Plastics Topics – Optical clarity of plastics

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Plastics Topics – Optical clarity of plastics

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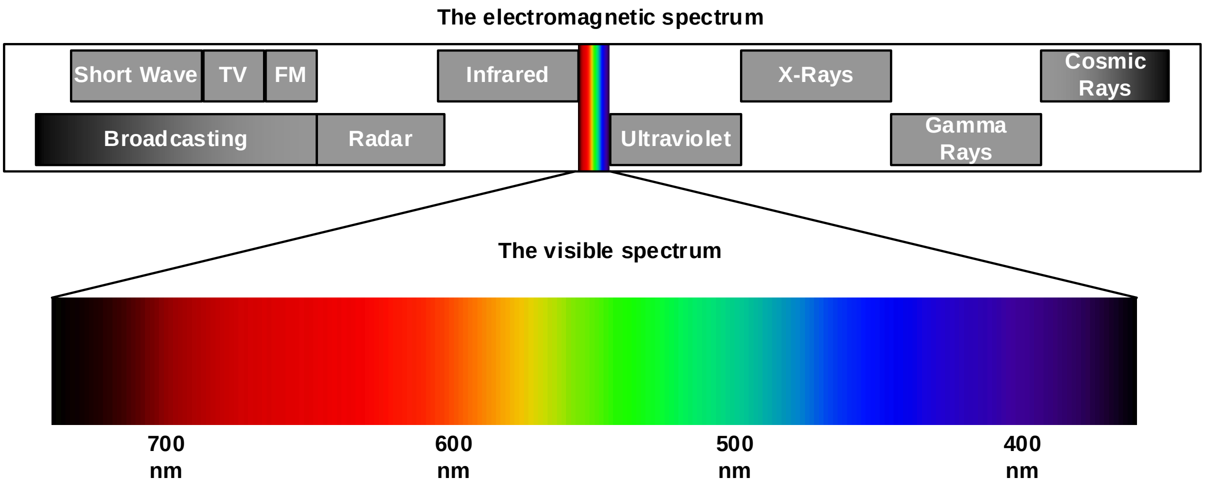
Plastics Topics – Optical clarity of plastics

1. Introduction

The dielectric properties of plastics can be directly related to the fundamental chemical structure of the basic polymer, i.e., if it was a polar or a non-polar molecule. It will therefore come as no surprise that if the dielectric properties are directly related to the structure, then the optical properties will also be directly related to the structure of the basic polymer.

In 1873, James Clerk Maxwell showed that visible light is an electromagnetic radiation and is simply one small part of the total electromagnetic spectrum (*Electricity and Magnetism: 1873*). The total electromagnetic spectrum and the visible spectrum are shown in the diagram below:



The electromagnetic and visible spectra. The wavelength of visible light ranges from approximately 400 nm to 700 nm (depending on the observer's eyes)

Dielectric properties and optical properties can be considered simply as responses by the polymer to different parts of the continuous electromagnetic spectrum. In fact, for non-polar plastics such as PTFE (and many other fluoropolymers), PE, PP and PS, where only electronic polarization is present, it is possible to calculate an optical property (n = the refractive index) directly from an electrical property (D = the dielectric constant) and for these plastics the relation is $D = n^2$.

As we have said before, understanding the structure of plastics allows an understanding of the properties because structure determines properties at all levels.

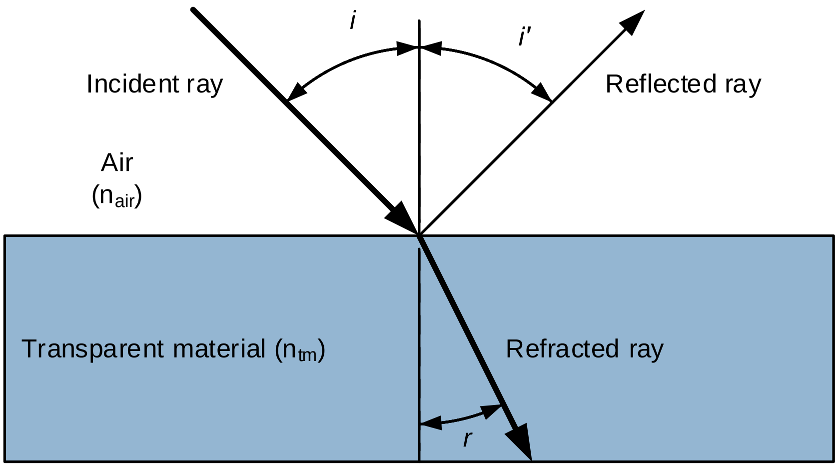
2. Optical definitions and basics

Refractive index

The refractive index is a measure of how much light is bent (or refracted) as it passes through a substance. It is defined by:

$n = \sin i / \sin r$, where *i* and *r* are the angles of incidence and refraction respectively.

The measurement of *i* and *r* are shown in the diagram below:

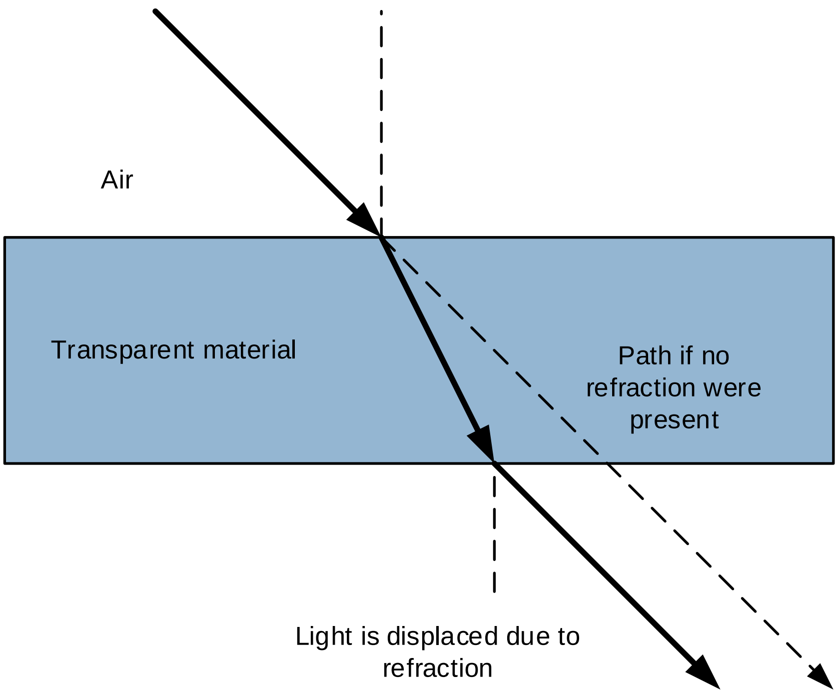


Measuring the angles of incidence and refraction

The refractive index is also the ratio of the speed of light in a vacuum to the speed in the transparent material.

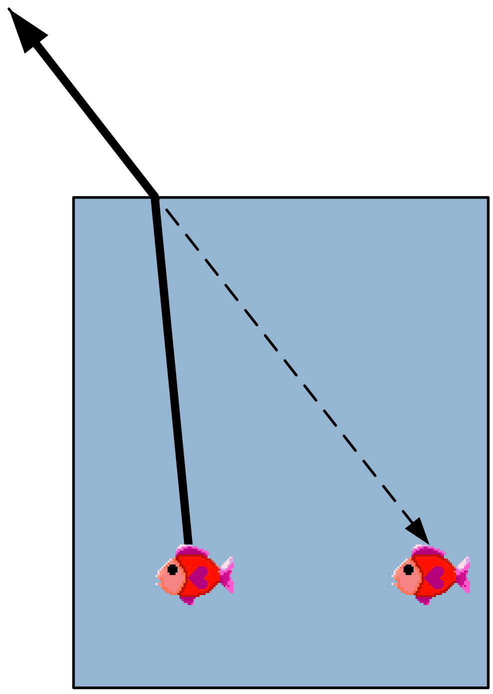
The refractive index will vary slightly with the wavelength of the light used to measure the refractive index and if 'white' light (a mixture of various wavelengths) is used as the incident beam then the variation in the refractive index for the various wavelengths will lead to splitting of light into the colours of the spectrum, a process known as dispersion. To allow comparison of refractive indices for materials, the light used is generally the sodium D line (a specific wavelength).

When light enters a dense material from a less dense material then the refracted ray is bent towards the normal and when entering a less dense material from a dense material the refracted ray is bent away from the normal. When light passes through a transparent material with parallel sides the refractions 'cancel out' and the path of the light is displaced due to the presence of the transparent material. The path of light through a transparent material is shown below:



The path of light through an optically clear material due to refraction

The refractive index is one reason why 'shooting fish is a barrel' is not as easy as it sounds. The path of light (and therefore the image of the fish) is shown by the solid line in the drawing – the light is refracted away from the normal as it enters the less dense air from the water. If we aim at the image of the fish and the bullet follows a straight line it will follow the dotted path and the fish will swim merrily on. The error effect gets worse as the fish is further below the surface, so if you must shoot at fish in a barrel then try to correct for refraction or aim for those closest to the surface!



'As easy as shooting fish in a barrel?'

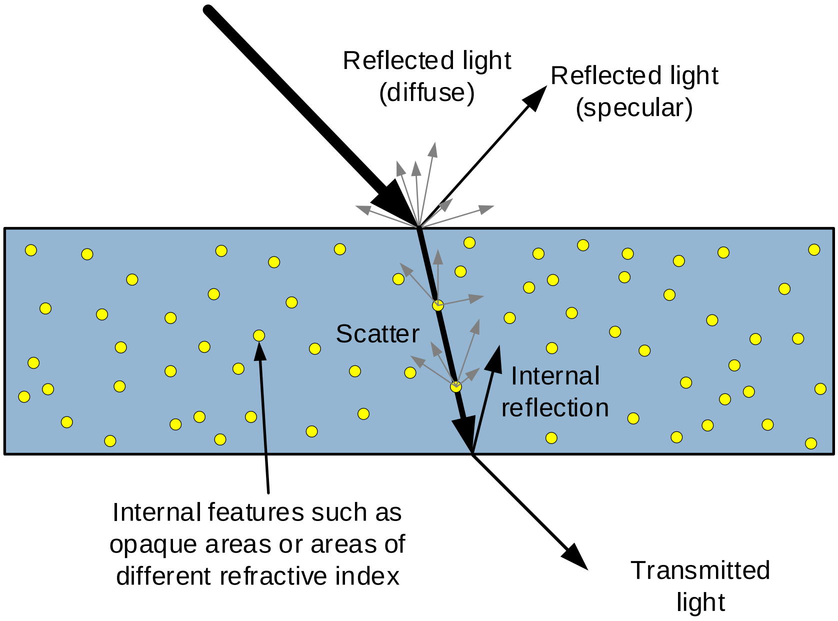
3. Optical clarity

The term 'optical clarity' is difficult to define and the boundaries between 'transparent' or 'clear' and 'translucent' or 'opaque' are often highly subjective. What is acceptable for one observer is possibly not acceptable for another observer. It is possible to measure the degree of light transmission using ASTM D-1003 (Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics) and this test method is used to evaluate light transmission and scattering of transparent plastics for a defined specimen thickness. As a general rule, light transmission percentages of over 85% measured using this test are considered to be 'transparent'. The perceived transparency or optical clarity is dependent on the thickness of the sample used for assessment and the optical clarity will decrease with increasing thickness. Standard glass can be relatively optically clear in thin sections but will show a green tint (due the iron in the glass) as the thickness increases.

Optical clarity can only be achieved when the refractive index is constant through the material in the viewing direction. Any areas of opaque material, such as colorants, or areas of different refractive index will result in a loss of optical clarity because the light passing through the material will be reflected and scattered by the opaque areas and the areas of different refractive index.

Optical clarity is also dependent on surface reflections from the sample. The surface reflections at the air/plastic interface create significant transmission losses, e.g., for PMMA around 93% of the transmission loss is from surface reflections and for PS around 88% of the transmission loss is from surface reflections. These surface reflections can come from two basic causes: specular reflection, which is the normal reflection from a smooth surface and diffuse reflection, which is dependent on the surface flatness of the sample. The transmission losses as a result of surface roughness or embedded particles are more often termed 'haze' and this is generally a production concern and not a material property. In producing blown film, haze can be caused either by melt fracture at the surface or by interfacial instability between the layers of the film.

This complex blend of surface reflections, internal scatter and refraction is shown in the diagram below:



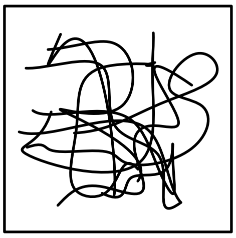
If a light ray is reflected, refracted or absorbed during transmission then the amount of transmitted light will decrease and optical clarity will also decrease.

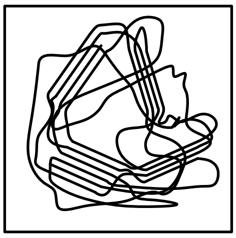
4. Optical clarity and polymer types

It is possible to classify most plastics as ‘semi-crystalline’ or ‘amorphous’.

- Amorphous plastics have a structure of long polymer chains that are randomly oriented. When the plastic is molten, the chains slide over one another like hot cooked spaghetti and if the plastic is cooled the chains freeze in the random orientation (similar to cold cooked spaghetti).
- Crystalline plastics are also randomly oriented in the molten state but when a crystalline plastic is cooled small ordered areas form to create polymer crystallites in a matrix of randomly oriented polymer chains - small areas where the polymer chains are aligned and folded in a regular manner to form spherulites that can have a diameter of up to 0.1 mm.

Amorphous plastics	Crystalline plastics
Random molecular orientation when either molten or solid.	Random molecular orientation when molten but form polymer crystals when solid.





Amorphous and crystalline plastics

Whichever type of plastic is used, the process of forming will result in flow and orientation of the long chain molecules along the direction of flow. This can result in moulded-in stresses and a condition known as birefringence where the plastic has two different refractive indices: one along the direction of flow and another across the direction of flow. Birefringence can be used to determine the degree of orientation and the flow direction to enable the flow process during mould filling to be visualized.

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Amorphous polymers

When no colorant has been used the amorphous plastics tend to be optically clear. Common amorphous plastics with high optical clarity are PMMA, PC, SAN, PS and ABS and the table below shows these ranked in terms of luminous transmittance and therefore optical clarity.

Polymer Family	Luminous transmittance of base polymer (%)
Optical glass	99.9
PMMA	92
PC	89
SAN	88
PS	88
ABS	79
PVC	76

Crystalline polymers

The optical behaviour of crystalline plastics is more complex because of the presence of the crystallites and their effect on the light.

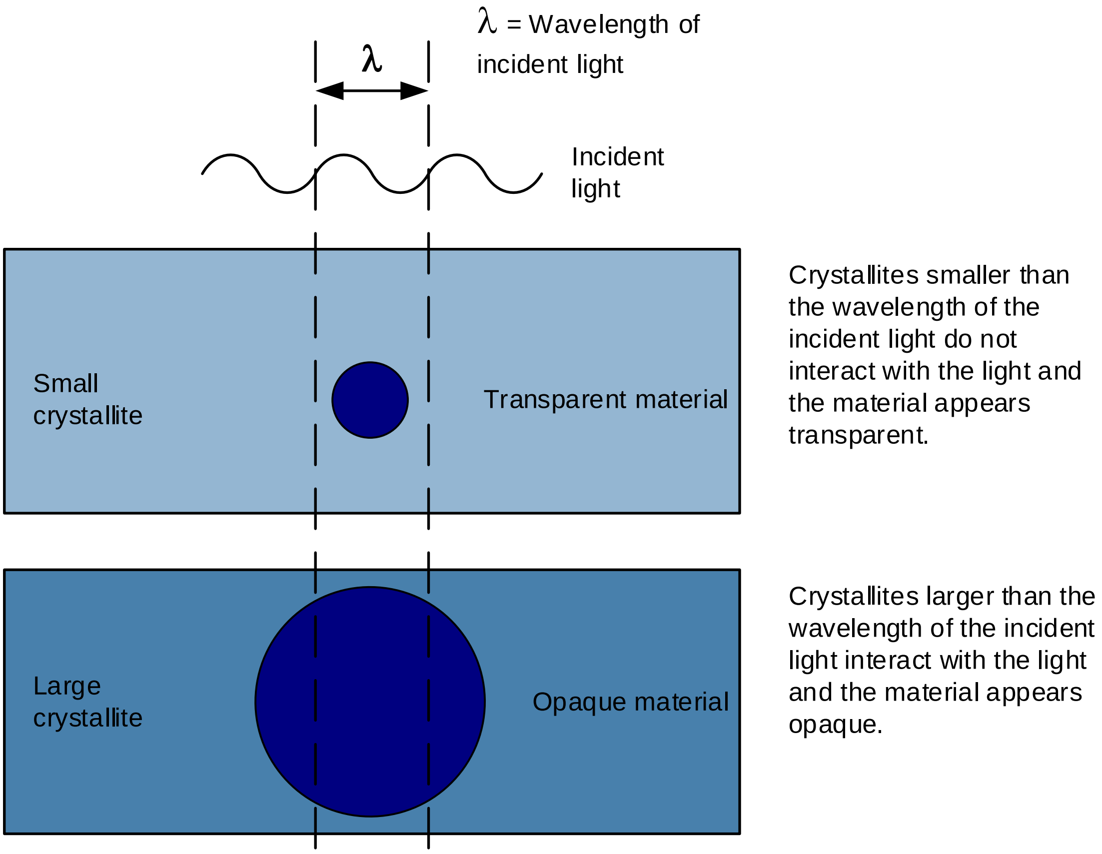
Crystal density

The density of the crystalline areas is a key factor in the optical clarity of crystalline plastics because the refractive index changes with the density of the material.

If the crystal density is the same or similar to that of the matrix then the material will generally be transparent because light transmission will be unaffected by the number or size of the crystal present. This is the case for PP and natural PP can be relatively transparent (but not as optically clear as amorphous plastics). If the crystal area density is much higher than the matrix density then the size of the crystals will be the determining factor for optical clarity.

Crystal size

Visible light has a wavelength of approximately 400-700 nm and if the crystal areas are smaller than this then they do not affect the passage of light and the material can appear clear. If the crystal areas are larger than 400-700 nm then the light will be scattered by refraction as it passes through the crystals and the material will be opaque. A spherulite with a diameter of 0.1 mm is 100,000 nm in diameter – a value significantly more than 700 nm and this will affect the passage of light. The crystal areas formed in PE are significantly denser than the matrix and in normal processing the crystal areas are larger than 700 nm and therefore standard PE is generally opaque at a reasonable thickness. It is, however, possible to rapidly quench PE (using chilled air in blown film production) to restrict the growth of the crystal areas to below 700 nm and the resulting PE film is significantly more transparent than film, which is not quenched.



If the crystals are large compared to the wavelength of the light, then the material will tend to be opaque if the density of the crystal areas is significantly different from the matrix density.

Typical crystalline plastics are PA (nylon), PP, PE, POM (acetal) and PEEK. In most cases, unless these plastics are specially treated, the optical clarity will in general be poor compared to the amorphous plastics and the materials will be typically translucent or opaque.

5. Summary

The above discussion for uncoloured polymers can be broadly summarized by the chart below:

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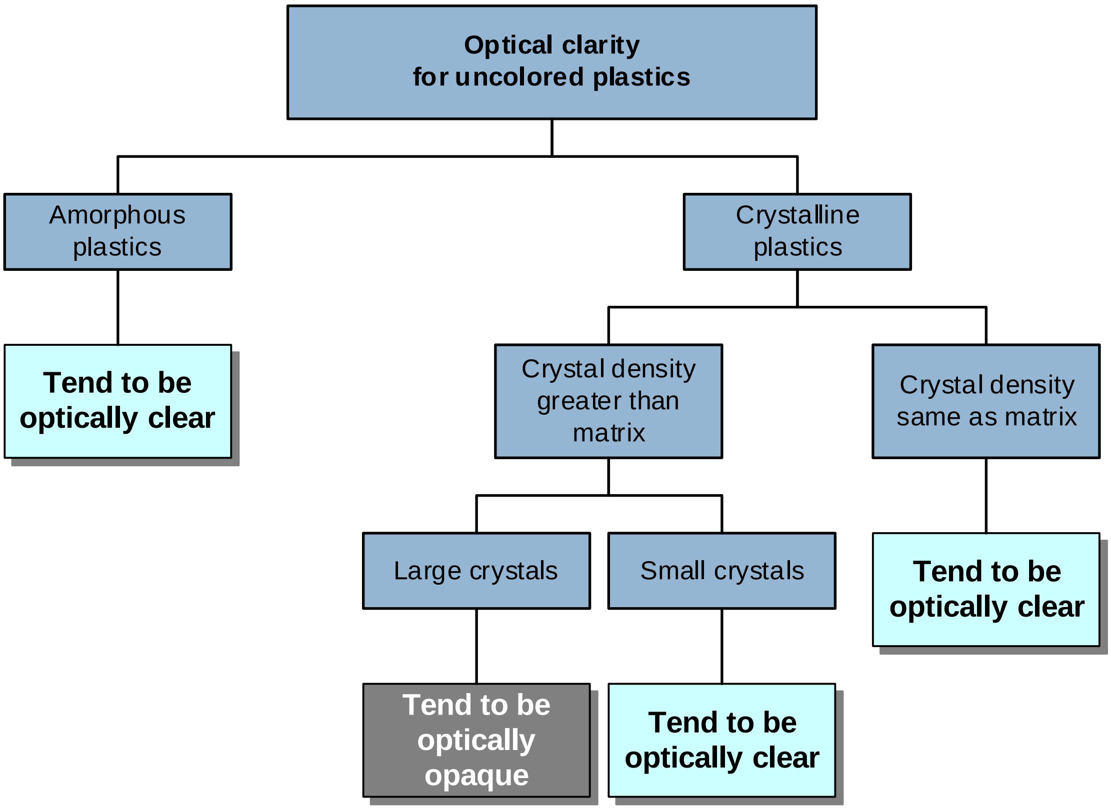

An approximate guide to optical clarity

Note: This chart refers to the optical clarity of base polymer only. The addition of fillers and other components (such as colours) to the plastic can change the response to visible light. The response to other wavelengths of the spectrum will also be different.