Fachverband Konstruktiver Glasbau e.V.

Technical Note FKG 01/2019

The visual quality of glass in building – anisotropies in heat treated flat glass

Date: May 2019

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All the information in this Guidance Sheet has been compiled to the best of our knowledge and belief. Please note that we are not liable for the accuracy, validity and completeness of the information provided. In particular, the content of this Guidance Sheet does not replace the technical advice given in individual cases.

1. Introduction

The term “anisotropies” has become an issue for architects, glass processors, façade constructors and clients in the context of heat treated flat glass. Although product standards and visual inspection guidelines do not define anisotropies (iridescences) as a justifiable defect, architects, clients, façade consultants and increasingly users of buildings view this effect as a visual defect (Figure 1). As a result the reduction of anisotropies is receiving increasing attention and is a key issue in seminars and presentations given at national and international specialist conferences. Another reason for this is new inline measurement methods (scanners) to detect and visualise anisotropies.

Bild 1 Anisotropies under (partially) polarised daylight (source: University of Applied Science Munich)

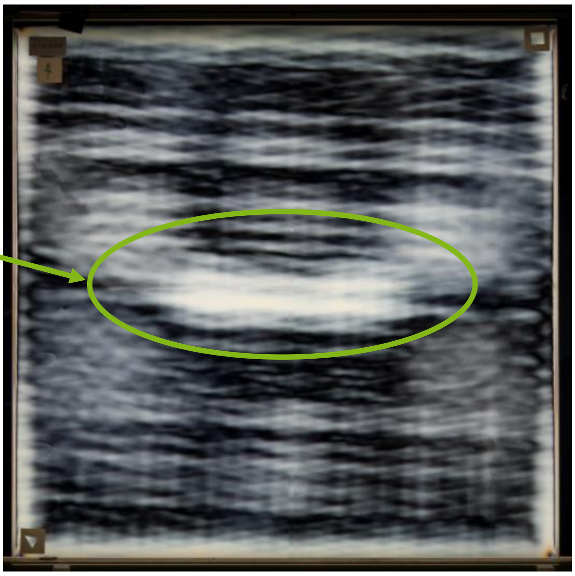


Bild 2 Anisotropies in the polariscope under maximum polarisation (source: University of Applied Science Munich)

The progress made in developing quantitative measuring systems is gradually enabling a method for the objective evaluation of anisotropies. The main contributions to this development are current and completed cooperative research projects by the RWTH Aachen University (RWTH), the University of Applied Science Munich (HSM) and the Technical University Darmstadt (TUD) as well as association activities in the Fachverband Konstruktiver Glasbau e. V. (FKG) (Structural Glass Design Trade Association) [1].

2. Anisotropy in standards, rules and regulations

According to national and international product standards, guidelines and regulations [2 - 5] for evaluating the visual quality of glass, anisotropies are not defined as irregularities or defects, but as visible effects or characteristics of toughened and heat strengthened glass, which are excluded from the criteria for evaluating visual quality.

3. Anisotropy – what is it?

The visual transparency of glass has made it a preferred material of choice in buildings. Glass is an isotropic material with identical physical properties in all directions. Internal (thermally induced) and external (load induced) stress, however, transform glass into a birefringent material with direction-dependent optical (anisotropic) properties. When polarised light enters an inhomogeneously heat treated glass sheet, visible iridescence phenomena are likely to appear in the form of grey, white or rainbow-coloured spots, rings or stripes as characteristic patterns in the glazed façade (Figure 1 and Figure 2). This phenomenon is called anisotropies and can be explained with the help of photoelasticity [6].

4. How do anisotropies develop?

4.1 General

Anisotropies result from residual stresses due to a non-homogeneous thermal toughening process and become visible to the human eye under polarised light and a special observation. When polarised light (see Section 4.3) enters a glass pane, upon entering the glass the light is split into two partial beams parallel to the principal stresses σ_1 and σ_2. If these principal stresses differ, the two partial beams travel at different speeds in the glass, creating a path difference when the beams exit the pane. This difference in the light paths is called path difference or retardation s. As the human eye perceives the retardation as interference colours (Figure 3) the retardation is directly related to visible anisotropies. The variation of the retardations/interference colours over the glass surface generates the typical anisotropic pattern (Figure 2).

Bild 3 Interference colour chart according to Michel-Lévy (analytical calculation) [7]

The retardation s depends on the photoelastic constant C of the glass and the integral of the principal stress difference σ_1 - σ_2 over the pane thickness d.

$$s = C \int_d \left(\sigma_1(z) - \sigma_2(z)\right) dz$$

s	retardation [nm]
C	photoelastic constant in [TPa^{-1}]
$\sigma_1 - \sigma_2$	principal stress difference in [N/mm²]
d	glass thickness in [mm]

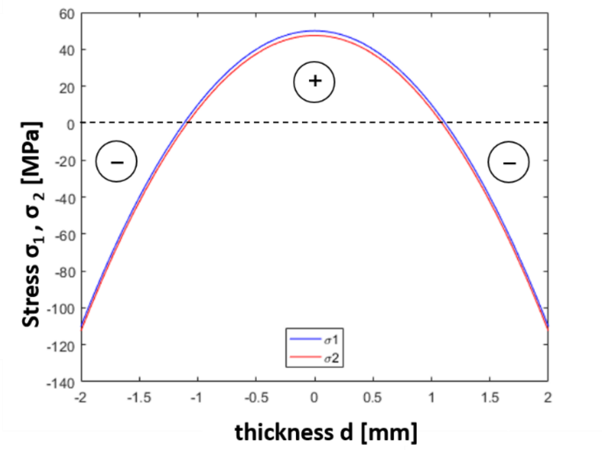
Formula 1: retardation [7]

4.2 Inhomogeneities in the production of heat treated glass

Thermal toughening increases mechanical strength and thermal shock resistance. This is usually achieved by heating a glass sheet in the toughening furnace to approx. 620 °C. The glass enters the furnace in a horizontal position on ceramic rollers and oscillates continuously during the heating process. This is followed by rapidly cooling the glass down to ambient temperature in what is known as the quenching area of the furnace to cause residual stresses to form in the glass. Typical cooling systems feature an array of rollers and cooling nozzles. The objective of the toughening process is to uniformly heat and cool down the two glass faces. The purpose of the large number of cooling nozzles and the oscillation of the sheet during toughening is to ensure uniform heat transfer and hence a direction-independent homogeneous residual stress profile (Figure 4) through the entire glass sheet. This cannot be fully achieved, however, because

- some areas of the glass sheet (e.g. edges, corners and holes) cool down faster than others (e.g. surface, centre, prints).
- heating and cooling of the glass sheets is not absolutely homogeneous due to the inevitable contact of the glass surface with the rollers and the layout of the rollers and air nozzles in the furnace.

The greater the temperature difference in the glass surface (Figure 5), the greater the resulting stress differences and optical anisotropies. This process does not allow the production of glass sheets without anisotropies.



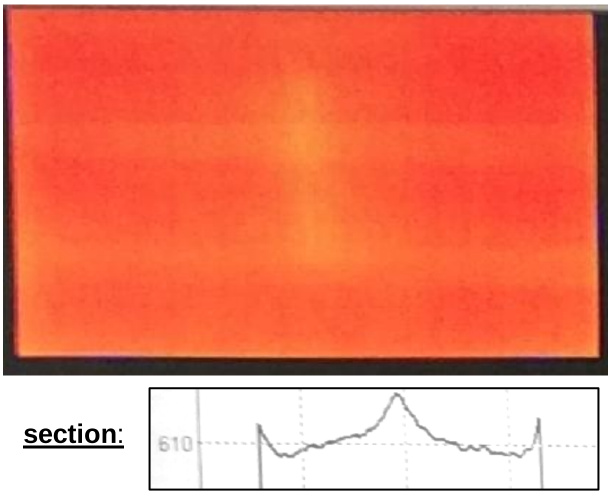


Bild 4 Sample toughening profile with 2.5 MPa stress differences at a discrete point in the glass surface (source: HSM)

Bild 5 Surface temperature scan before cooling with higher temperatures in the centre of the pane (source: anonymous)

4.3 Polarised light

Polarised light vibrates as an electromagnetic wave in a specific direction. Normal daylight contains polarised light fractions. They result from scattering of sunlight by air molecules in the atmosphere (Rayleigh scattering) or from light reflection by dielectric media such as large bodies of water or surrounding buildings with large glazed areas. The light is reflected at a specific incident angle, what is known as Brewster's angle αB (Figure 6), and is linearly polarised perpendicular to the beam direction [8].

Polarised light is divided into linearly, elliptically and circularly polarised light depending on the vibration mode [6]. Linearly polarised light vibrates only in one defined direction. If the vibration direction is a function of the incident light plane, the latter can be divided into two vectors perpendicular and parallel to the beam direction of the polarised light. In addition, circularly polarised light rotates in the direction of propagation. Natural light contains mainly the mixed form, elliptically polarised light. The amount of polarised light in daylight is referred to as the degree of polarisation [%].

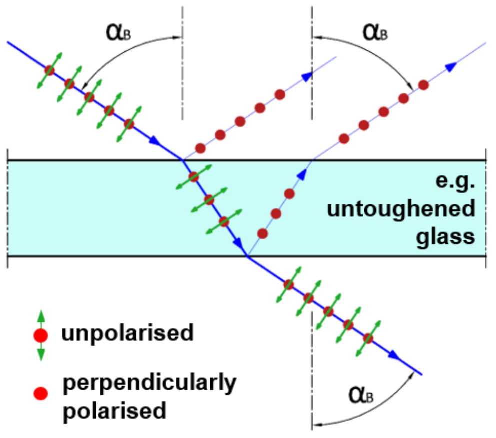


Bild 6 Formation of polarised light at Brewster's angle αB (source: HSM based on [8])

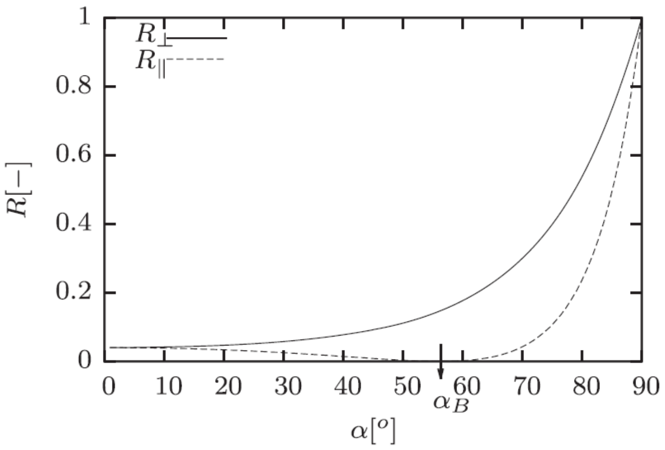


Bild 7 Reflection coefficient R as a function of the incident angle α [8]

4.4 Perception of anisotropic effects

Based on the laws of photoelasticity [6], in addition to polarised light and a birefringent medium, an analyser is required for the perception of anisotropies. The perception of iridescences in the natural environment depends strongly on the viewing angle if no optical devices, such as polarisation filters or sunglasses with polarising lenses are used as analysers. The intensity of the reflecting parallel light beam at Brewster's angle αB, which is ~56° for glass, is close to zero (Figure 7). Due to reduced reflection, anisotropic effects are most visible under parallel polarised light at an angle close to Brewster's angle (Figure 8).

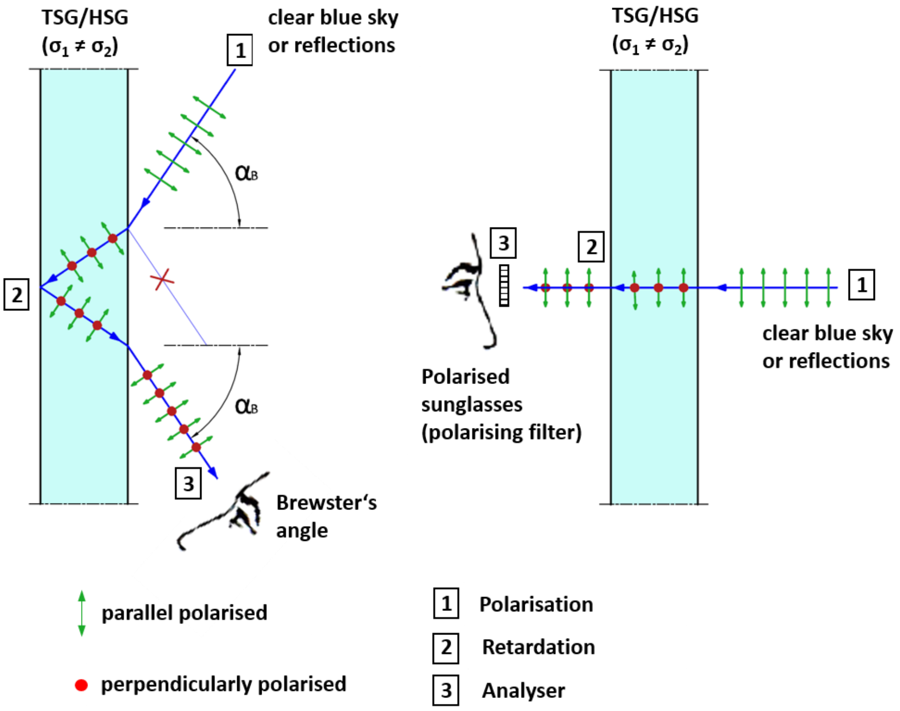


Bild 8 Scenarios for seeing anisotropies (source: HSM)

5. Parameters which affect the probability of visually perceiving anisotropies

In addition to the formation conditions described in Section 4, the parameters listed below (Figure 9**Fehler! Verweisquelle konnte nicht gefunden werden.**) have a significant influence on the visual perception of anisotropies. The more aspects or effects which occur simultaneously, the greater the probability that anisotropies are visible in the façade.

5.1 Glass type

Anisotropies appear only on heat treated glass (TSG [toughened safety glass] / HSG [heat-strengthened glass]). With annealed glass, there is usually no risk of this effect occurring. As mentioned previously, the quality of the toughening process plays a major role. However, compliance with additional technical characteristics, e.g. fracture pattern und mechanical strength set out by the relevant standards for glass products limits the possibility of reducing visible anisotropies.

5.2 Glass configuration and glass thickness

Processing heat treated glass into other glass products including laminated safety glass (LSG), insulating glass units (IGU) and coated glass increases the visual perception of anisotropies, for example due to the following parameters:

- increasing thickness of the glass panes
- change in transmission and reflection (e.g. by coatings)
- increasing number of heat treated glass sheets installed in a glass product
- special pane geometries, in particular acute angles, recesses and holes
- use of rigid lamination layers under certain conditions

5.3 Building surroundings

Location and context in terms of natural and urban surroundings of the building play an important role and may lead to a higher probability of anisotropies becoming visible. Reflected daylight (see Section 5.4) can increase the amount of polarised light (degree of polarisation) and the visibility of anisotropies. Buildings located close to the sea, lakes, rivers, snow-covered areas or other highly reflective surfaces will be exposed to greater amounts of polarised light resulting in greater visibility of anisotropies. Anisotropies are also likely to be more visible in high-rise buildings where façades are exposed to direct sunlight / the sky. This is partly due to the greater amount of partially polarised daylight resulting from Rayleigh scattering (see 5.4) and to the greater probability that more glazed façade sections are viewed at Brewster’s angle (see 5.5 and Figure 8).

5.4 Degree of polarisation of incident light

Section 4.3 describes the formation of polarised light. The degree of polarisation from Rayleigh scattering varies with the incident light angle and with the position of the sun relative to the glazing [8]. On days with a very clear blue sky it is higher than on days with a cloudy sky. The highest amount of polarised light in the atmosphere resulting from scattering occurs at low solar altitude. The degree of polarisation of light rays reflected by a dielectric medium (e.g. glass or water surface) is dependent on the angle of incidence of unpolarised light and is highest at Brewster’s angle (Figure 6 and Figure 7).

5.5 Viewing conditions

As mentioned, the viewing angle is crucial for the perception of anisotropies. They become more visible when the viewing angle is flatter and not perpendicular to the glass façade. Sunglasses with polarising lenses increase the visibility of anisotropies and reduce reflections, reinforcing the effect independently of the viewing angle (see 4.4).

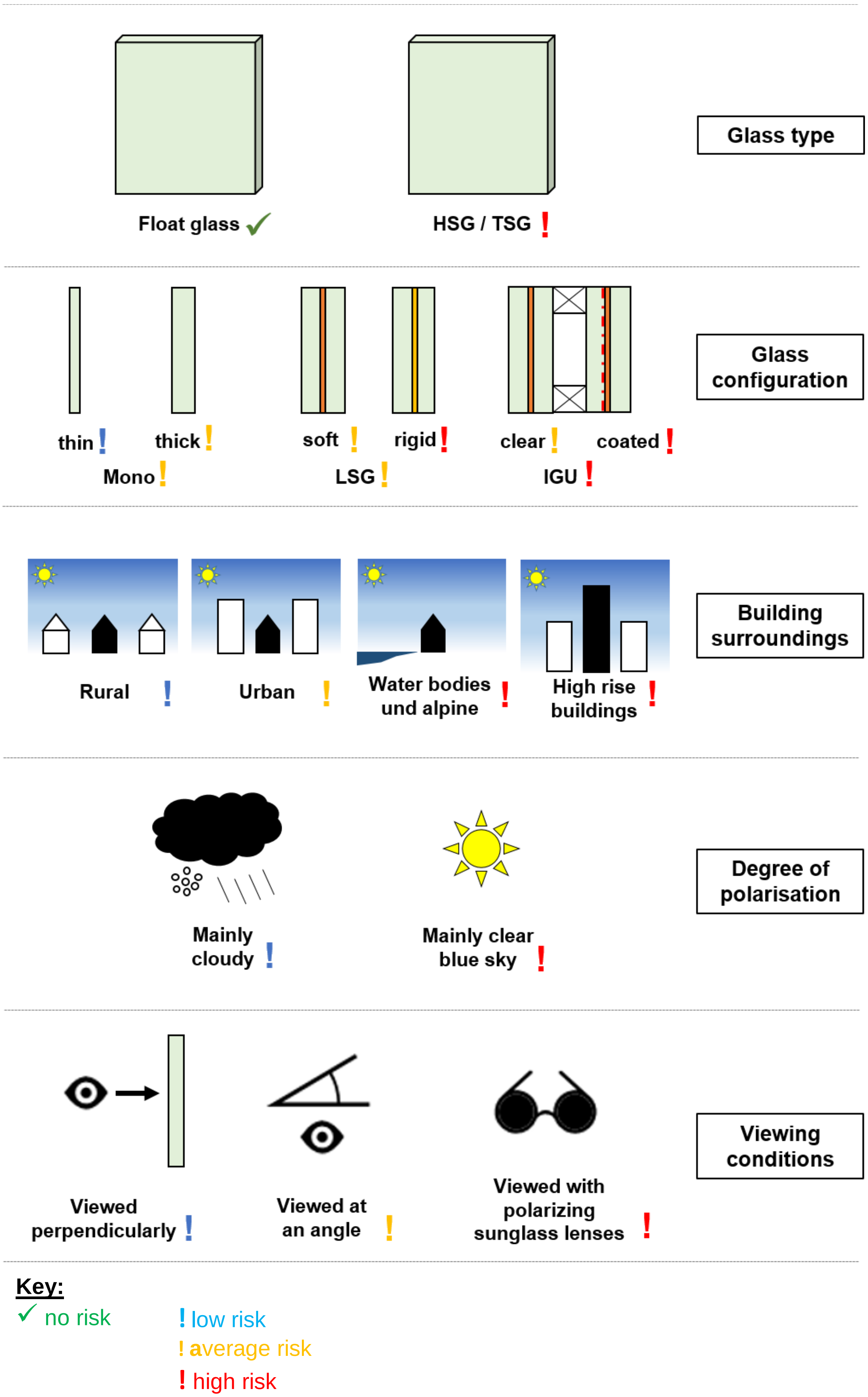


Bild 9 Probability of visual perception

6. Options for measuring anisotropies during the production process

In addition to the research-based measurement systems [10] used for the tests described in the Annex, there are now industrial measurement systems for quantifying the path differences or retardations associated with anisotropies [see 4.3.1]. These path differences can be determined by measuring the homogeneity of the formed residual stresses after processing to heat strengthened or toughened safety glass. The ideal approach is the inline measuring method (anisotropy scanner) which is used when the glass sheets exit the quenching area of the toughening furnace (Figure 10). This allows the assessment of anisotropies under consistent ambient conditions. These methods for measuring optical retardations are recommended by studies carried out by universities, trade associations and industry.

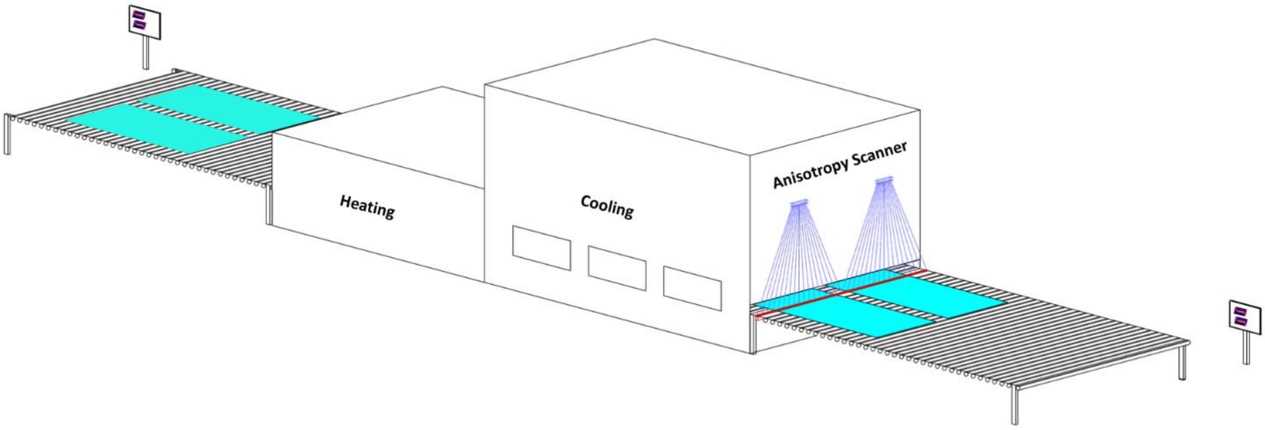


Bild 10 Schematic diagram of the layout of an inline anisotropy scanner at the exit of a tempering furnace (source: HSM)

7. Assessment of the visibility of anisotropies

As perception of anisotropies is influenced by the surrounding environment, the latter should be included as much as possible in the visible evaluation of "anisotropy visibility“. It is therefore recommended to evaluate the Visual Mockup (VMU) in the specific context of the project location. The viewing conditions must be agreed at an early stage by the parties involved in the project (architects, clients, consultants, façade designers, façade constructors, general contractors, glass processors) and documented when inspecting the VMU.

This enables those involved in the project to use the VMU to identify and document the risk of visible anisotropies at an early stage. Quantitative measurements via inline or offline measurement systems can be agreed with the glass processor as an objective evaluation criterion for the panes of the test façade and the project-specific panes (see Section 6). If during project acceptance there is disagreement on the evaluation of anisotropies, the measurement results can be compared together with the glass processor.

Anhang A …

The participants in the Anisotropy project of the Facade Technology Working Group (Arbeitskreis Fassadentechnik) of the FKG started work in mid-2016. The interim status described here gives an insight into the research results obtained so far.

A.1 Start and description of experimental research

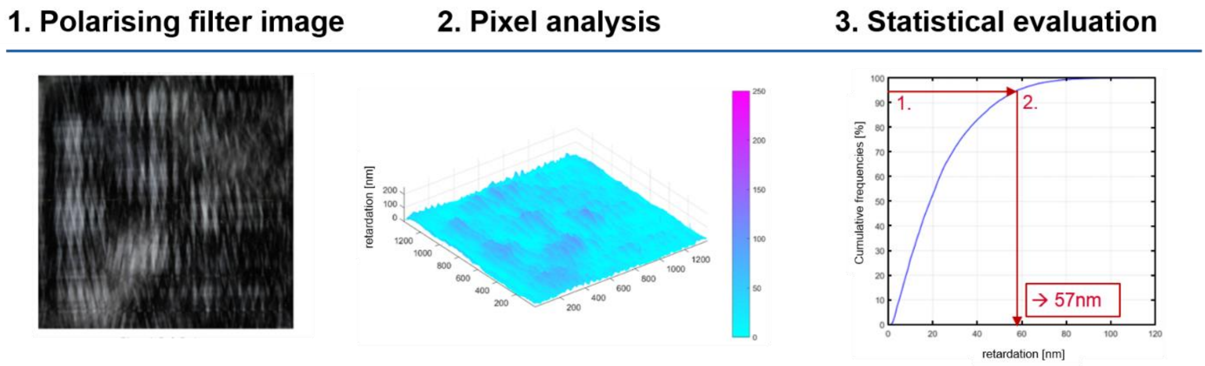
The participants agreed that a general evaluation guideline is possible only on the basis of uniform and objective evaluation criteria. The participating research institutions therefore proposed producing sample panes, subjecting them to suitable quantifiable measurement methods at the universities (RWTH, HSM) and then discussing the findings in the working group. The participants agreed that monolithic uncoated glass panes should be evaluated as a first step. The following matrix (Table 1) was drawn up for sample preparation:

Table 1 Matrix for test samples (width x height = 1.0 m x 1.0 m)

Glass processors:	7		
Glass type	clear float + low iron		
Glass thickness:	6 mm + 12 mm		
Toughening	HSG + TSG		
Edge finishing:	smooth ground edge		
Number per type:	2 samples		
Total number:	7 * 2 * 2 * 2 *2 = 112 pcs.		

The measurement methods for full-surface detection of anisotropies developed by the RWTH Aachen and the HSM Munich are based on the physical principles of photoelasticity [6] and the further development of digital image processing [9]. Photoelasticity uses the polariscope to visualise full-surface stress differences occurring in birefringent media by means of optical filters (polarising filters and retardation plates). Only circular polarising filters [6] allow extraction of the path difference (retardation) from the digitally generated images known as isochromatic images.

The directionally independent isochromatic images provide objective and reproducible measurement results under 100% polarisation. The HSM and RWTH have developed stationary offline measurement systems to evaluate heat treated glass sheets by measuring the retardations with stochastic variables. A detailed description of the two measurement methods is provided in [7] and [10]. After producing the isochromatic images, the steps are as detailed below:



- Read-in polarising filter image
- Algorithms analyse each pixel → assignment of retardation
- Statistical evaluation using cumulative frequencies

Bild 11 Steps with algorithms and statistical evaluation

The measurement methods are based on detection of the path difference (retardation) of the entire glass surface to pixel accuracy and evaluation by statistical methods. The glass was evaluated using the 95% quantile value. This means that the retardation [nm] is below this value for 95% of the analysed surface. The fewer anisotropies displayed by the pane, the lower its quantile value.

A.2 Current status of experimental research

As described above, 112 uncoated samples with dimensions 1.0 m x 1.0 m were tested by the research institutions. In a subsequent test another 36 samples (manufacturer X) were tested and measured. Figure 12 shows the results for all evaluated samples.

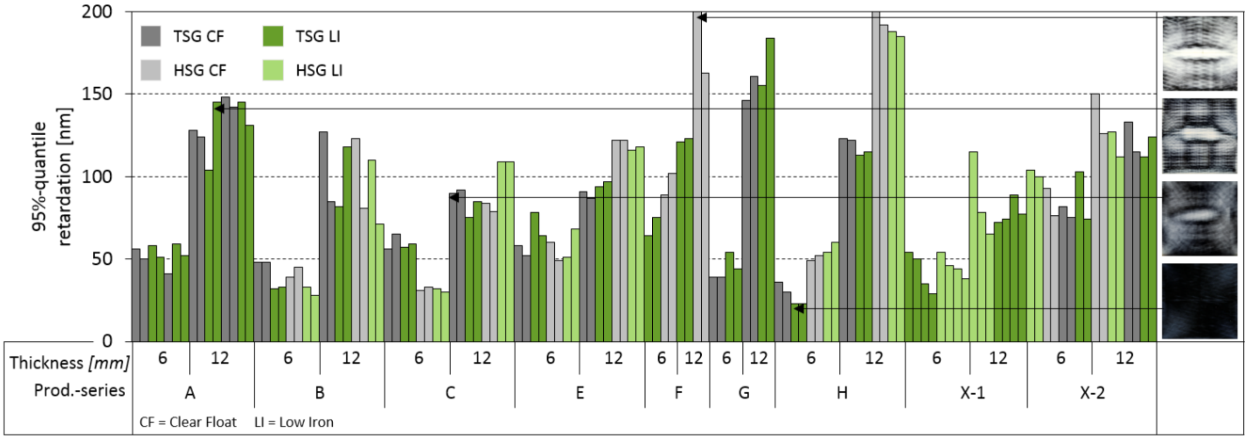


Bild 12 Uncoated samples (1.0 m x 1.0 m) – NO REFERENCE VALUES

The following laws were established during the tests:

- Differences depending on glass processor (quantile value and pattern)
- Thickness dependency: the thicker the glass pane the greater the retardation (retardation)
- No clear relationship could be detected between the degree of tempering (heat strengthened glass or toughened safety glass) and the retardation values.

A.3 First visual evaluation of the tested samples

The findings shown in Figure 12 were presented at the 4th meeting of the “Anisotropy” Façade Technology Working Group in Plattling and compared by visual inspection in daylight.

On the day of the meeting the requirements for a high degree of polarised light were met. The visual subjective inspection was conducted from 10.15 am under a cloud-free blue sky (see Figure 13).

Nine different heat treated glass panes from the production series A, B, C and X had been selected and installed in Interpane’s sample façade rigs. To evaluate the glass panes, the rig could be moved with an industrial truck to change the incident angle of sunlight and the viewing angle.

Bild 13 Subjective evaluation without optical devices

The glass panes were viewed at Brewster's angle. Subjective evaluation was classified into "conspicuous" and "good" glass sheets. This classification by visual criteria in the subjective evaluation correlates with the previously quantified measurement values. This finding is documented in Figure 14.

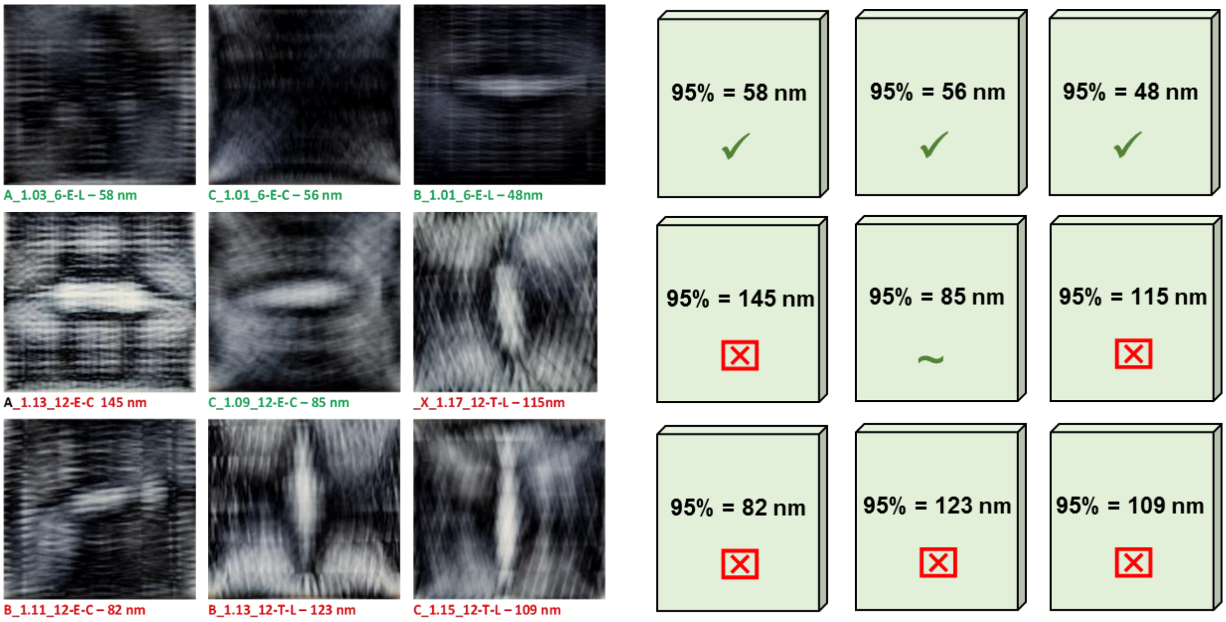


Bild 14 Quantitative measurement (left) versus subjective evaluation (right)

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