

*Measurement
Good Practice Guide*

**UV Embossed Optical
Microstructured
Surfaces**

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No. 6

**FREE
MICRO LENS
SAMPLES INSIDE**



NPL 
National Physical Laboratory

Measurement Good Practice Guide No 6

UV Embossed Optical Microstructured Surfaces

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Abstract: The purpose of this guide is to draw the attention of industry to the benefits and possibilities of using a UV embossing process for the production of optical microstructured surfaces and to offer guidance in designing systems to obtain the best results.

This new technology would benefit the following targeted industries.

- Display technology
- Advertising
- Security
- Building
- Automotive
- Instrumentation
- Telecommunications
- Optoelectronics
- Scientific

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- to demonstrate the contribution accurate measurement can make towards improving industrial competitiveness and compliance with standards and regulations
- to support the development and application of good measurement practice by providing a practical 'toolkit' that companies can use to improve measurement quality
- to back this up with access to local and national sources of measurement expertise and services.

For more information on Competing Precisely, contact Gareth Francis on 0181-943 6329 (e-mail: gareth.francis@npl.co.uk) or by post at National Physical Laboratory, Teddington, Middlesex, TW11 0LW.

UV Embossed Optical Microstructured Surfaces

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1 Introduction

Microstructured optical surfaces and UV microreplication are two technologies which have developed independently but which have recently come together and now offer an exciting series of new products with wide ranging applications in the industries listed in the abstract of this guide.

The history of microstructured optical surfaces spans many decades (more than a century and a half in the case of diffraction gratings). It received a significant boost with the availability of the laser which made holography and other forms of interference techniques feasible. In the last five years there has been an explosive growth of research interest following the availability of high grade photolithographic equipment.

As a result of this there now exist a great many interesting optical surfaces and components with a range of applications limited only by the imagination of the researchers who have developed them. Unfortunately most of them are high-cost items made with great precision for use in research and as a consequence large scale applications have not been fully explored.

UV microreplication provides a means of replicating fine structures with great precision in large areas at reasonable cost. It is far superior to hot embossing and is capable of producing both fine and coarse structures with much greater fidelity and in materials which possess greater durability. It is therefore now possible to reduce the unit price of these items to a level which is compatible with many consumer applications. There is within many of the industries listed, a growing awareness that microstructured optical surfaces can offer genuine advantages in performance and cost. However, because of the relatively specialised nature of the new technology it is often not fully understood by those who could profitably make use of it.

The purpose of this guide is to explain the features, possibilities and limitations of UV microreplication to a non specialist audience and to illustrate this with samples. This will offer guidance for the most effective use of the technology and will stimulate its wider and more rapid uptake.

2 UV Micro Replication

2.1 What is UV Micro replication?

This technique involves the use of UV casting technology to replicate precision surface topography into polymer surfaces. A casting resin in the form of a very fluid monomer flows easily into the fine details of the structure to be replicated. It is then exposed to ultraviolet (UV) radiation which causes it to polymerise and become hard and rigid. When separated from the original structure it yields a precise and durable copy.

2.2 How does it work in practice?

A low viscosity UV curable resin system coated onto a substrate is contacted with a master form. The substrate may be a flexible polymer carrier film, a rigid polymer or glass. The resin is hardened almost instantaneously by exposure to high intensity UV radiation transmitted through the substrate. The cured resin adheres strongly to the substrate and weakly to the master form from which it can readily be stripped.

In many cases it is convenient to use a thin nickel electroformed shim as the master. This makes it possible to replicate structures which in their original form are not sufficiently flexible or robust.

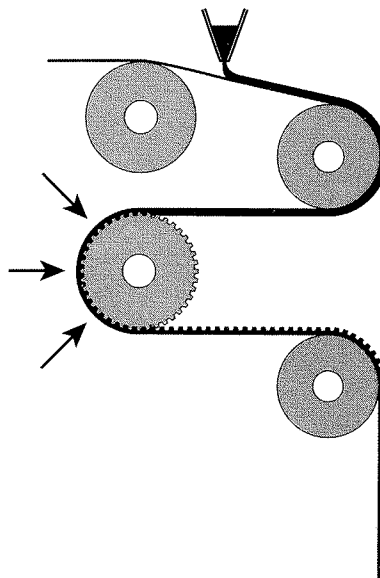


Figure 1: High volume reel-to-reel production

For high volume applications the process can be configured to operate on a continuous reel-to-reel basis at relatively high throughput speeds. The substrate polymer film must be sufficiently flexible to pass through a coating line, and must be transparent to the UV radiation required for curing. Common choices are therefore polyethylene, polyester, cellulose di- or tri-acetate and polycarbonate. The carrier substrate can be between 23 μm and 750 μm thick and non-birefringent and highly temperature resistant films may be used where required. The coating which carries the replicated surface is typically between 3 and 30 μm thick but thicker layers are feasible and have been demonstrated. Furthermore the coating can be stripped from the carrier to form a self supporting film of uniform composition.

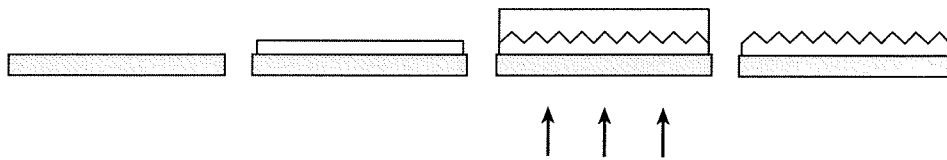


Figure 2: UV curable resin sytem

In applications where the final shape of the replica is important, a rigid substrate may be used which may for example be a glass optical flat.

The coating may be treated to give some resistance to UV light and humidity in order to produce materials that are durable outdoors. The coating surface and the surface of the carrier film may be treated to give adhesion to common printing inks including UV curable inks.

2.3 What does it offer that is new?

A unique combination of precision and low cost. A similar precision can be achieved by resin casting which is time consuming, labour intensive and expensive. Other low cost processes such as hot embossing are not capable of the same precision and resolution. The instantaneous hardening of the resin in the UV process while it is still in contact with the master prevents any deformation of the polymer as the cast is separated from the mould. In all thermal processes the aspect ratio of high resolution images is limited by this factor.

The resin film is highly cross-linked in its hardened state. For this reason it is more resistant to chemical attack and more thermally stable than the materials used for hot embossing or injection moulding.

3 Microstructured Optical Surfaces

There are three types of surface that are of interest which can be produced by this process.

- Fine arrays of micro-optical components such as microlenses and microprisms which steer beams of light by refraction
- Diffracting structures. These are in the form of very fine surface corrugations approximately the same size as the wavelength of light.
- Sub-wavelength structures. These are periodic structures which are smaller than the wavelength of light. Light does not resolve the structure but responds as though the material effectively had different optical properties.

3.1 Refracting micro-optical components

3.1.1 Micro-prism array

An object viewed through the material appears to be displaced sideways. Distant objects become blurred because of diffraction - the interaction of light with the very small dimensions of the prisms - but the material for example is very effective at redirecting daylight into buildings. An array of small prisms has the ability to deflect a beam of light as a normal prism, but is much lighter and less bulky.

3.1.2 Microlens arrays

Lenses with diameters between half a millimetre and 50mm have recently been developed and are finding a wide range of applications. They can be used to enhance the efficiency of detectors and displays, they are the basis of a form of 3D photography, they help telescopes see through a turbulent atmosphere, they can be used to study surface profiles and when combined together generate optical effects that are useful in advertising.

3.1.3 Fresnel lens

A conventional lens is reduced to a series of circular segments. The performance is basically the same but it is much lighter. Originally developed by Fresnel in the nineteenth century for use in lighthouses and developed in the 1960s by the 3M company for use with overhead projectors.

3.1.4 Diffusers

A diffuser transmits and redistributes light in such a way that a chosen area is uniformly illuminated. Diffusers may have a completely random structure, in which case light is diffused into all directions, they may be modified to reduce the angular spread, they may consist of regular arrays of microlenses with controlled properties, they may be generated holographically or they may be diffracting structures specially designed on a computer and generated photolithographically.

3.2 Diffracting Optical Surfaces

When light interacts with a periodic structure its path is deviated by an amount that depends upon the ratio of the period of the structure to the wavelength of light. Light of different wavelengths will be deviated by different amounts so different colours are spread out into a spectrum. This is why a CD appears coloured and it is also the basis of spectroscopic techniques for chemical analysis.

3.2.1 Diffraction grating

A range of diffraction gratings are available, for use in both reflection and transmission. The finer the grating the more the spectrum is dispersed. Gratings with a rectangular groove profile of the appropriate depth split the light into two so-called “diffracted orders”. An object viewed through it will appear double. The finer the grating the further the images are separated. Gratings with a triangular profile produce mainly one order. It is effectively a smaller version of the prism array, but the effect of diffraction is to introduce colour.

3.2.2 Fresnel zone-plates (not to be confused with Fresnel lenses)

These are circular gratings in which the spacing decreases towards the edge. They perform like lenses or spherical mirrors but with different focal lengths for different diffracted orders and focal lengths that vary with wavelength. They have been developed for use as bifocal contact lenses and implants and as optical displacement sensors.

3.2.3 Holograms

A hologram is a diffracting structure in which the fine grooves are produced from the fringe pattern that is generated when two light waves interfere. If one wave has been reflected from an object a 3D image of the object is reconstructed when the hologram is viewed.

3.2.4 Computer generated holograms

A computer can be used to design a pattern of grooves that will redirect light in any chosen way and then control a mask writer or electron beam writer to generate the pattern. In this way a beam can be split into an array of equally intense beams, or focused into any desired shape.

3.3 Sub-wavelength Structures

3.3.1 Moth eye antireflection surface

The eye of the night flying moth is covered with an array of protuberances that are small compared with the wavelength of light. This behaves like a gradient of refractive index at the surface and reduces the amount of light reflected. The moth needs it for camouflage but surface reflections are a serious problem in many applications. The moth eye can be simulated by combining two very fine gratings at right angles.

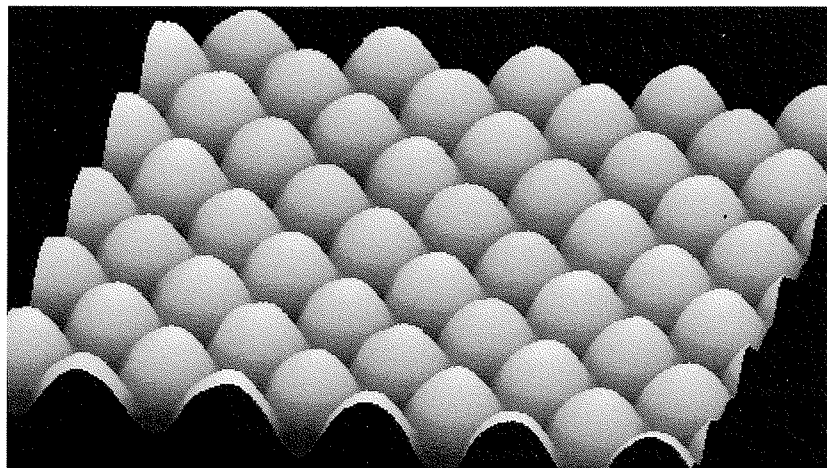


Figure 3: Motheye antireflection surface

4 Case Studies

Below are a list of commercially available microstructured optics available from Epigem Ltd. or Autotype International Ltd. who kindly contributed the microstructured surfaces enclosed in this guide. Samples of the microstructured surfaces are to be found in the pocket located on the back cover of this guide.

4.1 Rotation Encoder Disc

Epigem Ltd

Optical rotation encoders, as their name implies, are used to measure mechanical rotary motion. They work by detecting the patterns of light and dark reflected from the embossed surface of a spinning encoder disc mounted on the shaft whose rotation is being measured. Thousands of units per year are required in a wide range of industrial applications to monitor machinery spinning at high speed. Making the encoder smaller enables it to be integrated more closely with the mechanical shaft, even to the point where the encoder is located inside the head of a motor. However, smaller encoders require finer pitch marks on the encoder disc to maintain a large enough number of counts per revolution. This is where UV embossing technology plays an important role. A very accurate (and expensive) master grating, with a period of less than 1 mm, is made by electron beam lithography and converted into a nickel mould tool by electroforming. Finally, the nickel tool is used to emboss the radial grating pattern into UV curable polymer onto a large number of encoder discs. The prototype embossed gratings had only 0.01% ellipticity, high diffraction efficiency (36% at 633 nm) and reproduced the desired physical dimensions to within 0.03%. Quartz or glass substrates can be used to give the disc improved thermal stability over similar parts made entirely of plastic.

4.1.1 Table 1: Dimensions of measurements on rotation encoder samples

Sample	Disc Diameter (mm)	Error in diameter (μm)	Relative error in diameter	Ellipticity (μm)	Relative ellipticity
UV embossed radial grating on PET film	32.2088(EW)	9	0.03%	4	0.01%
	32.2053(NS)	5	0.02%		
Quartz radial grating made by photolithography and reactive ion etching	32.205(EW)	5	0.02%	0	0
	32.205(NS)	5	0.02%		

All dimension measurements made by Centre Suisse d'Electronique et de Microtechnique SA.
Relative error in measurement of diameter is $\pm 0.015\%$.

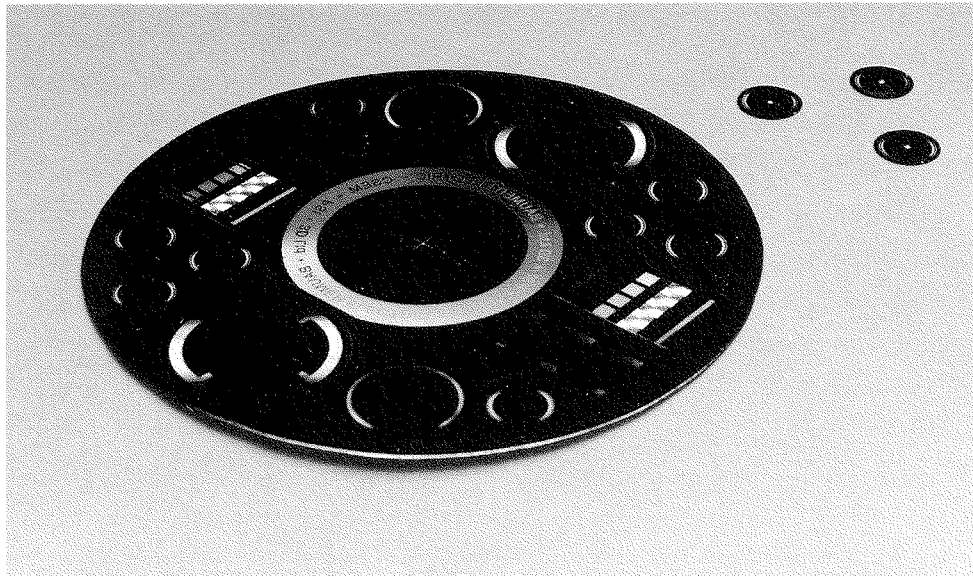


Figure 4: Rotation Encoder disc

4.2 Holographic Optical Backplane Epigem Ltd.

In high performance computing applications data needs to be distributed at high speed between micro-processor boards in rack mounted systems. Existing VME-based electrical backplanes can operate at frequencies up to 640 MHz but at higher frequencies both signal density and the distance over which the signal can be sent are limited. One way to overcome this information bottleneck is to use light to do the signal distribution. A holographic optical backplane is a reflective glass plate which mounts onto the front or back of the processor rack. Laser diode transmitters and photodiode receivers are located on the edge of each processor board. Laser light hits the optical backplane and is split by sub-micron period diffraction gratings embossed onto its surface. Light is distributed within the plate by means of total internal reflection.

Epigem has developed a cost-effective method of manufacturing the backplanes using UV embossing. The process involves high precision replication of the sub-micron period gratings into a thin polymer film coated on the surface of the glass. Pattern transfer is achieved along the full length of a 325 mm long backplane plate. This product is a collaboration between Epigem and EUREKA project EU-922 partners Thomson CSF, Corning Europe Inc., Institute für Oberflächenmodifizierung Leipzig, Friedrich-Schiller-University Jena, Heptagon Oy and Holtronic Technologies S.A.

Lead partner, Thomson-CSF expects to demonstrate a fully working system based on a standard VME rack incorporating the holographic optical backplane by the end of 1997.

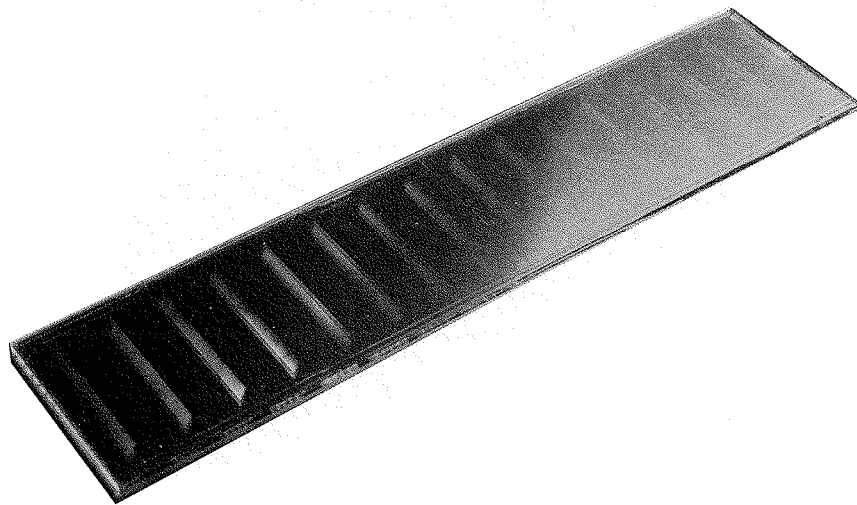


Figure 5: Holographic Optical Backplane

4.3 Microlens Arrays

Epigem Ltd and Autotype International Ltd

Over recent years several techniques have been developed for the manufacture of regular arrays of lenses with diameters between 50 μm and 1 mm. These include the melting of arrays of cylinders of photoresist which have been generated using standard photolithographic techniques, and "photosculpture", again in photoresist. Such lenses have fascinating optical properties and a wide range of applications. Much of the interest is fuelled by recent advances in optoelectronics and the ever-accelerating trend towards miniaturisation and parallelism. Some applications such as three dimensional photography have been known for a long time but have not been exploited commercially because suitable lens arrays were not available. UV embossing is a means of providing commercially useful areas of lens array at a modest cost, without sacrificing the high optical quality of the original lenses. Not only is the quality of the individual lenses preserved but so is that of the array. If an array of lenses has to be aligned with an array of electro-optic devices, photographic images, or other lenses, it is essential that there is no distortion of the array. Otherwise moiré fringes will be generated.

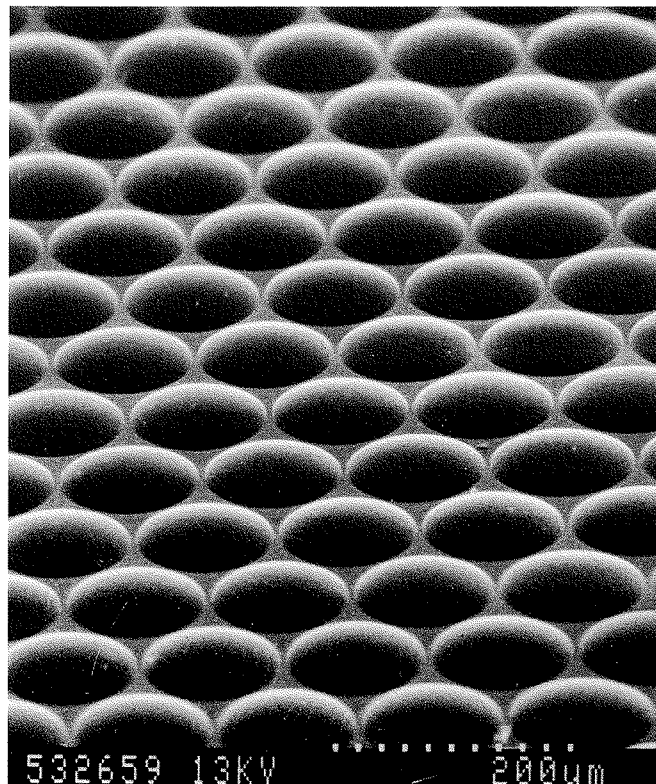


Figure 6: Microlens array

125μm Pitch Replicated Microlens Array

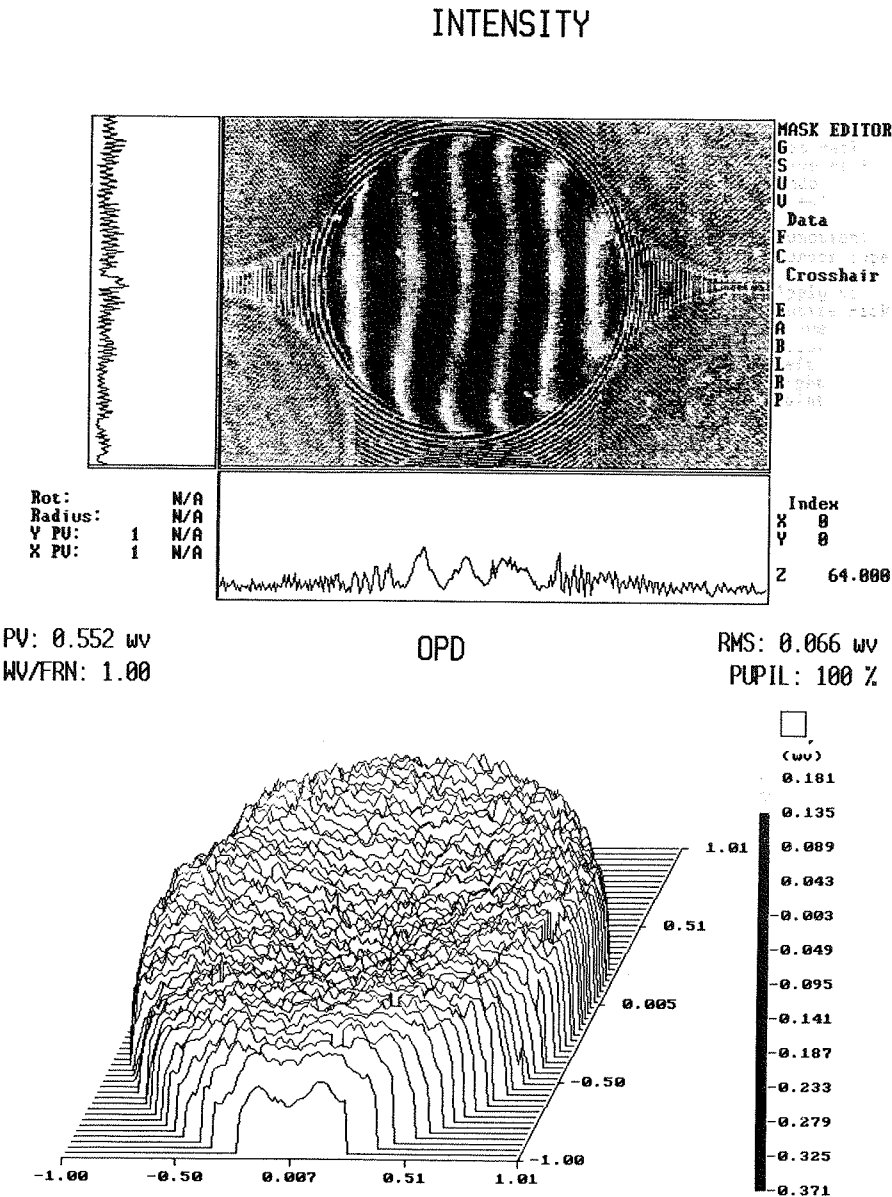


Figure 7: Deviation of replicated microlens array shape from spherical

4.4 Diffusers for Touch Switches

Autotype International Ltd.

The use of finely textured films in the manufacture of membrane switches, nameplates and fascia panels is a well established world-wide technology. Autotype has been involved for many years in the development of UV embossing to produce these materials and enjoys a leading commercial and technical position in the market. The coating process is typically carried out on polyester or polycarbonate film over a metre in width. Production is a large scale process involving the coating of millions of metres of film.

These films typically comprise a finely textured first surface and a printable second surface. The textured surface provides a flexible abrasion resistant coating which exhibits excellent chemical resistance by virtue of the degree of polymerisation produced by the UV curing process. This combination of properties is achieved by careful choice of the monomers and oligomers utilised in the cross-linking reactions. Thermoplastic moulding systems cannot offer this combination of properties.

For these types of materials the surface structure reproduced is essentially random in nature in order to provide the necessary optical properties. The feature size is tightly controlled by careful engineering of the master from which the product is cast and depending upon the requirements of the end user, are typically of the order of average roughness value 5 to 15 micrometres.

The great advantage of this process is its reproducibility over large production runs. This is most important as it guarantees consistent colour reproduction when the product is printed on the second surface prior to final fabrication into a switch or panel. Alternative methods employing mineral fillers dispersed in thermoplastic resins cannot guarantee this reproducibility.

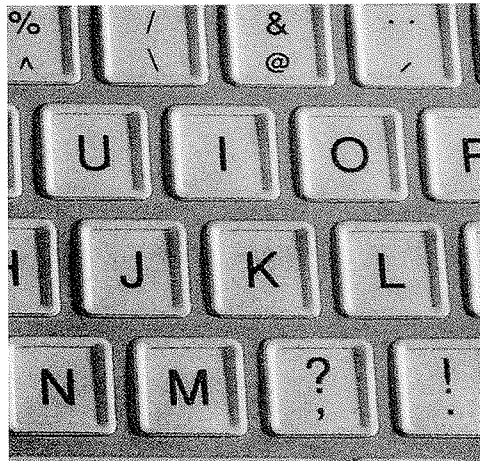


Figure 8: Diffusers for Touch Switches

4.5 Motheye Antireflection Surfaces

The Motheye Antireflection surface reduces the reflectance of an optical surface by copying a phenomenon found in nature. The eye of certain insects is covered with very fine arrays of tiny pimples which are smaller than the wavelength of light. This has the effect of providing a gradual change of refractive index across the boundary between air and the eye because the structure is too fine to be resolved. It "softens" the sudden change of index that gives rise to surface reflections and these are considerably reduced. For the night flying moth it is an essential part of its camouflage, but the need to reduce surface reflection arises in a variety of everyday and scientific areas. The structure is produced by recording in photoresist the very fine interference fringes that are generated when two beams of laser light intersect at high angles. This when suitably developed produces a corrugated surface (which may as it stands have antireflection properties), but by recording two patterns at right angles it was possible to produce a microscopic egg box structure.

Motheyes produced in this way show excellent antireflection properties that compare well with the best multilayer interference coatings. Not only are the values of reflectance very low, but because they do not depend upon interference, motheyes are broad band and less sensitive to angle of incidence. However, their practical application has been limited by the fragility of the surface and the cost.

UV embossing makes it possible to obtain large areas of antireflection surface at a price which makes it practical for use in applications such as double glazing, and displays. Not only is the replicated copy far cheaper than the photoresist original but it is also far more robust and is therefore capable of being cleaned.

The structure of the motheye surface is necessarily smaller than the wavelength of light and typically has a period of 200-300 nm. For it to work effectively it is necessary to preserve the shape of these very fine "pimples" and the fact that the optical properties are so well reproduced testifies to the extremely high resolution available from UV embossing.

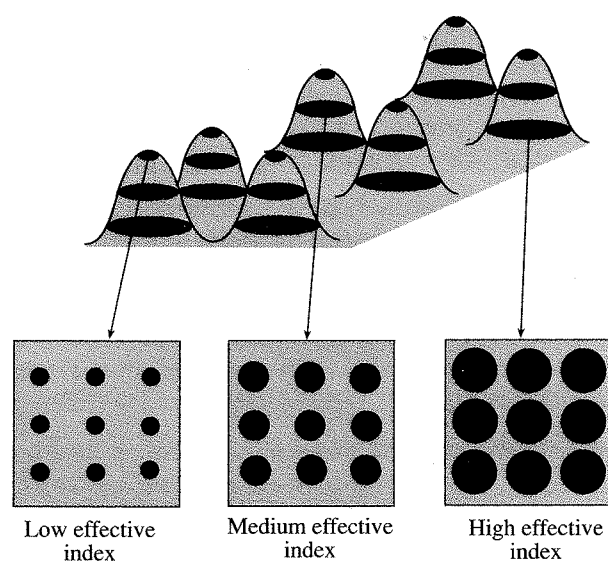
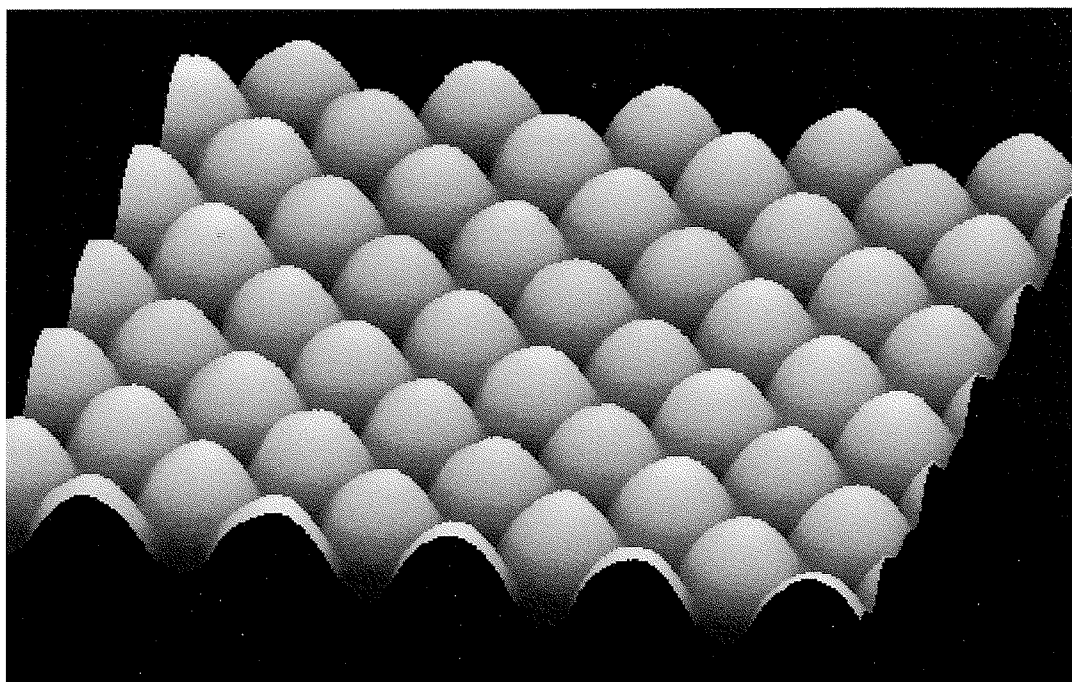


Figure 9: Motheye antireflection surface

4.6 Non-specular reflective surfaces

Autotype International Ltd

The production of non-specular reflective surfaces provides what is commonly known as "Anti-glare" effect. This is a most valuable property for touch screens and similar devices. UV embossing provides an established and successful means for the mass production of this type of surface onto polyester and polycarbonate films.

The surface structure is much finer than for the diffusers in membrane switches. The physical features of the anti-glare surface are fairly broad and of a well-defined shape with an average roughness value of the order of 0.2 μm . This provides both coating transparency and anti-glare behaviour which is of vital importance for use in liquid crystal displays and similar devices.

As with diffusers for membrane switches, much effort goes into producing a robust and carefully engineered master. This provides a reproducibility of the product over millions of metres of coated film in a way that would not be possible with products relying on the effect of fillers dispersed within a polymer matrix.

A high degree of abrasion resistance is required for this class of product, but this must be combined with flexibility. Fortunately there is now available a large range of radiation curable monomers and oligomers so that a skilled chemist is able successfully to formulate coatings with these apparently contradictory properties.

4.7 Microprisms for Daylighting

Autotype International Ltd.

It frequently happens that one would like to redirect the daylight entering a window. For example if the window is close to an adjacent building, only daylight from above will enter the window and that falls on the floor just inside the room. It has long been realised that if the window panes consisted of a series of small prisms, they would direct the light further into the room where it would be better used and would reduce the need for electric lighting and air conditioning.

Such materials have been produced but these have been too expensive to justify their cost on the grounds of energy savings and their use has generally been restricted to prestige buildings. However, if the prism structure is very fine they can be replicated using UV curing techniques at a cost which enables them to be used in common applications such as houses and offices.

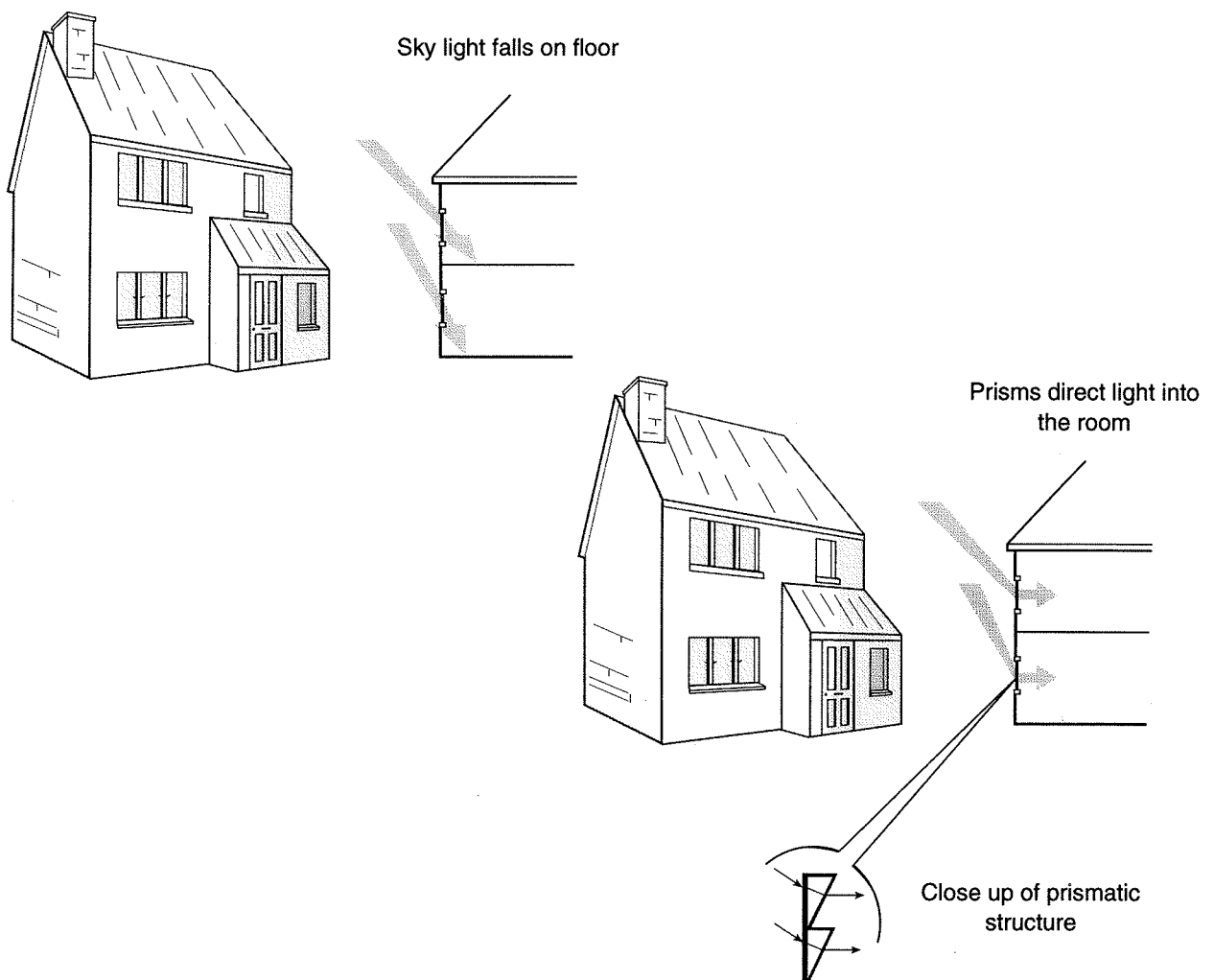


Figure 10: Micro prisms for Daylighting

5 Technical Details of the Process

5.1 How is it done?

The surface to be replicated is produced in glass or photoresist using one of several possible microfabrication techniques. A metal master mould tool is produced from this surface by a high precision electroforming process. For the continuous production of replicated structures, the monomer on a substrate is contacted with the patterned surface, typically a nickel shim attached to a roller. Exposure of the monomer to the UV irradiation through the back of the substrate polymerises the resin whilst in contact with the patterned surface. The polymerisation preserves the embossed features which are retained in the substrate coating when separated from the shim attached to the roller surface.

The polymer film must be sufficiently flexible to pass through a coating line and must be transparent to UV irradiation (wavelength 150 to 450nm). The substrate film is typically polypropylene, polyester, cellulose acetate or polycarbonate and can range in thickness from 12 to 750 μm in thickness. The coating which carries the replicated surface is typically between 3 and 30 μm thick. In applications where the final shape of the replica is important or extra thermal resistance of support is required, a rigid substrate may be used which, for example, could be a glass optical flat.

5.2 How does this process differ from other embossing methods?

In a traditional hot-press embossing process, a block of polymer or sheet of polymer film is heated beyond its glass transition temperature (T_g) until it is compliant enough for an embossing tool to be pressed into it to form the required surface relief. The polymer is then cooled back below T_g to retain the image before the tool is released. The pressures and temperatures involved can be high which produces distortion in the formed film. Furthermore, the properties of the polymer are limited to those few available in melt processable form. In our process the polymer coating is a low viscosity material which can be UV cured to form a highly cross-linked organic network. The process can be run at constant room temperature, with no heating/cooling cycle and at low embossing pressures. This enables us to emboss surface reliefs from sub micron to approximately 30 microns onto a wide range of substrate materials, including thin glass for example. The UV embossing process offers another advantage over hot embossing, where shallow, low aspect ratio features are the norm, in that more thermally stable cross linked polymer embossings are produced with a better brightness factor resulting from sharper resolution.

If structures of the order of several microns to 20 microns are to be replicated, the UV embossing process is preferred since excellent resolution and reproducibility can be achieved in the replicated part.

In some cases mould release treatments enable the polymer material to be cured in contact with the mould itself, thereby ensuring maximum fidelity of reproduction of the surface relief. The volume of polymer material required to form the surface relief can be kept to the absolute minimum so that volume expansion effects are minimised during use.

5.3 What materials are used?

The process uses UV-curable monomers and oligomeric resins selected for their good optical transparency, thermal and environmental stability. A range of materials is available and the choice of which material to use for a particular application is determined by the operating wavelength and refractive index required. Under the influence of UV irradiation, the resin turns almost instantaneously from low viscosity liquid to a hard organic glass. With some materials one can fine tune the refractive index by adding small amounts of index modifier so as to optimise the optical performance of a particular structure. Any modifiers are designed to bind covalently to the polymer network, thereby eliminating variability due to additive migration. The generation of free radicals within the resin from the irradiation results in a highly cross-linked polymeric network which imparts good physical and mechanical properties to the product. Covalent bonds are formed at the polymer to substrate interface to maximise adhesion.

The properties of the replicated film are governed by a number of factors such as polymer chain length, the quantity and nature of the monomers and oligomers, the number of cross-links present and the viscoelastic properties of the material. The chemistry of the polymer will determine flexibility, hardness, rigidity, solvent and acid/alkali resistance as well as optical properties such as clarity, colour and refractive index. Surface properties of the replicated film may be changed by including other components to effect the degree of hydrophobicity/hydrophilicity. Additives may be also incorporated into the resin formulation to impart improved environmental including UV stability.

In optical components where refractive index may be important, combinations of photocrosslinkable resins can be formulated to offer crosslinked film options ranging from 1.45 to 1.55 at 633nm.

5.4 Properties of the film

Below are summarised the main physical and optical properties of a standard material for UV embossing on glass. The coating material used for producing embossed grating structures on a film substrate such as polyester has similar properties.

■ Material type	acrylate photopolymer resin
■ Appearance	clear
■ Form	thin film
■ Glass transition temperature	80°C
■ Water uptake after 24 hrs in water.	0.09%
■ Thermal expansion	$100 \times 10^{-6} \text{ K}^{-1}$
■ Adhesion	Good adhesion to glass, quartz, polycarbonate
■ Optical transparency	Excellent over range 400 to 1650 nm. (see spectrum)
■ Refractive index	Between 1.45 - 1.55 at 633 nm
■ Dispersion	Abbe Number = 62
■ Hardness	Vickers Hardness 8 (4H pencil)
■ Climate resistance	(No change after 20 hrs at 95°C/98% humidity or 1 week at 70°C/98% humidity).
■ Chemical resistance	Resistant to acids, alkalis, keytones, alcohols etc.

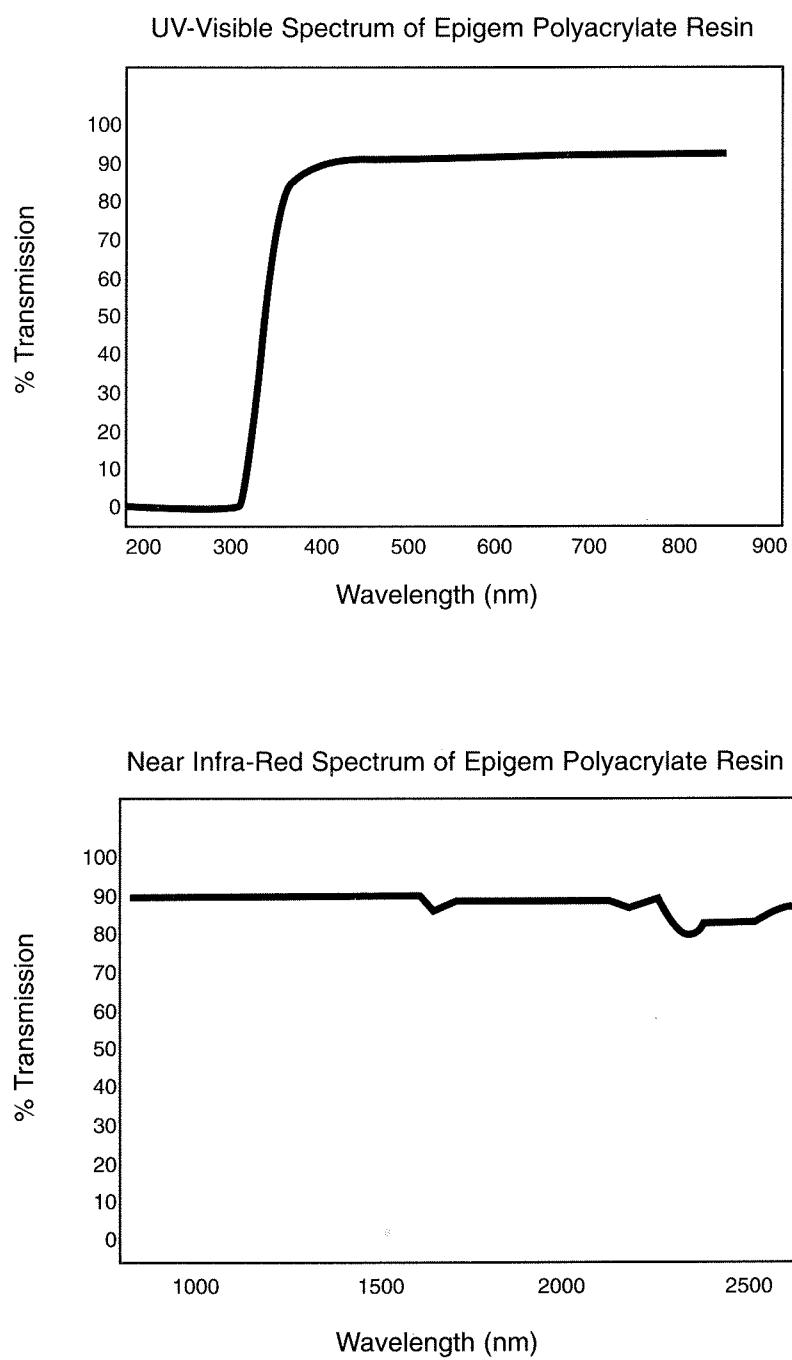
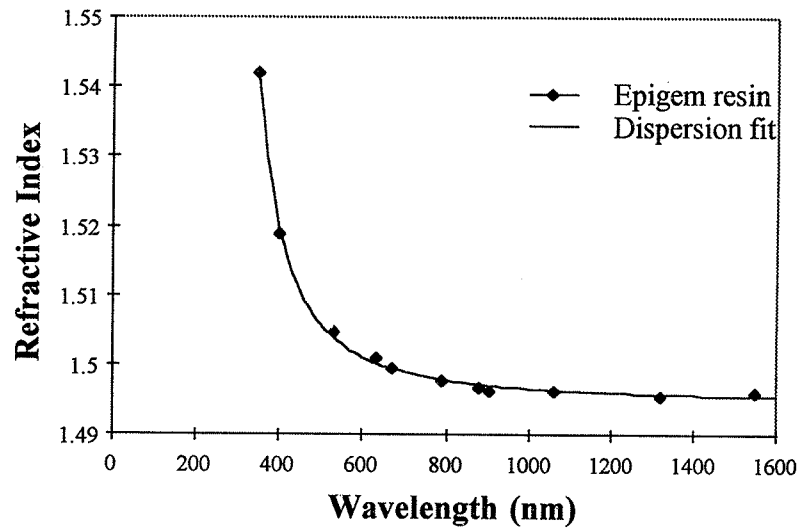


Figure 11: Spectrum of UV cure acrylate resin



$$n(\lambda) = n(\infty) + A/(\lambda^2 - \lambda_0^2) + B/(\lambda^2 - \lambda_0^2)^2$$

where $n(\infty)=1.495$; $\lambda_0=231$ nm ; $A=1.55 \times 10^3$; $B=1.17 \times 10^8$

Figure 12: Refractive index with wavelength

5.5 Capabilities of the process

- In plane resolution
 - Better than 200 nm.
- Aspect ratio
 - Up to 4:1 at 500 nm pitch.
- Excellent profile retention
- Suitable for large scale replication
(Millions of m² per annum)
- Maximum size (currently available).
 - Width 1250 mm - flexible substrate for use with rollers.
 - 350 mm x 450 mm on glass.

5.6 What size of surface can be produced?

Current prototype equipment is available for coated film widths of up to 365 mm for embossings on a flexible substrate. On glass, it is possible to replicate patterns up to 250 mm wide and 450 mm long as standard. It is however possible to manufacture larger moulds, their size being limited by the area of the original master part. For large scale production it is currently possible to cater for a width of 1.2 m with runs of several kilometres.

What is the smallest lateral feature size that can be reproduced?

A wide range of surface relief holograms which have features as small as 0.5 μm have successfully been reproduced. Motheye antireflection surfaces have periods as small as 200 nm. The fact that the form of the grooves has been faithfully copied suggests that features as small as a few nm can be reproduced.

5.7 What depth of surface relief can be achieved?

The maximum depth of the relief is limited by the thickness of the polymer coating that can be applied. Relief heights of up to 0.1 mm are possible. Standard relief heights would be in the range 0.5 to 20 μm . The shallowest relief produced so far is 0.12 μm deep and the deepest about 100 μm (0.1 mm).

5.8 What is the flatness of the surface after embossing?

Experiments have shown that with careful control the process does not significantly degrade the flatness of rigid substrates because the embossing mould conforms to the surface of the substrate during the embossing process and the overlayer of polymer resin between the substrate and the base of the embossed structure is less than 0.5 mm thick.

SELECTION FLOWCHART FOR UV EMBOSSING

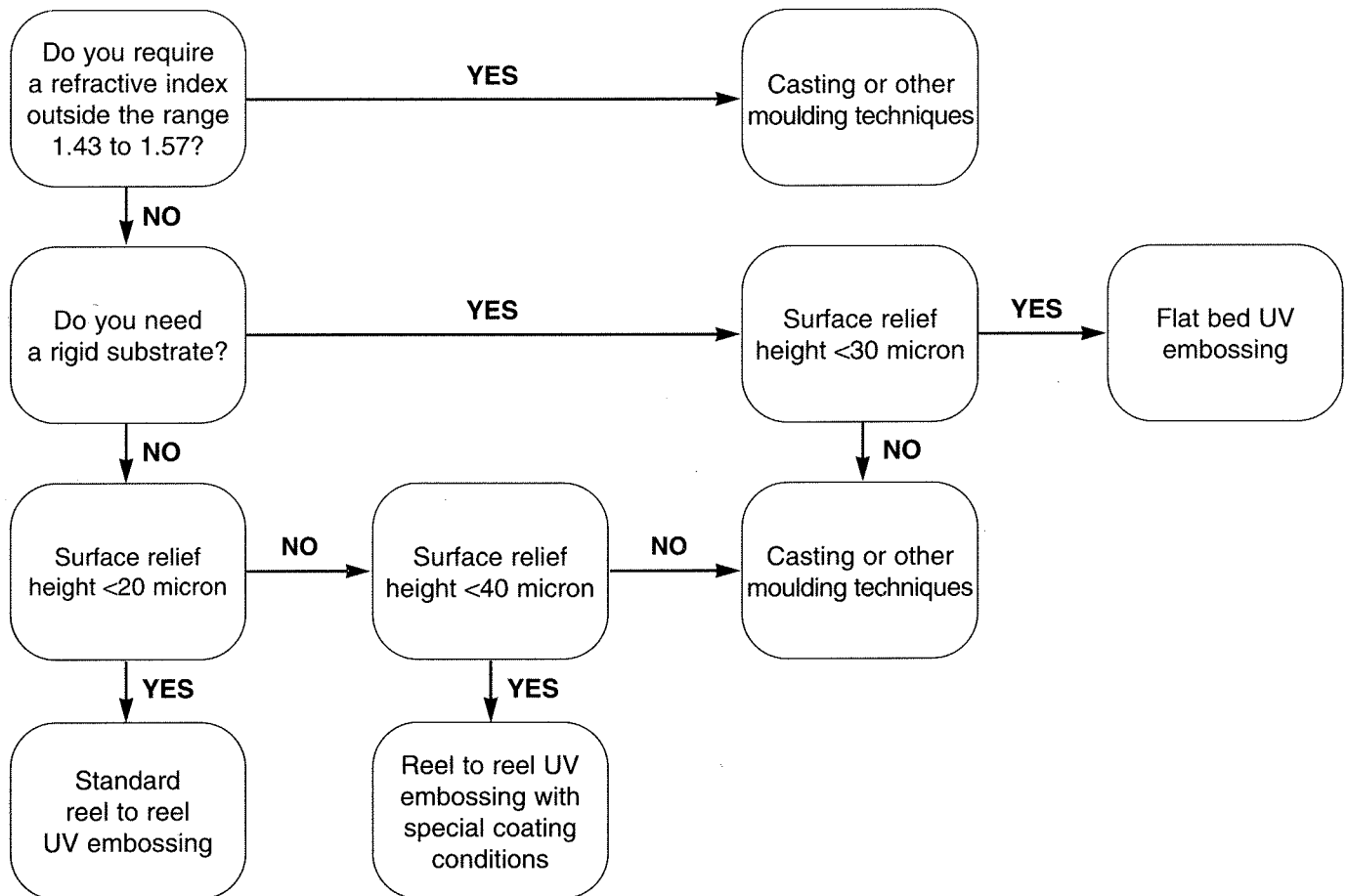
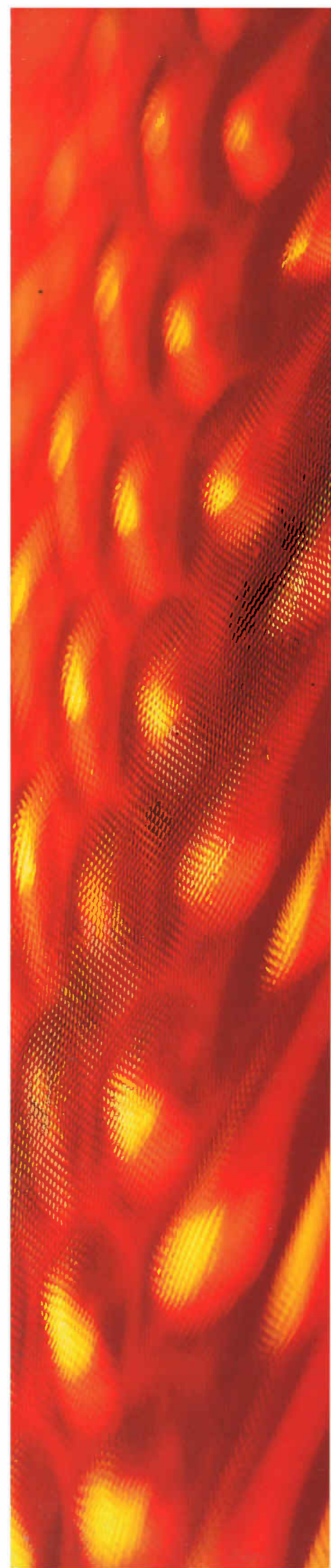


Figure 13: Flowchart for UV embossing



Recommended sale price £15.00