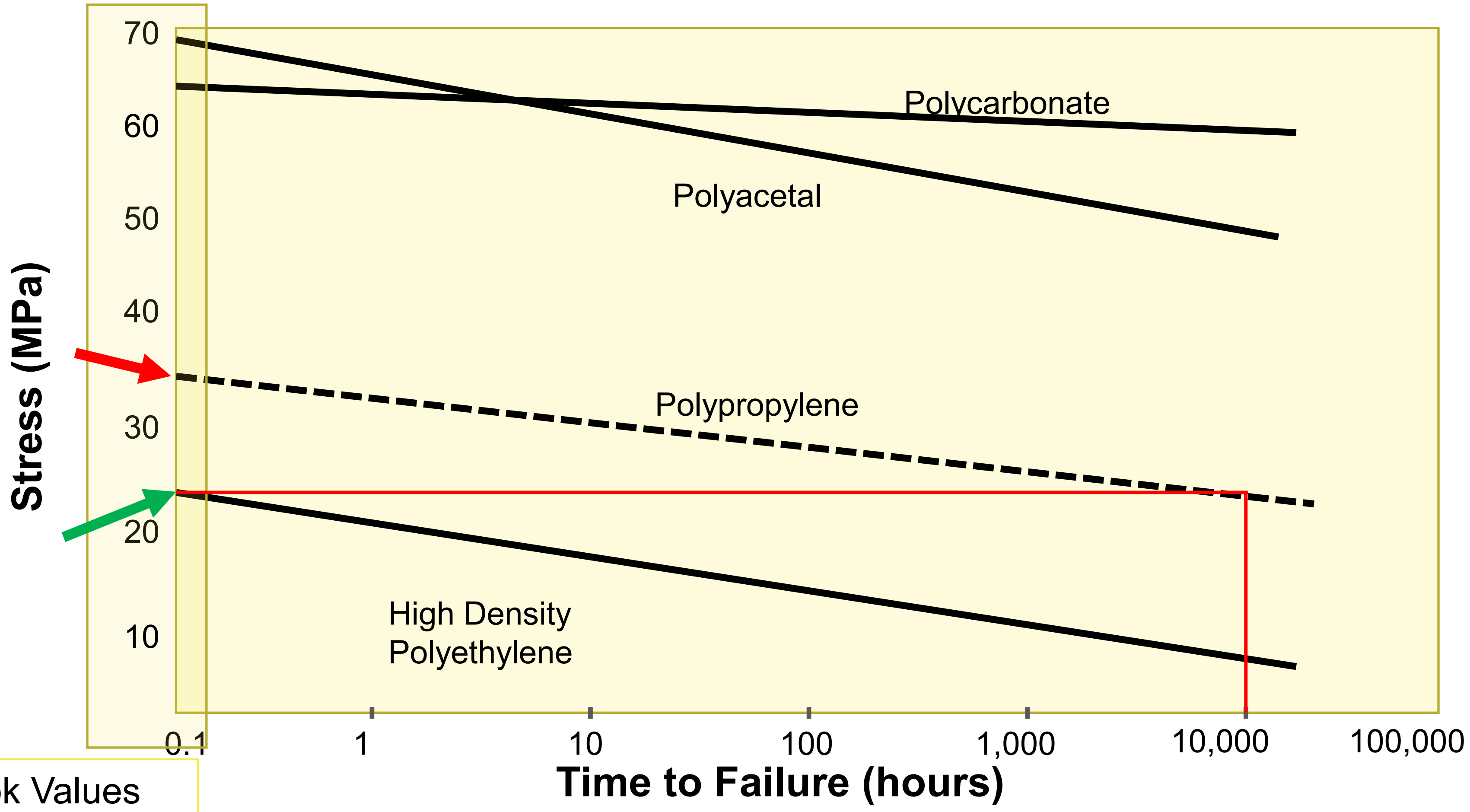
- Find available data, run DMA-TTS, do predictions.
- Creep behavior NEEDS to be considered in any application where a plastic is under continuous stress, this includes assembly stresses and residual stresses.
- Similarities apply to stress relaxation, compression set, ESC.

PPS 40% GF
DMA Curve





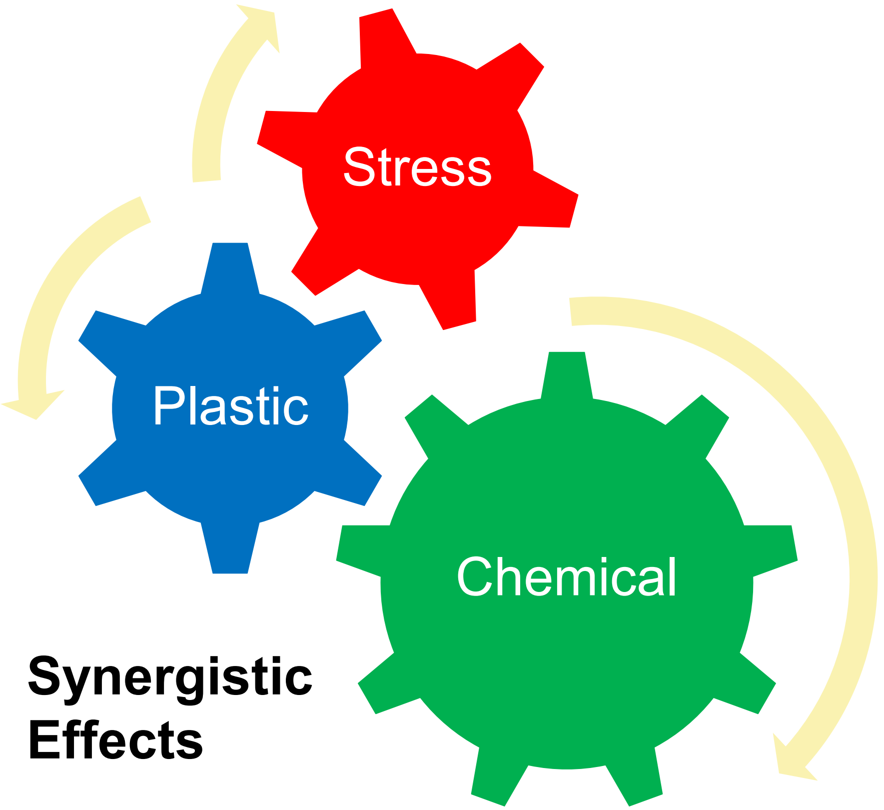
Accounting for Creep



Book Values
ASTM D 638

Environmental Stress Cracking (ESC)

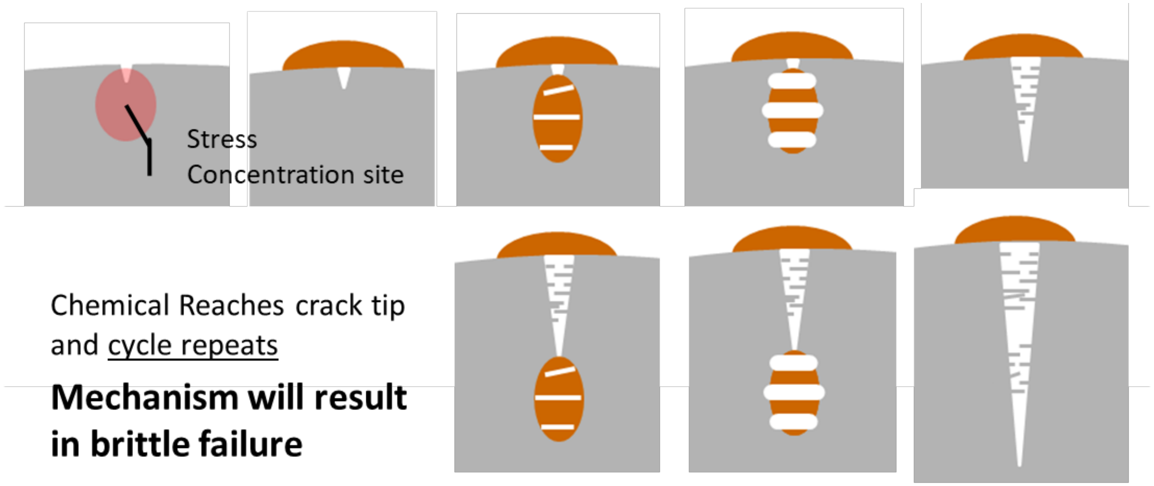
- Environmental Stress Cracking (ESC) is a mechanism that parallels creep, but ruptures happen faster because of chemical influences.
- A chemical agent reduces the polymer-polymer attractions allowing for faster molecular disentanglement than what would be possible without the chemical (creep).
- The chemical does not need to attack the polymer and cause degradation for the part to fail.
- Stress-Chemical Synergy



Synergistic Effects

Accounting for ESC

- Perform proper ESC testing. Apply both low and high stresses expanding within and beyond the application range.
- Testing either physical parts or molded tensile bars is appropriate and recommended.
- Consider the application temperature and the expected and unexpected in terms of possible chemical interactions.



Accounting for Dynamic Stresses

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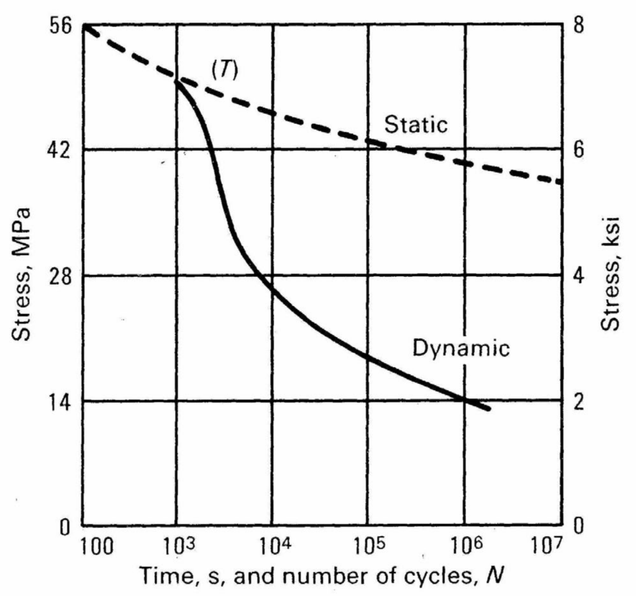
- Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading.
- Fatigue also results at stresses significantly below yield.
- *Like creep, fatigue produces an apparent decay in strength*.
- The more rapid failures are associated for fatigue due to a combination of hysteresis effects and the cyclic stress condition allowing for quicker molecular restructuring/slippage.



Comparison of apparent strength for Static vs. Cyclic stresses

Accounting for Creep, ESC, Fatigue

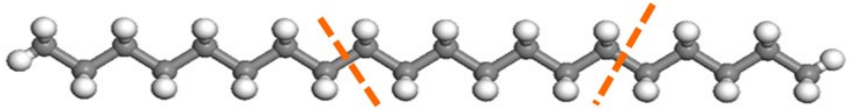
Summary:

- Higher temperature = more molecular mobility (energy)
- Application stresses need to be below the long-term strength
- Poor design = Higher stresses
  - Residual Stresses (uneven cooling, poor packing)
  - Stress concentration (sharp corners)
  - Weak spots (poorly placed weldlines and knitlines)
- Molecular weight

Mechanical Recycling and Regrind

Considerations

- Consumption of additives (processing aids, anti-oxidants, stabilizers)
- Molecular weight reduction
- Contaminants



Degradation is any mechanism that results in cleavage of the molecular bonds

Formulation: Reinforcements

- Reinforcements are solid structures that provide a significant enhancement in mechanical properties.
- Key elements to remember:
  - Increase Density
  - Significant Anisotropy
  - Sizing agents are critical
  - Length matters

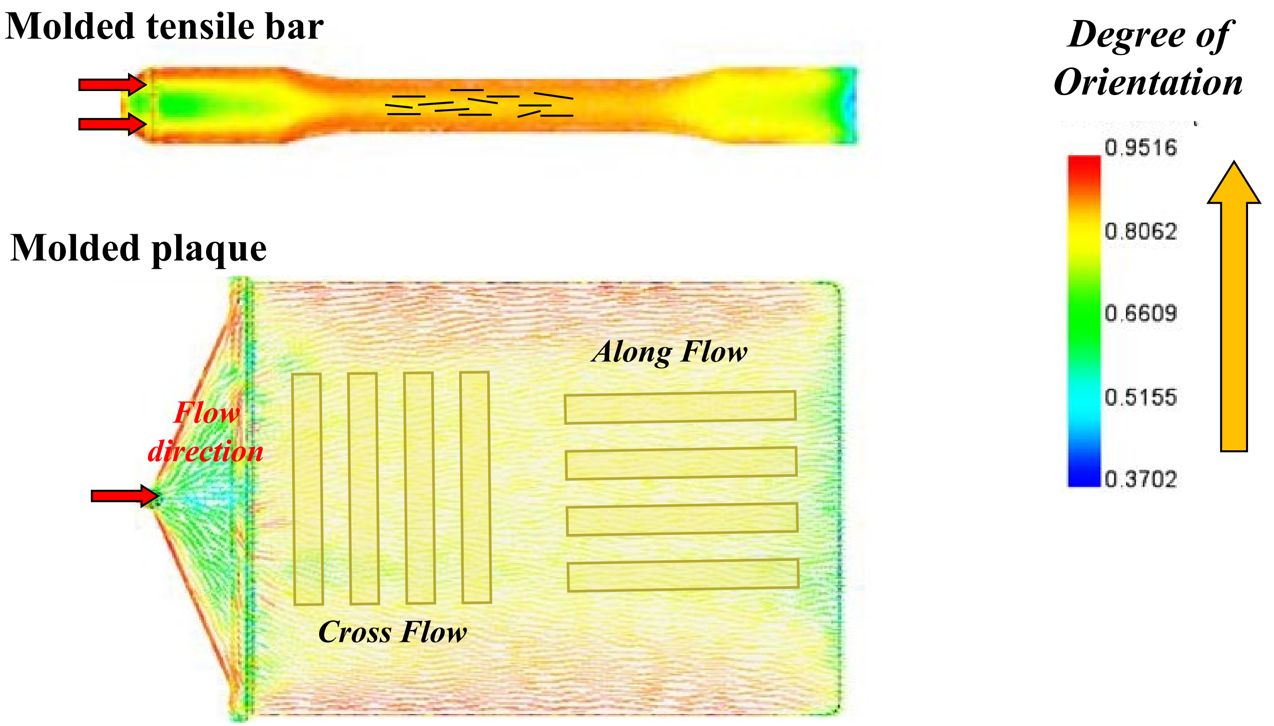
Compound Name	Density (g/cm^3)	Strength (Mpa)
E-glass	2.54	3,400
PP	0.92	35
30% LGF PP	1.15	125
40% LGF PA66	1.45	210
Mg – AM50	1.77	210
Mg – AZ91	1.81	240

Reinforcements Positives

- Using glass reinforcement can close the gap between metal & plastic.
  - Increased modulus (stiffness).
  - Increased strength.
  - Improved time dependent properties.
  - Thermal expansion can be reduced.
  - Flammability properties increased.
    - Less polymer to burn
    - Less dripping
    - Reduced flame spread and holes
  - Increased chemical and ESC resistance.

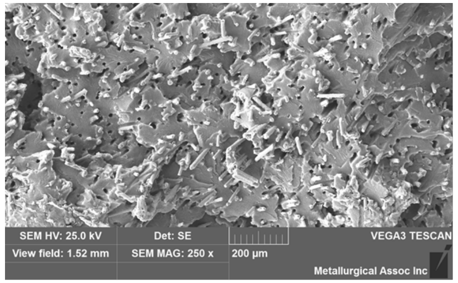
Reinforcements Concerns

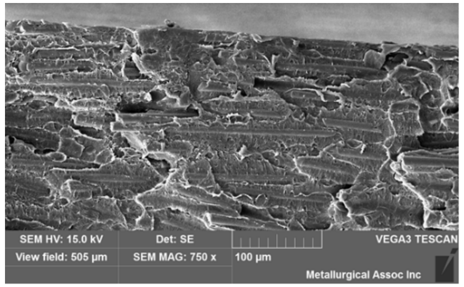
- As mentioned, fibers generate anisotropy during processing.
- Discontinuous fiber reinforced plastics undergo fiber orientation as a function of:
  - Fiber length
  - Fiber concentration
  - Resin Material (viscosity)
  - Geometry of the molded part
  - Process settings

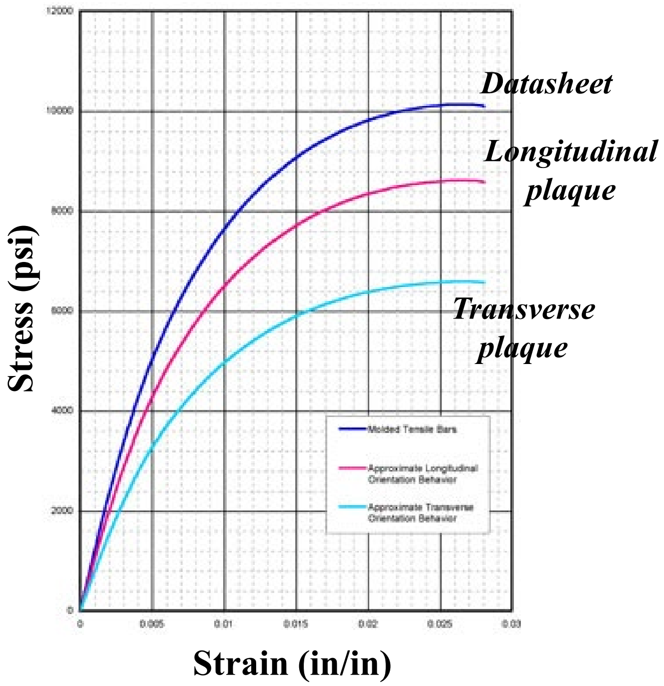


Reinforcements Concerns

- Datasheet properties vs. Real Properties







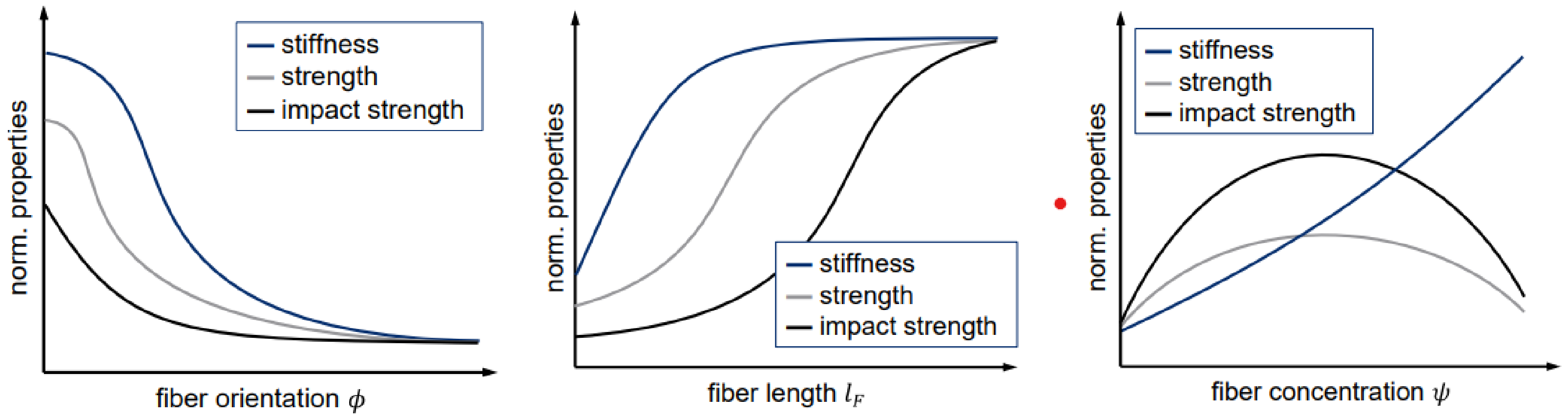
30% GF Polypropylene

Strength (psi)	Datasheet	Oriented (approx.)	Difference
Longitudinal	10,152	8500	**-16%**
Transverse	10,152	6,672	**-34%**

Source: RTP Company website(http://www.rtpcompany.com)

Reinforcements Concerns

- Anisotropy in mechanical properties in reinforced plastics



(**a**) fiber orientation (**b**) fiber length (**c**) fiber concentration

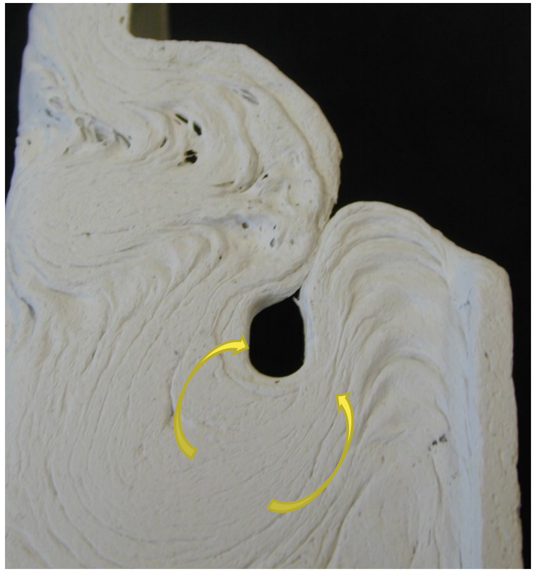
Figure 1. Influence of fiber orientation, length, and concentration on the resulting mechanical properties (schematically) according to [16,26,29].

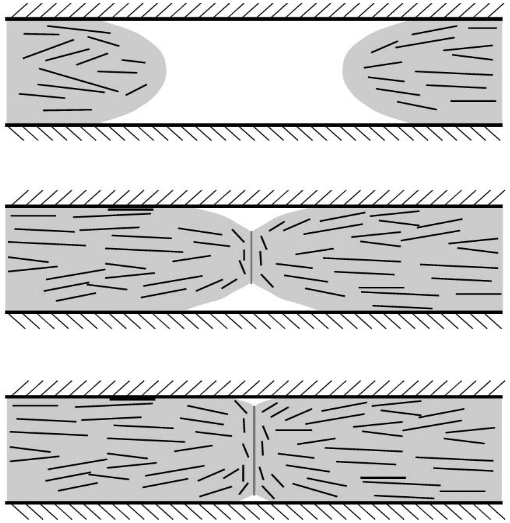
16-Osswald, 2017, 26-Thomason, 2002, 29-Thomason, 2007

Willems,MDPI
Composites 2020

Knitlines/Weldlines

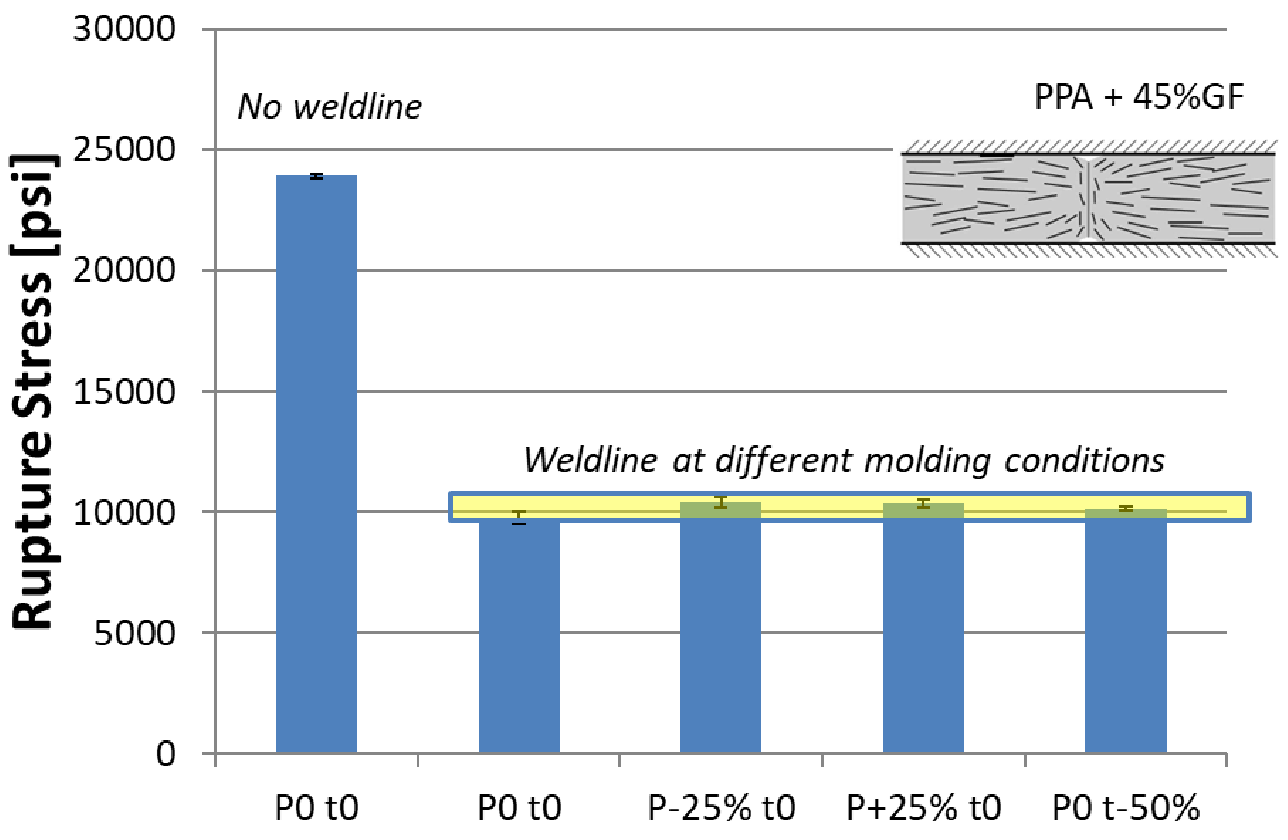
- Another critical important aspect to consider with fiber reinforcement is the orientation of fibers across knit lines.





Knitlines/Weldlines

- Knitlines at different molding conditions



Knitlines/Weldlines

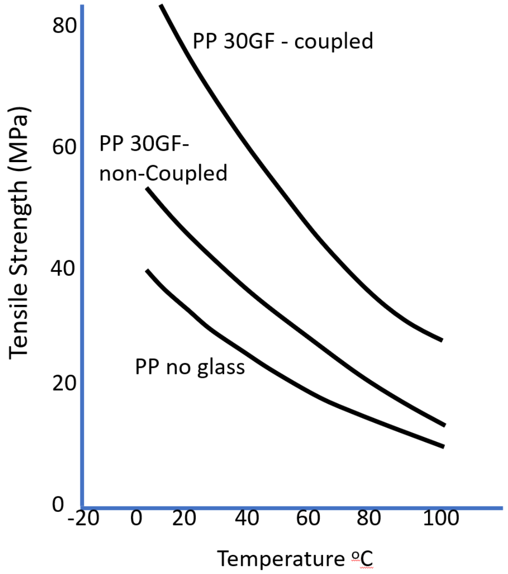
- Knit line strength variation

Material	Filler	Tensile strength (PSI)		Retention
		no weldline	w/ weldline	
Nylon 66 (PA66)	*None*	11,560	11,170	97%
Nylon 66 (PA66)	10% glass	13,980	13,060	93%
Nylon 66 (PA66)	40% glass	28,830	14,990	52%
Polypropylene (PP)	*None*	5,400	4,650	86%
Polypropylene (PP)	30% glass	9,800	3,330	34%
Styrene acrylonitrile (SAN)	*None*	11,300	9,625	85%
Styrene acrylonitrile (SAN)	30% glass	16,180	6,470	40%
Polysulfone (PSU)	*None*	9,600	9,600	100%
Polysulfone (PSU)	30% glass	16,800	10,400	62%

Source: J.P. Beaumont, "Runner and Gating Design Handbook"

Formulation: Coupling Agents

- Polypropylene Data



Ref: H. Domininghaus, Plastics for Engineers, Hanser 1993

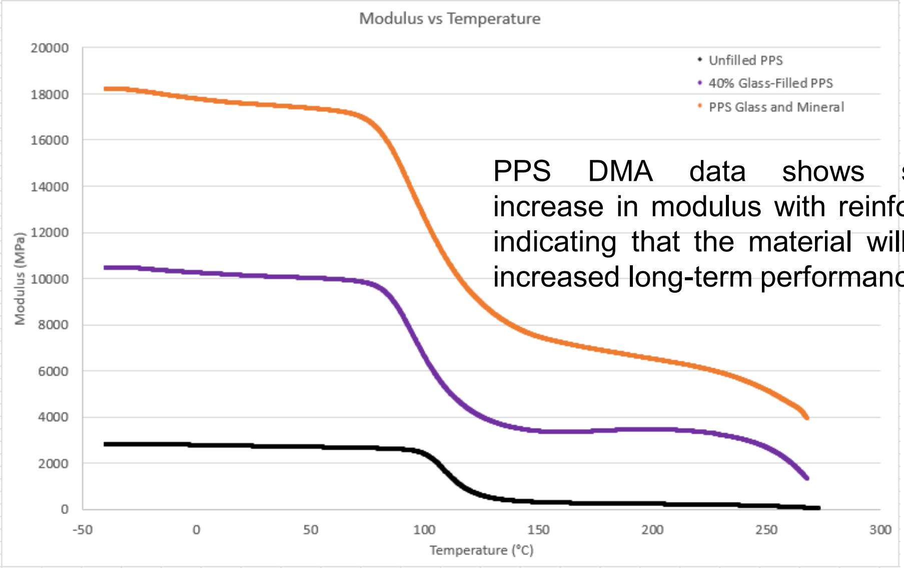
30% Fiber PP	With Chemical Coupling	Without Chemical Coupling	Difference
Strength (MPa)	96.7	72.9	-25%
Notched Impact [J/m]	100	63	-37%
Unnotched Impact [J/m]	684	246	-64%

Poor Fiber-Matrix Adhesion

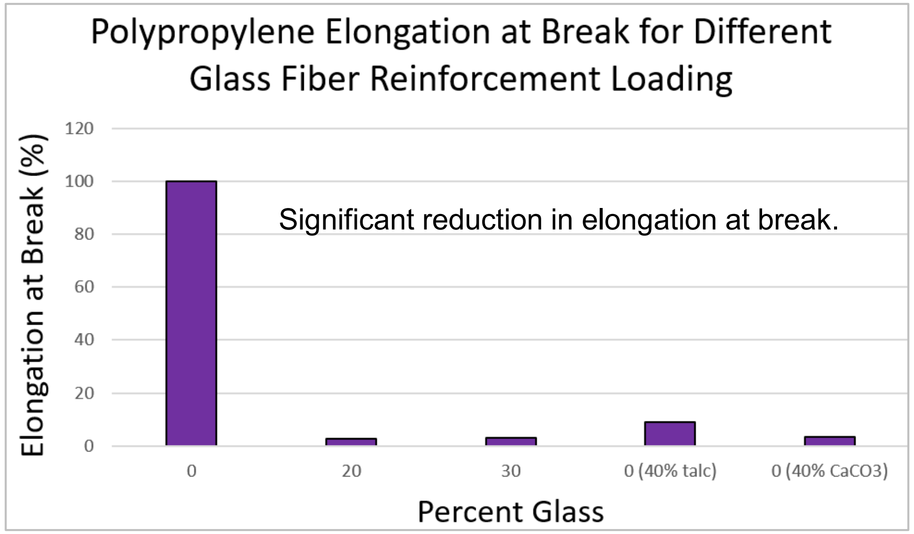
Good Fiber-Matrix Adhesion

Challenges of GF plastics

- Glass fiber increases stiffness but thermal transitions remain.
  - Glass transition temperature does not change.
  - Melt temperature does not change.
- Reduced ductile behavior.
  - Significant reduction in elongation at break.
- Harder to process
  - Shrinkage/warpage and surface cosmetics
- Reduced ability of additives to migrate.
  - Antioxidant migration reduced.
- Summary:
  - Increases unknowns and complexity of making a good part
  - Need to clearly understand the property effects of fibers



PPS DMA data shows significant increase in modulus with reinforcements indicating that the material will have an increased long-term performance.



Datasheets

- Datasheets are simplistic starting points to compare materials.
- Key points:
  - Short-term properties do not take into account changes over time.
  - Datasheets report ideal condition properties (i.e. simple tensile bar geometry tested in flow direction).
  - Properties of polymers are a function of time, strain rate, temperature and environment.
  - When **pushing the limits of plastic applications, long-term properties need to be fully considered.**

Datasheets

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LEXAN* 101 Resin
Polycarbonate
SABIC Innovative Plastics Web | Portal

UL IDES | Prospector

Datasheet | Processing | Literature | Visual Analysis | UL Yellow Card | Where to Buy

Compare to Typical Values | Find Alternatives | Add to My Materials
PDF Datasheet | E-Mail | Print | Contact UL IDES

All Data | General Information | Physical | Mechanical | Thermal | Electrical & Flammability | Optical | Processing Information — Units English | SI

Hardness	Nominal Value	Unit	Test Method
Rockwell Hardness			ASTM D785
M-Scale	70		
R-Scale	118		
Mechanical	**Nominal Value**	**Unit**	**Test Method**
Tensile Strength [3]			ASTM D638
Yield	[illegible]	psi	
Break	10000	psi	
Tensile Elongation [3]			ASTM D638
Yield	7.0	%	
Break	140	%	
Flexural Modulus [4] (1.97 in Span)	340000	psi	ASTM D790
Flexural Strength [4] (Yield, 1.97 in Span)	14200	psi	ASTM D790
Taber Abrasion Resistance (1000 Cycles, 1000 g, CS-17 Wheel)	10.0	mg	ASTM D1044
Impact	**Nominal Value**	**Unit**	**Test Method**
Notched Izod Impact (73°F)	17	ft·lb/in	ASTM D256
Unnotched Izod Impact (73°F)	60	ft·lb/in	ASTM D4812
Instrumented Dart Impact (73°F, Energy at Peak Load)	575	in·lb	ASTM D3763
Gardner Impact (73°F)	1500	in·lb	ASTM D3029
Tensile Impact Strength [5]	300	ft·lb/in²	ASTM D1822

Cannot predict long term properties

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The Madison Group is the recognized leader in plastics engineering. We understand how polymers behave, how to properly design with them, how they are processed, and the numerous manufacturing steps required to produce a successful product.

Javier C. Cruz, PhD.

javier@madisongroup.com

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Design Review

Material Support

Product Testing

Manufacturing Support

Failure Analysis

Customized Training