TECHNICAL NEWSLETTER

Strength & Stiffness of Plastics

Introduction

In previous Newsletters we have talked about the effect of various factors on the strength and stiffness of plastics, but despite this there is often confusion about the difference between the two terms and what they actually mean. Strength and stiffness are two of the defining characteristics of all materials. Understanding the difference is vital in defining what you want out of a material and how a material will behave under load. The failure to recognize this is one of the key reasons for failure of products under load.

The best, and most easily understood, definition of the two properties is given in J. E. Gordon's book *The New Science of Strong Materials or Why You Don't Fall Through the Floor* (ISBN 0-691-02380-8):

"Lest there be any possible, probable, shadow of doubt, strength is not, repeat not, the same thing as stiffness:

Stiffness, Young's modulus, is concerned with how stiff, flexible, springy or floppy a material is.

Strength is the force or stress needed to break a thing.

A biscuit is stiff but weak, steel is stiff and strong, nylon is flexible but strong, raspberry jelly is flexible and weak.

The two properties together describe a solid about as well as you can reasonably expect two figures to do."

You don't get much more succinct than that! This month's Newsletter looks at strength and stiffness in greater detail to give you the information behind the scenes.

Defining stress and strain

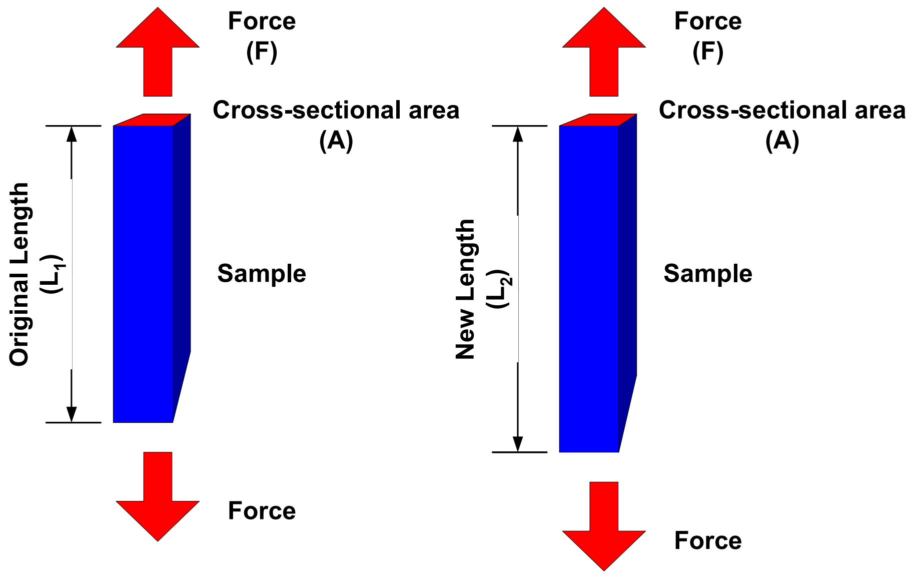
Stress

Stress (σ) is the force per unit area acting on the sample, in terms of the diagram below:
σ = **load / cross-sectional area = F / A**
Note: The stress shown here is tensile stress. Stress can also be compressive (when the force is acting to compress the sample), or shear (when the force is shearing the sample).

Strain

Strain (ε) is the relative change in length when a sample is subjected to a load, in terms of the diagram below:

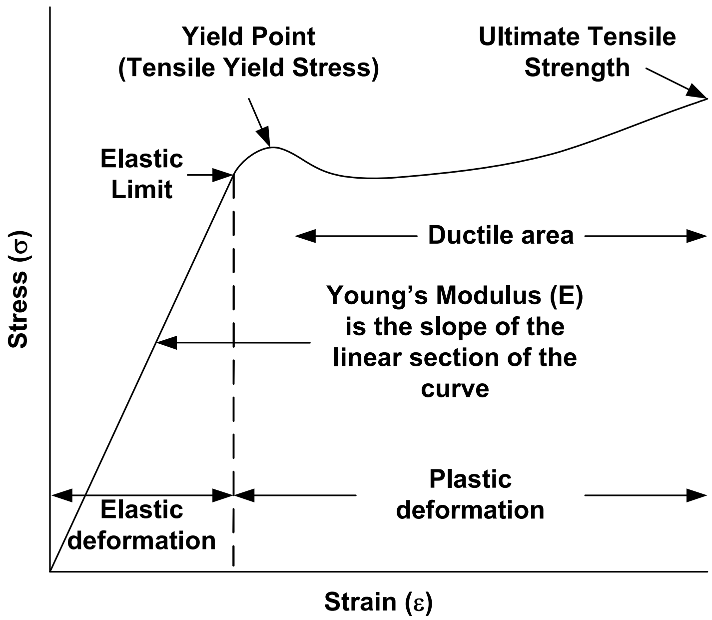
ε = **change in length / original length = ($L_1 - L_2$) / L_1**
Note: The strain shown here is tensile strain. As with stress, strain can also be compressive (when the force is acting to compress the sample), shear (when the force is shearing the sample), or even volumetric (where the volume of the sample changes).



The elements for defining stress and strain

The stress-strain curve for elastic materials (linear behavior)

An idealized stress-strain curve for a tensile test on a traditional and typical material is shown below:



Generalized stress-strain curve

As the stress is applied up to the elastic limit the initial stress creates only elastic deformation in the sample. If the stress is released while the strain is below the elastic limit, then the sample will eventually return to the original length. During elastic deformation the slope of the stress-strain curve indicates "…how stiff, flexible, springy or floppy a material is".

The slope of the curve in this area is known as **Young's Modulus** (named after Thomas Young, the British physicist and physician) or the **Modulus of Elasticity** and is represented by E where:
$E = \sigma / \varepsilon$ (when in the elastic deformation section of the stress-strain curve)
As more stress is applied the material eventually cannot continue to deform elastically and reaches the Elastic Limit. Any deformation past this point will be permanent (plastic), and if the stress is released the sample will not return to the original length.

Young's Modulus (named after Thomas Young, British physicist and physician) is the slope of the linear section of a stress-strain curve.

Further application of stress will cause many materials to reach a Yield Point at the Tensile Yield Stress, where the material yields and the stress decreases with a large increase in strain. Many materials will fail at this point, but some enter a ductile area where drawing occurs and the strain increases greatly for small increases in stress.

For all materials, fracture and failure will eventually occur at the Ultimate Tensile Strength. The final result of a tensile test is "…the force or stress needed to break a thing".

The stress-strain behavior of a material in a tensile test therefore gives a good insight into both the stiffness and strength of a material – the two figures that can be used to fundamentally describe a solid.

The stress-strain curve also gives an insight into the toughness of a material. The area under the curve is a measure of the amount of work required to break the sample, a measure of the toughness. **Toughness** is entirely different to strength and stiffness and will be covered in a future Newsletter.

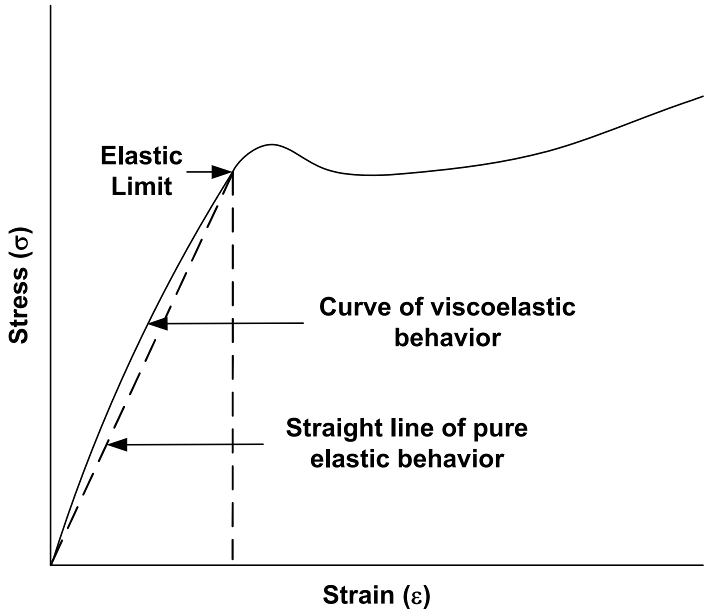
Note: While many materials will not break until the Ultimate Tensile Strength, the Yield Point or Tensile Yield Stress should always be regarded as the limit for practical design.

Stress and strain for plastics (viscoelastic behavior)

Plastics behave significantly different than many other materials in their response to stress because they are **viscoelastic**. This means that their behavior under an applied stress is both viscous and elastic at the same time, and they rarely have a significant linear elastic region as described above. A viscous material is one where applying and then removing a load leaves a permanent deformation of the material, and the material does not return to its original condition. Viscoelastic behavior means that the response of a plastic to a stress is dependent not only on the load applied, but also on the time and rate for which the load was applied.

Viscoelastic - behavior under an applied stress is both viscous and elastic at the same time.

The stress-strain curve of a typical plastic therefore does not often have an initial elastic section where stress is proportional to strain, but has a curved non-linear section from the start. A typical stress-strain curve for a plastic material is shown below:

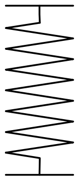


Stress-strain curve for a typical plastic

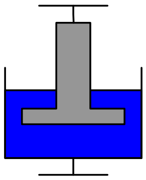
This means that it is often difficult to assign a conventional stiffness (Young's Modulus) to plastics because the curve is not a straight line and is also very dependent on the test conditions. Equally in these cases the Yield Point or Tensile Yield Stress (the fundamental design limit) may not be as well defined as it is in metals. Instead it is often defined in terms of a degree of offset (1%) from the initial section of the stress-strain curve.

To get a physical feel for the behavior of plastics, it is possible to model their viscoelastic behavior using a simple mechanical model of springs and dashpots.

- The spring obeys **Hooke's Law**, i.e. it extends instantaneously and linearly with constant applied load, and the deformation is independent of the time the load is applied. The extension of the spring is totally recoverable.
- The dashpot is a piston in a Newtonian fluid, i.e. it will extend continuously with a constant applied load, and the deformation depends on the time the load is applied. The extension of a dashpot is not recoverable unless an opposite load is applied.



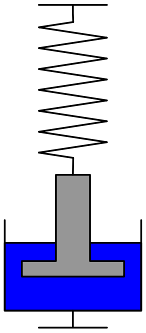
Spring model



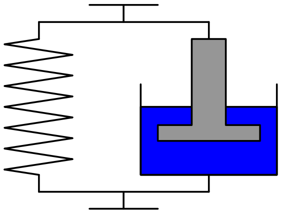
Dashpot model

The spring and dashpot can be combined into either the Maxwell or the Kelvin/Voigt elements:

- In the **Maxwell element** the spring and dashpot are combined in series – an applied load will lead to instantaneous extension of the spring and a slower movement of the dashpot. If the load is removed the spring extension will be instantaneously recovered whereas the dashpot extension will be permanent. This is not a full representation of the behavior of a typical plastic.
- In the **Kelvin (or Voigt) model** the spring and dashpot are combined in parallel – an applied load will give no instantaneous extension and the model shows retarded elastic behavior as the extension of the spring is dampened by the presence of the dashpot. If the load is removed the spring applies a load to return the dashpot to the original position and all the extension will be recovered. This is also not a full representation of the behavior of a typical plastic.

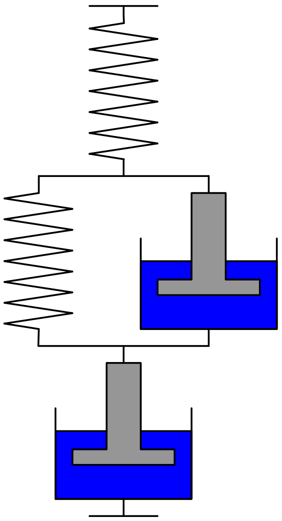


Maxwell element



Kelvin element

The Maxwell and Kelvin elements can be combined to form a more general mechanical model that is shown below:



General mechanical model for plastics

This model provides a more accurate representation of the behavior of a typical polymer to a range of stress conditions (including that of creep under constant load), and can be used to model many plastics simply by changing the parameters of the springs and dashpots.

Strength and stiffness of plastics

Plastics can fall into all of the various categories of strength and stiffness, i.e. stiff and weak, stiff and strong, flexible and weak, or flexible and strong, depending on the plastic and the test or application conditions.

The response of any plastic to an applied load is dependent not only on the size of the applied load, but also on the rate and temperature at which the load is applied. This is known as time-temperature superposition and has been discussed in previous Newsletters. Time-temperature superposition shows that time and temperature of loading can have the same (but inverse) effect on plastics – the strength and Young's Modulus of a plastic under rapid loading and low temperatures can be effectively the same as the strength and Young's Modulus of the same plastic under slow loading and higher temperatures.

A plastic that is stiff and weak at room temperature will become more flexible and weaker as the temperature is raised. A different example is a plastic that is flexible and weak at slow load application rates will become stiff and weaker at high load application rates (i.e. bend a plastic sample slowly and it may deform quite a lot; bend it very quickly and it may fail without deforming much at all).

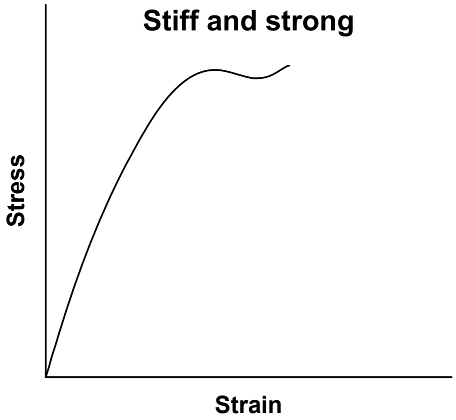
As a general rule increasing the load application rate will increase the strength and stiffness of plastics, and increasing the temperature will decrease their strength and stiffness. In assessing the suitability of a plastic for a particular application it is therefore essential to know not only about the range of mechanical loads that will be applied to the product (as with conventional mechanical design procedures), but also to know something about the rate and temperatures at which they will be applied.

For plastics, strength and stiffness "…will describe a solid about as well as you can reasonably expect two figures to do" but that is not the only information needed.
The various combinations of strength and stiffness seen in plastics are listed below.

Stiff and strong:

Stiff and strong plastics have a stress-strain curve as shown at right.

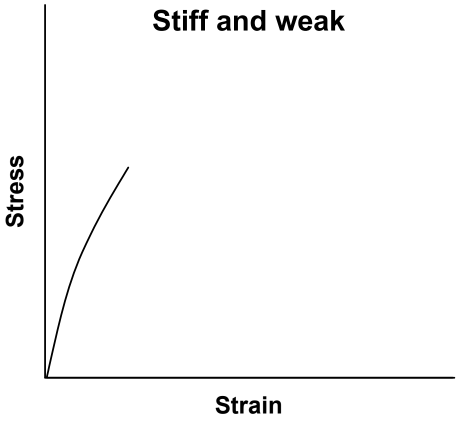
These materials have a high Young’s Modulus (the slope of the initial curve is steep) and also a high Yield Point (Tensile Yield Stress). In the example shown, yield occurs before fracture with some drawing before ultimate failure. A material showing this type of stress-strain curve would be relatively tough before ultimate failure because of the large area under the graph which indicates a high amount of energy that needs to be input to fracture the material. Fiber-filled plastics often show this type of curve but with these materials there is rarely any drawing, and fracture occurs soon after yield.



Stiff and weak:

Stiff and weak plastics have a stress-strain curve as shown at right.

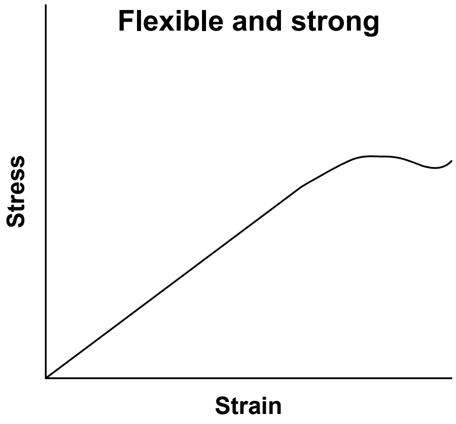
These materials have a high Young’s Modulus (the slope of the initial curve is steep) but have a low Yield Point (Tensile Yield Stress). In the example shown, fracture occurs with little or no extension. A material showing this type of stress-strain curve would be less tough than the stiff and strong plastic shown above because of the lower amount of energy that needs to be input to fracture the material. A material showing this type of curve would fail by brittle fracture.



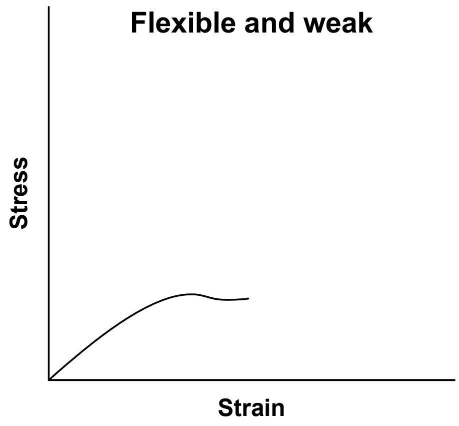
Flexible and strong:

Flexible and strong plastics have a stress-strain curve as shown at right.

These materials have a low Young’s Modulus (the slope of the initial curve is more gradual) and but also have a high Yield Point (Tensile Yield Stress). In the example shown, yield occurs before fracture with some drawing before ultimate failure. A material showing this type of stress-strain curve would be flexible but tough and would show considerable extension before failure.



Flexible and weak:



Flexible and weak plastics have a stress-strain curve as shown at right.

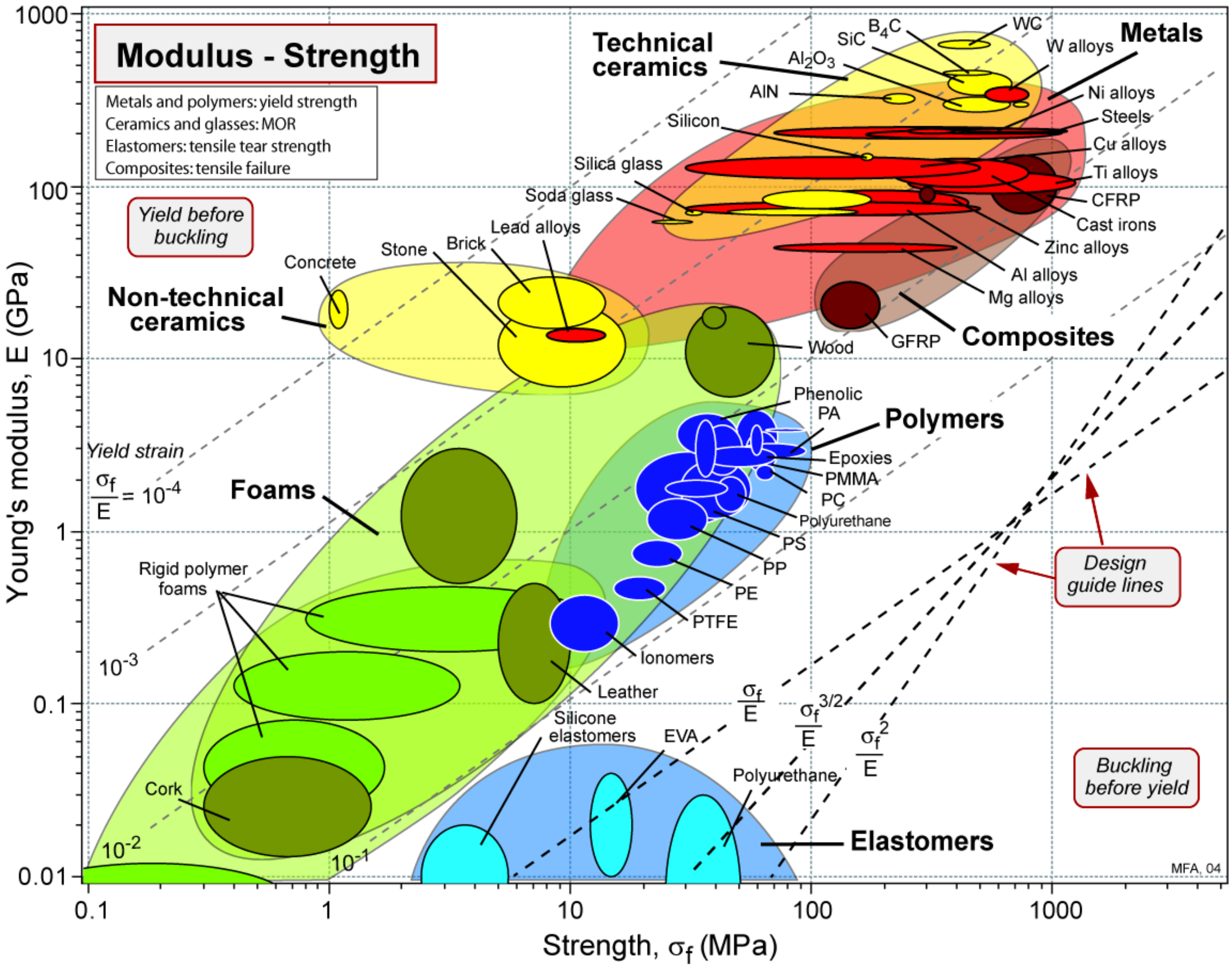
These materials have a low Young's Modulus (the slope of the initial curve is more gradual) and also a low Yield Point (Tensile Yield Stress). In the example shown, the material has yielded before fracture with a small amount of drawing before ultimate failure.

Making the choice – The Ashby diagram for temperature and strength

Prof. M. Ashby at the University of Cambridge, UK has developed a visual method for materials selection, making choices simpler for optimum strength and stiffness combinations. A typical Ashby chart for strength at failure (σ_f) versus Young's Modulus (E) is shown below.

The chart gives a birds-eye view of the areas of stiffness and strength across a wide range of materials. The bubble for each material is designed to represent the typical range of properties that might be achieved for the various grades of a family or class of materials. This chart allows for easy materials classification on the basis of stiffness and strength:

- Stiff and weak materials are located towards the top left.
- Stiff and strong materials are located towards the top right.
- Flexible and weak materials are located towards the bottom left.
- Flexible and strong materials are located towards the bottom right.



Young's Modulus (E) vs. Strength (□$_f$)

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Summary

Strength and stiffness are often loosely used terms and are frequently confused. Despite this, they have real physical meaning and vary in different properties. For plastics the issue is made more difficult by variations caused by the effect of the load application rate and temperature, but the result remains that strength and stiffness "…together describe a solid about as well as you can reasonably expect two figures to do". Ultimately, the question that needs to be answered is "how strong/stiff does the material need to be"? This in turn will determine which material needs to be chosen. Zeus can help you not only answer this question, but assist in the material selection from the wide array of resins and engineered polymers that we offer.

How Zeus Can Help

With a technical inside and outside sales force backed up with engineering and polymer experts, Zeus is prepared to assist in material selection and can provide product samples for evaluation. A dedicated R&D department staffed with PHD Polymer chemists and backed with the support of a world-class analytical lab allows Zeus an unparalleled position in polymer development and customization.

Since 1966 Zeus has been built upon the core technology of precision extrusion of high temperature plastics. Today, with a broad portfolio of engineered resins and secondary operations, Zeus can provide turnkey solutions for development and high-volume supply requirements.

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