Annealing of glass containers and holloware

John Hann* explains how planning for speed and time is an important parameter in the annealing process.

As with any glass forming process it is necessary to stress relieve or anneal the glass as it cools from a viscous state to its final rigid form. This of course holds true for the production of 'hollow glass products', which includes an almost infinite variety of tableware, food and beverage containers, consumer products and pharmaceuticals. Another common thread in the production of these products is speed. Many food and beverage containers are formed at a rate in excess of 500 pieces per minute. Tableware, consumer products and more speciality items can vary, but are also produced at rates that are continuously increasing due to improved forming processes and container design.

Process

Annealing glass is a time and temperature sensitive process dictated by elements of the specific hollow glass product including shape, weight, temperature at the start of the annealing process, maximum thickness and forming quality. Engineering and evaluating the overall glass thermal treatment process to assure the forming speed and annealing time requirements are compatible is critical.

Hollow glass products are usually produced by high speed forming machines and are stress relieved in a continuously conveying annealing lehr. Essentially the lehr equalises the temperature of the glass products being produced removing any strain introduced during the forming process. Once this is accomplished, the lehr controls the rate at which the glass cools to prevent reintroducing permanent annealing strain or fractured glass due to thermal shock.

To have a better understanding of the basic process described above some specific terms need to be defined. A typical textbook definition of the annealing point of glass sounds is: "The temperature at which internal stress in glass is potentially relieved through internal viscous flow." This typically indicates the upper end of the annealing range. The lower end of the annealing range or the strain point is defined as 'the highest temperature from which strain free glass can be cooled quickly without introducing permanent strains.' For typical soda-lime glass, annealing points average around 1000°F (537.7°C) and strain points 940°F (504.4°C).

Evaluation

To begin evaluating a glass thermal treatment process it is necessary to know both the annealing and the strain point of the glass. There must also be a good estimation of the glass entrance temperature. It is beneficial to the overall annealing process to maintain as much glass entrance temperature as possible. Be on the lookout for any factory conditions that contribute to temperature loss such as external equipment or cooling fans, draft-inducing open doors and exhaust louvers. As noted above, annealing or stress relieving the glass depends on bringing the entire piece to a state of temperature equilibrium. The more core

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glass temperature maintained the quicker and easier it is to accomplish this. Typically glass container entrance temperatures average 850 - 900°F (454.4 – 482.2°C)

Cooling

Due to its natural insulating properties, when glass cools from a liquid to a solid state there are large variations in the rate of cooling specifically through the thickness of the glass. The actual shape of the glassware can also contribute to this variation in cooling rate.

For instance a narrow neck container, if left to cool on its own in ambient temperature air after forming, can spontaneously fail or fracture. This is due to rapid cooling on the exterior surfaces of the container and a much slower cooling rate on the inside surfaces. Like most materials, when glass is heated the molecules become excited and expand. As a glass container cools the exterior surface cools at a higher rate than the interior allowing the molecules on the exterior surface to naturally realign and essentially contract.

This compressed outer layer then prevents natural alignment of the molecules in the inner glass surfaces creating opposing forces of compression on the exterior surface and tension on the interior surface. This actually occurs all the way through the thickness of the glass, creating layers and general lamination of the glass structure. The result is permanent annealing strain, which can be great enough to cause spontaneous failure of the glass container. As a rule, the last surface of any glass product to cool will be the surface with the most tension. When glass fails, it fails in tension (glass has significant strength in compression). For glass container producers, this explains the 'internal scratch test' – one method for determining how much permanent annealing strain remains in a container after it has left the annealing lehr.

Flat glass

When dealing with flat glass products (glass dinner plates, serving trays) where more of the external surface is exposed to the generally higher cooling rates, tension tends to build from the centre and diminish at the external surfaces.

In this case the entire glass product is essentially 'incased' in compression with the higher tension layers trapped in the middle.

Annealing

So, when glass is annealed with a typical annealing lehr, the first process objective is to equalise the glass product to the annealing point (1000°F/537.8°C).

This assures all the molecules are in a similar state of expansion, but not so excited as to cause the glass to begin transitioning back to a liquid state and slump or deform (viscous flow). The second objective is to control the cooling rate of the glass to avoid creating the large variations in temperature through the thickness of the glass as described above.

As the glass cools, molecule realignment also occurs at a diminishing rate. Eventually the glass reaches a point where the significant contraction due to molecule realignment (viscous flow) is complete. This, as noted above, is described as the lower annealing point or strain point. Once the cooling rate to this temperature is controlled the actual annealing process is complete.

Permanent annealing strain cannot be introduced into the glass. The third and final process aim is to continue cooling the glass to the required lehr exit temperature to allow for lubricity coating, handling, inspection and packaging, approximately 300°F – 148.9°C. What is not widely recognised is that after the glass is below the strain point it can be cooled right up to the rate of thermal shock without changing the quality of the annealing.

Thermal shock is defined as temporary strain as opposed to permanent annealing strain described above. Thermal shock results in violent and immediate excitement and expansion of the glass molecules (through rapid temperature change), which results in immediate failure or not. Thermal shock has no impact on the level of permanent annealing strain. Note that the forming quality of the glass can have an impact on how much thermal shock is required to result in fracture/failure.

As would be expected, successful execution of the process objectives above are dependent on creating the necessary glass time and temperature relationship with the annealing lehr. An understanding of the specific temperature goals is clear. The time requirements relate mainly to glass weight, thickness and heat transfer. Although weight does play a factor it is the glass products maximum thickness that has the greatest impact.

As noted above, glass is a natural insulator. The thicker the glass the more time required for conduction or heat transfer to take place. This is necessary

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Tunnel cooling.

to bring the glass to a state of temperature equilibrium (molecules in similar state of expansion through Viscous flow) and prevent variation in cooling rates as the glass passes below the strain point. If the following for a glass container is assumed:

- Entrance temperature = 900°F (482.2°C)
- Heating rate from entrance temperature to annealing point = 50°F/minute (27.8°C)
- Annealing point, soda-lime glass = 1000°F (537.7°C)
- Strain point, soda-lime glass = 940°F (504.4°C)
- Maximum thickness = .500” (12.7mm)
- Maximum cooling rate, annealing through strain point = 8°F/minute (4.4°C)
- Maximum cooling rate, strain point through lehr exit temperature = 25°F/minute (13.9°C)
- Proposed exit temperature = 250°C (121.1°C)

▲ Tunnel entrance.

The most critical portion of the process to control is the maximum cooling rate the glass will see from the annealing point through the strain point. The total temperature change required between the annealing and strain point is 60°F (33.3°C). By dividing this total change (ΔT) by the maximum cooling rate noted above the necessary time is arrived at to complete the process: approximately 7.5mins.

The next element to control and slightly less critical is the cooling rate from below the strain point to the lehr exit temperature. Following the same calculation detailed above the total required temperature change of ΔT 690°F (383.3°C) at a rate of 25°F/mins (13.9°C) requiring 27.6 mins to complete the process. Two of the three values necessary to estimate the total time required for complete thermal processing are arrived at.

The only value left to estimate is the time necessary for the glass product to reach the annealing point and achieve an equilibrium state relieving any thermal strain introduced during the forming process.

The rate at which this temperature increase occurs is the least critical. Glass can be heated at a much higher rate than it can be cooled without fracturing. It is difficult to introduce enough thermal shock causing the glass to fracture when heating up versus cooling down. If a heat up rate of 50°F (27.8°C) per minute is used, double the rate of cooling between the strain point and exit temperature, approximately 2mins for the glass product to reach equilibrium at the annealing point is needed. There has always been speculation that it is necessary to soak or hold the glass at the annealing point to relieve any strain, which may exist. Earlier published laboratory data indicated a soak time at the annealing point of 15 minutes was necessary to achieve full strain relief.

Time and experience has shown (specifically in glass articles with no more than .500” – 12.7mm maximum thickness) that once the annealing point is reached molecule alignment and subsequent strain release is almost instantaneous. Finally, if the three time values of 2 minutes, 7.5 minutes and 27.6 minutes is added it totals 37.1 minutes. This would be the minimum time required to completely process the subject glass container described above.

With some thought, it is easy to see that any variation of the critical product and process data detailed above, could result in increasing or decreasing the required time to thermally process the glass container.

Usually, the variations end up requiring slightly more overall time. For instance, if the glass entrance temperature decreases to 800°F (426.7°C), the required annealing temperature increases to 1010°F (543.3°C) and the desired exit temperature decreases to 225°F (107.2°C).

These changes combined add just over three minutes to the overall process for a revised total required process time of approximately 40 minutes. Several other factors related to glass production and factory conditions can affect the overall time necessary to thermally process a particular glass container or hollow glass product. In most cases it is prudent to allow for 10 to 15% additional time beyond the ‘calculated minimum.’

As expected a lighter glass container with thinner bottom and wall thicknesses would require less overall processing time. Less glass thickness allows for higher cooling rates between annealing and strain points.

For example, a light weight beverage container weighing 6oz. (170grams) with a maximum thickness of .125” (3.2mm) can be cooled from the annealing point through the strain point at rates in excess of 18°F/minute (10°C). Less overall weight allows for higher cooling rates from below the strain point to the proposed exit temperature. Typically, a lightweight item as described above can be thermally processed in 18 to 20 minutes.

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External lehr tunnel.

Evaluating annealing

With a good understanding of the glass containers time and temperature requirements, the specific lehr configuration necessary to carry out the annealing and thermal processing can be evaluated. A typical glass container and hollow ware annealing lehr can be broken down into two major areas.

First is the tunnel, which refers to the enclosed area of the lehr where the heating and cooling rate of the glass is controlled. The tunnel is comprised of individual modules or zones of equal length. Width varies widely based on capacity but remains uniform from zone to zone. These zones are designed to produce a gradually decreasing temperature curve, which typically starts slightly above the calculated annealing point of the glass and decreases zone by zone until the desired glass exit temperature is achieved.

For the most efficient heat transfer method most modern lehrs use convection fans and can be heated with gas burners or electric elements.

Second is the open packing table. Primarily this allows for any additional cooling, application of lubricity coating or simply provides an area for manual inspection or packaging. The critical area for evaluation is the configuration of the tunnel.

As mentioned earlier a typical glass container and hollow ware lehr continuously receives glassware directly from the forming process. Ware is conveyed through the tunnel via a metal mesh lehr belt that provides a stable surface for conveyance as well as allowing recirculated air to pass through and around the glass products. The combination of lehr belt speed and the individual temperature set points in each of the control zones produces the necessary cooling rates to properly anneal and cool the glass.

This is specifically where the speed and time elements come into play. To determine if the cooling rate and overall tunnel time requirements can be met, it must be known what lehr belt speed will be necessary to support the proposed forming speed.

To accomplish the maximum diameters/dimensions of the proposed glassware, the speed at which it will be produced (pieces per minute) as well as the lehr belt loading patterns, which includes the proposed bottle spacing must be known. See the example below:

- Lehr belt width = 3000mm.
- Glassware maximum diameter = 63.5mm.
- Proposed spacing between glassware = 19mm.
- Proposed forming speed = 500PPM.

With this information, the following calculation is made: 3000mm belt width/(63.5mm diameter + 19mm spacing) = 36.4, so 36 pieces loaded across the lehr belt.

500PPM / 36 pieces across the belt = 13.8 rows of glassware per minute (RPM).

13.8 RPM (63.5mm diameter + 19mm spacing) = 1,138.5mm/minute belt speed (44.9"/minute).

With the necessary belt speed now calculated the required thermal process time or tunnel time can be plugged in to confirm the necessary lehr tunnel length. If it is determined that the overall tunnel time to process this example is 20minutes, simply multiply the calculated belt speed 1,138.5mm/minute by the required tunnel time (20 minutes) to determine the required overall length of the tunnel -2770mm or approximately 75'-0".

It is important to evaluate lehr capacity based on a cross section of proposed products. Errors can be made by evaluating the total area of tunnel based on the maximum tonnage of the forming process. Loading pattern requirements coupled with individual variations in glassware thickness, weights and dimensions can result in a mismatch between forming speed and tunnel time.

Specifically with glass containers, it is necessary to load the lehr belt in a pattern typically referred to as 'mould in row'. This is where only a single forming machine cycle is loaded across the width of the lehr belt. Referencing the example above, a maximum of 36 pieces could be loaded across the 3000mm wide belt.

If for example this piece of glassware was being formed on a 10-section triple gob machine one complete machine cycle would produce 30 pieces of glassware. This process has no impact on the speed the glass is produced however, with six fewer pieces of glassware loaded across the lehr belt, it impacts the speed at which the lehr belt must travel. In this example the lehr belt speed would have to increase from 1,138.5mm/min to 1,369.5mm/min increasing the required tunnel length from 22,770mm (75'-0") to 27,390mm (90'-0"). This is usually where the glass producer places a phone call to the lehr supplier and states: "My glass tonnage has not changed but my annealing quality has…for the worse!" If the production conditions were not evaluated properly to assure speed and time compatibility, solutions for the glass producer and the lehr supplier may be in short supply.

Armed with a good basic understanding of glass container and hollowware annealing properties evaluating, engineering and planning for a successful overall thermal treatment process is assured. ■

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