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Measurement of optical distortion in tempered and laminated flat glass for architectural and solar applications

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Keywords

1=Optical distortion 2=Tempering 3=Laminating 4=Process control 5=Solar 6=Toughening

Abstract

Tempering of flat glass results in a change in the flatness of the glass and in associated optical distortion. The magnitude of optical distortion determines the quality and acceptability of the glass for window or solar applications.

Importance of flatness in glass panels after tempering by application:

Architectural: to ensure aesthetically acceptable windows.

Solar module: to avoid delamination and thermal stress breakage, both costly field failures.

On-line measurement of distortion and real-time process control have been demonstrated to produce tempered glass of superior flatness. Developments in tempering furnace technology combined with on-line measurement of optical distortion provide proven solutions to the distortion problem. Further, recent advancements in on-line distortion measurement systems offer improved accuracy and resolution for demanding solar applications.

The paper presents methods for monitoring distortion, the definition of critical units of measure for distortion, types and causes of distortion, and methods of process control to maintain flatness and minimize distortion in tempering.

Introduction – the importance of optical quality in flat glass

Poor optical quality in flat glass is due to poor control of the tempering and laminating processes. Architects and curtain wall designers increasingly specify optical quality to meet or exceed published standards. Standards exist or are being developed in China (CN, GB/T9963-1998), Japan (JIS-R 3206:2003), USA (ASTM C14, GANA Roll wave test method), and Europe (EN 12150, ISO TC 160, BS6206). Many other nations and markets reference these standards when specifying glass curtain wall. More forceful than written standards are market requirements. Architects increasingly express dissatisfaction with the poor optical quality in tempered and laminated glass. For example, in 2003 - 2005, over 6600 panels were replaced in the newly built Hong Kong airport due to distortion from tempering and delamination. A very considerable cost was incurred by the glass fabricator for this massive replacement effort.

Distortion in lamination typically is traced to distortion in the tempered glass entering the lamination process. Two glass panels are assembled. Autoclave forces flatten the panels to conform. Excessive distortion such as edge lift result in separation after installation (Fig 3) or to distort the transmitted image (Fig 1 and 2).

Main – On-line measurement of optical distortion a common practice

Distortion in glass is commonly measured by glass fabricators. The tempering process is complex and dynamic. The tempering process includes dynamic inputs including heat profile, temperatures throughout the furnace, time, velocity, glass thickness, glass absorption, glass coatings, bed utilization, and quench pressure. The quality of the tempered glass is a

Figure 3

Delamination of glass with edge lift distortion

Figure 4 and 5

On-line measurement systems, Zebra board and Osprey® Distortion Measurement System

Figure 1 and 2

Optical distortion in laminated panels at Hong Kong and Pittsburgh International Airports

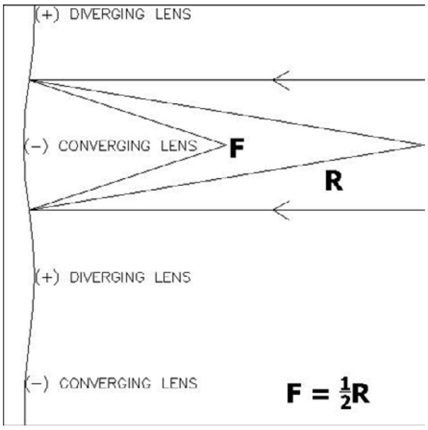


Figure 6

Millidiopter (mD) and sign convention defined

function of these many process variables. These process variables typically change with every load of glass and are too complex for the human operator to fully monitor and control.

On-line measurements techniques for optical distortion range from the simple zebra board (Fig 4) to automated systems such as the Osprey® Distortion Measurement System by LiteSentry (Fig 5). These on-line measurement techniques measure the glass immediately after tempering and provide feedback to the operator, allowing immediate adjustments to the tempering process. Timely feedback to the operator to correct the process is critical for successful quality control. Off-line measurement techniques such as the flat bottom gauge or feeler gauges are also used by the industry but are inherently inadequate in a time sensitive process. Process control can not be accomplished using sampling and slow off-line measurements.

Technique – Lens power of image reflected in glass

Tempering may impart a local curvature in the glass, resulting in a change in the size of a reflected image. Concave curvatures magnify the reflected image. Convex curvatures demagnify the reflected image. (Fig 6) Qualitative measurements using the zebra board are limited to the human perception of local waviness in the image. The human is unable to quantify the results. Use of the zebra board relies on subjective human judgment, with its inherent variation.

Automated measurement systems including the Osprey quantify the results in diopters or millidiopters (mD), the unit of measure of curvature in lens power.

Figure 7A and 7B

Edge Lift and Roller Wave distortion as observed and as measured

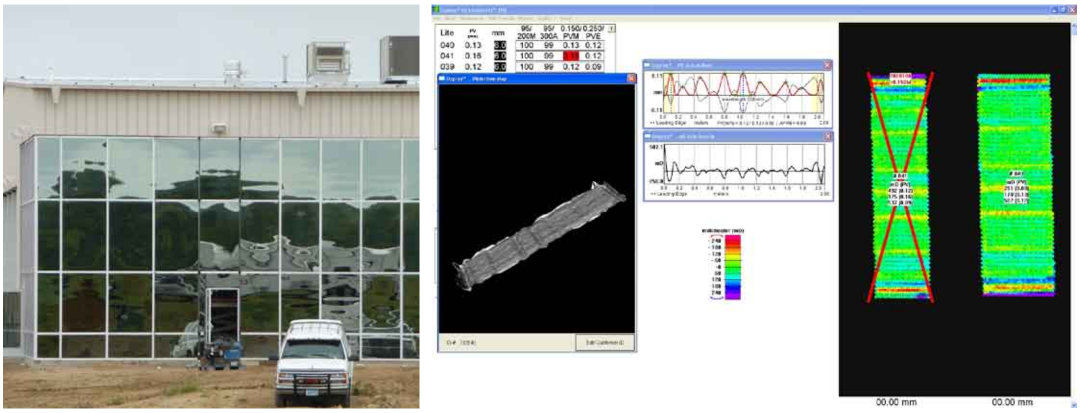


Figure 8A and 8B

Hammer distortion as observed and as measured

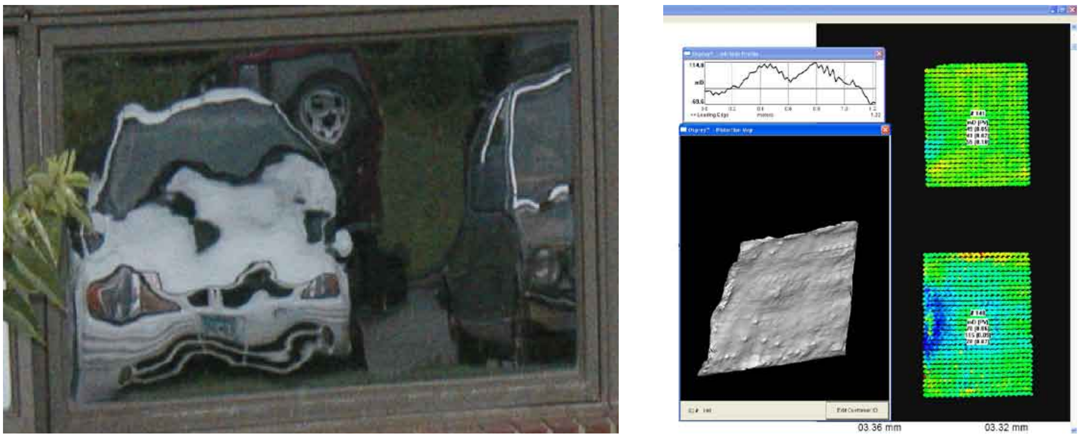
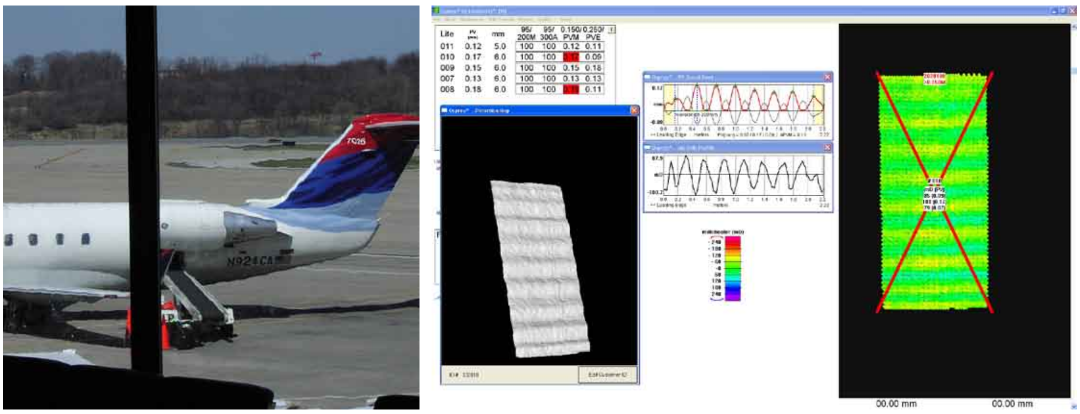


Figure 9A and 9B

Roll wave corrugation in laminate as observed and as measured



User	Problem	Result	Cost of defective glass & savings reported after installation of Osprey
Saint-Gobain	Bubbles in laminates	Significant increase in yield	Euro 4,000 / month
Flachglas	Delamination	Problem solved	Euro 5,000,000 rework
Solar customer	Edge lift	Improved process control	US $100,000 / container
Architectural customer	Roller wave	Problem solved	US $5,000 / month rework

Table 1

Significant improvements have been reported by users

The automated measurement system quantifies results for each panel. Results are reported and recorded to a database. The magnitude and pattern of distortion are displayed and recorded. Many architectural specifications now require the optical distortion data to be reported by panel or lot, and to be saved for later reference.

Results point to specific problems in tempering process

Specific examples of distortion types and causes are shown in the figures.

Roller wave and edge lift distortion are shown above (Fig 7A & 7B). Typical edge lift or edge kink distortion is caused by overheating of the glass and inconsistent elevation of the last ceramic furnace roller and the first steel quench roller. Very slight misalignment between these two critical rollers at the point where the glass is near 630 deg C will cause the hot glass to kick up or drop down as it is moving from the softened state to the solid state, resulting in edge lift.

Hammer distortion (Fig 8A & 8B) is caused by excessive sulfur dioxide use in the tempering furnace. As the sulfur dioxide disassociates in the hot furnace, the free oxygen molecules bond with the ceramic furnace rolls to form black high points of silicon dioxide. As the glass transfers over the black points, poor heat conduction from the rollers and the force of gravity cause the glass to form craters and related optical distortion. This problem can be corrected by washing the rollers when the automated inspection system indicates the problem is evident.

Roll wave distortion is defined as the periodic sine-wave corrugation in the glass (Fig 9A & 9B). Roll wave distortion has many causes, including overheating, poor geometry such as high roller run-out, damaged roller bearings, poor heat distribution, incorrect heat profile, inconsistent quench, clogged quench nozzles and other causes. This examples shows glass with roll wave that has been laminated with the resulting optical distortion in transmission.

The Osprey automated inspection system measures the distortion. Results are quantified and reported. Three courses of action may follow.

1. Process Control - immediate corrections to the furnace recipe solves many problems
2. Equipment – maintenance is performed on defective components
3. Personnel – training is provided to teach personnel the proper operation of the equipment

Summary

On-line measurement of optical distortion using automated measurement systems provide quantified results for each panel. Architectural customers are specifying flatness using optical distortion in millidiopters (mD). The glass fabricator can effectively minimize optical distortion in tempered and laminated glass by using real-time measurement, feedback to operators, and process control techniques. Measure optical distortion in order to control the process and improve the results. Such techniques are proven and result in superior optics in glass for architectural and solar applications.

在建筑和太阳能玻璃生产中用于钢化和夹层玻璃生产上的在线光学畸变监测

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关键字
1=光学畸变　2=钢化　3=夹层　4=过程控制　5=太阳能　6=强化

摘要

钢化过程中玻璃的平整度会受到影响，从而造成光学畸变，失真。在建筑波璃和太阳能玻璃的生产过程中，畸变程度决定了玻璃的质量和合格率。

钢化后平面玻璃平整度的重要性：

楼房建筑：　确保幕墙的美观和可靠性

太阳能电池模块：　避免由玻璃变形造成夹层玻璃的分离和热断裂，这两类次品会造成昂贵现场维修 。

在线畸变检测系统结合实时生产过程控制已生产出超级平坦的玻璃。在线光学畸变监测系统结合钢化炉技术已被证实可以解决平面玻璃的变形问题。最新为太阳能电池玻璃生产开发的在线玻璃畸变检测系统展现出更高的精度和分辨率。

在这篇文献里我们将报告检测光学畸变的方法，畸变的测量单位，玻璃畸变产生的原因，如何控制玻璃生产过程来保持玻璃平坦，减小畸变。

引言 - 平面玻璃的光学重要性

钢化和夹层玻璃生产过程中的错误和误差是造成平面玻璃光学特性差的主要原因。然而建筑师和幕墙设计师又不满于公认平面玻璃的光学特性标准，不断地提高平面玻璃的光学特性要求。中国（CN），日本（J），USA（ASTM C14, GANA Roll wave test method）和欧洲（EN 12150, ISO TC 160）已经有了或正在建立自己的标准。许多另外的国家和地区参照这些标准来制定他们自己光学幕墙标准。市场的需求已远大于这些标准说能保证的，建筑师们对于钢花后或夹层玻璃中普遍存在着光学性能差的问题连续不断地表现出严重不满（图1和图2）。例如，从2003年到2005年，由于钢化过程造成的畸变而产生的幕墙玻璃分离和光学失真，新建的香港国际机场共计更换6600多块幕墙。为了更换这些幕墙，幕墙制造商蒙受了巨额损失。

加层玻璃的光学畸变来至于钢化过程中产生玻璃畸变。畸变玻璃在未被发现时进入夹层加工过程。两个或多个玻璃面板被压制成夹层玻璃。在边缘和角落，严重玻璃变形会在安装后出现了加层分离（图3）或光学失真（图1和图2）。

正题 - 在线光学畸变监测

平面玻璃制造厂商通常在生产过程中测量玻璃畸变。钢化过程是个复杂而又动态的过程。控制钢化过程的动态参数有加热过程，炉内温度分布，加工时间，速度，玻璃厚度，玻璃热吸收能力，玻璃镀膜，炉内尺寸，和淬火压力。这些参数决定钢化玻璃的质量。一般情况下，每批玻璃入炉后，这些参数都要做相应的调整。整个监视和控制过程对于操作员来说是非常复杂。

在线光学畸变测量技术已由简单斑马板（图4）目测演变到自动监测系统，例如我公司生产的鱼鹰畸变监测系统（图5）。在玻璃被钢化后，检测系统马上测量玻璃的畸变，测量结果实时反馈给钢化炉的操作员或自动控制系统，用来调整钢化过程。这及时的反馈保证了玻璃的质量控制。离线技术不在此文阐述，因其精度和速度都无法配合钢化炉的动态控制。

图 1 and 2
香港机场和匹兹堡机场幕墙畸变和失真

图 3
玻璃边缘畸变造成幕墙玻璃分离

图 4 and 5

在线监测系统：斑马板和鱼鹰畸变监测系统

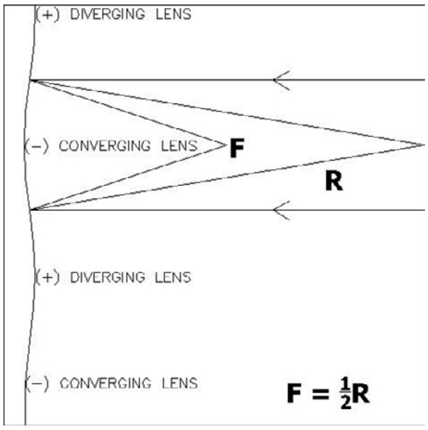


图 6

曲光度和符号定义

技术 – 在玻璃反射中应用镜片映像功能

钢化过程中有时会在玻璃表面产生区域性曲面。这些曲面会改变由其反射图像的大小。如果这曲面呈现凹面结构，反射图像将变大。如果这曲面呈现凸面结构，反射图像将变小。尽管斑马板（图4）也可以让人的肉眼看到波纹现象，但肉眼是无法给出数量级的变化。用斑马板通过肉眼来判断，这结果也是因人而异的。

类似于鱼鹰（图5）式自动监测系统可以将测试结果以屈光度或豪屈光度来数量化（图6）。自动监测系统监测每块玻璃板。显示测量畸变的大小和模型。再将结果报告存储到数据库。许多建筑玻璃要求测量每块或每批玻璃， 结果存储，为将来做参考。

检测结果直指钢化过程问题

下面的例子显示造成玻璃畸变的常见问题

最常见的玻璃边缘畸变（图7）是由于钢化炉内玻璃过热，外加最后一个陶瓷辊轴和第一个淬火钢轴高度不同。当玻璃从软状态过渡到淬火时，温度在630度左右。这两个滚轴的任何垂直方向上的误差都会给玻璃边缘上造成向上或向下的畸变。

弹坑式畸变（图8）是由于钢化炉内过高的二氧化硫造成。当二氧化硫在炉内高温下分解时，氧分子在炉内陶瓷辊轴上形成二氧化硅黑色凸斑。当玻璃从滚轴

图 7A and 7B

直观和测量玻璃边缘畸变和滚动波畸变

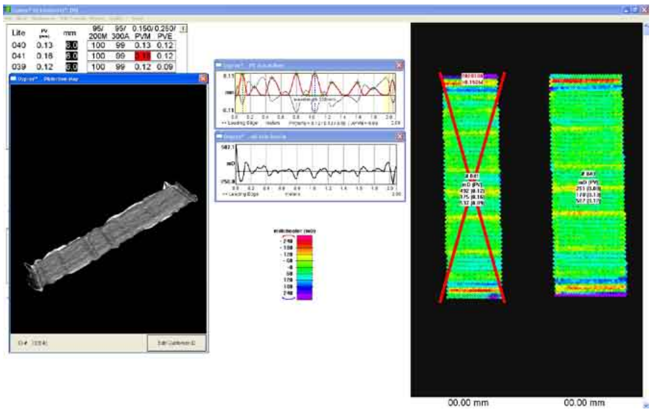


图 8A and 8B

直观和测量弹坑式畸变

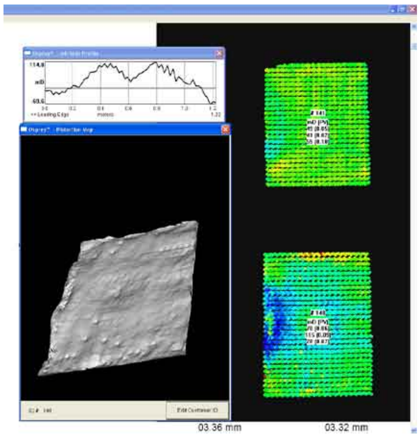
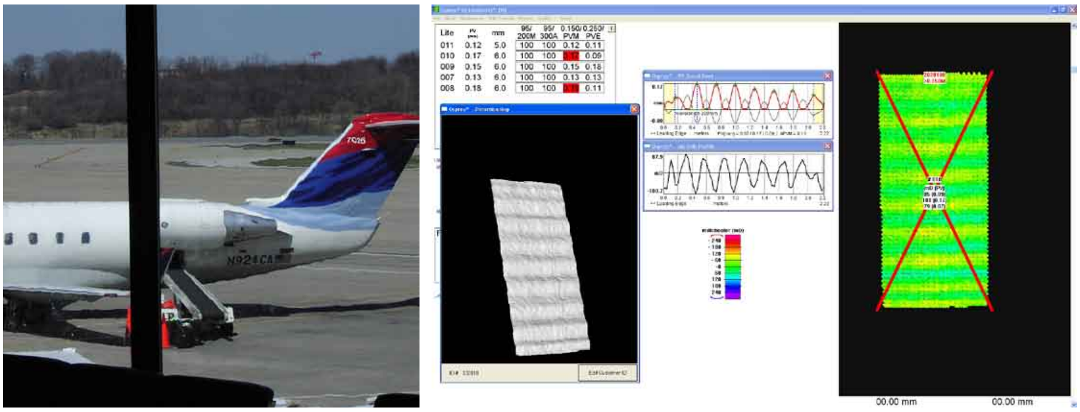


图 9A and 9B
直观和测量滚动波纹畸变



客户	问题	结果	减少次品提高产量的效益
Saint-Gobain圣戈班	夹层玻璃有气泡	月产量明显提高	每月4000欧元
Flachglas	夹层玻璃分离	发现问题并解决	节省500万欧元维修费
太阳能电池客户	夹层玻璃边缘翘起	改善控制参数，解决问题	每单节省10万美元
建筑玻璃客户	滚动波畸变	发现问题并解决	每月节省5千美元

客户的典型反映

上通过黑斑时，由于黑斑导热差，外加重力，便在玻璃上形成弹坑式畸变。当自动监测系统发现并显示这种问题后，维修人员对有黑斑的滚轴进行清洗即可解决弹坑式畸变。

玻璃上滚动波纹畸变定义为周期性正弦波（图9B）。多种原因造成滚动波纹畸变。最常见的有过热，滚动速度不适当，滚轴的轴承损毁，热分布不均匀，加热布局不适当，淬火速度不均匀，淬火出口堵塞等等。图9A显示带有滚动波畸变的玻璃被加工成幕墙后的光学失真现象。

当我们的鱼鹰自动监测系统测出畸变后，将问题数字化并产生报告。根据结果可做下面三件事：

1. 过程控制-马上对钢化炉的控制参数进行相应修改，基本上可解决大部分问题。
2. 设备-检修设备，更换有问题的部件。
3. 人员-培训操作人员正确使用钢化炉。

结论

在线自动光学畸变监测系统可对每块平板玻璃检测并给出数字化结果。建筑行业的客户现在已用豪曲光度来规定玻璃的失真度。钢化和夹层玻璃制造商可使用玻璃的实时监测结果来控制生产过程， 有效地减小平面玻璃的光学畸变。用测量光学畸变来控制质量和提高产量。在线自动光学畸变监测技术已在建筑玻璃和太阳能电池玻璃生产中证实其可行性，并已产出光学质量优秀的玻璃。