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Taking advantage of viscoelasticity, a unique property of plastics

Viscoelasticity gives plastic the ability to absorb energy, flex and spring back without cracking, which makes plastics so attractive over other materials. That property is achieved through molecular movement and rearrangement when a stress is applied and needs to be accounted for in the design to avoid creep.

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Plastics are wonderful. No other material offers such a variety of properties that can be tailored to specific needs, provide tremendous design freedom, and be manufactured at a relatively low cost and at very high rates. The primary property that makes most plastics so attractive over other materials is viscoelasticity. This gives plastic the ability to absorb energy, flex and spring back without cracking. Viscoelastic behavior is important in how a material will behave in many common applications:

Snap-fits—high deformation without breaking and snapping back to its original shape.
Press fits—forming to shape and staying joined to its mating piece.
Caps—elastic behavior to keep the cap attached and sealed to another part.
Impact applications—the ability to absorb and dissipate energy without cracking.
Rubber materials—high elongation without permanent deformation or fracture.
Living hinges—repeated high strains without fracture.
Design-to-crack—crack at a specific stress or strain.
Gaskets—plastic or rubber that will deform to create a seal and take up tolerance stack-up.

Let us dissect what the compound word "viscoelastic" actually means and how it influences the plastic part and its role in design. As the name suggests, a viscoelastic material has both viscous (liquid-like) and elastic (spring-like) properties. When a stress is applied to the plastic part, it will behave like a liquid and spring at the same time. It will *flow* with some resistance when a stress is applied. The part also will spring back when stress is removed. However, because the plastic has flowed, it will not return completely to its original state/position. The ability to choose how much viscous and elastic properties a material will have gives the designer great flexibility. The consequence on how each property will influence part behavior must be understood for the design to be successful.

This article will not go into the endless models that are used to numerically describe the viscoelastic response of a plastic. However, I think it is enlightening to understand how viscoelastic behavior can be visualized. As one might expect, the elastic part of plastics can be modeled with a spring (Figure 1). The force required to elongate the spring is based on its stiffness (E). When the load is removed, the spring will fully recover nearly instantaneously to its original configuration. The viscous effect of plastics is modeled with a damper (Figure 2). The response of the damper to a load depends not only on the level of the load, but also how rapidly it is applied. If the load is applied quickly, the instantaneous deformation may be relatively small. Apply this same load, or even a smaller load, over a long period of time, and the damper will open (deform) significantly. Does this sound similar to how a plastic part might behave? Putting springs and dampers in different configurations will provide a different response of the plastic deformation over time. Figure 3 is one configuration that is commonly used to describe the viscoelastic behavior of plastics over time [1]. Using this model or others similar to it, we can predict how the material behaves when a load is applied.

On a molecular level, a viscoelastic material consists of long-chain molecules that are intertwined/tangled together in a relatively ordered (partial) state (crystalline structure) and/or random state (amorphous). The molecules themselves are held together by extremely strong (intra-molecular) covalent bonds. The molecule-to-molecule, or inter-molecular, bonds are weak when compared to the intra-molecular bonds. These bonds play an important role in how the plastic material will behave in a viscoelastic manner. To get a better understanding and to measure viscoelasticity, we use a dynamic mechanical analysis (DMA) device. This is a highly precise flexural-testing instrument that allows us to analyze the viscous (loss modulus) and elastic (storage modulus) behavior at various temperatures. As one can imagine, at lower temperatures the elastic properties are more pronounced, but as the temperature increases, the viscous properties are more prominent.

When reviewing materials for a certain application, we can choose materials that have the correct *mix* of visco and elastic properties at the temperatures in which the product will be used. For instance, if we are designing a snap fit for an application that will be used in various outdoor temperatures, we can use DMA data to help find the correct material. The investigation would entail looking for materials with some viscous properties at cold temperatures to ensure the snap fit does not behave too stiffly and break at the high strains typically required when engaging the snap fit. Likewise, we would want to make sure the snap fit has some elastic/stiffness properties at high temperatures to ensure it does not easily open when a relatively low stress is applied. A common snap fit that falls under this description is found on most backpacks (Figure 4). This buckle must possess viscoelastic properties over a wide temperature range. In fact, the buckle may remind you in some ways to the spring that was described above. For this application, polyamide with a small amount of glass has proven to be the material of choice. The glass provides an increase in stiffness while also reducing the viscous portion of the viscoelastic behavior.

A viscoelastic property that is commonly overlooked or is not at the top of the list when choosing a plastic material, is sound dampening. This property is extremely important to industries such as automotive, HVAC and appliances. This viscous-related property of the plastic absorbs and dissipates the energy and other vibrations that can produce sound. Again, using DMA we can choose a plastic that has a high viscous property while having the appropriate level of stiffness.

Disadvantages of viscoelasticity

Since viscoelasticity involves molecular movement and rearrangement when a stress is applied, this needs to be accounted for in the design. This movement is referred to as creep, and results in the plastic part being irreversibly deformed over time—think of the movement of a damper. The structure of the plastic, glass transition temperature, stresses and environmental conditions (primarily temperature) are important in how susceptible the part will be to creep. Since molecular movement primarily takes place in the amorphous region of the plastic, amorphous plastics are typically more susceptible to creep. However, semi-crystalline materials that are typically used above their glass transition temperature, such as polyethylene, polypropylene and polyacetal, are highly susceptible to creep. Thermoplastic elastomers are not immune to creep, but may provide better creep performance than other materials. The use of reinforcements, such as glass fiber, can significantly reduce creep, but can come at the expense of other challenges, such as an increase in brittleness.

One reason why parts warp or crack after molding is because of viscoelasticity. You may have heard that everything wants to be at a zero state of stress. During injection molding, extrusion, compression molding and other processing techniques, the molecules of the molten plastic are sheared, stretched and compressed into a shape that they prefer not to be in. Considering the molecules to be individual springs that are compressed or elongated, after de-molding, these molecules will want to spring back to their natural, unstressed state. If molecules are frozen into place and not allowed to achieve a zero state of stress, a molded-in residual stress will develop. If this molded-in residual stress is high enough, the part can warp after the part is de-molded. This warpage can occur very quickly after molding or over time (creep). If the part does not have the ability to warp, the stress will remain in the part. This can result in a worse situation; creep rupture. This occurs when the molecules disentangle over time, resulting in a separation of molecules and cracking of the part. A critical point to consider is that the stress that causes this disentanglement and cracking is below the material's yield point.

A couple of years ago, we were contacted by a client about some medical parts that were cracking during shipment from their facility to the OEM. The polycarbonate parts were made of a high-quality resin with a high molecular weight (low melt-flow rate). Testing was done to ensure the molecular weight was not diminished during molding, and that there were no contaminants present. Microscopy determined that the cracks formed purely as a stress situation. Because the parts were unassembled and there were no other externally applied loads, this clued us into a high molded-in residual stress condition. It was decided that residual stress testing would be done using a specific set of chemicals at different concentrations. In this well-established technique, a series of plastic parts are put through environmental stress cracking to determine the approximate level of built-in stress. (We will discuss this testing technique in a future article.) In this case, testing showed the polycarbonate parts had over 3200 psi of molded-in residual stress. This particular polycarbonate having a tensile strength of 9000 psi, the stress was not high enough to cause instant cracking. However, it was high enough to cause cracking over time, which led to creep rupture. To solve the issue, our team utilized injection molding simulation to provide insight into several options to reduce the molded-in stress—gating, molding temperatures/pressure, and wall thickness. Follow-up testing showed that we were able to reduce the residual stress to below 800 psi (without changing part thickness), which was determined to be low enough not to cause warpage or creep rupture.

As one might expect, there are methods to reduce the viscoelastic behavior of plastics. Again, this is another reason why we love plastics so much—design, material, processing freedom. We will discuss these methods and the other issues that may arise in future articles. Furthermore, we will review specific design features that take advantage of viscoelasticity, such as snap-fits, living hinges, seals/gaskets and caps.

References:
[1] Osswald, T.A., G. Menges, Materials Science of Polymers for Engineers, Hanser, 1996.

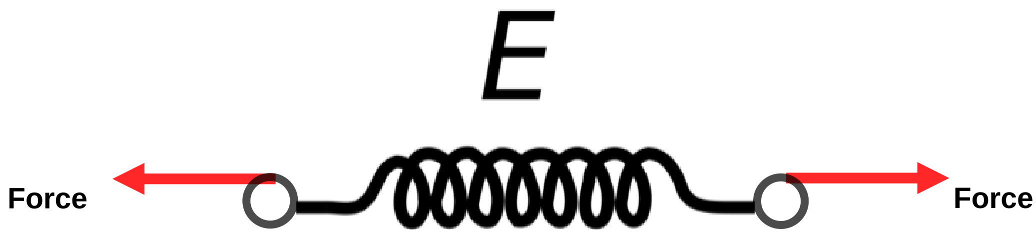

Figure 1. The elastic property (stiffness E) of plastics can be modeled with a spring.

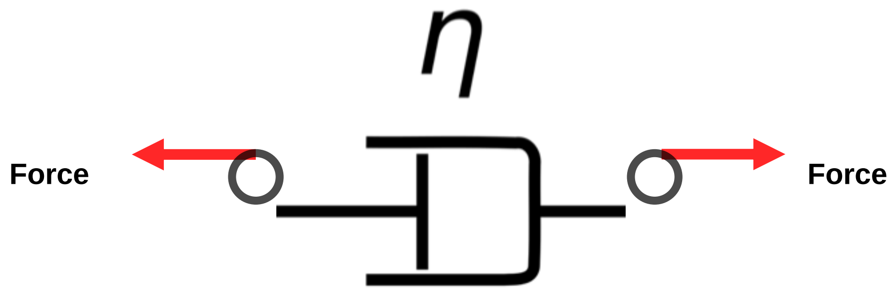

Figure 2. The viscous property (Ƞ) of plastics can be modeled with a damper.

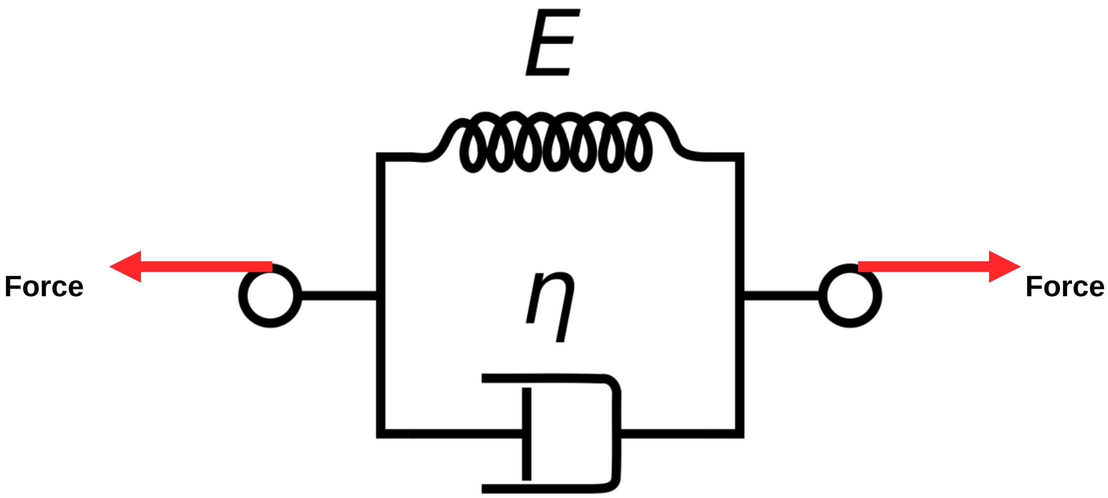

Figure 3. Damper and spring put in parallel configuration (Kelvin-Voigt model) to model the viscoelastic behavior of plastics [1].

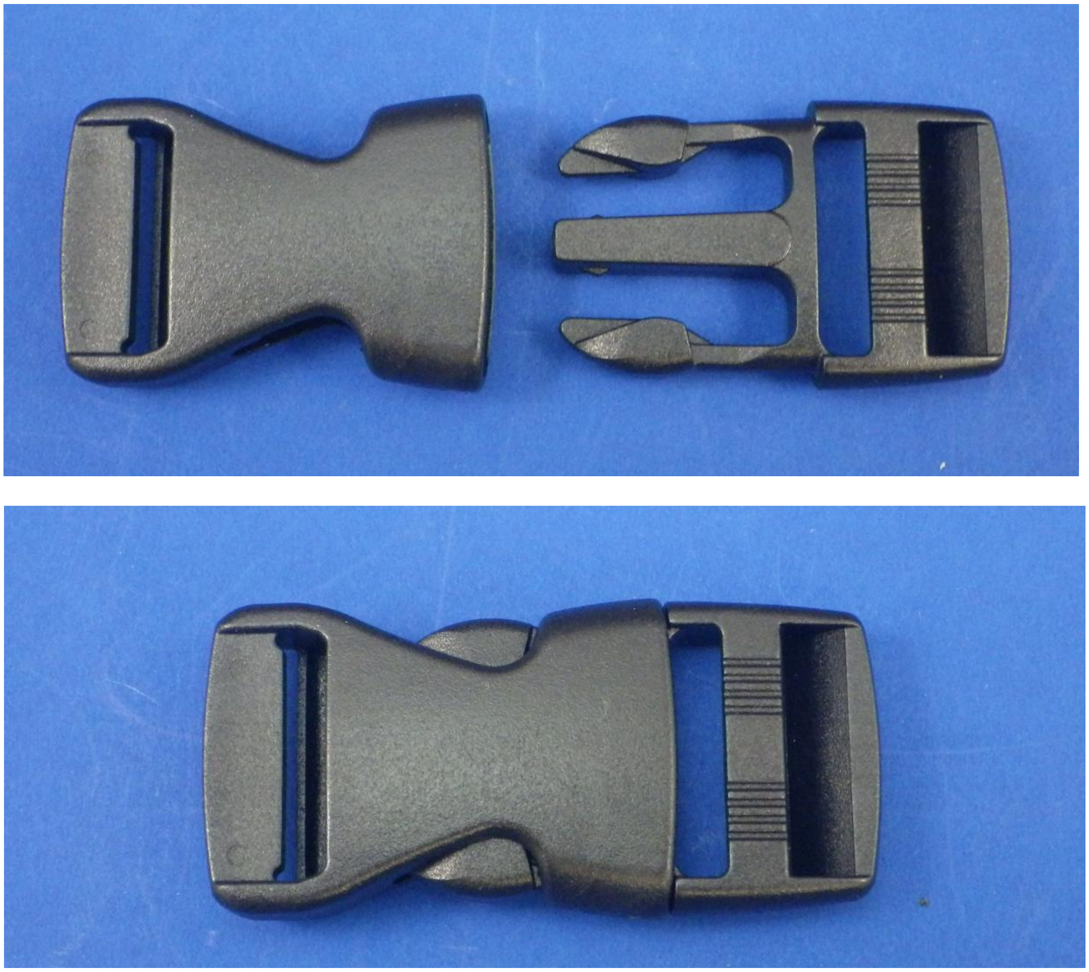

Figure 4. Backpack buckle that utilizes the viscoelastic properties of plastic.