Minimization of Annealing Costs by Automatic Measurement of the Residual Stress Distribution

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Overview

- Motivation for stress measurement
- Measuring principle
- Automatic measurement
- Optimization of the annealing process

ilis gmbh

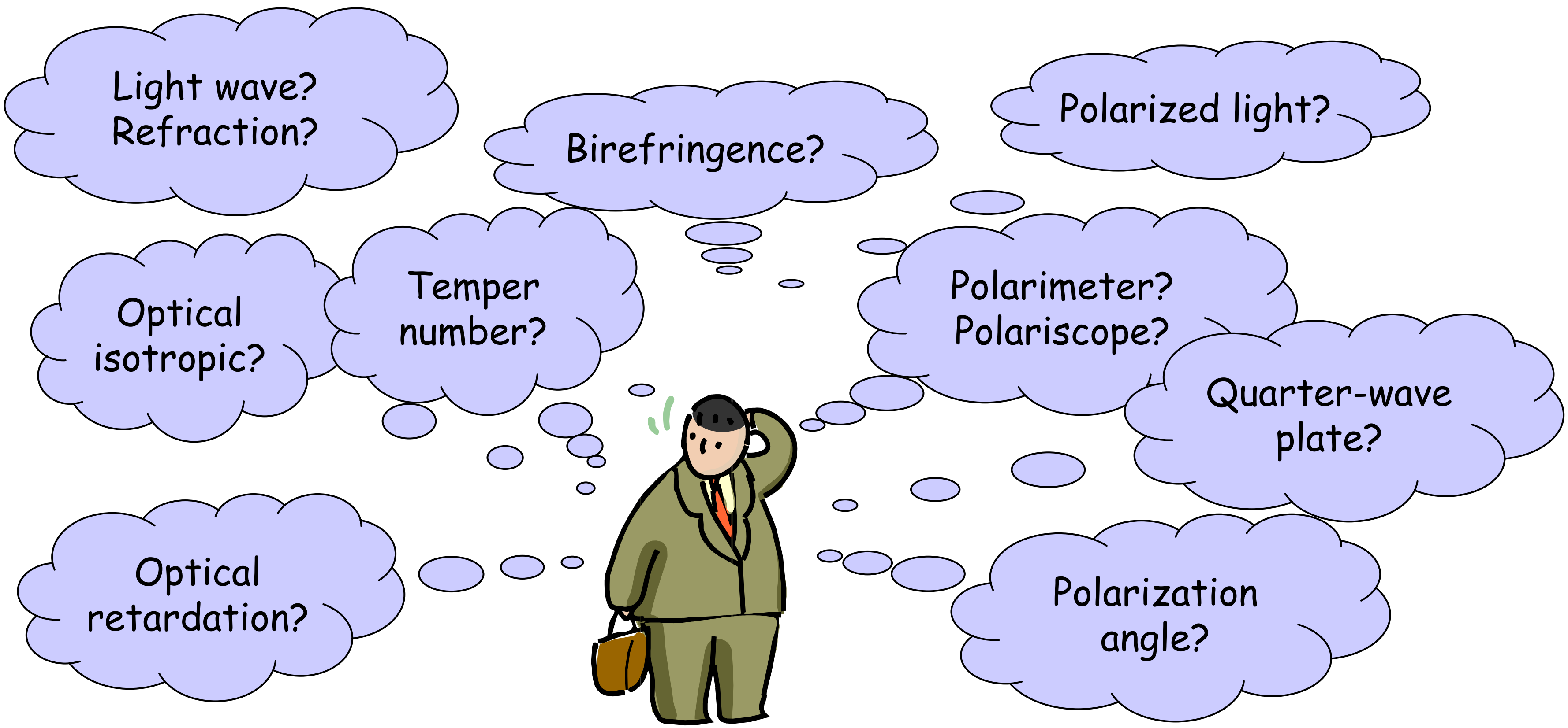
- Products and services for the glass and packaging industry
- Founded 1998 in Clausthal-Zellerfeld, based in Erlangen, Germany since 2001
- Privately owned and financed
- Main activities and products:
  - Measurement of glass color:
    PRISMA Software Package & **SmartSpec** Spectrometers
  - Batch calculation/glass property prediction:
    BatchMaker® Software Package
  - Measurement of residual stresses birefringence:
    StrainMatic® Polarimeter Systems
  - Corporation-wide operational data management:
    GLASDATA (developed for Saint-Gobain Oberland)

Motivation for Stress Measurement

- The strength of glass products and their ability to be processed is influenced strongly by mechanical stresses
- If at all, residual stresses are often determined using simple polariscopes (acc. to ASTM C148-00)
  - ☹ imprecise, subjective measurement
  - ☹ problematic for colored glasses
  - ☹ no automatic documentation of results

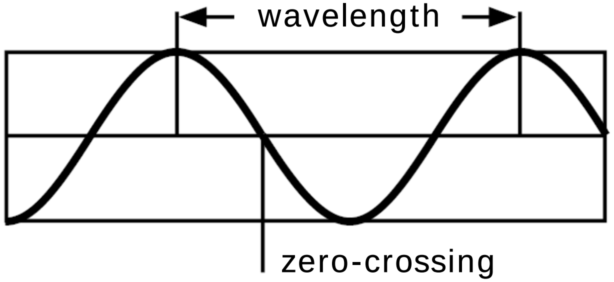
- Advantages of automatic measurement:
  - ☺ objective (i.e. operator-independent) and reliable results
  - ☺ measurement independent of product characteristics such as color
  - ☺ a precise measurement is a prerequisite for optimization of the annealing process (no control without measuring)

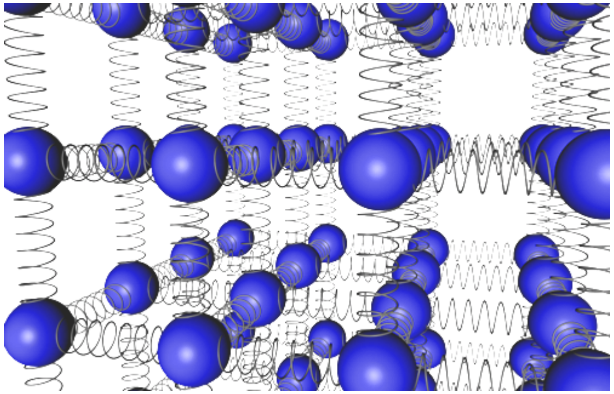
Fundamentals of Photoelasticity



What is Stress Birefringence?

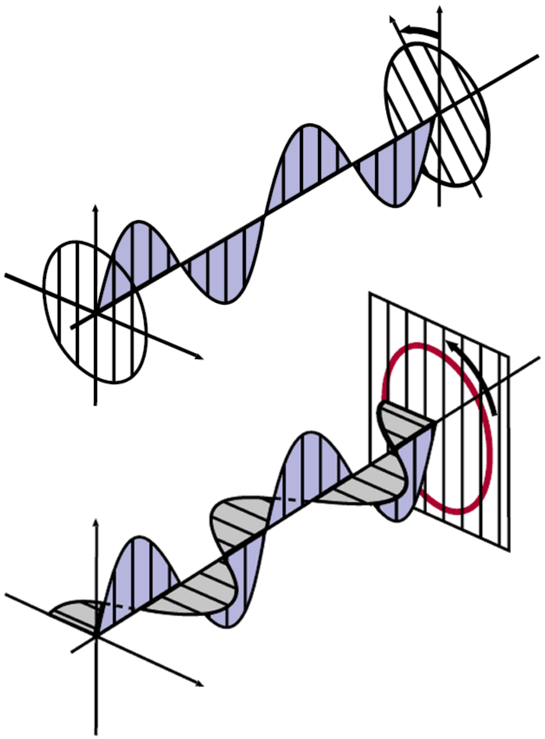
- **Light** is an electromagnetic wave that activates the oscillation of atom electron shells in a material; this in turn produces light.
- The **velocity of light** in a material depends on the particle density.
- The **refractive index** is the ratio of the velocity of light in vacuum and in material: $n = c/v$ (for CaNaSi-Glass: n ~ 1,5).
- **Mechanical stress** leads to deformation of the material structure and therefore changes the distance between the particles
- If the velocity of light (and therefore the refractive index) differs in different directions in space the material is called **birefringent**.
- Glass normally is **optically isotropic** but becomes birefringent when put under stress.

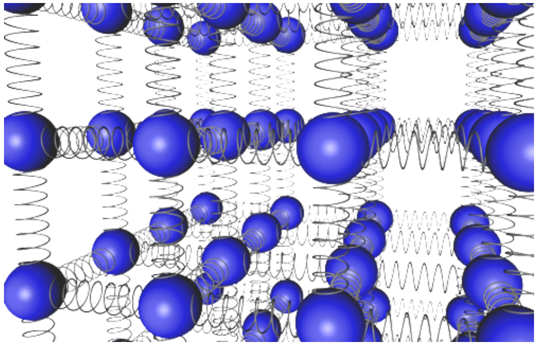




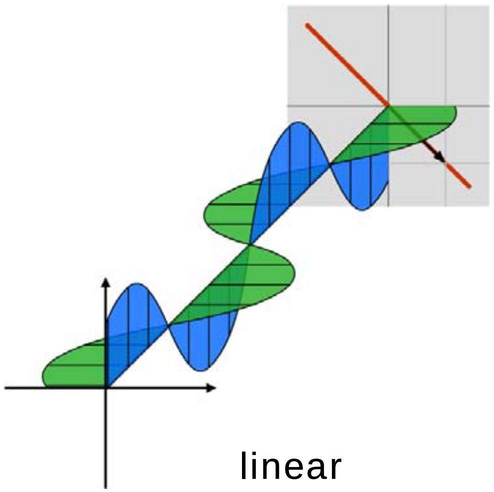
Polarized Light

- If the electric field of the light oscillates only within one plane the light is called **linearly polarized**.
- A (linear) **polarizer** only lets the light waves that are orientated parallel to its optical axis pass and thus creates linearly polarized light.
- In a birefringent material the light waves spread with different speed in the horizontal and vertical direction which results in **optical retardation**.
- Linearly polarized light leaves a birefringent material as a superposition of two light waves at right angles to one another with different phase.
- If the optical retardation is exactly a quarter of the wavelength the light is called **circularly polarized**.
- In general, the departing light is **elliptically polarized**. The ellipticity is a measure of the optical birefringence.

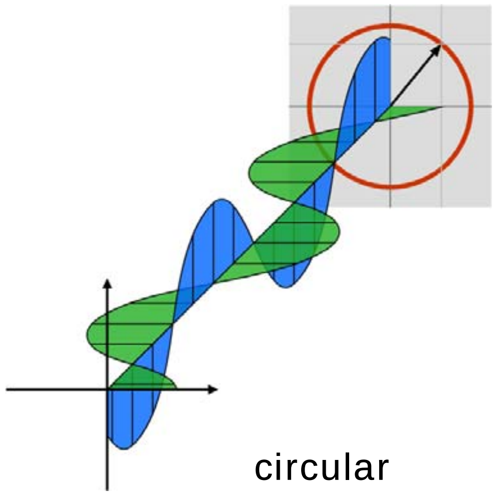




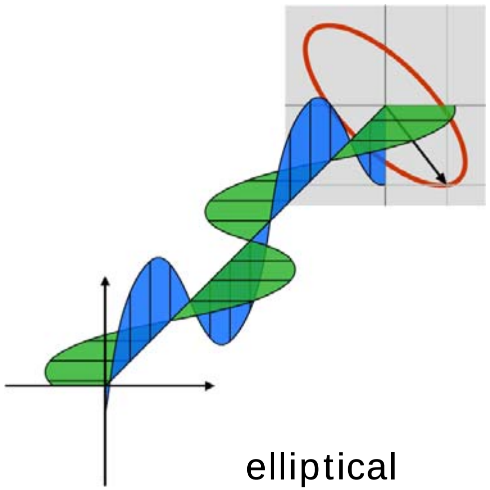
Polarized Light - Visualization



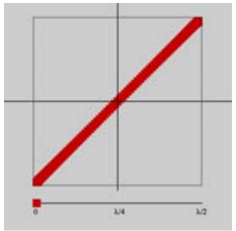
linear
polarization



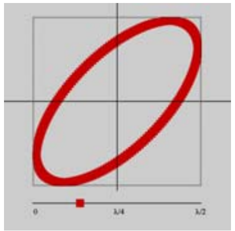
circular
polarization



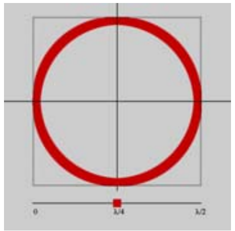
elliptical
polarization



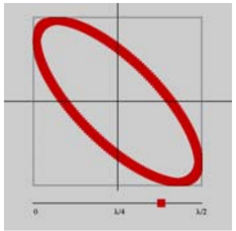
0 λ
(linear)



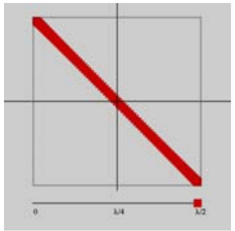
1/8 λ
(elliptical)



1/4 λ
(circular)

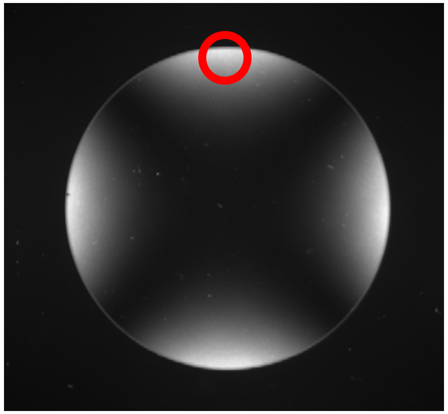


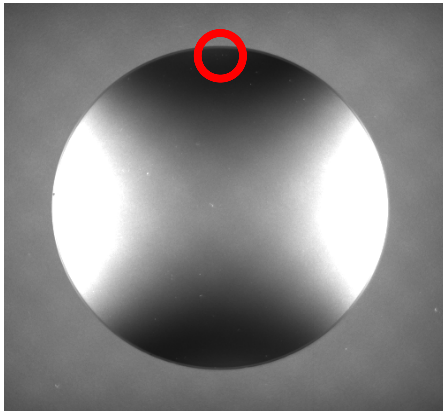
3/8 λ
(elliptical)



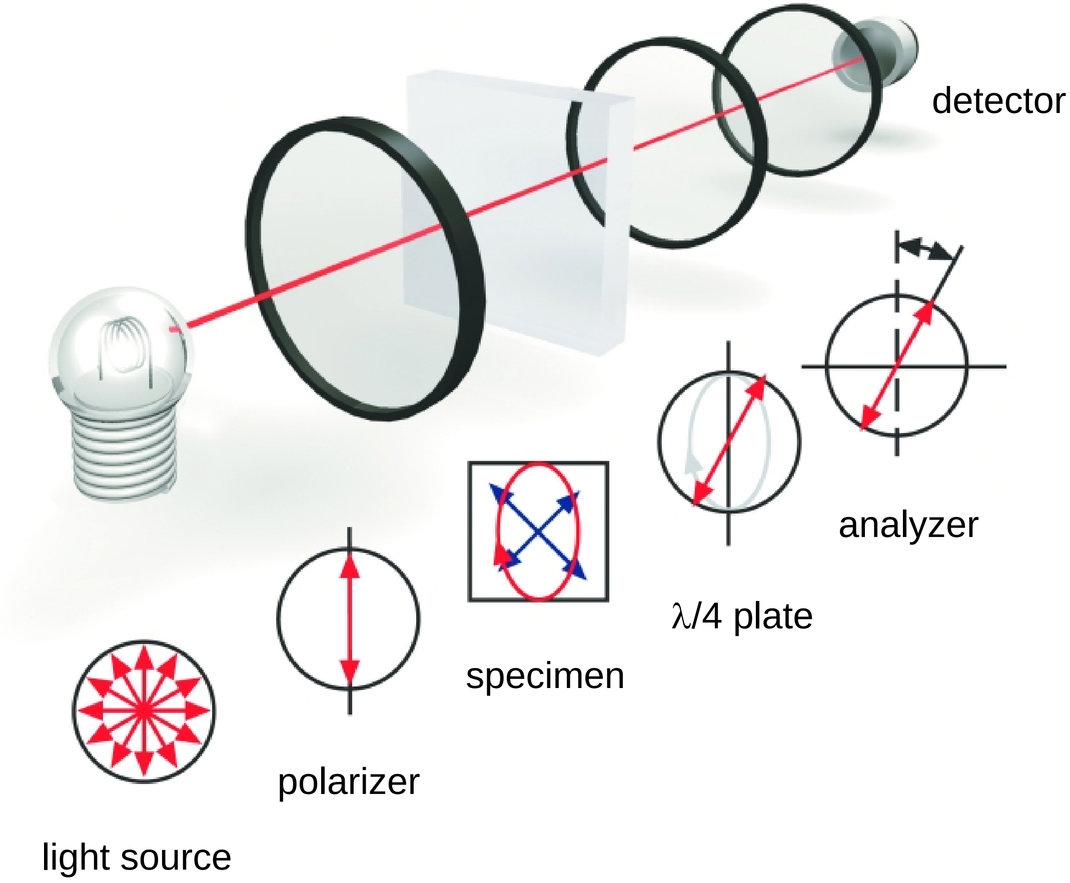
1/2 λ
(circular)

Polarimeter Setup





Intensity image of a strain disc at analyzer angles of 0° and 8°



Principle of a polarimeter for optical measurement of birefringence according to the photoelastic principle

Measuring Units

- From the polarization angle α the **optical retardation** R in nm can be calculated using a simple formula:

  $$R = \alpha \cdot \lambda / 180°$$

- When the birefringence is homogeneous along the optical path the optical retardation can be **normalized** to a standard thickness of 1 cm (for a given thickness d in mm):

  $$N = R \cdot (10 / d)$$

- In case of membrane stresses the optical retardation can be converted to **stress** in MPa, if the photoelastic coefficient C of the material is known:

  $$S = R / (d \cdot C)$$

- For describing the residual stress state in container glass, ASTM C 148-00 defines the unit **apparent temper number**, referring to the nominal retardation of a Strain Disc standard (which was originally used for visual comparison):

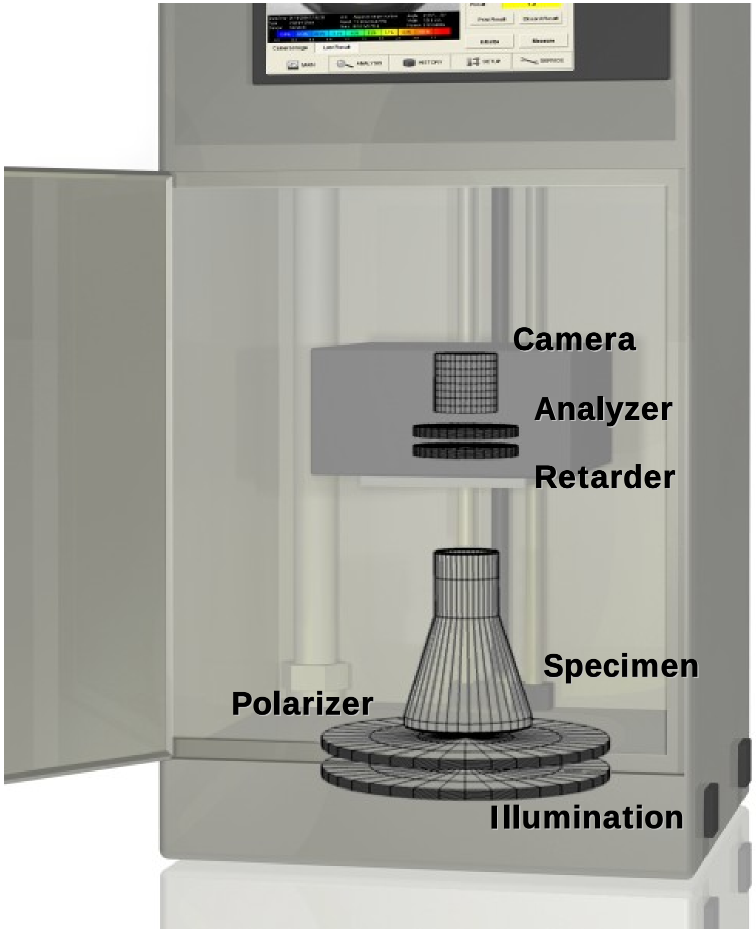
  $$T_A = R / 22.8 \text{ nm}$$

- Taking the thickness d into consideration the apparent temper number can be converted into a so-called **real temper number**:

  $$T_R = T_A \cdot (4.06 \text{ mm} / d)$$

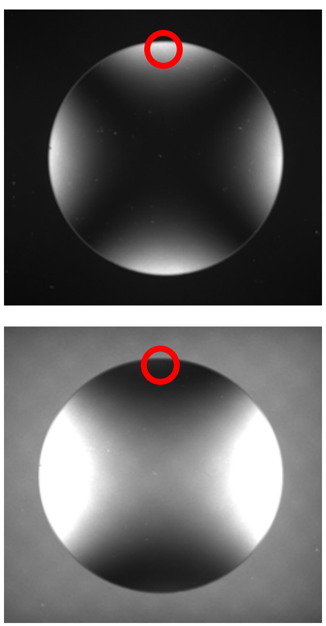
StrainMatic® Imaging Polarimeter Systems

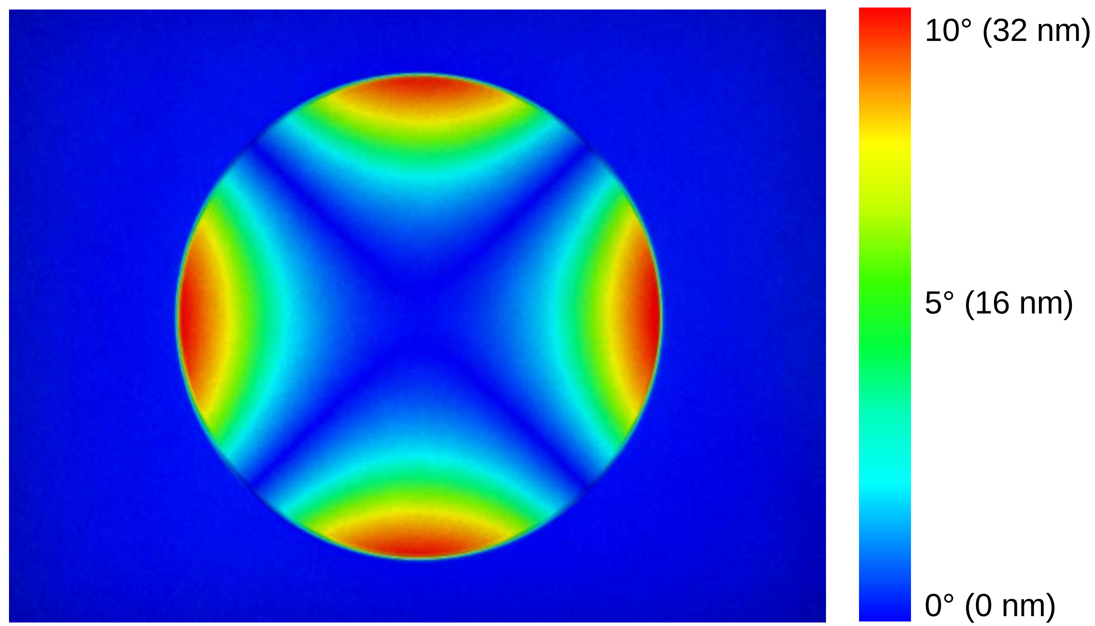
- Fully automated measurement analogous to a polarimeter
- Observation of the whole measuring area instead of individual measuring points
- Integrated PC for automatic analysis and documentation of the measuring results
- Measuring system:
  - Monochromatic light source
  - Polarizer
  - Retarder (quarter-wave plate)
  - Rotatable analyzer
  - CCD camera
  - PC with special operating software



StrainMatic® Measuring Principle

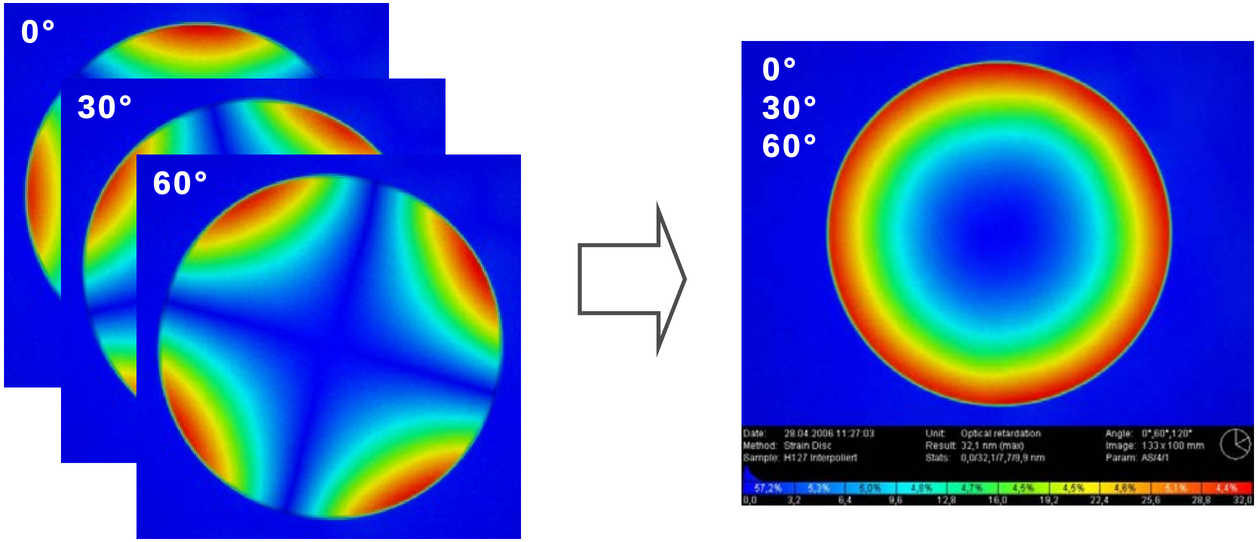
- Determination of the polarization angle for each pixel
- Calculation of temper number (apparent or real), optical retardation (nm), normalized retardation (nm/cm) and stress (MPa)
- Color-coded display of the measured values (e.g. 0 nm = blue, 32 nm = red)





StrainMatic® Measuring Principle (cont.)

- **Problem:** Due to the measuring principle only those stresses orientated at a 45° angle to the polarizer axis are visible. All other orientations are attenuated.
- **Solution**: Rotate the sample and repeat the measurement several times…
- **Better**: Change the polarization direction of the radiated light, e.g. 0°, 30° and 60° (i.e. three measurements), and combine the results.



StrainMatic® Models

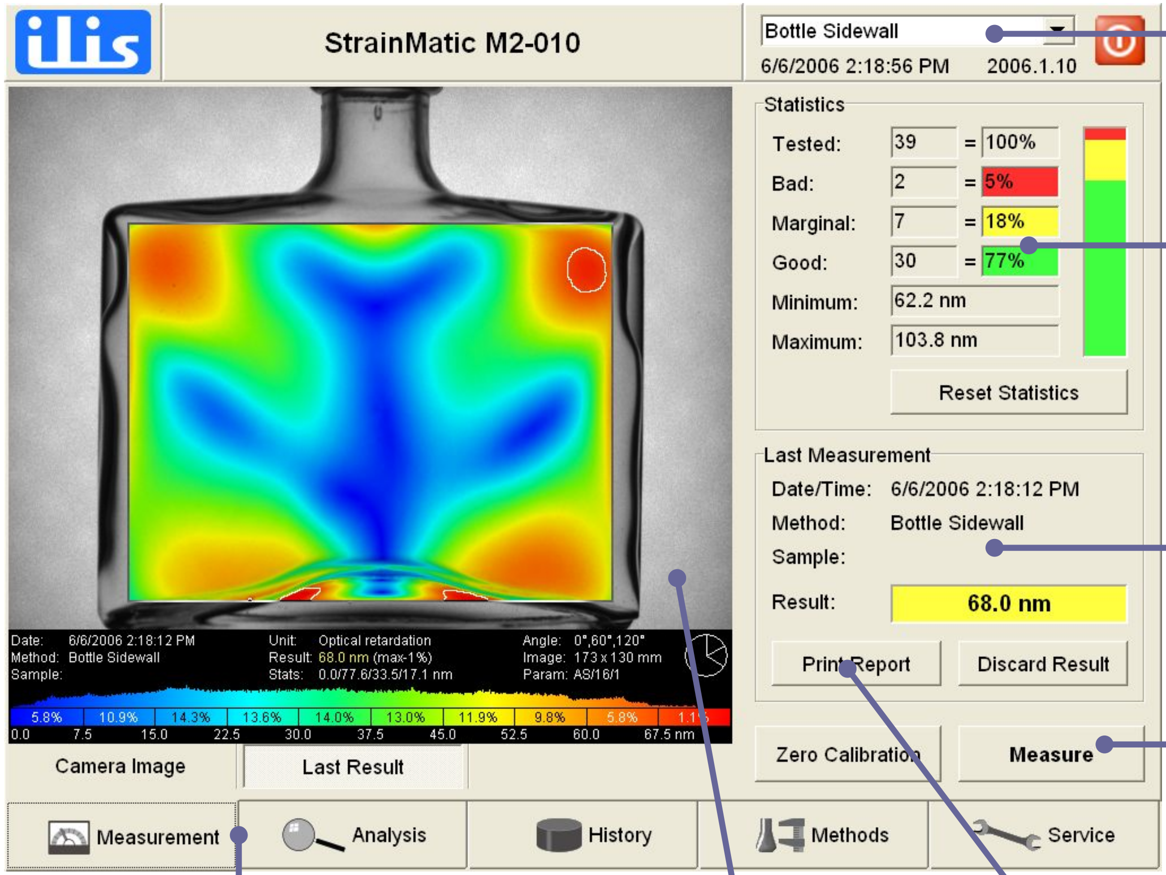
StrainMatic® M2 Series

StrainMatic® M2 / M

- Movable measuring head (motorized, working distance approx. 120 to 450 mm)
- Integrated PC with touch-screen operation for usage close to production
- Image size: 193 x 145 mm² to 61 x 46 mm²
- Lateral resolution: 0.31 mm to 0.11 mm
- Reproducibility: < ± 0.2 nm (mean absolute deviation)
- Especially suited for non-destructive testing of glass bottles (camera looks through the bottleneck)

StrainMatic® M2/M

StrainMatic® Software – Measurement



Selected measuring method

Good/bad statistics

Result of the latest measurement

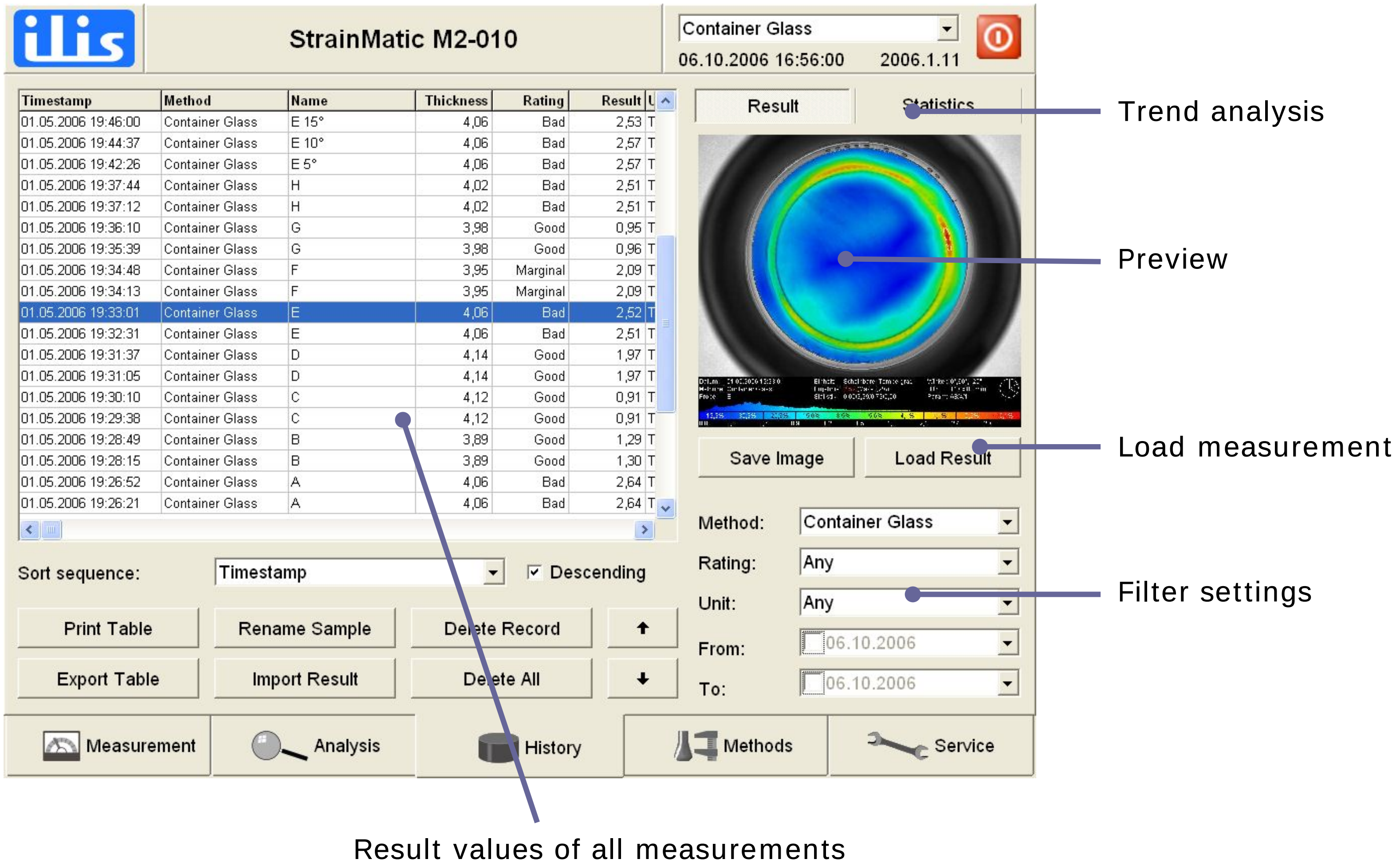
Perform a new measurement

Selection of the operating area

Result presentation

Print test report

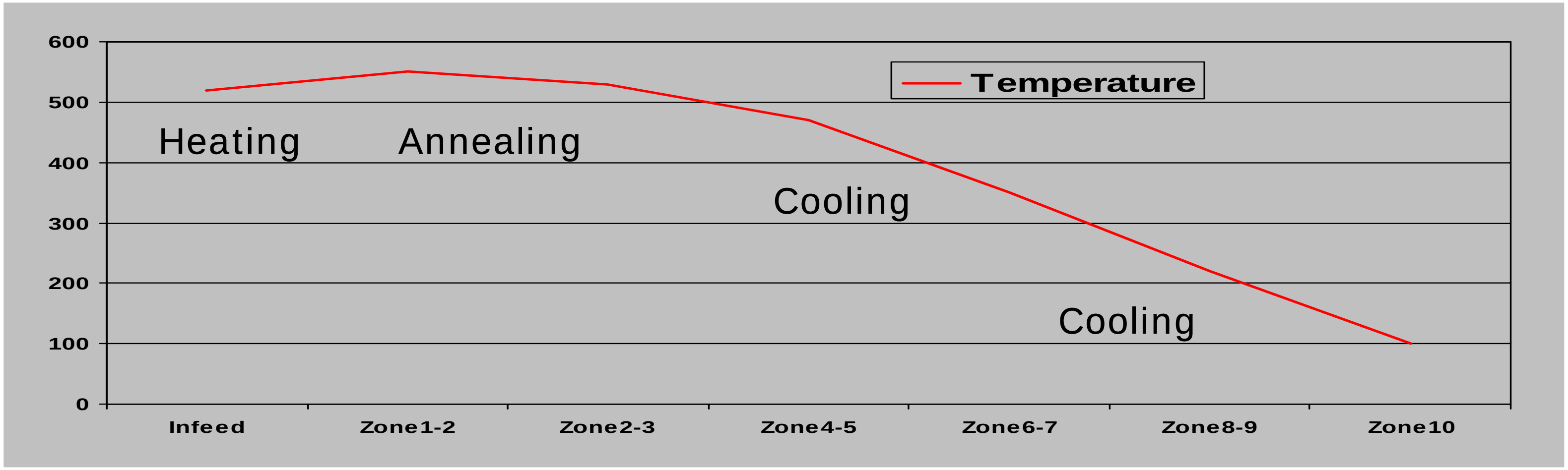
StrainMatic® Software – Result Archiving

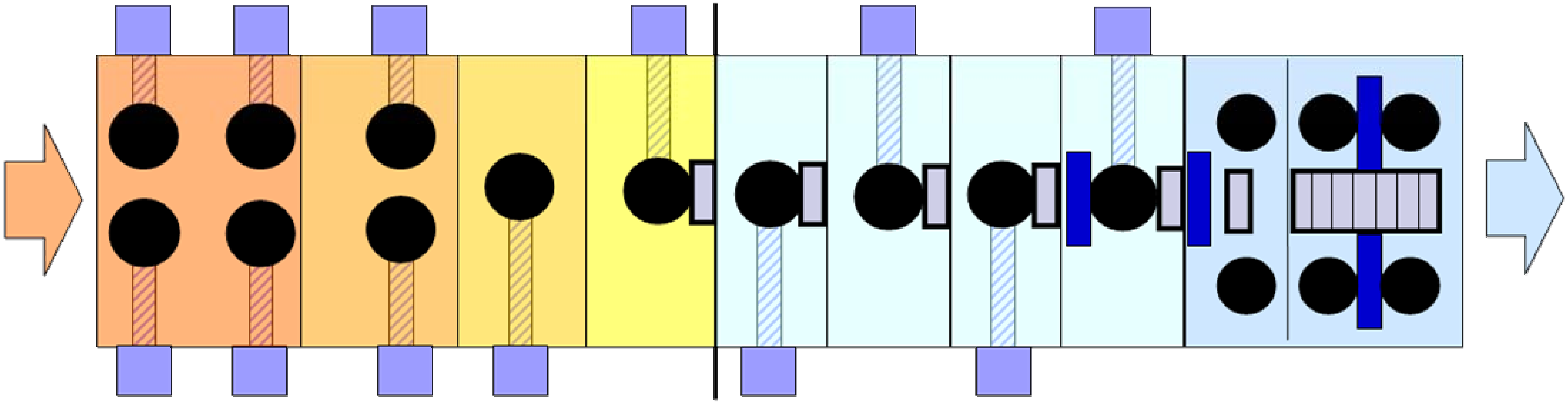


Objective of Annealing

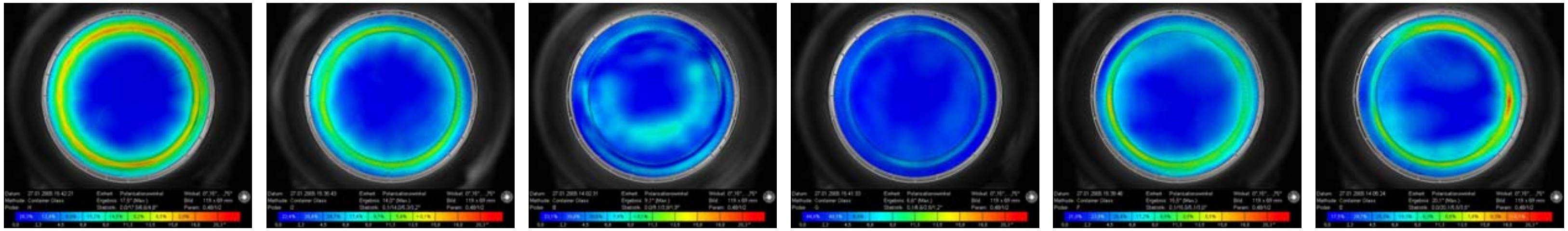
- During forming the container is cooled at a large heat transfer rate. Since glass is a bad heat conductor it cools inconsistently and internal stresses are created especially in the container base area.
- The annealing lehr relieves stresses by heating the container to the annealing point (approx. 520 °C) and keeping it at this level for a sufficient period of time.
- Afterwards a defined cooling procedure allows the container to cool down to room temperature without creating new stresses during the temperature reduction.

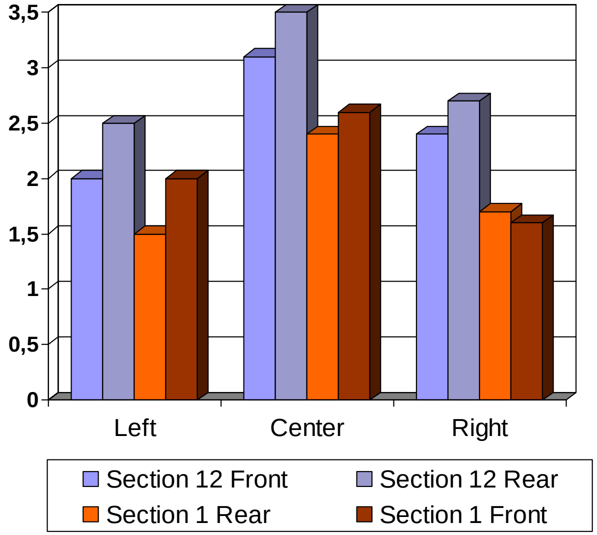
Annealing Curve

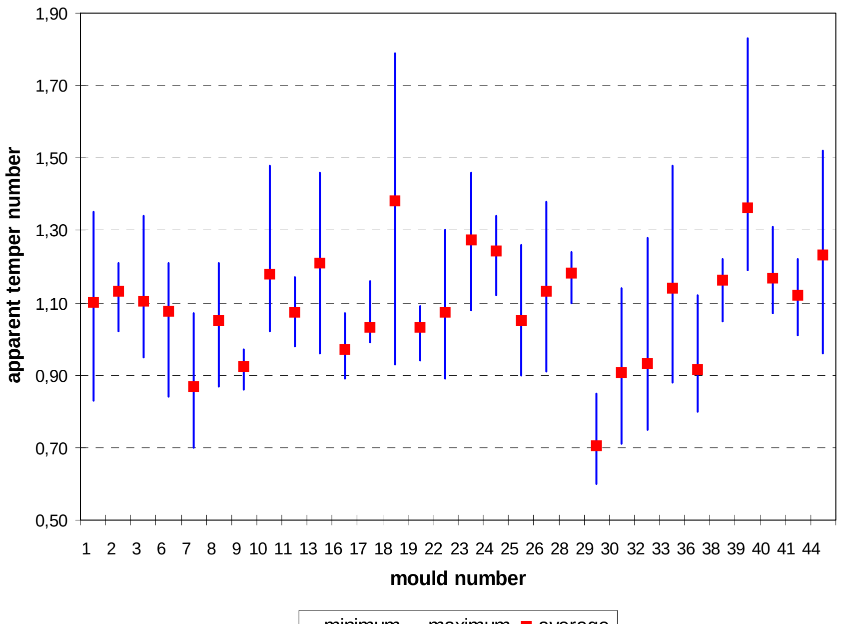




Correlation between residual stress level with the position in the annealing lehr and in the IS machine







Annealing Optimization

- Each container type has an individual optimal annealing requirement depending on production speed, container size and glass thickness
- In many cases the annealing lehr settings are not optimal in means of energy efficiency, i.e. the residual stress level is frequently much lower than acceptable, resulting in waste of energy (and money).
- In order to find optimal settings the process needs to be monitored using a reliable measuring tool.
- By using SPC methods the annealing curve can be optimized without influencing the quality negatively.

Optimization Results

- Measurement of residual stress in 72 glass bottles (two complete conveyor rows)
- The results indicate the position within the conveyor (left, middle, right) as well as the position in the IS machine.
- By systematic optimization of the annealing lehr settings, based on the measurement results, the quality was enhanced and **the energy use was reduced by 50 %**.

Summary and Prospects

- An objective measurement of the residual stress level is a prerequisite for optimization of the annealing process
- In many cases the energy consumption of the annealing lehr can be reduced significantly by using the **StrainMatic® M2** polarimeter system
- Further developments:
  - Integration into the production (sample lines, inspection machines)
  - Automatic control and optimization of the annealing settings
  - Automatic optimization of the forming process

Thank you for your attention!

Questions?