

Introduction to Dynamic Mechanical Analysis (DMA)



A Beginner's Guide

This booklet provides an introduction to the concepts of Dynamic Mechanical Analysis (DMA). It is written for the materials scientist unfamiliar with DMA.

Contents

20 Questions about DMA	3
Common Symbols	11
Regions of Viscoelastic Behavior	12
DMA Glossary	13
What the Data Tells You	22
Further Readings	23

20 Basic Questions on Dynamic Mechanical Analysis

1. What is DMA?

Dynamic Mechanical Analysis, otherwise known as DMA, is a technique where a small deformation is applied to a sample in a cyclic manner. This allows the materials response to stress, temperature, frequency and other values to be studied. The term is also used to refer to the analyzer that performs the test. DMA is also called DMTA for Dynamic Mechanical Thermal Analysis.

2. How does DMA differ from Thermomechanical Analysis?

Thermomechanical Analysis, or TMA, applies a constant static force to a material and watches the material change as temperature or time varies. It reports dimensional changes. On the other hand, DMA applies an oscillatory force at a set frequency to the sample and reports changes in stiffness and damping. DMA data is used to obtain modulus information while TMA gives coefficient of thermal expansion, or CTE. Both detect transitions, but DMA is much more sensitive. Some TMAs can do limited DMA and the PerkinElmer® DMA 8000 is the only DMA that can do TMA.

3. How does a DMA work?

DMA works by applying a sinusoidal deformation to a sample of known geometry. The sample can be subjected by a controlled stress or a controlled strain. For a known stress, the sample will then deform a certain amount. In DMA this is done sinusoidally. How much it deforms is related to its stiffness. A force motor is used to generate the sinusoidal wave and this is transmitted to the sample via a drive shaft. One concern has always been the compliance of this drive shaft and the affect of any stabilizing bearing to hold it in position. A schematic of the analytic train of the DMA 8000, Figure 1, shows its innovative design that requires neither springs nor air-bearings to support the drive shaft.

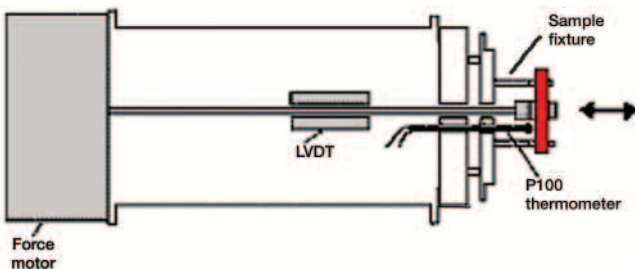


Figure 1. Schematic of the DMA 8000 analytic train.

4. What does DMA measure?

DMA measures stiffness and damping, these are reported as modulus and tan delta. Because we are applying a sinusoidal force, we can express the modulus as an in-phase component, the storage modulus, and an out of phase component, the loss modulus, see Figure 2. The storage modulus, either E' or G' , is the measure of the sample's elastic behavior. The ratio of the loss to the storage is the tan delta and is often called damping. It is a measure of the energy dissipation of a material.

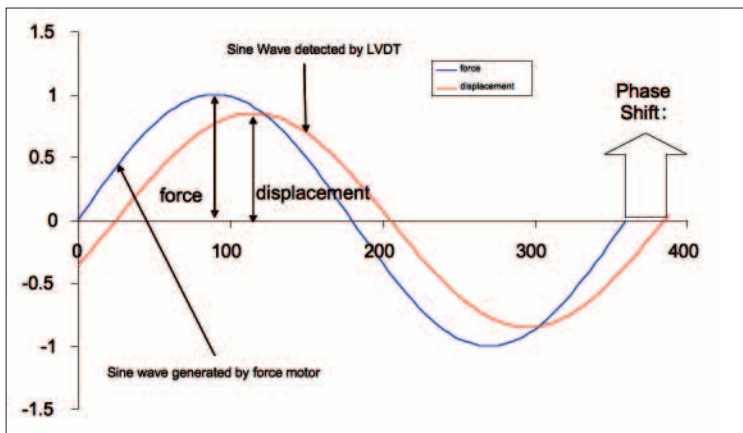


Figure 2. The relationship of the applied sinusoidal stress to strain is shown, with the resultant phase lag and deformation.

5. How does the storage modulus in a DMA run compare to Young's modulus?

While Young's modulus, which is calculated from the slope of the initial part of a stress-strain curve, is similar conceptually to the storage modulus, they are not the same. Just as shear, bulk and compressive moduli for a material will differ, Young's modulus will not have the same value as the storage modulus.

6. What is damping?

Damping is the dissipation of energy in a material under cyclic load. It is a measure of how well a material can get rid of energy and is reported as the tangent of the phase angle. It tells us how good a material will be at absorbing energy. It varies with the state of the material, its temperature, and with the frequency.

7. Why would I want to scan modulus as a function of temperature?

Modulus values change with temperature and transitions in materials can be seen as changes in the E' or $\tan \delta$ curves. This includes not only the glass transition and the melt, but also other transitions that occur in the glassy or rubbery plateau, shown in Figure 3. These transitions indicate subtler changes in the material. The DMA 8000's unique low starting temperature of $-190\text{ }^\circ\text{C}$ in the standard furnace and of $-196\text{ }^\circ\text{C}$ in the Fluid Bath let you easily look for these small molecular motions, Figure 3.

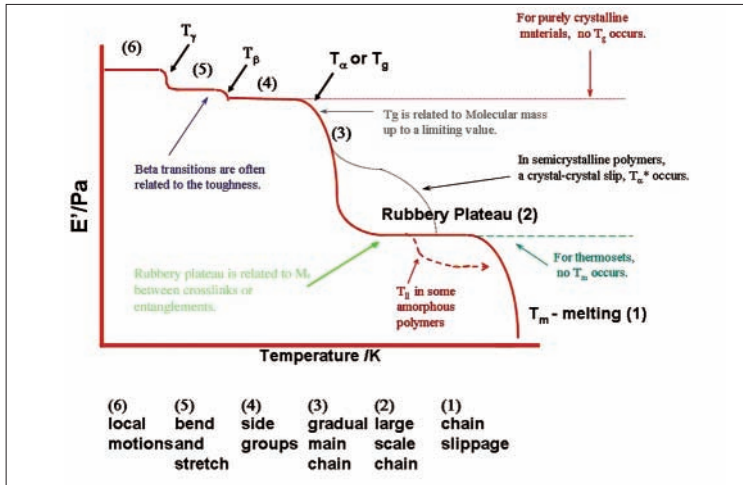


Figure 3. Modulus values change with temperature and transitions in materials can be seen as changes in the E' or $\tan \delta$ curves.

8. How do I get good data?

Good data requires several things: a properly calibrated instrument, a properly prepared specimen with a reasonable aspect ratio, using the right geometry, and applying both reasonable strains and heating rates. A properly calibrated instrument requires calibration for both temperature and force. A well prepared specimen should be of even thickness with parallel sides and right angle. Assuming the correct choice of geometry for the sample, a deformation of 50 microns and heating rates of 2-3 $^\circ\text{C}/\text{minute}$ normally work fine.

9. How do I know what geometry to use?

The choice of the geometry you run your sample in is dictated by the sample's physical state at the beginning of the experiment, its difficulty in loading, and the experiment you want to run. For example, a stiff bar of polymer can be run in all of the flexure fixtures, but single cantilever is often used because it is simple to load and allows thermal expansion of the specimen, shown in Figure 4. Uncured thermosets are often run in shear. The DMA 8000 not only has the a full range of fixtures covering the normal 3-point bending, single cantilever, dual cantilever, tension, compression and shear fixtures, but also offers the novel Material Pocket for holding powders and soft samples that can not support their own weight. In addition, the design and flexible software make it possible to develop custom fixtures for your application.

Best Choice	Sample Modulus/Pa	Preferred Geometry <i>(for indicated sample size)</i>	Sample Thickness/mm	Free Length /mm	Ideal Heating/Cooling Rate/°C/min
	10^{10} to 10^6	Tension	<0.02	2	5
X	10^{10} to 10^5	Tension	0.02 to 1	2 to 10	5
X	10^{10} to 10^6	Single cantilever	1 to 2	5 to 10	3
X	10^{10} to 10^6	Single cantilever	2 to 4	10 to 15	2
	10^{10} to 10^6	Single cantilever	>4	15 to 20	1
X*	10^{10} to 10^6	Dual cantilever	2 to 4	10 to 15	2
		<i>*for highly orientated samples that are likely to retract above Tg.</i>			
X	10^{12} to 10^8	Three-point bending	1 to 3	10 to 20	3
	10^{11} to 10^7	Three-point bending	>4	15 to 20	2
X	10^7 to 10^2	Simple shear	0.5 to 2	5 to 10 (dia)	≤2
	10^7 to 10^2	Compression <i>(good for irregularly shaped samples and any others that are difficult to mount)</i>	0.5 to 10 <i>(height or thickness)</i>	5 to 10 (dia)	≤2

width Generally sample width is uncritical and 5 mm is recommended (a wider sample may not be held uniformly in the clamps). A smaller value should be used for stiff sample in tension (1 to 2 mm).

Figure 4. Preferred geometry for indicated sample size.

10. How can I detect a Tg?

The glass transition (T_g) is seen as a large drop (a decade or more) in the storage modulus when viewed on a log scale against a linear temperature scale, shown in Figure 5. A concurrent peak in the tan delta is also seen. The value reported as the T_g varies with industry with the onset of the E' drop, the peak of the tan delta, and the peak of the E' curve being the most commonly used.

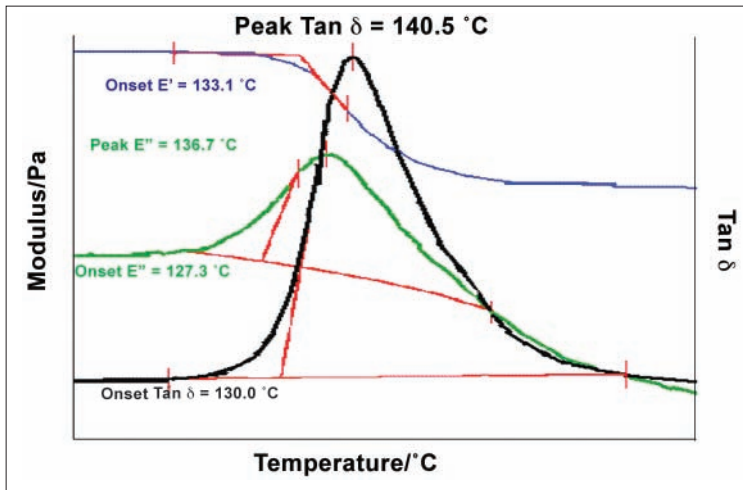


Figure 5. The glass transition (T_g) in the storage modulus and tan delta.

11. How do I know it's really a T_g ?

Running a multi-frequency scan and calculating the activation energy of the transition allows you to decide if the transition is really a T_g . The activation energy for a T_g is roughly 300-400 kJmol^{-1} . In comparison a T_b has an activation energy of about 30-50 kJmol^{-1} and at the melt or T_m , the frequency dependency collapses.

12. Why does my T_g value sometimes not agree with my DSC value?

That's actually not surprising. The glass transition is really a range of behavior where scientist have agreed to accept a single temperature as the indicator per certain standards. Different industries have used different points from the same data set that can vary as much as 15 °C. DSC, TMA, and DMA measure different processes and therefore, the numbers vary a bit. You can see as much as a 25 degree difference in data from a DSC to DMA data reported as peak of tan delta. See Figure 5 for an example.

13. Can I do TMA in my DMA?

It depends on what you are looking for. Most tests like flexure, penetration, creep or a simple stress-strain run can be done. In the past, most dynamic mechanical analyzers have not been able to generate coefficient of thermal expansion (CTE) data, but the DMA 8000 can run TMA type experiments and obtain excellent CTE values for a wide range of samples run in extension. CTE tells you how your material will expand as a function of temperature. This information is vital for products where dissimilar materials will be heated together (for example motors and circuit boards) as well as curing systems where contraction on curing occurs.

14. Can I use DMA to study curing?

DMA is commonly used to study curing of materials as this process involves a dramatic increase in the modulus values. It is commonly used to get both the point of gelation and the point of vitrification for thermosetting materials. Cures can be studied with temperature ramps and isothermally at a fixed temperature. The DMA 8000 can be configured with optional quartz windows and special fixtures to allow the study of photo-curing systems.



Figure 6. DMA 8000 with special fixture to allow the study of photo-curing systems.

15. Why should I be concerned about frequency scans and multiple frequency runs?

Most materials can see many frequencies in their final product. An example is the rubber used in a windshield wiper which see a range of operating frequencies and temperatures in use. Modulus-frequency plots can tell you how your material will change as frequency changes. For viscous materials, this can give useful information about its flow. It is often advisable to not just look at modulus-frequency at one temperature, but to scan many frequencies as you heat a material. This allows you to see how transitions shift under the influence of frequency. For example, in some polymers a shift from 1 to 100 hertz will move a T_g by 14 degrees, which could cause a material to fail if the high frequency is not considered in its design.

16. What does Time-Temperature Superposition (TTS) tell me?

The Williams-Landel-Ferry model, or WLF, says that under certain conditions, time and temperature can be mathematically interchanged. A TTS, shown in Figure 7, lets you use data collected as frequency scans at a range of temperatures to predict behavior

at frequencies that are not directly measurable. The DMA 8000 has advanced software that makes this a fairly simple process. The data is often converted to time to predict lifetime performance. One should note that TTS calculations rest on some assumptions and is often invalid if these assumptions aren't met. One basic assumption is a single relaxation time and is tested by using a wicket or Cole-Cole plot.

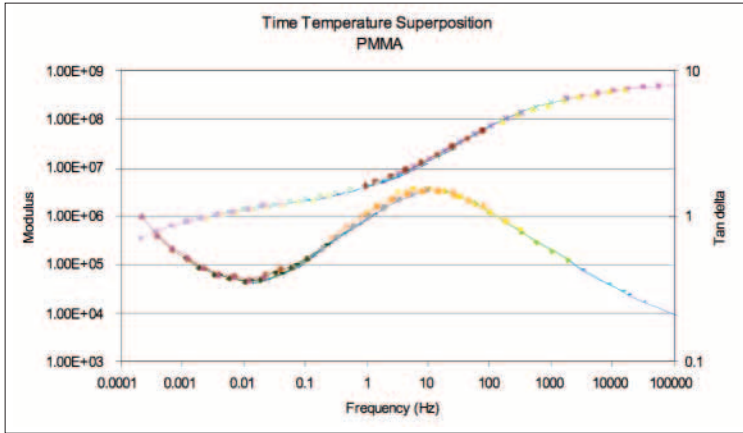


Figure 7. Time Temperature Superposition.

17. How can I tell if a TTS is valid?

You can tell if a TTS is valid by using the DMA 8000's software to generate a Cole-Cole or wicket plot. Plotting E' against either E'' or $\tan \delta$ should give a nice half circle plot if the assumptions of the William Landel Ferry model are met. If they aren't, then the material is not rheologically simple and a WLF superposition will fail.

18. Why would I want to run my samples immersed in a fluid?

Certain solvents can cause a material to soften while they are exposed to them. Others can react with and harden the material. Both of these effects can cause failure in biomedical devices, coating, paints and gaskets to name only a few. In addition, the effect of a stress and a solvent often is different than just soaking a material in a solvent and then testing it in air. The DMA 8000's Fluid Bath allows collecting data of sample immersed in solutions under a variety of conditions.



Figure 8. DMA 8000 with Fluid Bath.

19. Can I use DMA to see if humidity affects my sample?

Humidity is known to have tremendous effects on the properties of materials from polymers to papers to natural products. The DMA 8000 has the option of being configured with an integrated humidity generator that allows precise control of the humidity in the furnace. This permits accurate and precise studies on how humidity affects the properties of your materials.

20. Is UV curing an important application for my DMA if I have a photo-calorimeter?

Yes, a photo-calorimeter only looks at the energy of photo-curing. Photo-curing in the DMA lets you see how the physical properties change and when the modulus of the curing material has reached acceptable limits in terms of strength and stiffness. This information is important for cost effective design of your cure cycle. Using a DMA with UV also allows you to investigate the degradation of materials and so evaluate additive packages, formulations, etc.

Common Symbols in the DMA Literature

A	Shift factor	How much a curve was moved to make it align with the reference curve.
D	Molecular weight distribution	The ratio of M_n and M_w (see molecular weight) types of molecular weights related to the horizontal movement of crossover point of frequency scan.
δ	delta	Phase angle or phase lag. See also $\tan \delta$.
E	Modulus	Modulus measured in flexure, tension or compression geometry.
E'	Storage modulus	A measure of the elastic response of a material but not the same as Young's modulus. Also called the in-phase component.
E''	Loss modulus	A measure of the viscous response of a material. Also called the imaginary modulus or out of phase component.
E^*	Complex modulus	The sum of the in and out of phase components.
E_a	Activation Energy	Energy needed to cause a transition or reaction.
ϵ	Epsilon	Strain measured in flexure, tensile or compression geometry. Also used for dielectric properties in DETA as modulus is above.
G	Shear modulus	Modulus measured in shear geometry.
γ	Gamma	Strain measured in shear geometry.
J	Compliance	The ratio of sample strain to sample stress in the linear region of Creep Ramp.
Λ	Lambda	Modulus measured in torsion pendulum geometry, similar to E.
M	Molecular weight	The molecular mass or chain length of a material, important in polymers for determining the materials properties like the T_g . After monomer type, it is the single most important property of polymers. These are normally reported as number (M_n) and weight (M_w) averages. Related to the vertical movement of crossover point of frequency scan.
η	eta	Viscosity.

σ	sigma	Stress applied to a sample in flexure, tension, compression or shear.
T_α	Alpha transition	See Tg.
T_β	Beta Transition	Onset decrease in storage modulus during heating, accompanied by peak in tan delta, during a temperature scan. Found above the Tg, this is associated with localized backbone or side chain motions.
Tg	Glass Transition	The temperature indicating the relaxation in a polymer where a material changes from a glass to a rubber.
Tan δ	tan delta	Damping – the tangent of the phase angle and the ratio of E''/E'.
ν	Poisson's ratio	A ratio of the change in sample depth and width as the sample length is changed. Typically 0.5 for polymers.
ν_f	free volume	The space inside a polymer between molecules.
ω	radians	Frequency when reported in radians per second.

Regions of Viscoelastic Behavior

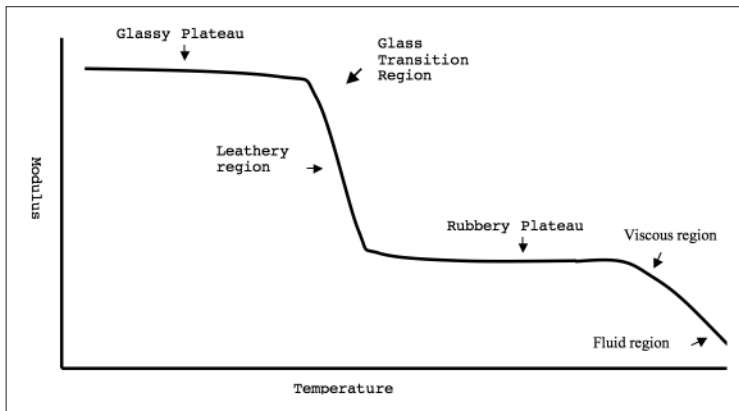



Figure 9. Regions of viscoelastic behavior.

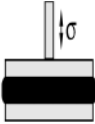

Glassy plateau Sample is hard, springy or rock like. Bending and stretching of bonds is occurring. Tan delta is below 0.01. It is below the Tg.

Glass transition region	Sample becomes less hard as storage modulus decreases and tan delta peaks. Tan delta peak height is typically between 0.1 and 1.2. The onset can be taken as the Tg.
Leathery region	Sample is tough but flexible. Side groups and cooperative segmental motion of the backbone occurs. Tan delta is below 1.0. This is slightly above the Tg.
Rubbery plateau	Sample is springy, putty like. Main backbone chain exhibits gradual slippage. Tan delta is near 1.0. This is above the Tg.
Viscous region	Sample is flowing, fluid as temperature increases. Large scale main chain mobility occurs. Tan delta is above 1.0. This is well above the Tg. Power law behavior is seen.
Fluid region	Sample is flowing, water like. Free chain movement and interchain slipping occurs. Tan delta is much higher than 1.0. This is above the Tm in crystalline materials. Often treated as part of viscous region.

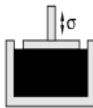
DMA Glossary

Activation Energy	Energy needed to cause a motion. Frequency dependent activation energy can be used to identify transition types.
Additives	Compare isothermal storage modulus.
Alloys	Mechanically blended combinations of polymers.
Alpha transition	The next transition in temperature below the melt. Normally the Tg.
Amorphous	Chemical structure that allows random folding and intertwining, not organized.
Amorphous content	Estimated by comparing the area of loss modulus peak at Tg.
Amorphous phase	Random portion chemical structure. Random orientation of the polymer backbone. Non-crystalline glass.

Amplitude  Height of sinusoidal displacement.

Anisotropy		Directionality of material properties within a sample.
Annealing temperature		The onset of the step decrease in the storage modulus, accompanied by a step increase in tan delta, during Temperature Scan heating. Just below the Tg. The temperature a polymer is heated to so that it relaxes from trapped stresses.
Backbone		The primary structure of a polymer. Typically a continuous chain of carbon atoms.
Beta transition		Onset decrease in storage modulus during heating, accompanied by peak in tan delta, during Temperature Scan heating.
Blending		Mixing of two polymers. A blend is a polymer mixture and can have one or more Tg depending on how it was mixed.
Branching		Estimated by comparing the storage modulus terminal zone in a frequency scan.
Cole-Cole Plot		Plot of E' versus E'' (or tan δ) used to check the validity of a TTS study. Also called a wicket plot.
Compatibility of polymer blends		How well two or more different polymers combine with each other.
Complex modulus		Bulk sample behavior. An indicator of viscoelasticity.
Compliance		The ratio of sample strain to sample stress in the linear region of Creep Ramp.
Compression		Disks or rectangles are deformed using cup and plate, plate and tray, sintered parallel plates, cone and plate measuring systems. This gives compressive modulus, an important value used in Finite Element Analysis (FEA).
Copolymer		Compare isothermal modulus or slope of storage modulus decrease at Tg.
Creep		Observe sample strain as sample stress is increased and temperature is held constant. Gives time dependent behavior as a function of pressure (stress) or temperature.

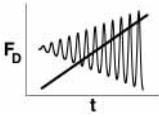
Cross link	Chemical bond between molecules.
Crossover point	Normally the crossover of storage modulus and complex viscosity on axes of the same scale on a log-log-log plot of a frequency scan. Also the crossover of E' and E'' (when $\tan \delta = 1$) in a cure study.
Crystalline	Chemical structure that is highly organized, compacted in very low energy states.
Crystalline phase	Highly ordered chemical structure. Closely packed and ordered orientation of a polymer backbone. This is typically the lowest energy state of a polymer.
CTE	Coefficient of thermal expansion. See dilatometry, LCTE, and TMA below.
Cure of thermosetts	Chemical connection between polymer backbones.
Cure rate (kinetics)	Compare slope of storage modulus increase during isothermal cure.
Damping	Dissipation (loss) of mechanical energy. Modeled by a dashpot.
Deborah number	The time of the experiment divided by the time of the property measured.
Degree of cure	How cured a material is. Normally estimated from either modulus values or the T_g in DMA.
Degree of polymerization	A measure of how far a polymerization reaction has gone. See degree of cure.
Dilatometer	Measures volumetric expansion by translating a three dimensional expansion into a deflection. This gives bulk (volumetric) expansion of irregularly shaped samples or the bulk modulus, which can be used with other values to calculate Poisson's ratio.
DMA	Dynamic Mechanical Analyzer. Applies a sinusoidal force and measures sample response at a given temperature.
DMA fingerprint	Frequency scan at a temperature above the T_g and below the T_m .



DMA modulus test

A quick 30 second test where you mount the sample and read the real time display for storage modulus. Used for QC.

Dynamic Scan



Observe sample strain as sample stress is increased while temperature and frequency are held constant. Slope gives DMA modulus which includes effect of damping.

Elastic



The ability of a material to return to its original shape. Modeled by a spring.

Elastomers

Materials that exhibit elastic properties, may be thermoplastic or thermosett.

End use properties

The properties (tests) used for deciding the fitness of a polymer for a task.

Entanglement

Physical (steric) interference of polymer movement.

Equilibrium modulus

Size of recovery portion of creep-recovery analysis or slope of creep strain back extrapolated to intercept the start of the creep cycle.

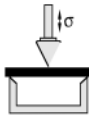
Equilibrium viscosity

Size of non-recovery portion of creep-recovery analysis or slope of creep strain.

Extensometer

Large pull testing analyzers.

Flexural



Rods or cylinders are deformed using 3 point bending, 4 point bending, single and dual cantilever measuring systems. This is the easiest geometry to use.

Fluid

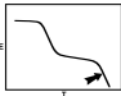


Flowing, water like.

Fluid bath

An alternative furnace that allows the sample to be immersed in a solution.

Fluid region



Sample is flowing, water like. Free chain movement and interchain slipping occurs. Tan delta is much higher than 1.0. This is above the Tm in crystalline materials.

Force

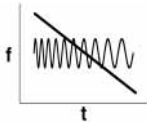


Application of mechanical energy.

Force motor

Applies a force to the sample that causes a sample deflection.

Frequency scan



Observes sample strain while increasing frequency of oscillation and holding stress and temperature constant. Used for fingerprint type identification of polymers and identifying the resonant and harmonic frequencies. Also used for calculating TTS and activation energy.

Friction

The force required to overcome surface molecular interaction between two materials.

Functional group

A chemical compound attached to a polymer backbone.

Furnace

Controls the sample temperature.

Gel point

Onset of the increase of storage modulus during Time Scan isothermal cure. The point where frequency dependence in E' disappears. The crossover point of E' and E'' in a cure.

Glass transition (T_g)

The temperature range where a material softens. The onset decrease in the storage modulus, accompanied by a peak in $\tan \delta$, during Temperature Scan heating. "Melting of the amorphous phase".

Glassy



Hard, springy, or rock like.

Heterogeneity

Inconsistent material content within a sample.

Homogeneity

Consistency of material content within a sample. A homogenous material is same in all directions.

Hooke's law $F = kx$

Describes the elastic behavior of springs.

Humidity generator

An alternative furnace that allows the sample to be studied in a controlled humidity environment.

Hysteresis

Energy stored after each cyclic deformation causes the difference between loadings.

Impact modifiers

Compare isothermal storage modulus.

Isotropy

Consistency of material properties within a sample.



Leathery



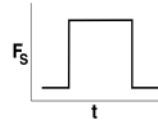
Tough, but flexible.

Linear coefficient of thermal expansion (LCTE)

Slope of sample height (TMA probe position) from beginning of run to just below T_g , during Temperature Scan heating.

Linear Variable Differential Transformer (LVDT)	An electronic ruler that measures the sample's response to the applied force.	
Log scale	Used to display changes that occur over large ranges. Modulus is normally displayed on a log scale.	
Mechanical properties	Physical characteristics of a sample. What a polymer does when physically disturbed or tested.	
Melt viscosity	Compare complex viscosity of frequency scan at melt temperature.	
Modifiers	Compare isothermal storage modulus.	
Molecular weight	The molecular mass or chain length of a material, important in polymers for determining the materials properties like the Tg. After monomer type, it is the single most important property of polymers. These are normally reported as number (Mn) and weight (Mw) averages. Related to the vertical movement of crossover point of frequency scan.	
Molecular weight distribution	The ratio of Mn and Mw (see molecular weight) types of molecular weights. Related to the horizontal movement of crossover point of frequency scan.	
Modulus $E = \frac{\sigma}{\epsilon}$	Ratio of stress to strain.	
Newton's law		Describes the behavior of flowing materials.
Omega ω	Frequency in radians per second.	
Orientation	Non-crystalline organization where polymer backbones become closely packed in a direction. Also seen with Polymer Liquid Crystal and nano-material fillers where the material is lying in a specific direction.	
Period	The time it takes to complete one event.	
Permanent set	Irrecoverable flow that exists after a material has been deformed.	
Phase	Part of or "section of" a polymer. For example, many types of polyurethane have rubbery and crystalline phases.	
Phase lag (δ)		Delay between applied force and material response. Also called the phase angle. The delta (δ) in $\tan \delta$.

Plasticity	Exhibited by polymers that are stressed beyond the yield point. Deformation.
Plots of $\log f$ vs. $1/T \times 10^3$ ($^{\circ}\text{C}^{-1}$)	Used to show the frequency shift of phase transitions as the sample is cooled.
Poisson's ratio	A ratio of the change in sample depth and width as the sample length is changed. Typically 0.5 for polymers.
Polymer transitions	Changes in the physical appearance or behavior as a sample is heated.
Prediction of long term behavior	Often done by comparing recovery cycles of Recovery Analysis from the critical pressure (stress) and temperature, experiments with many creep-recovery or DMA cycles, and TTS.
Proportional limit	The greatest stress a material can withstand without permanently deforming.
Rate	How fast something happens, i.e. how fast you heat in degrees per minute.
Recovery	Observe sample strain as stress is increased and temperature is held constant. Gives time dependent relaxation behavior as a function of pressure (stress) or temperature.
Recovery time	The time when the sample stops changing after a recovery analysis.
Relaxation time	The time needed for molecules to relax after applying a stress to a material.
Resonance	The amplification of natural harmonics within a sample. A non-quantitative mechanical technique.
Resonant	A material that resonates; the frequency at which resonance occurs.
Resonant frequency	Amplification of natural harmonic oscillation.
Rheology	The study of flow and deformation of material.
Roller Kinetics	Method of using isothermal or temperature scanning cure studies to calculate the activation energy for curing.
Rubbery	Springy, putty-like.

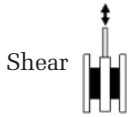


Rubbery plateau

Sample is springy, putty like. Main backbone chain exhibits gradual slippage. Tan delta is near 1.0. This is above the T_g.

Semi-crystalline polymers

Polymers that have some of their backbones organized into crystals and some of them random.



Sliding of one part of a material past another. A fixture that holds two samples so they exhibit shear behavior.

Side chain

A branch of the main polymer backbone.

Sinusoidal

A cyclic event, relating to the sine.

Solid-solid phase transition

Small transitions caused by changes in the solid state. Polymorphism in pharmaceutical or eutectic transitions in liquid crystals.

Spring constant

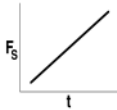


Description of force exerted by a material as it is deformed.

Static modulus

Slope of the stress vs. strain curve in the linear region of Creep Ramp.

Static Scan
(Creep Ramp)



Observed sample strain as sample stress is increased while temperature is held constant. Gives Young's modulus.

Steric effects

Effect of the physical position of atoms in a molecule relative to each other.

Storage modulus (E')

An indicator of elasticity. The in phase component of a DMA signal.

Strain

$$\epsilon = \frac{\Delta L}{L}$$

Ratio between the change in length and the original length of an extension sample.

Strain %

$$\epsilon\% = \frac{\epsilon}{100}$$

Strain multiplied by 100 to report conventional units.

Stress



The load applied to sample, adjusted for the geometry of the specimen.

Structure

Physical position of molecules relative to each other.

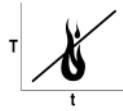
Structure-property relationships

How specific parts of the polymer contribute to specific physical behavior.

Tangent delta

The tangent of the phase angle. The ratio of loss to elasticity. An indicator of the viscoelasticity of a sample. Sometimes called damping.

Temperature Scan



Observing the sample strain while increasing sample temperature and holding frequency and stress constant. Used for characterizing thermally dependent behavior, like the Tg.

Tensile



Films or fibers are deformed using extension measuring systems. This is the best for films and fibers. TMA is often run in this geometry.

Terminal zone

Onset point in a frequency scan where storage modulus dramatically decreases.

Terpolymer

A copolymer with three repeating units.

Thermal expansion

The change in sample dimensions as it is subject to a controlled temperature program.

Thermal history

Previous thermal conditioning applied to the sample.

Thermoplastics

Materials that reversibly change when heated. i.e. ice-water-ice.

Thermosetts

Materials irreversibly change when heated. i.e. egg-hard boiled egg.

Thermosetting (crosslinked) polymers

Polymers that have their backbone chemically bonded to each other. This process is monitored in the DMA to develop cure cycles.

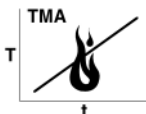
Time or isothermal scan

Observing the sample strain while holding temperature, frequency and stress constant. Used for curing, aging, and quick modulus reports. Often used with fluid baths, humidity generators, or UV accessories.


Time-dependent behavior

Sample behavior over time. An affect of the viscoelastic nature of polymers.

TMA



Thermomechanical Analyzer. Applying a weak static force and measuring sample response normally while changing temperature One observes sample height as temperature is increased. Gives coefficient of thermal expansion and identifies thermal transitions, like Tg.

Tougheners	Additives used to make a polymer less brittle. Often seen in the DMA as step changes in E' at low temperature.
Toughness	The ability of a material to absorb mechanical energy without fracturing or deforming.
Ultimate strength	The greatest stress a material can withstand without failing, breaking apart.
UV or Optical Furnace	A furnace that allows both visual monitoring of the sample as well as its irradiation to study photo-curing.
Viscoelasticity	The ability of a material to exhibit both elastic and viscous behavior.
Viscosity	The ability of a material to flow and deform.
Viscous 	Flowing, gooey.
Vitrification	Point where curing systems reach a viscosity so high as to limit further curing. Normally taken as the onset plateau of storage modulus during Time Scan isothermal cure.
Yield point	The stress that causes a material to permanently deform.
Yield strength	Stress that will cause a permanent physical change in the shape of a sample.
Young's modulus	The ratio of strain when an increasing stress is applied to a sample.

What do the changes in the data mean?

Technique	Data shows	This tells us
Thermomechanical Analysis	Changes in slope Slope of curve with temperature Change in volume (dilatometry)	Transition temperature Thermal expansivity or CTE Shrinkage on curing, volumetric expansion
Static Stress-Strain	Slope Yield Point, Yield Strength Proportional limit Ultimate Strength Elongation at break Area under curve	Young's Modulus Strength before distortion Load capacity End of linear region (max. F_T) Strength at breaking point Ductility Toughness

Dynamic Stress-Strain	Dynamic Proportional limit Storage, Loss Modulus Complex viscosity Tan δ Ultimate strength	End of linear region (max. F_D) Stiffness as function of load Flow under dynamic load Damping Strength at break by tugging
Creep-Recovery	Equilibrium Compliance, Modulus, Equilibrium Viscosity Creep Compliance Creep Rupture Relaxation spectra	Long-term behavior Extensional Viscosity Effect of load Strength Molecular Modeling
Stress Relaxation	Compliance and Modulus Retardation spectra Force as a function of temperature	Long-term behavior, MW, crosslinks, and entanglements Molecular modeling Shrinkage/expansion force
Dynamic Temperature/ Time Scan	Storage and Loss Modulus Complex Viscosity Tan δ Temperature of transitions as drops or peaks Modulus of rubbery plateau Crossover of E' and E'' on curing Shape of viscosity curve on curing	Change in stiffness. Mapping modulus Change in flow Damping, energy dissipation T_M T_g T_α T_β T_γ T_δ Molecular weight between crosslinks, entanglements Gel point Minimum viscosity, E_{act} Vitrification point
Dynamic Frequency Scan	Complex viscosity, loss modulus Storage modulus E'/E'' or n^* crossover Plateau regions Mastercurve	Flow as function of frequency Elasticity or stiffness as function of frequency Relative MW and D MW estimation MWD, long-term behavior, wide range behavior, molecular modeling

Further Readings

Dynamic Mechanical Analysis: A Practical Introduction, 2nd Edition, Kevin Menard, CRC Press, 2008.

The basic book dealing with DMA as a tool in the modern laboratory

Thermal Characterization of Polymeric Materials – 2nd Ed., Edith Turi, Editor, Academic Press, 1997.

Complete text on Thermal Analysis. An excellent practical and theoretical reference for the thermal analyst.

Anelastic and Dielectric Effects in Polymer Solids, N. G. McCrum, B. E. Read and G. Williams, Dover, New York, 1967.

Review of basic polymer types and their behavior as measured by DMA and dielectric analysis. This text is an excellent tool for the interpretation of DMA results and still a useful reference.

Handbook of Plastics Testing Technology, Vishu Shah, Wiley, New York, 1984.

Overview of standard test methods used to characterize polymers

Introduction to Polymer Viscoelasticity, Montgomery Shaw and, William J. MacKnight, Wiley, New York, 2005.

A good first book before reading Ferry, it offers a good general introduction to the basic theory and equations of DMA. This text is an excellent resource for very simple descriptions of DMA theory

Mechanical Properties of Polymers and Composites 2nd Ed., Lawrence E. Nielsen and Robert Landel, Marcel Dekker, New York, 1994.

General text for understanding the mechanical properties of polymeric materials.

Handbook of Polymer Analysis, Hubert Lobo and Jose Bonilla, Editors, Dekker, 2003.

A survey of modern techniques in testing plastics and polymers.

Performance of Plastics, Witold Brostow, Editor, Hanser, 2001.

Overview of issues in how plastics perform with chapters on thermal analysis and rheology.

Rheology Principles, Christopher Mascosko, VCH, New York, 1994.

Excellent introduction to rheology. Very mathematical.

Viscoelastic Properties of Polymers, John D. Ferry, Wiley, New York, 1980.

Definitive text on rheology and DMA for the experienced. Provides in depth information about experimentally observed DMA and dielectric results.

Principles and Applications of Thermal Analysis, Paul Gabbott, Editor, Blackwell Publishing, Oxford, UK, 2008. *Overview of current applications in thermal analysis with a chapter focused on DMA.*

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