ophthalmic optics files

1. LENS MATERIALS
Ophthalmic lenses

Materials

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Making lenses for spectacle wearers requires a wide range of production facilities if they are to meet the two following requirements:

— correspond to the prescription;
— be adapted to the specific morphological and psychological characteristics of the person who will be wearing them.

The means used to meet these two requirements essentially are the following:

— the measuring instruments,
— the lenses,
— the frames.

An ophthalmic lens is made of a transparent material the size and shape of which have been calculated to produce certain pre-determined effects.

The transparent material used in lens production is either glass or plastic. Each of these two materials has, in addition to similar optical properties, specific physical properties which are dealt with in the first chapter of this brochure.
### General composition of the main types of optical glass

<table>
<thead>
<tr>
<th></th>
<th>CROWN</th>
<th>FLINT</th>
<th>BORO SILICATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica (SiO₂)</td>
<td>73.6%</td>
<td>16.6%</td>
<td>67.3%</td>
</tr>
<tr>
<td>Aluminium oxide (Al₂O₃)</td>
<td>1.0%</td>
<td>1.4%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Calcium oxide CaO</td>
<td>5.2%</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>— magnesium oxide (MgO)</td>
<td>3.6%</td>
<td>—</td>
<td>0.2%</td>
</tr>
<tr>
<td>— sodium oxide (Na₂O)</td>
<td>16.0%</td>
<td>4.0%</td>
<td>4.6%</td>
</tr>
<tr>
<td>— potassium oxide (K₂O)</td>
<td>0.6%</td>
<td>8.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>— lead oxide (PbO)</td>
<td>—</td>
<td>3.0%</td>
<td>—</td>
</tr>
<tr>
<td>— barium oxide (Ba₂O₃)</td>
<td>—</td>
<td>—</td>
<td>24.6%</td>
</tr>
</tbody>
</table>

Glass manufacturers can make a wide range of lenses from melted silica (pure silica, transparent to UV light) to glasses with no or a very low silica content, such as a glass with a high lead content (81%) through which X-rays cannot pass.

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1. Flow process

2. Liquid glass casting

3. Blank cooling

4. Blank casting

5. Blanks leaving the casting line
1. Glass lenses

Definition of glass

Glass is a very special material, neither a gas, nor a liquid, nor a true solid (the three states of matter). It is the result of the high temperature fusion of an inorganic compound which does not crystallize upon cooling and thus remains in an amorphous state.

Composition

The basic element of glass is silica (SiO₂) which accounts for 65% to 80% of the mix. (In France, the extremely pure white sand of Fontainebleau contains 99% silica).

In addition to silica, a wide range of other materials are used in glass production. The main ones used for manufacturing optical glass are;

- Soda (sodium carbonate or sulphate), potash, lime (calcium), lead (lead oxide or minium), boric acid (sodium borate) and, very recently, titanium (titanium oxide) and niobium.

Metallic salts are added to the mixture to produce the various types of tinted glass. These include nickel and cobalt (purple), cobalt and copper (blue), chromium (green), iron, carbon and cadmium (yellow), gold, copper and selenium (red).

Rare earth elements (neodymium, didymium, preseodymium) provide selective absorbing characteristics.

- Flow process

The very large number of lenses which need to be produced coupled with attempts to reduce production costs led glass makers to develop a continuous production process.

Today, the components of the pre-melt mixture enter at one end of a single machine while at the other end the glass casting comes out of the machine.

All the mixing, melting, stirring, cooling, casting and annealing operations are done in the various parts of a single immense machine.

The blanks produced have all the qualities required for subsequent transformation into optical lenses.

Special lenses and certain tinted lenses are still produced by the traditional method.

- Blanks

The castings produced at the end of the line are obtained by pressing a small quantity of glass, still in a viscous state, between two specially shaped dies in a cast iron mould.

These castings are slowly cooled and then annealed in order to eliminate casting stress.

When meant to be used in spectacles, these castings are called lens blanks. Their shape, diameter and thickness vary in order to meet production needs for optical lenses.

Glass lens manufacturing

- Cyclic process (traditional method)

Until recently, the manufacturing of optical glass was carried out by craftsmen making each batch separately.

The production and drying of hand made dyes or crucibles made of refractory earth was long and delicate. In these crucibles, the sand mixture was brought to melting point (1500°C).

Then by means of continuous, regular mechanical stirring throughout the entire melting procedure, the melted glass was degassed and bubble formation prevented.

The liquid was then allowed to cool down slowly until its viscosity was such that it could be cast into various objects or it could be used to produce slabs from which sections were cut and then moulded.

For several centuries it was believed that this method, and only this method, could produce a uniform, defect free glass. However, new techniques show that this is not the case.
Refraction index

- absolute
- relative to air

If \( v_1 \) and \( v_2 \) are the speeds of light in a vacuum and in a medium 1 respectively, the absolute refractive index (with respect to a vacuum) is defined as follows:

\[
N = \frac{S_1}{S_2}
\]

If medium 1 is air:

\[
\frac{1}{n_{air}} = \frac{S_{air}}{S_0}
\]

From this it follows that the refractive index relative to air is:

\[
\frac{n}{n_{air}} = \frac{S}{S_{air}}
\]

This is the index which is generally considered as all measurements are made in the atmosphere.

Monochromatic light refractive index for a given wavelength

White light is composed of an infinite number of monochromatic light waves (i.e., of single colored rays which cannot be broken down). Monochromatic light is characterized by its wavelength, \( \lambda \), measured in nanometers \( (1 \text{nm} = 10^{-9} \text{m}) \) or in microns \( (\mu = 10^{-6} \text{m}) \) or in angstroms \( (\AA = 10^{-10} \text{m}) \). Visible white light consists of radiation whose wavelength is between 0.39 \( \mu \) (violet) and 0.76 \( \mu \) (red).

To each wavelength corresponds a wave propagation speed \( S_1 \) and therefore a refractive index \( n_1 \).

Dispersion, dispersive power

The refractive index of a medium can be measured for any color of the spectrum. In order to achieve this, a source of monochromatic light must be used, usually the yellow light produced by sodium, the rays of a mercury vapor lamp, a hydrogen lamp but any other source producing this type of light is suitable.

The refractive index can be measured for any wavelength by means of a special refractometer. This is done, for example for the "F" (blue) and "C" (red) lines of hydrogen in the solar spectrum or for the "D" Fraunhofer line of sodium. These values are respectively designated by \( n_F, n_C, n_D \).

The dispersion between lines F and C is expressed as follows:

\[
\frac{1}{n_F} - \frac{1}{n_C} = \frac{\lambda}{c}
\]

The dispersive power \( (m) \) is defined as the difference of the "F" and "C" indices divided by the "D" index diminished by 1.

\[
\frac{1}{n_F} - \frac{1}{n_C} = \frac{1}{n_D} - 1
\]

For lens calculations, the reciprocal of this quantity, called the constringency, is used, in particular for calculations concerning chromatic aberration.

\[
1 = \frac{1}{n_F} - \frac{1}{n_C} = \frac{1}{n_D} - 1
\]

The relation between refractive index and constringency

A high refractive index is generally associated with a high dispersive power (low \( f' \)). This incompatibility is one which lens makers attempt to overcome.

For example, crown glass has, \( n = 1.48 \) to 1.54 and so \( f' \) varies from 60 to 62. For dense flint glass, \( n = 1.60 \) to 1.65, while \( f' \) varies from 40 to 36.

Recently, glass with titanium additives have been used (\( n = 1.706, f' = 30 \)) as well as glass with titanium and niobium additives (\( n = 1.706, f' = 40 \)). This latter type of glass has extremely good optical qualities.

* Niobium is a simple metallic element discovered in 1801 by Englishman Charles Hatchett who named it Columbium. It is extremely rare and has properties close to those of tantalum.

atomic weight: 92.51
specific gravity: 8.57
melting point: 2470°C
Optical properties

The composition of each type of glass determines two values which play the key role in defining the path taken by light passing through it. These are:
- the refractive index
- the dispersive power (or its reciprocal, contingency)

● The refractive index

(sometimes called simply the index)

This is a value (between 1.4 and 1.8 for the most common types of glass) which indicates by how much a ray of light passing from the air into the transparent material deviates from its original path.

● Dispersive power

The dispersive power is an important characteristic in ophthalmic optics as a high dispersive power creates colour fringes around objects when seen through greatly powered lenses (high myopia or hyperopia). This can be a source of complaint with people wearing these lenses.

● Homogeneity

Refractive indices, measured for a variety of wavelengths, are known with great precision.

For example, for a certain type of low density glass, when \( \lambda = 589.32 \text{ nm} \), \( n = 0.011391 \).

Consequently, the values of average dispersion and dispersive power are known with the same degree of accuracy \( (n F - n C) = 0.011391 \).

For these figures to have a significant meaning, it is essential to have an even glass quality.

This is obtained by the use of pre-melt mixture and by continuous and regular stirring of the melted glass at a temperature of approximately 1500°C.

● Transparency

Clear optical glass allows a very high percentage of visible light to go through it. A beam of light falling perpendicularly on an optical crown surface gives the following light transmission factors for a 1 cm thickness of glass (if we do not take into account reflections):

<table>
<thead>
<tr>
<th>(in nm)</th>
<th>396</th>
<th>415</th>
<th>425</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>98.6</td>
<td>98.5</td>
<td>99.3</td>
<td>99.3</td>
</tr>
</tbody>
</table>

It absorbs UV light with wavelengths under 300 nm and infrared light with wavelengths over 3500 nm.

Physical characteristics

● Density

Comfort is one of the essential qualities that wearers expect from their spectacles it is determined, to a large extent, by the weight of the lenses, especially when they are large and powerful.

The density of the lens material is therefore very important. It depends on the oxides used for its manufacture. A comparison of three types of glass shows that:

- ordinary crown: \( d = 2.53 \)
- flint glass: \( d = 2.9 \) to 6.3
- glass with titanium + niobium: \( d = 2.99 \)

● Hardness

Even though glass is fragile, it is extremely hard. Materials even harder that the glass itself must be used to scratch it. These include steel, titanium carbide, zirconium derivatives and, especially, diamond which is used for cutting glass.

After a long period of use or if basic precautions are not taken (spectacles in contact with hard objects), originally well-polished and completely clear spectacle lenses may lose their polish. This is the result of a large number of small, surface scratches which diffuse incoming light, and alter the glass transparency and image quality.

● Impact resistance

This is the term used to express the ability of a material to withstand the impact of a hard body under normal conditions; children's activities, sports, professional activities or driving, without breaking.

In order to measure the impact resistance of spectacle lenses, a measuring method has been laid down to define standards in a number of countries, such as Great Britain, Germany, the United States and France.

This method consists of dropping a steel ball fall on to the convex surface of the lens from a certain height in order to find out whether the lens will break...

Glass lenses of average thickness break under the impact of a 16 gram ball falling from a height of a few inches. These lenses have a poor impact resistance rating and are not completely safe to wear.
Stress comparison diagrams

Heat toughening

Chemical toughening

Compression areas
Expansion areas

Diagrams showing stresses along the central cross-section of a pane of glass supported at each end

Un-loaded

Lightly loaded

Heavily loaded

Untoughened

Toughened

Chemically toughened

These diagrams show that as the load on the glass increases, the compression forces increase on the upper side and decrease on the opposite side. As long as the opposite side remains "compressed", the glass will not break.
- Safety standards

Lenses breakages which cause injuries or the loss of vision are fortunately fairly rare. However, when this does occur, the consequences are so serious that, as a preventative action, lenses with improved impact resistance are often recommended and are sometimes compulsory as for example Industrial Safety Spectacles which are made to British Standards (BS 2092).

In certain countries such as the United States, all spectacle lenses must satisfy the Food and Drug Administration standards.

- Resistance to impacts of medium force for general purpose:
  the lens must be able to withstand the impact of a 16 gram ball dropped from 127 cm;

- Resistance to heavy impacts:
  the glass must withstand the impact from a 44 gram ball dropped from 130 cm;

- Similarly, British standards (BS 2092 section) provide for the impact resistance of lenses. Three resistances to impact are defined: general purpose, grade 1 and grade 2.

In France, these standards only apply to "safety lenses":

- 2 types of lenses comply with these standards.
- toughened glass lenses (cf. page 12)
- plastic lenses (cf. page 23).

- Glass fragility

The fragility of glass is caused by the following phenomenon. If a pane of glass is loaded at its centre while holding its ends fixed, it bends. Beyond a certain value, it breaks. If a weight is placed at the centre of a pane of glass supported at either end, the glass will bend.

The load (impact or vibration) creates compression forces on the side in contact with the load and extension forces on the opposite side.

Glass has a good compression resistance (100 kg per mm²), but breaks easily when subjected to expansion forces (4 kg per mm²).

For this reason, even under relatively low loads the side of the glass breaks when being subjected to expansion.

- Micro-cracks

The basic fragility of glass caused by its structure is made worse by the existence of micro-cracks on its surface, even when it has been highly polished. Tensile stress increases the size of these cracks and consequently weakens the surface to breaking point.

Wear further reduces its strength as accidental scratches of varying depths appear on the lens in addition to the original micro-cracks.

Wear, similarly tends to reduce glass impact resistance.

Blown up cross section: these cracks produce weak areas.

- Toughened lenses

Object of toughening

This is a process which consists in creating permanent compression areas on both sides of the glass pane in order to maintain a balance with corresponding extension areas inside the glass.
The weight is applied to a pane of glass as before. Its upper surface is subjected to increased compression while its lower surface, instead of being "stretched" from an uncompressed state, simply has its amount of induced compression diminished.

A relatively high weight is required to cancel the induced compression and cause the glass to break.

At the same time, this compression stress also tends to reduce the formation of micro-cracks on well polished surfaces. There are two methods of tempering glass:

— heat tempering,
— and chemical tempering.

Heat Tempering

The glass is heated in an oven to a temperature below the melting temperature but sufficiently high for the glass molecules to be in motion. This temperature is between 600° and 650° C.

As the glass is heated, it expands. Then when leaving the oven, it is rapidly cooled down by two streams of cold air directed to the centre of both surfaces.

The outside layers cool down immediately, contracting and hardening in their final shape, while the inner layers remain hot and in expansion. These inner layers cool down gradually but are prevented from contracting by the outer layers.

In this manner a state of equilibrium between the "compressed" outer layers (this being at a maximum on the two surfaces) and the expanded inner layers is created (the tensile forces are maximum at the centre of the glass).

The tempered glass then has the impact and load resistance properties described above.

Chemical tempering

The same results can be obtained chemically. The underlying principle of the method is as follows:

Sodium glass (Na) which is specially designed for this chemical tempering process is immersed for several hours (from 6 to 12 depending on the process used) in a bath containing potassium salts (K) at approximately 400° C.

The larger K+ ions replace the Na+ ions. They compress the several tenths of a millimeter deep portion of glass they penetrate. The degree of compression obtained in this way is very high, much more than the compression obtained by heat tempering. This results in a higher strengthening factor (between 4 and 7) compared to untempered glass, instead of a 2 to 3 factor for heat treated glass.

In addition, the high compression of the surface has the effect of improving the "filling-in" of the micro-cracks which further improves the results obtained by this process.

Advantages and disadvantages of tempered glass for ophthalmic lenses

If a lens of sufficient thickness can withstand the impact of a 16-gram ball dropped from 1.27 metres for general purposes and a 44-gram ball dropped from 1.30 metres for industrial purposes (thickness of approximately 2.5 to 3 mm), the tempered lens is said to be a safety lens (French standards).

However, it must be noted that any damage to the surfaces of tempered glass, including deep scratches, cutting, polishing or repolishing which reduces or removes the compressed layer, causes the glass to lose its robustness. In fact, the glass may even suddenly shatter for no apparent reason (Prince Rupert's drop). This means that spectacle lenses must be cut to their exact size before tempering. Once cut lenses are toughened they cannot be retouched.

Chemical pre-tempering

An entirely new process allows the manufacturer to pre-temper the glass prior to edging. The tempering process is completed after the lens has been edged.
Chemical properties

- **Resistance to chemicals**
  
  Under normal conditions, the glass used for manufacturing ophthalmic lenses is not affected by the various chemicals which it might occasionally come into contact for short periods of time.

  However, the glass can be attacked by a number of agents, in particular:
  - hydrofluoric and phosphoric acids and their derivatives,
  - alkaline bases, caustic soda sodium and potassium carbonate,
  - water, especially at high temperature, can eventually frost polished surfaces,
  - air, by the combined effect of humidity, carbonic gas and high temperature, can tamish surfaces.

2 - Classification according to absorption properties

- clear lenses,
- absorptive lenses, with a solid tint,
- absorptive lenses, with an even tint,
- specially coated lenses.

- **Clear glass**
  The perfect transparency which is required for clear glass is obtained by ensuring that there are no metal oxides present in the glass melt. Metal oxides such as iron oxides which are frequently found in sand would tint the glass.

- **Absorptive lenses with a solid tint**
  Conversely the type of metallic oxides added to the mixture, the amount of these additions and the melting conditions of the glass result in:
  - specific absorbent properties for each wavelength of the spectrum,
  - a selective degree of absorption which can be perfectly illustrated by a light transmission graph and corresponds to a specific tint.

Filtering oxides

Ultraviolet light is absorbed by titanium, cerium and ferric oxides.

Visible spectrum. Any coloured glass selectively absorbs, to a varying degree, certain wavelengths of the visible spectrum. The colour of the glass, be it blue, green, brown, yellow or grey, comes from the combination of the various wavelengths which are not absorbed. Various oxides of heavy metals are used singly or are combined to tint the glass.

Infra-red radiations are absorbed by ferrous oxide.

*Colour and filtering properties*

The colour of the glass gives an indication regarding its filtering properties. However, these do not necessarily correspond to the requirements of ophthalmic optics (see graphs), in particular:

- the absorption of UV and IR light which can be harmful to the eyes,
- well defined selective filtering of visible spectrum so as not to modify the perception of colours (neutral).

Studying the light transmission charts is essential to get to know the properties of tinted lenses.

Various types of glass used in ophthalmic optics

1 - Classification according to their refractive index

- **Standard crown**
  \[ \frac{n}{e} = 2.53 \]
  \[ \frac{2}{e} = 1.525 \]
  \[ \frac{y}{e} = 58.6 \]

  All standard lenses are made from this type of glass. This includes clear as well as tinted lenses.

- **High refractive index glass**
  This type of glass is used for manufacturing high power lenses for myopia, aphakia and extreme farsightedness. Everything else being equal, lenses made of high index glass are thinner and therefore more attractive than if they were made of standard crown glass.

  With more recent types of high index glass, lead has been replaced to good advantage by titanium. Glassmakers have been able to produce glass with a high refractive index but with a much lower density than glass containing lead.

  However, glass which only contains titanium, produces significant chromatic aberration (Abbe number: 30).

  FIT 40 glass, which also contains niobium, has the same refractive index and density as titanium glass, but has a much lower chromatic aberration factor.
Light transmission graphs

Thanks to laboratory tests using monochromatic light sources of given wavelengths, the amount of light transmitted by a 2 mm thick sample of glass can be measured.

The light transmission graph is obtained by plotting the wavelength (shown horizontally) against the percentage of light transmitted (shown vertically).

Graph 1 shows a sample of green glass whose light absorbing properties are not particularly good.

Graph 2, on the other hand, shows a glass sample which has very satisfactory UV and IR absorption properties and shows relatively good neutrality in the visible spectrum, with a relative absorption maximum in the red band and a relative minimum in the yellow band.
A filtering glass with a tint can be slightly tinted, relatively dark or very dark, for example, light brown (A, AB) or dark brown lenses (B, C).

**Tints and graduations**

- **Corrective lenses**
  
  The tints which are the most frequently used are:
  - Pink
  - Pink and blue
  - Brown
  - Green
  - Grey

- **Sunglasses**

  The above range is completed by a series of tints, often based more on fashion than on absorption properties, such as:
  - Yellow
  - Blue
  - Purple

- **Protective lenses**

  This is a special category of lenses used by people carrying out specific tasks like welders, doctors exposed to X-rays, radium or intense infra-red radiation, etc.

  These lenses will be described later in a special chapter.

**Gradation and standards**

In order to precisely define the properties of a glass, standards have been adopted by AFNOR.

<table>
<thead>
<tr>
<th></th>
<th>% absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>very light tint</td>
</tr>
<tr>
<td>AB</td>
<td>moderate tint</td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>dark tint</td>
</tr>
<tr>
<td>D</td>
<td>very dark</td>
</tr>
</tbody>
</table>

These values have been measured using a 2 mm thick glass lens which has not been anti reflection coated.

Multi-layer coatings reduce absorption by approximately 7% (see paragraph on “anti-reflection coatings”).

**Classification of absorptive lenses**

Light solid tints are usually only available in pink and brown.
Composition and properties of photochromic glass
(Corning type)

This type of glass belongs to the aluminium borosilicate group to which has been added photochromic elements such as silver halides. These crystals, whose dimensions must necessarily fall between 50 and 300 A, darken when activated by UV light (as found in the sunlight spectrum) but become clear again when they stop being exposed to sunlight.

These graphs show the darkening and lightening times for photochromic crystals, like Photogray and Isomatic Rapid and indicate the results obtained after 1 minute at 25°C.

Darkening: 13 to 69% compared to 19 to 40%
Lightening: from 78 to 50% compared to 57 to 53%
**Photochromic glass**

This type of glass has a variable degree of absorption depending on the amount of the sunlight passing through it. This property is indefinitely reversible.

Under low illumination, its tint is equivalent to the grade A of the AFNOR range. After several minutes in full sunlight, it darkens to a B tint or somewhere between B and C.

When no longer activated by sunlight, the glass returns to a grade A tint.

Until recently, for a given illumination, the glass became darker as the temperature dropped. There are now new types of photochromic glass which are almost unaffected by temperature changes. Their absorption is practically the same between 0 and 25°C.

The photochromic material is usually grey or brown.

A part from high index lenses, all lens types, including fused biconvex lenses, can be made of photochromic glass.

- **Uniform tinting**

Lenses for short or far sightedness have a different thickness at the centre and at edge. Consequently, if the glass itself is tinted, the tint is not constant. This method of tinting is no longer used except for "A" tint. The darker tints (AB, B, etc.) are produced so as to obtain a uniform tint over the entire surface of the lens.

**Thin layer method**

The first solution to this problem consisted of gluing (with Canada balsam), fusing (at high temperature), or polymerising (with polymerising glues) a thin layer (1.0 to 1.5 mm) of tinted glass (type C or D) onto the clear glass blank.

**The 3 disadvantages of this method are:**

- heavier lenses;
- lenses costly to manufacture because the surfaces of the tinted layer and the clear carrier must be carefully polished and must have precisely the same shape;
- risk that the top layer might come off.

This process has now been abandoned.

**"clip-on" lenses**

This is an old technique, but still often used, in which a "clip-on" front of 2 tinted lenses connected by a flexible bridge is attached to the wearer's spectacles by means of small clips.

The shape of these lenses follows as closely as possible the spectacle rims as closely as possible.

They may be put on or taken off at any time.

**Disadvantages**

The practical advantages are seriously reduced by the poor appearance and additional weight of the clip-ons.
Vacuum tinting

Principle of a vacuum coating unit

1. The lenses are placed on a rotary tray.

2. Magnesium fluoride ($\text{MgF}_2$) placed in a crucible is heated and vaporized.

3. The mirror $M_1$ allow the observer $O$ to check the correct tinting of the lens surface and to stop the oxide emission by bringing the cover $d$ over the crucible.

4. The mirror $M_2$ is used to observe the crucible when heated.

When a single, uniform layer approximately $1 \mu$ thick has been obtained, reflected light produces very unsightly metallic reflections. Successive additional layers allow the refractive index to be increased from $1.5$ to $2.4$ and then to be brought down to $1.5$. This method eliminates unwanted reflection and provides a uniform tint.
- Coated lenses

**Tinting by vacuum coating**

A modern solution consists in applying, under vacuum conditions, a very thin layer, a few microns thick, of a metal oxide which has been selected for:
- its compatibility with glass to ensure good adhesion.
- its absorbing properties.
- the tint obtained.

**Single Layer Coating**

With the most simple techniques, the coating is uniform but the lens has unsightly metallic reflections.

**Multi Layer Coating**

More sophisticated techniques are used to apply several layers. By carefully programming the evaporation of the silica/oxide most inside the vacuum unit, the index of the layers vary from 1.5 to 2.4 then returns to 1.5. The result is a soft uniform tint.

**Qualities of a good coating**

It is very difficult to manufacture good quality coated lenses. Their characteristics are as follows:
- good adhesion of the layer.
- good scratch resistance, at least equal to the substrate.
- non selective absorbtion.
- free from metallic reflection.
- does not show finger prints, which happens when coating is carried out with inadequate methods or equipment.

**Which Lenses can be vacuum tinted?**

All ophthalmic lenses without exception, including multifocal lenses, provided they are made of white glass, can be tinted by vacuum coating.

In addition, when a multi-layer coating is used, the light transmission of these lenses is improved on average by 7%.

**Reflections and unwanted images**

These reflection fall into 2 categories:
- Those resulting from multiple reflections come from a variety of luminous areas. The visual field is then encumbered by ghost images, which although less luminous than the object itself, are highly mobile and bothersome.
- The front side of lenses act as convex mirrors which reflect some of the light.

---

**Ghost images of a luminous point 0**

after reflection on the internal and external surfaces of the lens.
Cause of reflections and ghost images

When a beam of light falls on a glass surface, it is broken up in the following manner:

- the largest part of the light is transmitted, I,
- a very small percentage is absorbed by the glass, I,
- finally some of it is reflected, R. This gives I = I + I + R.

This occurs whenever light falls on a surface of glass in air as shown on the diagram.

Reflection factor

This factor gives the percentage of the incident light which is reflected.

\[ r = \frac{|r|}{I} \]

The reflection factor depends on the angle of incidence of the incoming light beam. For a light beam which is approximately perpendicular to the glass surface, this value depends only on the refractive index of the glass.

\[ r = \frac{(n - 1)^2}{(n + 1)^2} \]

for flint glass \((n = 1.731)\)

\[ r = 0.0713 \text{ or } 7\% \text{ of } I \]

The higher the refractive index, the greater the amount of reflected light ("a diamond sparkles like a thousand stars", \(n = 2.4\)).

Multiple reflections

If the value of the light of the incoming beam is represented by a value of 100, the beam \(R_1\) is 4, beam \(T_1\) is 96 (the amount of light absorbed by the glass, except for very thin glass is negligible). At \(B\), the reflected beam is only 96 \(0.04 = 3.98\), etc.

Reflected images

Each time reflected light reaches the eye and coincides with the direction of this visual axis, the wearer can see the image "P" of the object where the light originated.

Anti-reflection coating

The principle of this process is to produce an interference between the two reflected light beams.

With monochromatic light, the reflected beams will cancel each other out if the thickness of the layer, its refractive index \(n\) and the wavelength of the incoming light are related in the following way:

\[ t = \frac{\lambda}{4n} \quad (t = 0.102 \mu \text{ if } \lambda = 0.56 \mu) \]

Magnesium fluoride with a refractive index of 1.38 which has the appropriate physical and chemical properties required to eliminate reflections, is used for anti-reflection coatings.

With daylight, there cannot be complete cancellation of the reflected light. However, the effect is maximum for yellow monochromatic light \((P, e = 0.56 \mu)\) to which the eye is most sensitive.

Images produced by reflection

Multiple reflections

Reflection factor
These reflections do not impede vision but tend to hide the wearer's eyes behind his spectacles which can sometimes be annoying to observers.

The spectacle industry has produced anti-reflection coated lenses based on the "Lens Blueing" techniques used for scientific instruments with a view to reducing loss of light through unwanted surface reflections.

Which lenses can be anti-reflection coated?

All ophthalmic lenses can be coated.

However, fused bifocal lenses for hyperopes with an upper part used for "long distance" vision made of crown glass and a segment used for "close vision" made of flint shows a slight difference. These variations however, do not affect the properties of the lenses and are difficult to detect.

The principle of anti-reflection coatings

One or both sides of the lens are coated with a thin layer with a refractive index and a thickness which ensures that the reflected light rays interfere and cancel each other out.

A. 1μ layer of magnesium fluoride which has a 1.38 refractive index meets these conditions well enough to practically eliminate all the reflected light.

With multi-layer techniques, the cancellation of reflected light rays can be achieved to such an extent that the spectacles do not seem to have lenses in them.

The qualities of a good coating

As with vacuum tinted lenses, anti-reflection coated lenses require sophisticated technology and equipment.

The qualities required are as follows:

- A significant decrease of the reflection on the lens surfaces combined with a reduction of the brilliance of ghost images;
- A very good adherence of the anti-reflection layers;
- An abrasion resistance of the layer at least equal to that of the substrate;
- A discrete tint without metallic brilliance combined with the surface of a high quality ophthalmic lens.

Lens surfacing

This operation consists in transforming the original blank into a finished ophthalmic lens with the required optical characteristics.

There are 3 distinct stages, each requiring the appropriate machines, tools and procedures.

- Generating

The blank used for generating has the same diameter, curves similar to the finished lenses. The lens is ground to its final thickness and curves with a diamond tool.
- **Smoothing**

  - Smoothing consists in removing the grinding marks without changing its radius of curvature. Prior to the final polish this result is obtained by the combined action of abrasive powders of finer and finer grades and a tool made of soft cast-iron having the radius of the lens. The emery particles are suspended in water which is sprayed onto the lens during smoothing.

  When this operation is completed, the lens has the exact required curvature, thickness and diameter. However, the surface has a frosted appearance and must be polished.

- **Polishing**

  This operation is identical to the previous one. The tool is covered with a felt pad or a special plastic film. The emery is replaced by an even finer abrasive, for example, cerium or titanium oxide mixed with water.

  During polishing, nothing is removed from the lens. Glass creep occurs, progressively pushing the “bumps” of the surface into the “depressions”. In this manner, the surface of the lens is made perfectly smooth.

- **Type of surfaces produced in ophthalmic optics**

  These can be spherical, cylindrical, toric, aspherical, with variable powers, convex or concave and more rarely flat.

- **Mass or individual production**

  Surfacing in large batches is only used for prescriptions which are very frequently used, whenever stocking and distribution costs justify these large batches.

  Mass production is also applied to the manufacturing of semi-finished lenses which will subsequently be finished on an individual basis.

  Individual lens surfacing is used for prescriptions which are less frequently ordered or when the lens types are not suited to mass production techniques (bifocal, multifocal, toric, aspheric lenses, special lenses, etc.).

**Ophthalmic glass Conclusion**

Glass lenses are available in a variety of types which can receive various coatings. Its properties made glass, for a great many years, the only basic material from which ophthalmic lenses could be made.

However, changes brought about by modern life have meant that two of the problems associated with glass have become more and more critical. These are:

- Its weight, much increased by the size of current lenses, runs counter to the ever increasing desire for comfort;
- Its fragility has been given greater consideration with the increased risk of breaking the lenses.

In order to meet these new requirements, another optical material had to be used. This explains the advent and exceedingly rapid development of plastic lenses throughout the world.
2. Plastic lenses

Bakelite, celluloid, polymerisable resins, acroleins, styrolene and others had already been used in scientific optics when an ester of methacrylic acid was selected by the optical industry for making ophthalmic lenses.

Methyl-methacrylate

Better known by its trademark Plexiglas or Perspex, this material was a major development during the period extending between 1937 and 1938.

Originally used to make strong lenses for the correction of short sightedness and aphakia, the use of this material rapidly spread to all types of correction.

• Properties

This plastic material is very light with a density of 1.18 at 20°C and has a refractive index which is approximately the same as that of normal glass, n = 1.498. In addition, it has a good impact resistance.

• Manufacturing process

Methyl-methacrylate is a thermoplastic resin whose melting temperature is between 75°C and 80°C. The manufacturing process used in the optical industry is based on this characteristic.

Round blanks of the desired diameters (50 and 55 mm in diameter at that time) were cut out of a plate of the appropriate thickness. These blanks were then shaped on precision lathes. This technique provided the pre-cast blanks for each broad category of ophthalmic lenses.

• These lathe generated blanks were then given their shape by hot pressing them between the 2 dies of a press.

Finally, the finished lenses were left to cool down.

The surface quality of the lenses depended on surface finish of the steel dies used.

• Advantages and disadvantages of methacrylate

This brief description of the manufacturing process indicates the problems encountered with methyl-methacrylate, namely:

— The precision and quality of the lens surfaces depended on the mechanical means used and could not match the quality obtained with other techniques used in optics.

— Relying on the thermoplasticity of the material to obtain the lens curves could not guarantee the stability of the lens produced.

— Finally and even more important, spectacle lenses made from this plastic material became scratched very rapidly and consequently had to be replaced frequently.

In spite of its shortcomings, this material confirmed the great advantages of using plastic material in ophthalmic optics and paved the way for the introduction of the diallyl glycol carbonate or CR39. This basic material, the most popular today, is used for manufacturing Orma CR39 lenses.
Diallyl glycol carbonate or CR39

Plastics fall into two main categories: they are either thermoplastic or thermosetting.

- The thermoplastics have their molecules arranged in long linear chains (two dimensions) and when heated, soften and can be compressed.

- The thermosetting plastics have molecules which arrange themselves in a three dimensional structure during polymerisation. The polymer obtained neither softens nor bends when heated.

\[
\begin{align*}
\text{CH}_2 \cdot \text{CH}_2 \cdot \text{O} \cdot \text{CO} \cdot \text{O} \cdot \text{CH}_2 \cdot \text{CH} & = \text{CH}_2 \\
\text{CH}_2 \cdot \text{CH}_2 \cdot \text{O} \cdot \text{CO} \cdot \text{O} \cdot \text{CH}_2 \cdot \text{CH} & = \text{CH}_2
\end{align*}
\]

Synthesis of the monomer

This is done in 2 stages:

- Preparation of an ester of phosgene and diethylene glycol chlorofomate;
- Reaction of diethylene glycol chlorofomate with allylic alcohol.
Diallyl glycol carbonate

Also referred to as CR39, this plastic was discovered at the beginning of the 1940's by chemists at the Columbia Corporation in Pittsburg (USA) and was originally intended for scientific use.

CR39 is a petroleum derivative of the polyester group, a new family of polymerisable thermosetting resins.

The manufacturing process of CR39 lenses is based on the dual property of CR39 which gives lenses specific qualities.

The synthesis of the product is done in several stages. First of all a monomer is obtained: a limpid liquid with the viscosity of glycerine oil is obtained.

The monomer remains in a liquid state as long as it is kept in cold storage (it hardens after several months at room temperature).

In order to speed up hardening or polymerisation, a certain quantity of catalyst must be added to the monomer and the mixture is heated.

• Properties of the polymer

These properties essentially depend on the way the polymerisation has been carried out i.e. the amount of catalyst used and heating cycle (temperature and duration) as well as, naturally, the composition of the monomer which must contain no impurities which could act as inhibitors.

The optimum properties of a very well polymerised lens must be as follows:

• Optical properties

refractive index $n = 1.498$

dispensive power

$$\frac{n_\infty - n_C}{n_\infty - 1} = \frac{1}{T} \text{ et } T = 57.8$$

average transparency of the clear polymer: 92% transmission of the visible spectrum.
Impact resistance and abrasion tests

Ball drop test
(16 gram ball from 1.27 metres)
Impact resistance

Measurement of abrasion resistance
• Physical properties

- Density or specific gravity: 1.32
- Scratch resistance. This property is determined in two ways:
  - rubbing test: a lens sample is rubbed with a cloth. The
    time it takes for the plastic lens to begin to get scratched is
    measured (it takes four hours to produce scratches on an
    Orma lens).
  - falling test: emery or sand dropped on a lens sample
    leaves traces of frosting (The resistance of Orma lenses is
    high).
  - impact resistance: The ball drop method described in
    the first chapter on ophthalmic glass lenses, is used on
    finished lenses.

A good quality plastic lens made from CR39 can withstand
impacts from a 16 gram ball falling from a height of 2 metres
(The FDA safety standard in the United States requires a drop
height of 1.27 metres and the British Standard a 44 gram ball
falling from a height of 1.27 metres).

- Resistance to small particles moving at high speeds. This is
  very different from the impact resistance (ball drop) test.

The lens to be tested is bombarded with particles 2 to 3 mm
in diameter and moving at a speed of 100 m/s (360 km/h).

Of all the materials tested by the Institut National de
Recherches de Sécurité (National Safety Research Institute)
and at the Aerospace Medical School in Texas, USA, CR39
proved one of the strongest material of this type even com-
pared to laminated or toughened glass.

• Chemical properties

Resistance to chemical agents

CR39 resists all common chemicals except:

- 98% concentrated sulphuric acid. After immersion for 7
days, it loses 9.4% of its original weight;
- concentrated nitric acid dissolves it after 7 days immersion.

• Filtering and tinting properties

- Clear lenses made of CR39, such as the Orma lens, absorb
  all UV light up to 360 nm. This is due to the addition of a UV
  inhibitor to the monomer.
- Tinting is carried out by dipping lenses in very hot water
  coloured by organic pigments.

The most commonly used tints are brown, green, grey and
yellow with standardized density graduations such as A, AB, B,
C and D. Lenses can receive a full tint or a graduated tint ie.
darker at the top than at the bottom.
Diagram of the major steps involved in lens production by polymerisation

- **CATALYST**
- **UNPROCESSED MONOMER**
- **FILTRATION**
- **POLYMERISATION**
- **MOULD FILLING**
- **MOULD OPENING**

The 2 parts of a mould:
- the gasket
- the clip

The moulds, filled with monomer, are put in an oven.
CR39 lens manufacturing

Two processes are used:
— direct polymerisation,
— polymerisation of a semi-finished lens the concave side of which will be surfaced afterwards.

• Manufacturing by direct polymerisation

• Preparation of the monomer
This involves filtering, de-gassing and the addition of a catalyst.

• Mould assembly
The crown glass moulds play a very important role in CR39 lens manufacturing. Not only do they give the correct shape to the lens according to the optical characteristics required but the surface qualities of the finished lens will also depend on the accuracy of these moulds since the surfaces of the lenses are a precise reproduction of the inner mould surfaces. The mould surfaces are prepared with extreme care and precision. They are checked very frequently in order to ensure that they produce high quality lenses.

• Mould filling
— The empty space created by the gasket which separates the two polished surfaces of the mould is filled with liquid monomer.

• Polymerisation
— The filled moulds are stored in racks and put into an oven. They remain there for 14 to 16 hours to undergo a temperature cycle which is controlled to provide the correct degree of polymerisation.

• Mould opening
— The gasket is removed, the moulds are opened and the lens is removed. The manufacturing process is almost complete. All that remain are the finishing stages.

• Finishing stages
These are: edge trimming, annealing to eliminate casting stress, visual checks to eliminate lenses which might have defects, lens power checking with a focimeter, packing and possibly storage for stock lenses.

• Tinting
If the lenses are to be tinted, they are sent to a tinting room after a surface inspection. They will be checked again after tinting and put into bags.

• Polymerisation of a semi-finished blank and blank surfacing

Very powerful lenses for short sightedness or long sightedness, aphakic lenses or lenses with a very high cylindrical power cannot be made by direct polymerisation. The difference in thickness between the centre and the edges of the lenses would create sufficient stress to break the glass moulds. These lenses are therefore made in stages i.e. moulded semi finished which are surfaced afterwards. This means that one curve of the lens generally the spherical side, is obtained by polymerisation to its definitive curve while the other side is left rough.

The completed surface can be the segment side of a bifocal lens or the variable power surface of a varifocal lens.

Manufacturing of a semi-finished lens involves the same procedures as a finished lens, except that the polymerisation cycle is longer.

Semi finished lenses are generally put into stock and used when needed. The other side is surfaced exactly in the same way as glass lenses but other abrasives are used. This surface can either be spherical or toric.

All lens types used in ophthalmic optics can be made from CR39.

Plastic lenses

Conclusion

With the use of the CR39 material and the production of high quality lenses in all powers, plastic lenses have finally come of age.

The very positive results obtained with this exceptional material explains the current interest in fashionable eyewear.
Semi-finished lenses
After polymerisation

When going from a liquid state (monomer) to a solid state (polymer), CR39 contracts.
The reduction in volume of the liquid is substantial: 14%. It corresponds to a similar reduction in thickness. This is a major problem when moulding CR39 lenses and explains why it is difficult to polymerize lenses with a very high prescription.
## General properties of Orma lenses

### Physical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific weight at 25° C</td>
<td>1.314 - 1.320</td>
</tr>
<tr>
<td>Hardness:</td>
<td></td>
</tr>
<tr>
<td>Rockwell</td>
<td>M95 - M100</td>
</tr>
<tr>
<td>Barcol 15 sec</td>
<td>25-28 - 28-31</td>
</tr>
<tr>
<td>Knoop</td>
<td>11 - 24</td>
</tr>
<tr>
<td>Bending at 25° C</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Bending at 50° C</td>
<td>0.56 mm</td>
</tr>
<tr>
<td>Tensile strength, kg/m²</td>
<td>3.5 - 4.2</td>
</tr>
<tr>
<td>Elasticity modulus under stress</td>
<td>0.20</td>
</tr>
<tr>
<td>Breaking modulus, kg/m²</td>
<td></td>
</tr>
<tr>
<td>50° C</td>
<td>3.5 - 4.9</td>
</tr>
<tr>
<td>25° C</td>
<td>5.6 - 7</td>
</tr>
<tr>
<td>−10° C</td>
<td>9.1 - 10.5</td>
</tr>
<tr>
<td>−57° C</td>
<td>11.3</td>
</tr>
<tr>
<td>Elasticity modulus, kg/m²</td>
<td></td>
</tr>
<tr>
<td>for traction</td>
<td>210</td>
</tr>
<tr>
<td>in 50° C flexion</td>
<td>110 - 140</td>
</tr>
<tr>
<td>in 25° C flexion</td>
<td>170 - 230</td>
</tr>
<tr>
<td>in −10° C flexion</td>
<td>300 - 320</td>
</tr>
<tr>
<td>in −57° C flexion</td>
<td>380</td>
</tr>
<tr>
<td>during compression</td>
<td>210</td>
</tr>
<tr>
<td>Limiting compression strength kg/m²</td>
<td>16</td>
</tr>
</tbody>
</table>

### Chemical properties

Variation in weight after 7 days of immersion (%):

<table>
<thead>
<tr>
<th>Substance</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% sodium chloride</td>
<td>0.6</td>
</tr>
<tr>
<td>3% hydrogen peroxide</td>
<td>0.7</td>
</tr>
<tr>
<td>15% calcium hypochlorite</td>
<td>0.2</td>
</tr>
<tr>
<td>95% ethyl alcohol</td>
<td>0.1</td>
</tr>
<tr>
<td>50% ethyl alcohol</td>
<td>0.2</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.4</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>0.0</td>
</tr>
<tr>
<td>Chloroform</td>
<td>1.5</td>
</tr>
<tr>
<td>5% acetic acid</td>
<td>0.8</td>
</tr>
<tr>
<td>Oleic acid</td>
<td>0.3</td>
</tr>
<tr>
<td>Petrol</td>
<td>0.1</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.2</td>
</tr>
<tr>
<td>Toluene (methyl benzine)</td>
<td>0.2</td>
</tr>
<tr>
<td>Hexam</td>
<td>0.2</td>
</tr>
<tr>
<td>Olive oil</td>
<td>0.2</td>
</tr>
<tr>
<td>Mineral oil</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substance</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.4</td>
</tr>
<tr>
<td>98% sulphuric acid</td>
<td>9.4</td>
</tr>
<tr>
<td>30% sulphuric acid</td>
<td>0.2</td>
</tr>
<tr>
<td>3% sulphuric acid</td>
<td>0.3</td>
</tr>
<tr>
<td>Concentrated nitric acid</td>
<td>dissolved</td>
</tr>
<tr>
<td>10% nitric acid</td>
<td>0.3</td>
</tr>
<tr>
<td>Concentrated hydrochloric acid</td>
<td>0.1</td>
</tr>
<tr>
<td>10% hydrochloric acid</td>
<td>0.4</td>
</tr>
<tr>
<td>48% hydrochloric acid</td>
<td>9.3</td>
</tr>
<tr>
<td>12% hydrochloric acid</td>
<td>0.7</td>
</tr>
<tr>
<td>Concentrated ammonium hydrxide</td>
<td>0.5</td>
</tr>
<tr>
<td>10% ammonium hydrxide</td>
<td>0.4</td>
</tr>
<tr>
<td>50% sodium hydrxide</td>
<td>0.5</td>
</tr>
<tr>
<td>10% sodium hydrxide</td>
<td>0.2</td>
</tr>
<tr>
<td>1% sodium hydrxide</td>
<td>0.8</td>
</tr>
<tr>
<td>2% sodium carbonite</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Additional properties:

- Tangent limit satisfactory for compression, kg/cm²: 499
- Resistance to shock, 25° C, kg/cm²:
  - Izod test, grooved: 1.1 - 2.2
  - Izod test, non grooved: 11 - 16
  - Charpy, grooved: 1.1 - 2.2
  - Charpy, non grooved: 16 - 26
- Johnson shear resistance, kg/mm²: 3.4
- At 10 times 1.4
- Bending temperature under stress: 60 - 75°C
- Distortion temperature, mls: 10
- Distortion at 130°: 0.9 - 1.6
- Recommended max. operating temperature without any stress:
  - Continuous operation: 100°C
  - Intermittent operation (for 1 hour): 150°C
- Specific heat, cal/g°C: 0.55
- Thermic conductivity, cal/s/cm²°C: 5 x 10⁴
- Rate of combustion in cm/mm: 0.13
- Warping: 0.00
- Water absorption, 24 hours at 25°: 0.2%