



American
Gear Manufacturers
Association

AGMA 920-B15
(Revision of AGMA 920-A01)

AGMA Information Sheet

Materials for Plastic Gears

AGMA 920-B15

**American
Gear
Manufacturers
Association**

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ABSTRACT

The purpose of this document is to aid the gear designer in understanding the unique physical, mechanical and thermal behavior of plastic materials. The use of plastic materials for gear applications has grown considerably due to cost and performance issues. Growing markets include the automotive, business machine, and consumer-related industries. Topics covered include general plastic material behavior, gear operating conditions, plastic gear manufacturing, tests for gear related material properties, and typical plastic gear materials. There are no quantitative details on material properties or any comparative evaluations of plastic types. Such specific information is left to be provided by material suppliers and gear manufacturers.

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Foreword

[The foreword, footnotes and annexes, if any, in this document are provided for informational purposes only and are not to be construed as a part of AGMA 920-B15, *Materials for Plastic Gears*.]

Plastic materials differ considerably from metals in performance and processing. Many of the important differences, especially those that are critical to gear applications, are not widely recognized. This is partly because many plastic materials specialists are not familiar with gear requirements. Similarly, many gear specialists are not familiar with plastic material characteristics. Hence the need for reference material which will help bridge these gaps.

The AGMA Plastics Gearing Committee has brought together technical representatives from plastic material suppliers, gear manufacturers and designers. This document represents their efforts to further this exchange of information. It will not supply answers to many of the questions that arise in the application of plastic materials to gears, but it should encourage inquiry and information exchange.

One issue that requires special attention is the availability of plastic material properties in the form most suitable for plastic gear design. This includes properties that are counterparts of those used in the design of metal gears, and those that are special to plastic materials in these applications. To a very large extent, plastic gear designers have access only to property data taken from ASTM tests as reported by material suppliers even though such tests were created to meet other objectives. It was therefore judged essential to include brief descriptions of these tests supplemented by comments on any limitations of such test data when applied to gears. Various industry initiatives are now underway to develop gear specific property data, which will in time supplement the information provided here.

The first draft of AGMA 920-A01 was made in 1993. It was approved by the AGMA membership in October 2000 and approved for publication by the Technical Division Executive Committee on October 22, 2000.

This edition of the information sheet, AGMA 920-B15, was created to:

- revise definition of i found in Clause 5.1.3.3;
- renumber figures to meet current style guidelines;
- revise title of Figure 12, which previously appeared as Figure 11 in 920-A01.

The first draft of AGMA 920-B15 was made in January 2015. It was approved by the AGMA Plastics Gearing Committee in October 2015.

Suggestions for improvement of this standard will be welcome. They may be submitted to tech@agma.org.

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Materials for Plastic Gears

1 Scope

This information sheet provides descriptions of plastic materials commonly used in gearing. It relates the general properties of these materials to typical operating conditions of gears. Properties that relate to the manufacturing processes of machining and molding are discussed, including the property of shrink rate in molding. It also describes the types of tests that are customarily used to obtain published values of these properties.

It is intended that this information sheet serve only as an introductory guide to the designer of plastic gears when it comes to selecting candidate materials. The designer is advised to look to material suppliers and plastic gear manufacturers for their expert guidance on selecting materials for specific applications. It is also important to recognize that thorough application testing is often needed to confirm the suitability of a material choice.

Only a limited number of plastic materials are mentioned here as commonly used for gears. Gears have been made from other plastics as well, but generally because some special material property or commercial consideration was judged essential to a particular application. It is also possible that the suitability of other materials for gears has not yet been recognized. Furthermore, new plastic materials are continually being developed and some, no doubt, will prove themselves as important additions to those discussed in this information sheet.

2 General nature of plastic materials

Although plastic materials are successfully used in place of metals in load carrying applications such as gears, there are important differences between the two types of materials. These differences generally appear in combination and can have a significant effect on plastic gear performance.

2.1 Elastic and viscoelastic behavior

Most structural metals behave as essentially elastic materials. Plastics, on the other hand, behave as a combination of elastic and viscous materials, with the balance varying considerably with the type of plastic, its molecular structure, and the type, quantity, and orientation of any additives. This special nature of plastic materials does not interfere with their use in a very wide range of applications which benefit from their many other special properties. It does, however, require a thorough understanding of reported material properties data and their relationship to the specific application.

2.2 Response to load

When load is applied to elastic materials such as steel, the resulting deformation is essentially immediate, constant over time, independent of a wide range of temperature, and fully recoverable when the load is removed. When the material has a viscous component combined with the elastic, the initial deformation will increase with time under load (creep deformation) and will depend to a considerable degree on temperature. When the load is removed, there will be some delayed recovery and, possibly some permanent deformation.

The time dependent deformation of ductile polymers under constant load is quantified in creep testing. A family of curves resulting from varying the constant load (stress) and recording the increasing creep strain is shown in Figure 1. As the polymer is held under constant stress (load) over time, the creep strain initially increases at a rapid rate (primary creep) and then plateaus to a significantly lower creep strain rate (secondary creep). For nonductile polymers the material will experience creep rupture while deforming under secondary creep (see Figure 2). However, for ductile polymers, the material will

experience another increase in creep strain rate (tertiary creep) and will creep rupture in tertiary creep. For non-ductile polymers the locus of creep rupture points forms the creep rupture envelope. However, the creep rupture envelope for ductile polymers is the locus of points resulting from the transition from secondary to tertiary creep.

Creep deformation appears not to be a factor in gears under continuous operation because the load is applied to gear teeth only for a short time duration. However, for gears run into stalled conditions creep deformation and creep rupture of polymers needs to be considered.

2.3 Effect of rate of load application

Because of the time dependent nature of viscoelastic plastic materials, the strength properties and elasticity modulus are typically greater when the load is applied and removed more rapidly. See Figure 3. This characteristic is especially important in gear applications.

2.4 Effect of temperature

2.4.1 Strength and deformation

Because a higher temperature reduces the resistance to movement of the polymer chains, the material at high temperatures can be viewed as less viscous (decrease of the viscous component). This decrease in the viscous component of polymers at higher temperatures causes the strength and stiffness properties to decrease with increasing temperatures (see Figure 3). Temperature increases of the polymer at critical locations in gears could result from friction, hysteresis, or both in combination. This temperature rise of the gear material at critical locations could, therefore, reduce the load resisting capability of the gear. This condition is a significant factor to consider in gear performance.

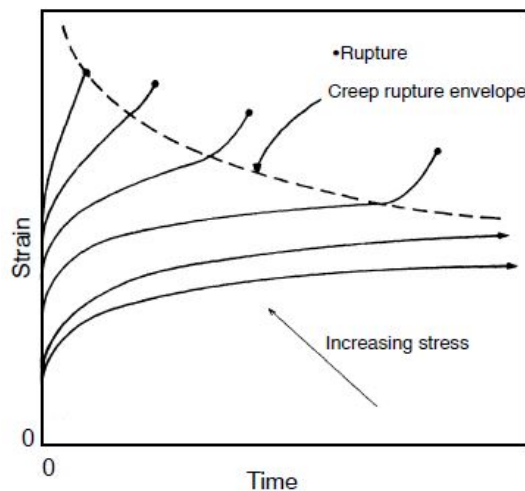


Figure 1 – Representative creep behavior of ductile plastic

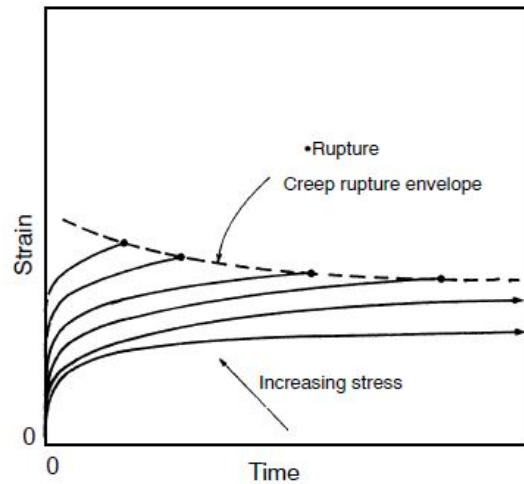


Figure 2 – Representative creep behavior of non-ductile plastic

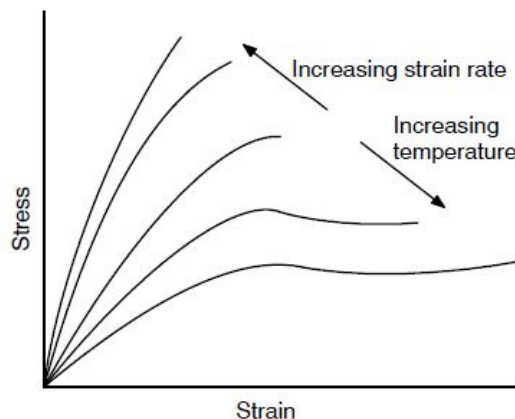


Figure 3 – Effect of strain rate and temperature on stress-strain curves

2.4.2 Expansion

Plastics have higher thermal expansion rates than metals. These high rates can be partially offset by compounding the plastics with various fillers and reinforcements. Thermal expansion should be considered in those applications in which the gears operate over broad ranges of temperature and the structure that controls gear center distance is made from a material of a significantly different expansion rate. See 3.1.3.1.

2.4.3 Heat aging

If a plastic material is subjected to an elevated temperature for an extended period of time, its properties at the end of the period may be degraded from those before the high temperature exposure.

2.5 Effect of moisture

A change in moisture content can act in a manner similar to a change in temperature in its effect on strength, deformation and expansion. Materials vary considerably in their moisture absorption, making this influence more significant in some materials than in others.

3 Gear operating conditions and related material properties

In order to evaluate a material for a specific gear application, the operating conditions should be recognized along with the related properties of the material. Some of these properties are much more significant in gears made from plastics than in gears made from metals, and require special attention.

3.1 General operating conditions

These conditions apply in nearly all gear applications.

3.1.1 Repeated load

Gear teeth experience repeated loading during successive engagements. Under continuous rotation, the load on an individual tooth is applied and released rapidly. There is also some delay between load cycles while the single tooth is rotating towards its next engagement.

The property of the material that resists fatigue failure breakage under this type of load is approximated by the flexural (bending) fatigue limit, see Figure 4. Standard tests that report this property, and the limitations of those tests, are described in 5.1.

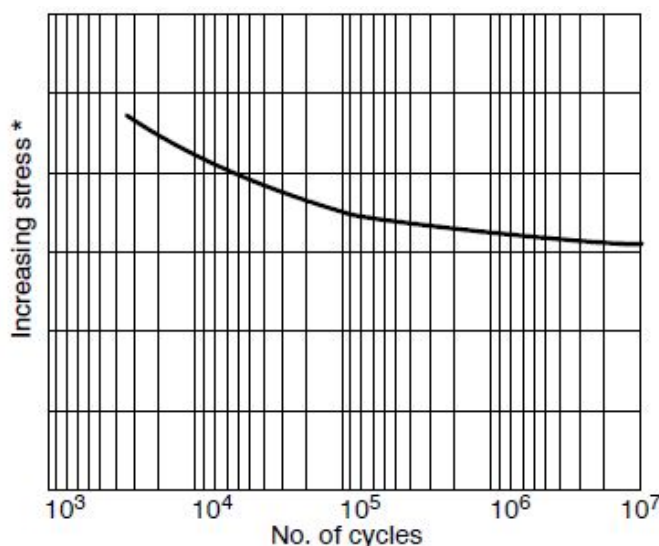


Figure 4 – Typical fatigue curve
(NOTE: Linear scale used for stress axis.)

3.1.2 Rolling and sliding under load

Load is transmitted between the curved surfaces of engaging teeth through contact over a relatively small area. This contact between the tooth surfaces takes place during a rolling action combined with sliding. In certain types of gear sets (spur, helical and bevel), the relative sliding during each tooth's engagement cycle varies in magnitude and typically reverses in direction. In other types (worm, crossed helical and hypoid), the relative sliding is more nearly constant. Since many plastic gear applications do not employ the type of lubrication that keeps the contacting tooth surfaces separated by a fluid film, the sliding action often results in significant friction. However, this friction between contacting plastic surfaces is often less than that experienced with many metals similarly employed under non-lubricated conditions.

3.1.2.1 Failure due to pitting

The repeated contact force on the gear tooth creates repeated shear stresses just below the tooth surface. Under certain conditions, these stresses can cause failure of the gear through the formation of local subsurface cracks which progress into pitting. Normally, when a plastic gear surface is subjected to high loads for a large number of cycles, failure takes place first in the form of excessive wear. See 3.1.2.3. However, if the gear is well lubricated and wear is minimal, failure by pitting may appear.

3.1.2.2 Friction forces and power loss

The friction from the relative motion between the contact surfaces has other effects on the operation of gears. The static coefficient of friction between the two contacting materials will influence the starting load in a gear train. The dynamic coefficient of friction will generally have several effects. It determines the power loss at that part of the gear train and the overall train efficiency. It can also influence the rise in temperature of the gear teeth and the corresponding loss in strength and stiffness properties. The rise in temperature may also lead to softening of the surface and change in friction properties. Standard tests for static and dynamic coefficients of friction are described in 5.2.

3.1.2.3 Wear

The interaction between the loaded surfaces will often lead to wear. If the wear progresses far enough to modify the gear profiles, it may produce excessive vibration and noise. Further wear may progress to the point that insufficient material remains to support the load. The wear characteristics of the material combination are often expressed by a rate of material removal. Common tests for this characteristic, and their limitations, are described in 5.2.

3.1.3 Dimensional changes under operating conditions

Plastic gears commonly operate under conditions that will cause significant dimensional changes in some plastic materials.

3.1.3.1 Thermal conditions

If a gear is operated at a temperature much different than the temperature at which its dimensions were originally specified and measured, its size will be different. Unless there is a compensating change in center distance, the size change will alter the operating backlash and root clearance. If the two mating gears change in a disproportionate manner, the two tooth profiles can become mismatched due to differences in base pitch and axial pitch, resulting in an increase in vibration, noise and dynamic loads. The material property which directly relates to the size change is the thermal coefficient of expansion. The standard tests for these properties are described in 5.3.

3.1.3.2 Humidity changes

Plastic materials change in size with the level of moisture they contain, giving results similar to thermal size changes. This moisture level is determined by the relative humidity to which the material has been exposed over an extended period of time and to the tendency of the material to absorb moisture. The plastic property used to indicate this tendency is the percent of water absorption in the type of test described in 5.4.1.

3.1.3.3 Chemical conditions

An incompatible chemical acting on a plastic material during product manufacture, storage or operation generally leads to an increase in size. An improperly selected lubricant might produce such a result.

3.1.4 Mechanical property changes under operating conditions

3.1.4.1 Thermal conditions

As noted in 2.4, strength and modulus properties decrease with increased temperature. Although these properties improve with a decreased temperature, these are typically accompanied by increased brittleness or a reduction in impact strength. See Figure 5. These effects can vary considerably with the plastic selected and its additives.

3.1.4.2 Humidity conditions

The property changes due to humidity are qualitatively similar to those of temperature. See Figure 6. Here also, the degree of change can vary considerably with material selection.

3.1.4.3 Chemical environment

Plastics, in contrast to most metals, are generally resistant to a broad variety of chemicals. However, individual plastics may be vulnerable to particular chemicals. The effect of chemical action is generally a reduction in fatigue and impact strength and change in other mechanical properties. See 3.2.6.2.

3.2 Special operating conditions

These conditions are encountered less commonly in gear applications, but, when they do, they direct attention to other properties of the plastic material.

3.2.1 Impact loading

In some gear applications, the gears may be subject to a suddenly applied load which requires the material to absorb considerable energy associated with the load. This energy tends to be absorbed around design features that, because of their slender shape and reduced size, are most compliant and develop the highest stresses. The contacting gear teeth are commonly most vulnerable. Such loads may appear with sudden starts of the gear train driver, a sudden change or reversal in the driven load, or with sudden braking. The energy to be absorbed is even greater if there has been travel across a substantial backlash gap before the load impacts the gear teeth.

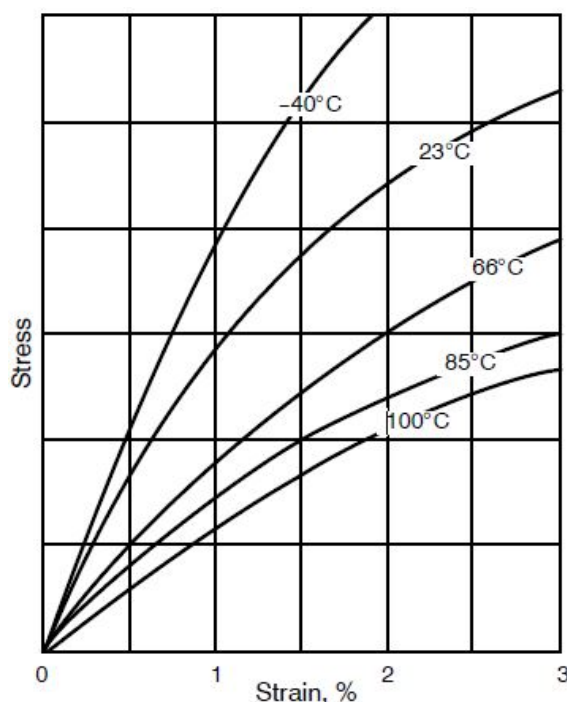


Figure 5 – Effect of temperature on stress vs. strain for acetal (POM)

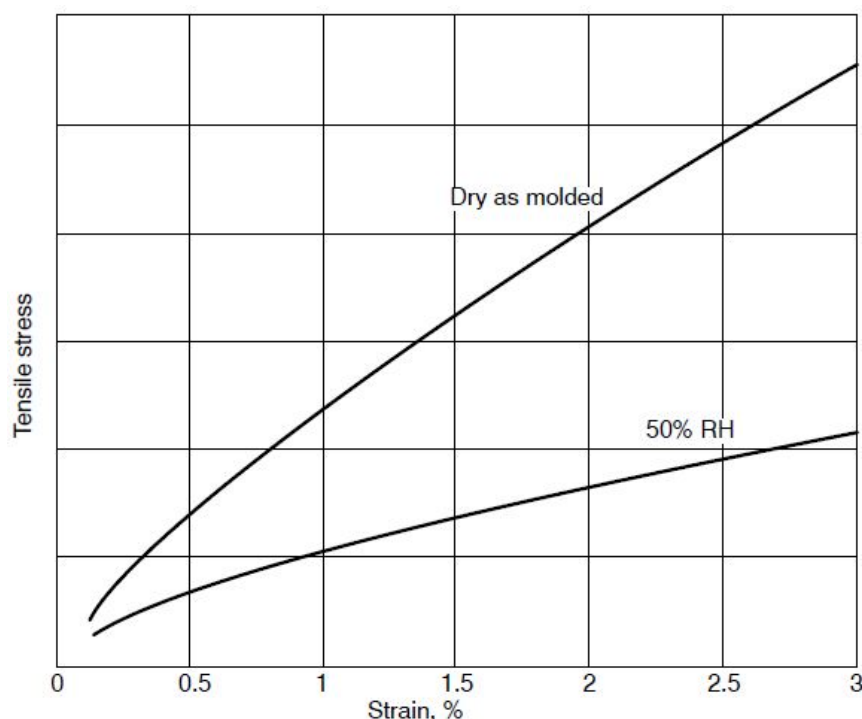


Figure 6 – Effect of moisture on stress vs. strain for nylon 6-6 (PA 6,6) at 23°C

Impact loading tends to be smaller in a gear drive made with plastic gears than in a drive of similar size made with metal gears. The difference can be attributed to the lower inertia and greater compliance of most plastics over most metals. Nevertheless, this type of loading can be severe enough to cause failure in plastic gears. There are significant differences in how otherwise suitable plastic materials respond. This response is indicated, at least to a comparative degree, by some standard tests described in 5.1.4 and 5.1.5.

3.2.2 Short-term overloads

In addition to the normal repeated loads encountered in gear applications, there are sometimes higher loads that appear occasionally for brief intervals, or with a much smaller frequency, on any individual tooth. Failure due to this type of load often takes the form of excessive deformation of the gear tooth or, in the case of brittle materials, fracture of the tooth.

The material property that needs to be considered in evaluating the risk of failure by excessive deformation is the stress-strain curve. The standard test, along with its limitations, that measures this set of properties is described in 5.1.

3.2.3 Long-term loads

Loads that remain applied to an individual tooth for an extended period of time, whether greater or smaller than the normal repeated load, can also cause failure by permanent deformation. See Figures 1 and 2. While this type of failure is not a factor in most structural metals except at very high temperatures, it can appear in many plastics at typical operating temperatures.

The deformation that continues to increase without an increase in load is called creep. The relative degree of creep in a plastic material is reported in a variety of data. Each shows how some characteristic changes over extended time. Plots of strain versus time, for various stress levels, most closely indicate the relative effect of creep in gears. Description and evaluation of the test to collect this data is given in 5.1.8.

3.2.4 High temperature

Gears are sometimes required to operate at temperatures well above 23°C, the temperature at which their properties are typically measured. The higher temperature is generally the ambient temperature of the application, but may, in whole or in part, result from heating due to friction, hysteresis or both.

3.2.4.1 Various strength properties

Just about all of the material properties noted above change with temperature. Often the best indicator of gear material performance at an elevated temperature is the stress-strain curves measured at or close to the operating temperature (see Figure 4). The tests used to report material properties at the standard temperature can also be applied at the higher temperature, as noted in Clause 5.

3.2.4.2 Deflection temperature under load (DTUL)

This property, previously known as heat distortion temperature (HDT), is a measure of the temperature at which the flexural modulus falls below a predetermined value associated with a particular stress. It serves mostly as a relative indicator of material serviceability as a gear operating at elevated temperatures. The test is described in 5.3.3.

3.2.4.3 UL temperature index

This is a commercially used indicator of the effect of heat aging described in 2.4.3. It suggests the highest temperature, above 50°C, at which the plastic material is to be used. The temperature index is the temperature at which the specific property will decrease to one-half its original value after exposure for a long time at that temperature. There are separate ratings for mechanical properties with impact and without impact. Index values can be found in the UL “Yellow Card.” The test is described in 5.3.4.

3.2.4.4 Coefficient of thermal conductivity

Where high temperature results substantially from heat generated by friction or hysteresis, the coefficient of thermal conductivity becomes an important property. A higher coefficient indicates that such heat will be more rapidly conducted away and the teeth will see less of a temperature increase. See 5.3.2.

3.2.4.5 Coefficient of thermal expansion

As described in 3.1.3.1, this property plays a role in the design of gears which are to operate over a wide range of temperatures. Very often, the design process can accommodate the expansion rate of a material selected on the basis of its other essential properties. In special applications, this property can become a controlling factor in material selection. Large differences in expansion coefficients between the housing and the gears can introduce excessive variations in backlash and in depth of engagement. Large differences between the two gears can cause excessive mismatch of gear pitch, enough to generate high dynamic loads, vibration and noise. See 5.3.1.

3.2.4.6 Electrical conductivity

Plastic materials are generally considered to be electrically insulating. However, when gears are required to conduct static electricity to some electrical ground, it becomes necessary to use a plastic which has been modified to supply the conductivity. The static electricity may be generated elsewhere in the product or in the gears themselves. The body of the gear, or some feature molded integrally with the gear, may sometimes be used to conduct system electrical current. This will also require conductivity in the plastic. It is not recommended that high system electrical current be transmitted through the contacting tooth surfaces because of the risk of damage to these surfaces and risk of being a source of ignition.

3.2.5 Low temperature

Operation at temperatures much below the usual material testing temperature also has an effect on gear material performance. As the temperature decreases, strength properties usually improve, especially those related to stress-strain testing and creep testing. This is true also for impact resistance as seen in Figure 7. However, as the temperature decreases, a region is encountered where impact resistance severely decreases, called the ductile-brittle transition temperature (DBTT). Therefore, when choosing a polymer for gears required to perform under sudden changes in load at low temperatures, the DBTT of each considered polymer should be evaluated and compared.

3.2.6 Other environmental conditions

There are environmental conditions other than temperature extremes which can also affect material performance.

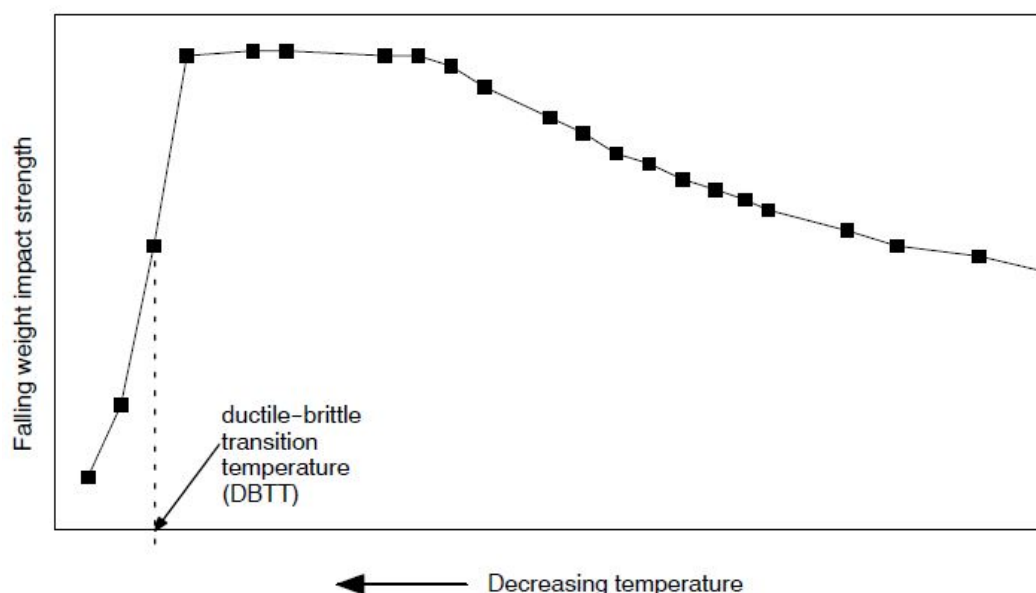


Figure 7 – Polymer impact strength as a function of temperature

3.2.6.1 High humidity

The water absorbed by extended exposure to a high humidity environment not only affects dimensions, as noted in 3.1.3.2, but also affects strength properties. Testing for these properties under high humidity is the same except that material test specimens are first conditioned to the desired moisture content.

3.2.6.2 Chemical conditions

Although most plastics are more resistant than most metals to many kinds of chemical environments, there are important exceptions in combinations of material and chemically active substances. Exposure of the gears to these chemicals may come from the outside environment, from process material in the gear driven equipment, and, in some cases, even from the lubricant applied to the gears. Description of tests for chemical resistance is beyond the scope of this document.

3.3 Vibration and noise

When the application is especially concerned with limiting vibration and noise, and design factors such as adequate backlash have been provided, material selection may be influenced by an additional set of properties.

3.3.1 Modulus of elasticity

One approach to reducing vibration and noise is to introduce greater compliance into the gears without introducing resonance or excessive loss of load capacity or wear properties. Gear teeth that deflect more readily can reduce the dynamic excitation that originates in imperfect tooth geometry. One of the properties that indicate the relative compliance of the material is the modulus of elasticity. This property is generally determined as part of yield strength testing, as described in 5.1.1, 5.1.2 and 5.1.3.

3.3.2 Hardness durometer

When selection of material for increased compliance leads to materials of a rubbery character, the hardness durometer becomes the preferred indicator. Testing for this property is described in 5.5.1 and 5.5.2.

3.3.3 Internal damping

Another approach to limiting vibration and noise in a gear train is to increase the degree of internal damping in the gear materials. This serves as a means of absorbing dynamic energy. See 5.1.3.

4 Gear manufacturing and related material properties

When materials are selected for a gear application, the concern for performance should be coordinated with manufacturing considerations. These manufacturing considerations may rule out materials not suited, economically or otherwise, to the planned manufacturing process. Certain manufacturing related characteristics or measurable properties of the material may determine its suitability.

CAUTION: Safety is an important consideration in the manufacture of gears from plastic materials. Information on safe handling and processing is available in the Material Safety Data Sheet provided by the material supplier. Also, see 4.1.2.6 and 4.2.4.3.

4.1 Manufacture by machining

Machining may be selected over molding as the plastic gear manufacturing process for several reasons:

- the quantities may be too small to justify the tooling cost for molding;
- the required accuracy or some special design feature (such as very thick section) may be too difficult for molding;
- the desired plastic material may not be suited to precision molding.

Machining may also be selected as a means for obtaining sample gears for testing before the design is approved for mold tooling. Such samples will be useful as long as consideration is given to the potential differences between a machined and molded gear.

4.1.1 Stock material

The machining of gears starts with the stock material and its fabricated form. Not every material, especially a material with desired additives, is commercially available in a form which suits the machining process or which results in a gear with the desired performance.

Sometimes a molded blank is used in place of stock material. Machining gear teeth into a molded blank will give satisfactory results only if the material and its processing have been carefully selected to avoid the difficulties described below.

4.1.1.1 Skin-core effects

Some of the properties of the material in stock form can vary considerably between the outer surface material, or skin, which has formed through more rapid cooling, than the inner material, or core. Machining invariably leaves the gear teeth made from the core material, which generally has different strength, wear resistance, and chemical resistance. In addition, machining may expose voids in the stock.

4.1.1.2 Reinforcements in extruded stock

Non-reinforced extruded stock is widely used for machining gears. However, reinforced stock is not as widely used for machined gears. If the application requires the greater strength that comes from the addition of reinforcements, such stock may not be suitable.

While it may be possible to extrude the plastic with reinforcements included, the resulting direction of the reinforcement fibers will generally be random and not in the radial direction required for the reinforcement to contribute to the bending strength of the gear tooth. Further disadvantages of machining most reinforced stock relate to the potential accelerated tool wear due to the abrasive qualities of some reinforcements and to the hazards associated with the fine reinforcement particles produced.

4.1.1.3 Reinforcement in laminated stock

Gears are also machined from blanks cut from laminated sheets or plates. The reinforcing layers in the laminated material are often in the form of a woven fabric. If the weave of this fabric is too coarse in comparison with the size of the machined gear tooth, the full beneficial effect on gear tooth strength will be lost. The fabric may serve the additional purpose of retaining lubricant used in the application.

If the fabric is made from an abrasive or hazardous material, the disadvantages noted in 4.1.1.2 will apply.