MITSUBISHI CHEMICAL ADVANCED MATERIALS

MITSUBISHI CHEMICAL ADVANCED MATERIALS SHAPE DATA APPROACH

THE EFFECTS OF PROCESSING ON THERMOPLASTICS

WHITE PAPER

THE EFFECTS OF PROCESSING ON THERMOPLASTICS

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Advanced high-tech industries (including Medical, Semiconductor, Aerospace, and Oil & Gas) are dynamic, evolving markets that rely heavily on material specifications to ensure consistency, reliability, and safety. Today, many engineers use the Internet to choose the right polymeric materials for their applications. Engineers also use resources that come directly from raw material suppliers, which often only report the “as produced” pellet data.

This paper focuses on how the processing of thermoplastics impacts physical properties, theories behind the differences, and the availability of various materials for use in prototypes or production—all emphasizing the need for strong material certifications and purchasing standards.

Depending upon the volume and size of the needed thermoplastic components, parts may be produced by injection molding or machined from extruded or compression molded shapes. Parts can even be machined from near net injection molded blanks. In each instance, the design engineer must understand how different processing methods will impact physical properties and the thermoplastic material’s overall success.

INTRODUCTION

Even today, engineers and designers frequently misunderstand polymers. With very few classrooms dedicated to teaching polymers and a plethora of different materials, manufacturers, and trade names, confusion around plastics is quite common. This paper is dedicated to clarifying some of that confusion, specifically related to the physical mechanical properties expected by designers when compared to their final component results.

This paper will show that processing the same polymer resin using different manufacturing methods can result in significantly different mechanical properties. If specifiers or designers are not aware of the potential for such property differences, they may not get the results that they initially designed for.

There are data-driven reasons why one polymer manufacturing method is used versus another—this paper will briefly discuss those differences. Ignoring or assuming the manufacturing method that was used when writing a material specification could lead to unexpected failures. An example of this would be when a component is designed using “resin” data, but then a part is used that was manufactured using a method that results in much lower physical properties. Reviewing a few of the most common polymer processing conversion methods and the effect that each of these conversion methods has on the resulting physical properties, will help eliminate some of this confusion.

Today, advanced high-tech industries are growing markets that rely heavily on material specifications to ensure consistency, reliability, and safety. If you are responsible for the design, engineering, installation, use of, or purchasing of a plastic component, this paper is intended to help you clarify your options and ultimately select the best material.

THE PROBLEM

Lightweight polymers and composites have the ability to yield tremendous value, in even the most demanding applications. Some of these benefits can include extending wear life, improving corrosion resistance, lowering maintenance costs while increasing production time—ultimately improving overall system efficiencies. However, polymers can also fail if used in the wrong environment. Proper material specification is critical to ensure application success. To ensure proper polymer material specification, designers and engineers must understand the impact that manufacturing processes can have on the physical properties of polymers.

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Because polymers can be manufactured in multiple ways, material specification confusion is common. For example, injection molded resin properties are frequently called out on a material specification, but the end-user actually purchases a component machined from an extruded stock shape. The designer may not be aware of the fact that the extruded material properties likely will not meet the resin properties specified. This section will define a few common manufacturing processes and how such processes may influence mechanical properties.

Resin Data

The Internet is full of raw material "resin" data. These resins are the base materials that get converted into a functional part, through a variety of processing options. A final part may be injection molded, machined from a plastic stock shape manufactured by extrusion or compression molding, or even manufactured through additive manufacturing (3D printing). Regardless of the conversion method, the base raw material for the stock shape is resin pellets or powder. The large chemical companies that supply resin to the converters have their own material datasheets, based on injection molded dog-bones or test sample plaques. This is important because injection molding a test sample (like an ASTM D 638 tensile bar) may yield different mechanical properties than other conversion methods.

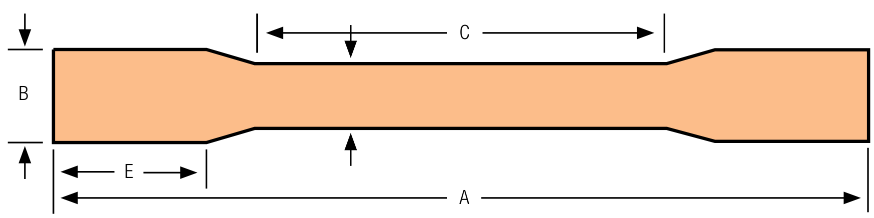
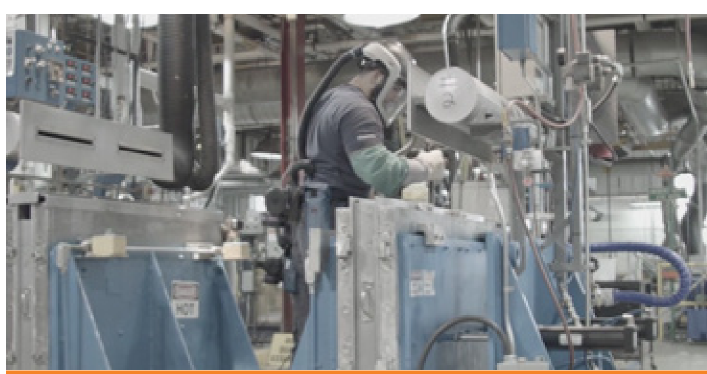


Figure 1. A typical tensile bar per ASTM D 638 [Standard Test Method for Tensile Properties of Plastics].

Stock Shape Data – Injection Molded Method

The injection molding process is typically used for high volume needs. Hot resin is injected through a small nozzle into a mold at a high speed and then quick cooled for fast release from the mold. Consider the molding of a long, thin tensile bar used for mechanical property testing. Typically, such a test bar will be gated on one end (where the polymer enters the mold) and vented on the opposite end. The flow of resin into such a mold design (a long and thin component) results in unique alignment of the polymer chains, a result that you may not get with processes like extrusion or compression molding. Fiber alignment could also occur if the polymer is a fiber-filled material, like a glass or carbon-filled resin. It is important to note that this paper does not examine mold-flow



Injection Molded Method

analysis, nor provide specific examples of polymer or fiber filler alignment. This paper speaks generally of fiber alignment expected by manufacturing process.

Any alignment of the polymer and the fillers within such a test samples (i.e. dog bones) will result in higher mechanical values compared to processes where less—or no—alignment occurs.

Stock Shape Data – Extrusion Method

Functional plastic parts are often machined from polymer stock shapes rather than through injection molding. The machining method is based on volume requirements, part size, and part configuration. For example, someone needing 100 parts with tight tolerance requirements would have their components machined from a stock shape plastic rather than through injection molding (which has tolerance limitations and requires significant tooling investment). A stock shape may be a rod, sheet, tube, or even a near-net configuration. These stock shapes are processed through extrusion, compression molding, or some other melt processable method.

Extrusion Method

The extrusion method of polymer processing is often used to manufacture smaller cross-section shapes in longer lengths. Extrusion is a conversion process where the resin passes through a screw and barrel section where it is melted. Then the resin is slowly pushed through a die and has time to cool while it comes out of the extruder. There should be significantly less alignment of the polymer chains and the filler in this slower manufacturing method compared to that of injection molding. Consider a 30% fiber filled material. Is it feasible that such a material may have different properties if manufactured through extrusion versus the injection molding of a test sample? To accurately test the mechanical properties of an extruded polymer, a test plaque must be machined from the product. Based on a history of machined test samples from Mitsubishi Chemical Advanced Materials (a stock shape converter), mechanical property test samples machined from fiber-filled extruded shapes typically have lower values compared to injection molded test samples as produced by the raw material suppliers and discussed as "resin" properties. While less true with neat (unfilled) materials, this is especially true of fiber-filled polymers.

Stock Shape Data – Compression Molded Method

Compression molding conversion of polymer resin is typically used to manufacturer larger cross-section shapes, including large outside diameter/inside diameter (OD/ID) tubes, rods, or thicker plates. Compression molding also lends itself to manufacturing small volumes where there would otherwise be too much waste through extrusion or injection molding. Additionally, some of the most extreme polymers only lend themselves to this process.

Compression Molded Method

The compression molding process involves placing resin powder or pellets into a mold and squeezing the resin under pressure and temperature. There is no passing of the resin through a small die, and really no opportunity for any specific orientation of the material and its fillers. Like extrusion, standard compression molded shape properties must be obtained by machining test samples from the product. With random fiber orientation and zero directionality, Mitsubishi Chemical Advanced Materials typically measures lower mechanical property values for compression molded materials (machined test samples) versus extrusion (machined test samples) or injection molded materials (direct molded test samples).

The remainder of this paper will show the mechanical property differences for a common 30% carbon fiber-filled poly-ether-ether-ketone (PEEK) polymer material, along with a comparison of a 30% glass fiber-filled PEEK.

THE EXPERIMENTATION: SHAPE VERSUS RESIN

Understanding that various processing methods for polymers may yield different levels of polymer and filler alignment, it starts to become clear why the physical properties would vary significantly. Pulling apart a tensile bar with significant fiber alignment will take more force when compared to one with less or no fiber alignment. Figure 2 is an exaggerated rendering of what fiber alignment in a test sample may look like. Per section titled *The Problem* of this paper, an injection molded tensile bar should have more fiber alignment than a sample machined from extruded material, which in turn should have more than a sample machined from compression molded material.

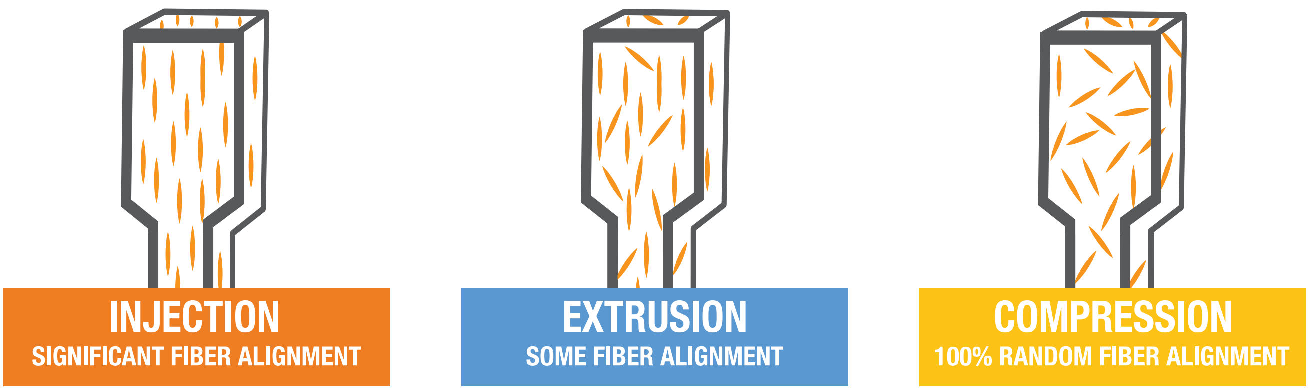


Figure 2. Fiber alignment exaggeration for various polymer processing methods.

Let's consider poly-ether-ether-ketone (PEEK), a common fiber-filled advanced engineered polymer. A typical rule of thumb cited by Quadrant EPP (based on their database of stock shape mechanical properties) for fiber filled materials—like a 30% carbon filled PEEK—is that injection molding properties can be over 50% above extrusion properties, and that extrusion properties will be yet another 15% above compression molded properties. Many design engineers and material specifiers are not aware of this difference in properties. While these are just estimates, you can begin to see how such a difference in mechanical properties would be extremely important.

Experimentation

There were two parts to the experimentation. First, a simple mechanical property test comparison of a common fiber-filled polymer processed using three common manufacturing methods. Second, the mechanical properties of another fiber-filled material, injection molded in two different configurations, was analyzed. This second analysis compared injection molded test samples to test samples machined from the wall of an injection molded tube.

Mechanical Property Comparison – Three Processing Methods

Using the same 30% carbon-filled PEEK resin, test specimens were obtained through three processing methods: injection molding, extrusion, and compression molding. Each of the specimens was tested for various mechanical properties utilizing standard ASTM testing methods (including tensile strength, flexural strength, and compressive strength). The injection molding test samples were direct molded into test plaques, while both the extrusion and compression molding test samples were machined from stock shapes.

Mechanical Property Comparison - Molded Samples versus Molded Tube

In a follow-up test, the mechanical properties of direct injection molded 30% glass-filled PEEK test bars were compared against test samples machined from the wall of an injection molded tube. The same resin was injection molded into both configurations. This part of the experiment aimed to show that not only process, but also component configuration might drive mechanical properties of polymers, particularly in the case of fiber-filled materials.

RESULTS:

Data Comparison – Three Processing Methods

Depicted in Table 1 are the mechanical properties for the same 30% carbon-filled PEEK resin, manufactured using different processing methods. These three processes are also compared to Victrex® 150CA30 PEEK resin property data. The Victrex® 150CA30 PEEK is a 30% carbon filled PEEK, and the base resin used for our testing. In theory, the Victrex® data should closely resemble our injection molded test samples, as both our data sets are obtained using direct molded test samples.

As anticipated, our results show significantly higher mechanical property values—specifically related to strength and modulus—for the injection molded test samples. While extrusion and compression molded physical property values are closer together, the values are both far below the injection molded data.

While both injection molded test samples were high compared to extrusion and compression data, our injection molded test samples were higher than even the Victrex® resin data. Keep in mind that our test was limited to a small sample size (less than ten test samples) compared to the typical Victrex® property datasheet.

In Figure 3, the same data from all three manufacturing processes is plotted graphically for both the tensile strength and flexural strength properties. Again, injection molded properties are the highest, followed by extrusion, with compression molding close behind.

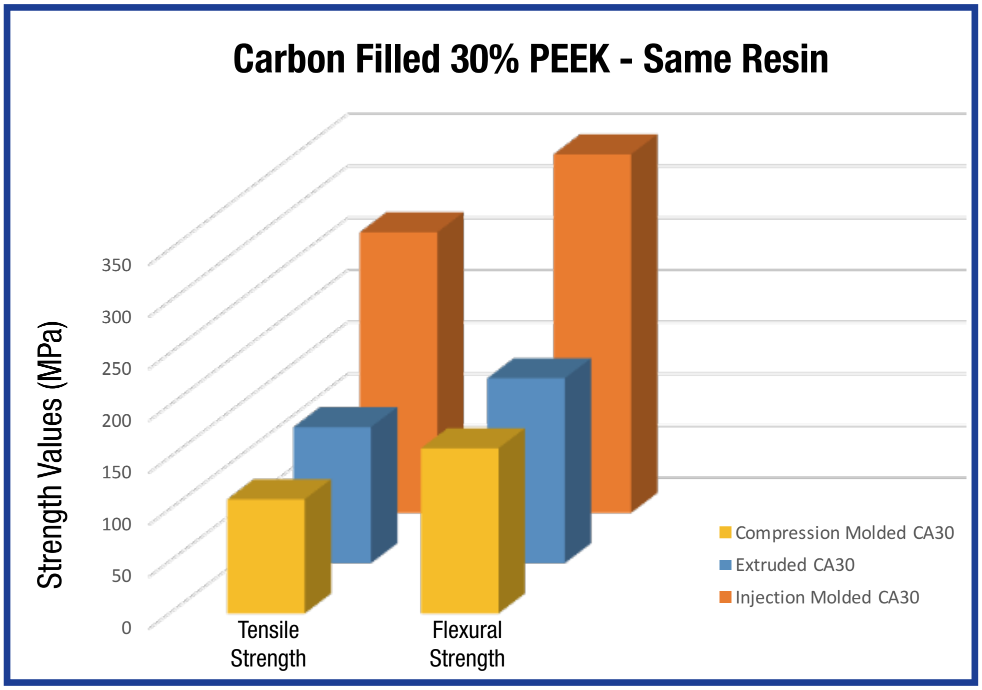


Figure 3. Mechanical Property Comparison for CA30 PEEK processed using three different conversion processes.

Mechanical Property Comparison – 30% Carbon Filled PEEK Material					
Mechanical Property	Test Method	Published Resin Data Sheet Victrex® 150CA30 PEEK	Injection Molded Test Plaques CA30 PEEK	Ketron® CA30 PEEK	Ketron® CM CA30 PEEK
		SAME BASE RESIN USED			
Samples Converted via →		Injection Mold direct formed samples	Injection Mold direct formed samples	Extrusion machined samples	Compression Mold machined samples
Specific Gravity @ 73°F	ASTM D 792	-	1.42	1.41	1.42
Ultimate Tensile Strength @ 73°F, MPa (psi)	ASTM D 638	230 (33,300)	270 (39,159)	131 (19,000)	110 (16,000)
Tensile Modulus @ 73°F, MPA (psi)	ASTM D 638	22,063 (3,200,000)	28,172 (4,086,000)	7,586 (1,100,000)	9,655 (1,400,000)
Elongation, at break @ 73°F, %	ASTM D 638	1.8	1.4	5.0	3.0
Flexural Strength @ 73°F, MPa (psi)	ASTM D 790	345 (50,100)	382 (55,339)	178 (25,750)	159 (23,000)
Flexural Modulus of Elasticity @ 73°F, MPa (psi)	ASTM D 790	19,995 (2,900,000)	24,736 (3,580,700)	8,621 (1,250,000)	6,897 (1,000,000)
Compressive Strength @ 73°F, MPa (psi)	ASTM D 695	240 (34,800)	-	200 (29,000)	193 (28,000)

Table 1. Mechanical property comparison of the same resins manufactured three different ways. [Victrex® 150CA30 data taken from Victrex® Material Properties Guide]

Dynamic Mechanical Analysis (DMA)

Visually, the true difference in mechanical properties becomes very apparent using a Dynamic Mechanical Analysis (DMA) comparison. Figure 4 is a DMA curve showing the relationship between a material's modulus (stiffness) and temperature with three polymer processing methods. The injection molded data is again significantly above the extrusion and compression molded graphs.

Designers specifying parts based on injection molded data (i.e. resin datasheets) may be surprised to learn that their actual machined components may test closer in line with the two lower graphs rather than the top graph.

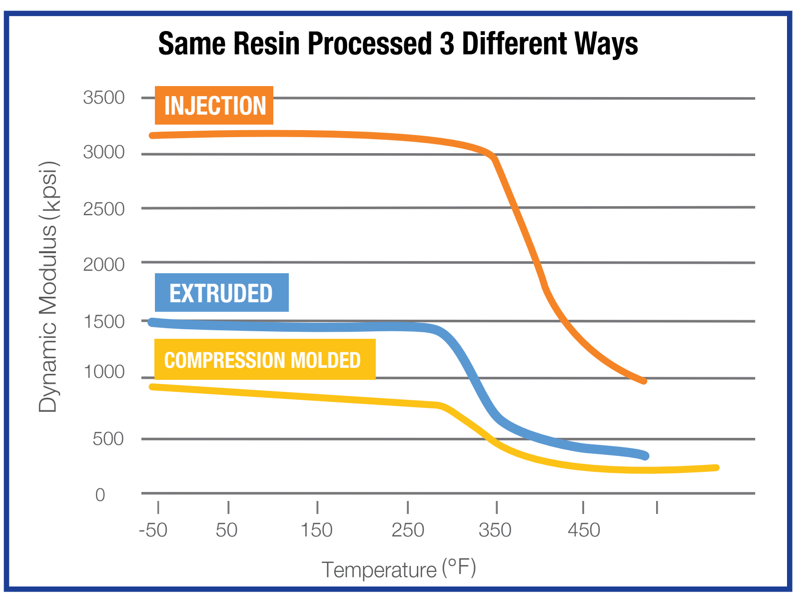


Figure 4. DMA (Dynamic Mechanical Analysis) Curve for CA30 PEEK processed using three different conversion methods.

Coefficient of Linear Thermal Expansion (CLTE) Data

The Coefficient of Linear Thermal Expansion (CLTE) is the amount at which a material will expand or contract relative to a change in temperature. The higher the CLTE value, the more movement with temperature change the designer should expect. A lower CLTE value represents a more stable product. It is often this value that is important to designers who wish to hold a tight tolerance on their components. Depending on processing methods, plastics may have different values of CLTE/stability in one direction versus another. This can also be affected by process.

The CLTE was analyzed in two directions (x and y axis) for all three processing methods. Figure 5 shows that the CLTE values for both extruded and compression molded polymers were close together, with only minor differences between them. However, the injection molded CLTE values differed highly between flow and transverse direction. This difference in the CLTE suggests that fibers are aligned differently due the way a material is processed.

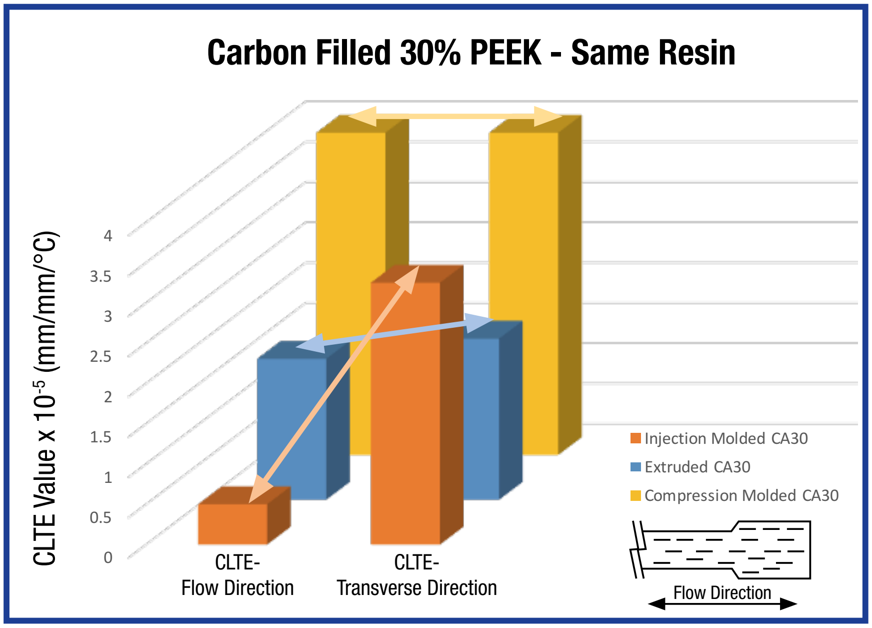


Figure 5. Coefficient of Linear Thermal Expansion (CLTE) properties in two directions for CA30 PEEK processed using three different conversion methods.

Data Comparison – Molded Samples versus Molded Tube

Figure 6 shows two injection molded 30% carbon-filled PEEK tensile bars and two injection molded stock shape tubes. All four pieces are injection molded, yet are their properties the same?

Testers anticipated that the long, thin molded test samples would yield higher mechanical properties compared to the test samples machined from the walls of the injection molded tubes. This hypothesis was tested on injection molded 30% glass-filled PEEK tubes, comparing them to injection molded test bars using the same resin. Test samples were machined from the walls of the injection molded GF30 PEEK tube. In Table 2, this data is shown in comparison to injection molded test bars. In theory, since the material flow is different into a tube compared to a long, thin molded test plaque, it stands to reason that the fiber alignment may be different and could impact the material's mechanical properties.

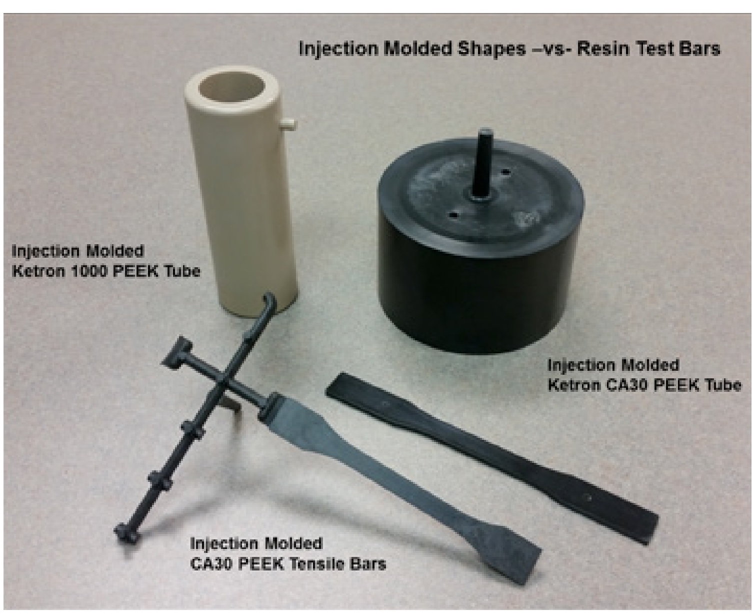


Figure 6. Injection molded polymer shapes and tensile bars.

The mechanical properties of the injection molded 30% glass-filled PEEK tube were significantly lower (50% in most cases) compared to the direct injection molded test samples. Such a difference in property data is significant and one could conclude that manufacturing process, along with shape configuration, can greatly impact the resulting mechanical properties.

Mechanical Property Comparison – Injection Molded Resin Plaques and Tubes			
Mechanical Property	Test Method	Injection Molded Test Plaques GF30 PEEK	Injection Molded Tubes Ketron® IM GF30 PEEK
		SAME BASE RESIN USED	
Samples Converted via →		Injection Molded Test Plaques direct formed samples	Injection Molded Tube machined samples
Specific Gravity @ 73°F	ASTM D 792	1.52	1.53
Ultimate Tensile Strength @ 73°F, MPa (psi)	ASTM D 638	184 (26,615)	66 (9,600)
Tensile Modulus @ 73°F, MPA (psi)	ASTM D 638	11,592 (1,681,243)	5,910 (857,000)
Elongation, at break @ 73°F, %	ASTM D 638	2.4	8.5
Flexural Strength @ 73°F, MPa (psi)	ASTM D 790	278 (40,274)	137 (19,800)
Flexural Modulus of Elasticity @ 73°F, MPa (psi)	ASTM D 790	11,742 (1,703,089)	6,345 (920,000)
Compressive Strength @ 73°F, MPa (psi)	ASTM D 695	-	145 (21,000)

Table 2. Mechanical property comparison of same resin injection molded into two configurations (test plaques and tube).

CONCLUSION:

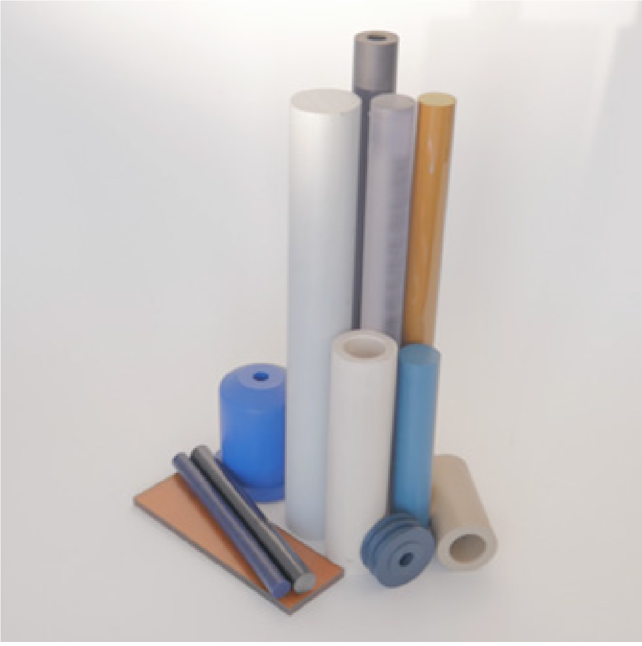
Know Your Data

Polymer processing methods can greatly influence the final mechanical property values of a plastic material. This is very true for fiber-filled materials like typical 30% glass and 30% carbon-filled materials. The higher the fiber level, the greater the influence processing may have.

Typical data from resin manufacturers is obtained by injection molded test samples. As shown, these values may be significantly higher than actual data for the same polymer processed using other conversion methods like extrusion and compression molding. While one process is not necessarily better than the others, they can yield different results. Designers should understand and account for this.

Importance of Proper Material Specification Writing

Considering the results of experiments outlined here, the importance of designing with the right data is clear. Part designers must know what process will be used to manufacture their plastic component. Will the part be injection molded? Will the part be machined from a stock shape? Obtaining the correct data during the design phase is imperative. It is critical for a material specifier to properly call out a material process when writing a material specification.



In some cases, resin properties are specified, yet the finished part is to be machined from a stock shape. If not clearly defined, this may leave stock shape suppliers confused and unable to certify their products. At best, a supplier can certify their material with deviations. Working through these deviations wastes precious time and money.

When writing a material specification, consideration into how the finished component will be sourced must be taken into account. Initial prototypes are almost always machined or even printed through additive manufacturing. Engineers tend to understand the limitations of 3D printing and that properties will not be the same as final injection molded components. But, what about prototypes machined from a stock shape?

The processing method for the desired plastic is often driven by the size or volume of parts required. Components are often injection molded when high volumes of finished parts are required. Machined parts from stock shapes are used for much smaller volume requirements, in cases where the cost of a mold is not practical. The decision between using extruded shapes and compression molded shapes is often based on the cross-section or size of the finished part. Clear definition of the origin of the mechanical properties on the material specification is critical to eliminate any certification confusion.

Final Thoughts

This paper has shown that there can be significant differences in plastic mechanical properties depending on the processing method used. Whether you are an engineer, designer, fixer, user, or buyer, understanding this fact is critical. A few simple rules to follow include:

1. Consider the data that you are using to design your component.
2. Consider the processing method for how your component will be manufactured.
3. Clearly call out the processing method and correct properties when making your material specification.

If you do not have the correct data, simply ask your material supplier. But be careful—some polymer converters simply pass on resin data. If you are using stock shapes or machined components, don't be afraid to ask your converter to supply actual data based on their processing method. The best suppliers will provide the data that you need.

Eliminating confusion saves everyone time and energy, and also helps to avoid critical component failures. Writing a proper polymer material specification is critical to ensure that you are getting a material that not only meets your material specification, but also meets the demands of your application.

Resource Center

- Access more tools, education and resources about Mitsubishi Chemical Advanced Materials Shape Data Approach.
- Watch a Video explaining Data Dumping.
- Try our Material Selector Tool that makes plastic selection simple.
- View material specific Data Sheets.

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References:
Test Method: ASTM D638-14 Standard Test Method for Tensile Properties of Plastics
Supplier Design Guide: Victrex® Material Properties Guide