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Foreword

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This document was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 7, *Ophthalmic optics and instruments*.

Ophthalmic optics and instruments — Free form technology — Spectacle lenses and measurement

1 Scope

This document outlines all the steps from refraction to dispensing of spectacles, with particular attention to the benefits added by using free form technology, and provides a collection of relevant terms and descriptions.

This document does not contain the proprietary features of lens designs provided by suppliers.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Technical introduction

4.1 Preliminaries

4.1.1 There are various ways of spelling the term “free form”. This document uses two separate words.

4.1.2 There are various terms explaining spectacle lens optical power design which are commonly used such as “optical function”, “optical characteristics”, “optical properties”, or “design property”. For purpose of simplicity, this document uses the word “characteristics”. The phrase “optical properties” is used simply to describe the optical results of the geometry of the lens, but not an intended design or characteristic.

4.1.3 A typical flowchart including refraction, dispensing and manufacturing is shown in Figure A.1 (see Annex A).

4.1.4 A glossary of terms and their descriptions is provided in Annex C.

4.2 What is free form?

In ophthalmic optics, the term “free form surfacing” refers to a spectacle lens surfacing process that is capable of producing continuous, smooth, non-symmetrical lens surfaces that lack point, axial or plane symmetry and are described by three-dimensional coordinates created by mathematical formulation. This design and surfacing process enables optimization of the lens performance.

Conventional lens surfacing technology which smooths and polishes using hard lap tools can produce only simple spherical or toroidal lens surfaces.

Modern free form lens surfacing methods are now capable of generating surfaces that are much more complex than simple spherical and toroidal surfaces, allowing local optical laboratories to manufacture progressive-power and other lens designs directly onto the lens blank with the required prescription curves. In order to produce these complex surface shapes, free form surfacing utilizes precise, computer-driven control of the cutter with three or more axes of movement. Often, the surface is machined using single-point diamond turning and then polished using flexible lap tools.

A “free form process” can thus be summarized as a lens surfacing process using Computer Numeric Control (CNC) devices capable of producing a free form surface with optical characteristics on either or both side(s) of the lens.

It should be noted that when simpler surfaces that can be manufactured by conventional methods are produced by free form processing, these simpler surfaces should not be termed free form surfaces nor the resulting lenses free form lenses.

4.3 Does free form equal better vision?

As an enabling technology, free form surfacing makes possible the application of optical characteristics, using information specific to the individual wearer, immediately prior to lens manufacture.

The use of free form surfacing as a manufacturing method does not guarantee any visual benefit to the wearer. It is true that the soft lap tool polishing process used during free form surfacing is not subject to the rounding errors of conventional lens surfacing. Conversely, it can maintain an accurately generated free form surface. Hence, soft lap polishing actually relies on more extensive process engineering and quality control in order to achieve high quality lens surfaces.

Free form surfacing provides a powerful vehicle for overcoming the limitations of conventional semi-finished lens manufacturing when utilized in conjunction with sufficiently advanced optical design software by delivering lenses custom-designed for the specific visual requirements of the individual wearer. It becomes possible to optimize the optical design of the lens individually (i.e. upon the exact prescription power and orientation of the fitted lens) before the lens is actually manufactured, in order to preserve the intended optical lens characteristics for each and every wearer.

In addition to preserving the intended optical lens characteristics for any combination of prescription power or as-worn position, it is also possible to customize other features of the lens design for the individual wearer. The lens can be adapted further in order to modify the corridor length for the fitting height in small increments, optimize the viewing zones for occupational demands, and adjust peripheral power gradients for the head-eye movement behaviour, and so on. It is important to note, however, that only custom-designed free form lenses will offer this level of sophistication and design properties for the wearer.

Nevertheless, without the application of real-time optical design to optimize the lens design for the individual wearer, the potential visual advantages of using free form surfacing are relatively small.

4.4 Classification

With free form surfacing, an optical laboratory can surface a variety of lens designs directly onto a semi-finished lens blank in addition to the prescription curves that are normally applied. With two separate surfaces to work with, the optical characteristics, addition power, if any, and prescription components of a free form lens can be applied to the lens blank in a variety of possible lens surface configurations. Each type of free form lens represents a particular combination of factory-moulded and directly-surfaced lens curves. The lens surfaces involved range in complexity from simple spherical surfaces to individually-optimized progressive power surfaces that simultaneously fulfil all of the prescription requirements of the wearer.

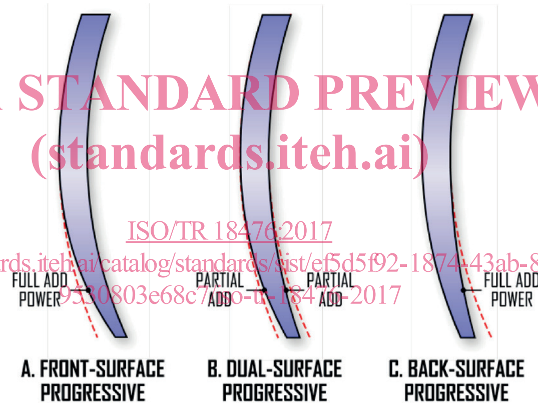
When free form surfacing is used to transfer the optical characteristics onto the lens blank, free form progressive-power lenses may be classified by the distribution of the optical characteristics between the front and back surfaces (see Figure 1).

a) *Front surface free form lenses* (A in Figure 1) employ a directly-surfaced progressive surface with the full addition power on the front and conventionally-surfaced prescription curves on the back. The progressive optics are surfaced directly onto the lens. While less common, this configuration may, for instance, be utilized to achieve broader prescription ranges.

b) *Dual-surface free form lenses* (B in Figure 1) employ a factory-moulded (or, in some cases, a directly-surfaced) progressive-like surface with a component of the total addition power on the front and a digitally-surfaced progressive surface with, for instance, the remaining addition power that has been combined with the prescription curves on the back. The progressive-power optics are distributed between both lens surfaces.

c) *Back-surface free form lenses* (C in Figure 1) employ a factory-moulded spherical surface on the front and a directly-surfaced progressive surface that has been combined with the prescription curves on the back. The progressive lens design may be a standard (fixed) design or an optically-optimized design.

For the purpose of simplicity, the rest of this document will refer only to full back surface lenses (C in Figure 1).



NOTE Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 1 — Classification of free form progressive-power lenses by the distribution of the addition power between the front and back surfaces

5 Manufacturing

5.1 General

Whatever the process used to manufacture the lens, the lens manufacturing cycle is the same. The general lens manufacturing flow is described in Figure 2.

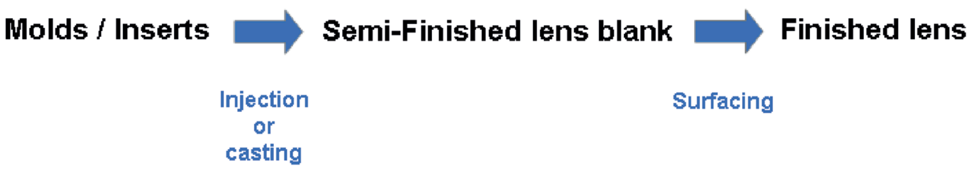


Figure 2 — General lens manufacturing flow with semi-finished lens blanks and surfacing

5.2 Conventional surfacing

Conventional surfacing is a four-step process for finishing the unfinished back surface of a semi-finished lens blank with the required prescription curves (see Figure 3). Semi-finished lens blanks have an optical-quality front surface that has been moulded by a manufacturer.

In the first step termed "blocking", the semi-finished lens blank is mounted by its finished surface on a support to hold it for the next three steps.

In the second step, the unfinished surface of the lens is machined by a generator to approximately the required shape using a grinding, turning or milling process.

In the third step, known as fining or smoothing, the worked surface is ground to the precise surface shape by a toroidal smoothing/polishing machine that rapidly moves the lens surface in a cyclical motion over a hard lap tool fitted with abrasive pads that matches the intended curvature of lens surface. This brings the lens surface to a quality suitable for polishing.

In the fourth and final manufacturing step, known as polishing, the abrasive pad is replaced by a polishing pad. The lens surface is once again cycled over the hard lap tool in a toroidal smoothing/polishing machine, while the pad is soaked with polishing slurry. The lens is then "de-blocked".

See Figure 3 a) and b). In Figure 3 b) the hard lap tool copies the fixed two principal meridians' curvatures to the lens's concave surface.

a) Scheme of conventional surfacing process **b) Fining process used in conventional surfacing**

Figure 3 — Conventional surfacing process

The simplest generators are two-axis machines that utilize a diamond-impregnated grinding wheel to generate a spherical or toroidal lens surface. The emphasis of a conventional generating process is on throughput and rapid removal of lens material. Any inaccuracy in the shape of the generated lens surface is ultimately corrected during the fining process by the hard lap tool. In particular, the fining process with hard lap tools exploits the rotational or meridional circular symmetry of spherical or toroidal lens surfaces, since these surfaces can be cycled over the hard lap tool using a uniform rocking motion that produces relatively constant fining and polishing pressure over the lens blank [see Figure 3 b)]. The use of hard lap tools during the fining and polishing processes therefore restricts the range of possible lens surface shapes to simple spherical and toroidal surfaces. Moreover, in practice, hard lap tools are only available in discrete increments of surface curvature. Due to the need for reasonable inventory requirements, hard lap tools are often stocked in eighth-dioptre (0,12 D) or tenth-dioptre (0,10 D) steps for the sphere power, although larger laboratories may stock tools in 0,06 D steps. This can potentially result in rounding errors of up to ±0,05 D from the desired surface curvature, which will limit the accuracy of the prescription power of the surfaced lens and increase the likelihood of failure during a quality inspection.

5.3 Free form surfacing

In conjunction with the Laboratory Management System (LMS), a *Lens Design Server* (LDS; computer and appropriate sophisticated software) is first used to calculate a *surface description file* (SDF) (also known as a "*points file*") from the prescription and lens order parameters. The points file contains surface height (and possibly slope) data [see Axis 1 in Figure 4 b)] that characterize the required three-dimensional geometry of the lens surface to be cut[7]. The required lens surface is then generated from the points file using a CNC cutting process. With three or more axes of precisely controlled movement, the single-point cutting tools of these generators can produce virtually any continuously smooth surface shape with a high degree of accuracy and smoothness that requires minimal polishing.

The machine may also orientate the cutter to be at right angles to the orientation of the lens surface in the immediate area in which it is cutting; hence, there may be three or five axis machines, double that if they can surface the left and right lenses simultaneously.

a) Scheme of free form surfacing process **b) Free form CNC machining**

Figure 4 — Free form surfacing process

With most free form lenses, the prescription powers are combined into the required lens design, and then processed as a single surface onto the back of a semi-finished lens blank, as in Figure 2[8]. This allows the fabrication of a lens design and the prescription curves in a single step. The worked lens surface is then polished by a free form polisher using a soft lap polishing tool that is also dynamically controlled by a computer. Unlike hard lap tools, which are only available in specific increments of surface curvature, soft lap tools can polish a lens surface to within very small increments.

Because this technology allows the laboratory to fabricate complex lens design directly onto the lens blank, free form surfacing is sometimes referred to as *direct surfacing*. Because free form lens surfacing relies on computer (points) files that describe the desired surface shape, free form lens surfacing is also referred to as *digital surfacing*. However, the term "digital surfacing" is often used more generally to refer to any lens surfacing process that utilizes free form surfacing equipment, even when surfacing conventional spherical or toroidal surfaces, which makes the use of this particular term potentially misleading.

In summary, a conventional surfacing process cannot produce the complex surfaces utilized for complicated lens designs like progressive-power lenses due to limitations in both the range of possible surface-shape geometries and the quality of the finished surface produced by conventional generators. Free form surfacing is, however, a more sophisticated surfacing process that is capable of producing virtually any continuously smooth surface, including aspheric, atoroidal, and progressive-power surfaces, in addition to basic spherical and toroidal surfaces. This allows local optical laboratories to manufacture progressive-power and other complicated continuous surfaces that previously needed moulding using a mass-manufacturing process.

5.4 Comparison of conventional and free form manufacturing

Table 1 — Comparison of steps of conventional and free from manufacturing

Manufacturing step	Conventional process	Free form process
Inputs from order	— **Prescription:** SPH, CYL, Axis, addition, Prism base and value, CD.	— **Prescription:** SPH, CYL, Axis, addition, Prism base and value, CD. — **Fitting and personalised parameters**
Lens blank selection	— The base curve is selected from the prescription according to the Rx range. — The complex surface already exists on the front surface of the lens blank. — **Number of lens blank stock keeping units (SKUs) needed is high** to cover all additions and all prescriptions.	— The base curve is selected from the prescription according to the Rx range. — A part of the complexity may exist on the front surface of the lens blank. — **Number of lens blank SKUs needed can be reduced** in the case of full back surface lenses.
Calculation of the back surface	— **Simple and limited surfaces:** the back surface of the lens can be only spherical or toroidal because of the surfacing tools. — The optical characteristics are managed through the front surface. — The calculation delivers **the radii of curvature and axis of the back surface and its positioning relative to the front surface (thickness and prism).** — **The output of calculation is rounded according to the tooling steps available (e.g. 0,12 D, 0,10 D or 0,06 D).**	— **Free form surfaces:** the surface of the lens can be spherical, toroidal, aspherical or progressive/degressive-power or a combination of both or even more complex. — The optical characteristics are managed through the back surface only (full back) or through both surfaces (dual). — Usually based on **complex ray-tracing algorithms**, the calculation delivers either one **surface that will have to be made and its positioning relative to the other surface or both surfaces.** — **Output of the calculation is the exact lens surface target without any rounding.**
Taping	Use of a plastic film deposited on the front surface both to protect it and to ensure adhesion for blocking (not always needed by alternative method, e.g. water soluble spray).	
Blocking	Mechanical 3D positioning of the blank (centring, axis, tilts, etc.)	
Generating	— **Rough milling.** — Use of **cup wheel introducing elliptical errors.** — Generating of the back surface curvatures. — Generated surface can be approximated as the **final geometry is given by fining/polishing tools.**	— **Rough turning** with a rotating cutter disc. — **Fine turning with a single point diamond tool.** — Cutting machines need **high precision trajectory in high acceleration conditions.** — **Machined surface has the exact final expected shape.**

Table 1 *(continued)*

Manufacturing step	Conventional process	Free form process
Fining	— **Smoothing by abrasive pad on rigid tool.** — **Gives the final expected curve.**	This step is not necessary.
Polishing	— **Respects the fined surface shape.** — **Hard polishing** with **Rigid tool.** — 1 tool = 1 spherical or toroidal surface.	— **Respects the generated shape.** — **Soft polishing** with **flexible tool.** — 1 tool = infinity of surfaces.
Engraving	**Generally put on the front surface of the semi-finished lens blank**	For spherical front surface semi-finished lens blank, **generally done on the back surface** of the finished lens, although some free form lenses uses pre-engraved semi-finished lens blanks.

There has been a steady process in improving conventional surfacing. Lap tools may be cut on re-usable or disposable laps, thus avoiding the need to keep such tools in fine steps. More sophisticated lens surface generators can produce more accurate surfaces that do not necessarily require hard lap polishing.

Differences between the two processes also exist in terms of power/prism conformity and integrity of the intended surface (see Table 2). Consequently, a specific process control is needed for a free form process to ensure integrity of the intended surface.

Table 2 — Power/prism conformity and integrity of the intended surface shape

Conventional process	Free form process
Integrity of the intended surface is guaranteed by controlling moulds, inserts and the semi-finished lens manufacturing process **Distance vision and prism reference point (PRP) prism conformity guaranteed by laboratories.**	Integrity of the intended surface also relies on the back side manufacturing phase: **responsibility mostly (fully in case of full back side) transferred to laboratories** — **Distance vision and prism reference point (PRP) prism conformity guaranteed by laboratories.**

6 Potential benefits of free form lens calculation

6.1 Oblique astigmatism

When the line of sight passes through the lens at an angle to the optical axis of the lens, an optical aberration known as *oblique astigmatism* is produced due to the oblique refraction of light rays through the lens. Oblique astigmatism results in unwanted spherical and cylindrical power errors that are perceived by the wearer as deviations from the desired prescription. Oblique astigmatism is introduced when either the lens is tilted with respect to the wearer due to the fit of the frame or the wearer views an object through the periphery of the lens. In either case, the line of sight forms an angle to the optical axis of the lens that can result in an astigmatic focus that departs from the intended focus, if the lens design does not adequately account for this effect (see Figure 5).

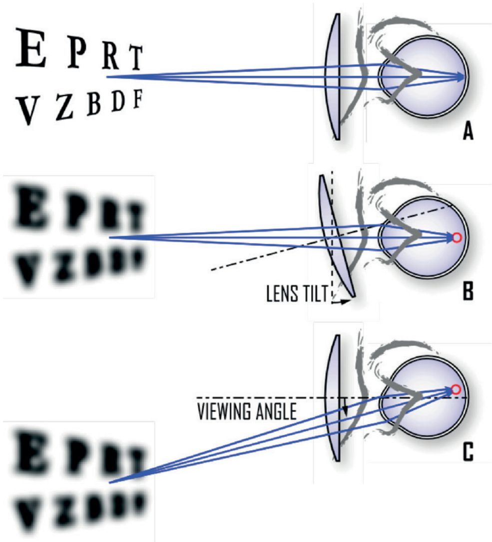


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Figure 5 — Degradation of the image because the line of sight is not along the optical axis of the lens

Oblique astigmatism does not occur when the line of sight coincides with the optical axis of the lens and the object is seen clearly (see Figure 5):

a) line of sight aligned to the optical axis of the lens gives a good image (A in Figure 5);

b) blurred image with tilted lens (B in Figure 5);

c) blurred image with oblique line of sight (C in Figure 5).

For spherical prescriptions, oblique astigmatism introduced during off-axis vision can be eliminated by selecting a spherical front curve that corresponds to a Tscherning's ellipse for a given set of lens design parameters. See the example in Figure 6[9] which represents the power of the lens's convex surface needed in distance vision to eliminate oblique astigmatism when the line of sight is rotated 30° to the optical axis. For a prescription of −5,00 D, the power of the convex surface will need to be about either +3,50 D or +17,00 D.

This results in a *best form* lens design. Alternatively, an aspheric lens design can be utilized, which frees the lens designer from the relatively steep lens form requirements of Tscherning's ellipse in order to provide flatter, thinner lenses. However, as with best form lenses, each spherical power requires a separate aspheric lens design.

