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The Faculty of Alfred University

AN EVALUATION OF THE VARIABLES THAT CONTRIBUTE TO THE QUALITY OF THE PUNTY SCAR

by

Ruby Wisniewski

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Under the Supervision of:

Chair: William Carty, Ph.D.

Committee Members:

Darren Stohr, PhD.

Monir Madkour

Misty Long-Donoho

SUMMARY

The following thesis was performed to provide glassblowing artists with a partial qualitative guide to the characteristics of an ideal dome-style punty used with soda-lime glass. Most experienced glassblowers discover a feel for what will and will not make a successful vessel. This is something that can be difficult to convey to the beginner.

Introduction

The glassblowing process often requires transfer of the glass piece from the blowpipe it was formed on to a new holding rod. To transfer the piece, a gob of hot glass on the end of the new rod, called a punty, makes an adhesive connection with the glass vessel which is then detached from the original pipe. (Hot glass sticks easily to other glass.) Punties are designed to be easily detached from the vessel and their temporary nature makes them difficult to learn to use. It can be catastrophic for the vessel if the punty fails too early or if the punty refuses to release the vessel. Even punties that successfully receive a vessel, hold it for the duration of its forming, and detach from the vessel all without breaking the vessel almost always leave a defect on the vessel where the punty was previously attached, called a punty scar. This study explores various characteristics of punties to identify those that influence punty scar shape, size, and severity, thereby resulting in a usable vessel or not. If the punty detaches cleanly from the vessel a relatively flat profile scar will remain. However, if the punty is attached too strongly to the vessel it may take a chip out of the bottom of the vessel; this chip is usually not structurally problematic but it may be sharp and require polishing. Sometimes part of the punty becomes fused to the vessel, when it

breaks off it leaves a protrusion attached to the bottom of the vessel that would cause it to wobble. This protrusion would require even more polishing than the chipping would. Polishing a vessel is time intensive and undesirable. (Some artists will discard a piece if it needs polishing, even if nothing else is wrong with it.)

This study sought to identify what factors might correspond to punty scars that were less likely to require additional polishing. The diameter and total height of each sample's punty scar was analyzed. (The height is the sum of the greatest chip into the vessel and the greatest protrusion from the vessel in the individual scar.) The scars were also analyzed on their profile, whether they were flat, indented, protruding, or a combination there-of.

Each punty scar was analyzed in regards to various characteristics of the punty and vessel. Many of the characteristics relate to the glassblowing process itself. They involve the transfer of the vessel to the punty and the later detaching of the finished vessel from the punty. Other features are characteristic of the forms of the vessel and punty, namely, their size and shape. The tested characteristics include the difference in temperature between the punty and vessel at the time of their attachment, the amount of glass at the base of the vessel, the mass of the vessel, the area of the fracture surface where the vessel broke away from the blowpipe as it transferred to the punty (called a jackline), the relative size of the punty, and the temperature of the punty when the vessel was removed from it.

Procedure

Various amateur glassblowing students and one professional glassblower made a series of vessels in the glassblowing shop at Alfred University; the vessels were transferred onto a punty, briefly reheated once, and removed from the punty. Each punty was photographed prior to being attached to the vessel. The vessels were kept a consistent shape by using a mass-production tool called a blow-mold to form their shape. A thermal imaging camera was used to record the temperature of the punty as it was attached to the vessel and the temperature as the vessel was detached from the punty. The vessel's physical attributes were analyzed after they were slowly cooled to room temperature in an annealer.

Results

The data suggests that increasing the temperature difference between the vessel and the punty, and increasing the jackline area, both corresponded to a slightly smaller punty scar height and an increasing punty scar diameter. This divergence indicates a choice between preferring to tailor these punty characteristics towards a smaller diameter scar *or* a smaller height of the scar. In many cases it would be easier to polish a shallow-wide scar than one that is narrow-deep, also the deeper the punty scar the more likely a vessel is to have structural damage from the scar. An increase in the thickness of the bottom of the vessel corresponded to a smaller diameter of the punty scar but was unrelated to the height of the scar. A greater the mass of the vessel corresponded with an added height to the punty scar but had no apparent relation with the punty scar diameter. Increasing punty size increased both the punty scar diameter and height. The temperature that the vessel was detached from the punty had no effect on the height, diameter, or shape of the punty scar.

The scar profile was more likely to protrude from the vessel (causing a wobble if not polished later) when the vessel was similar in temperature to the punty at attachment. Also identified was a correlation between the size of the punty and the scar height and height. As punty scar size increased, scar diameter increased, and the height of chipping into the vessel also increased.

The professional glassblower's punties were very consistent while the amateur punties ranged widely in all the characteristics tested. The professional samples tended to have a large temperature difference between the vessel and punty at attachment (the punties were hotter that the vessels), large jackline area, thin vessel bottom, and less vessel mass. These samples also had a shallower punty scar with a greater diameter and no significant scar protrusions from the vessel bottom.

Conclusion

When the punty scar is approached from the perspective that minimal polishing is ideal the data suggests a number of characteristics should be sought. A deeper scar risks structurally damaging the vessel, and it would be easier to polish a shallow-wide scar than one that is narrow-deep. To avoid deeper scars less massive vessels are recommended. For the shallowest punty scar it is recommended to use: a hotter punty connecting to a cooler vessel, a larger jackline area, with a thicker cup base, and a smaller punty. A smaller punty would also correspond with a smaller diameter but the punty needs to be made to fit the physical requirements placed on it by the vessel first and foremost. (Smaller punties are more delicate.) These guidelines will aid glassblowers in producing optimized punties for their needs, minimizing finishing work, and improving workflow.

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ABSTRACT

In glassblowing, a glass object is often transferred from the blowpipe onto a secondary rod for further shaping using a gob of glass known as a punty. The punty forms the connection between the glass object and the rod. After the vessel is finished it is removed from the rod by fracturing the punty. If performed correctly the fracture surface, or "punty scar," left on the vessel is relatively small and ideally flat. To develop the skill and knowledge necessary to routinely form an ideal punty scar takes hours of dedicated work and practice by the glass blower. This study sought to define the parameters of punties that left the least amount of scarring on the glass vessel: this study-defined version of the ideal punty. Several variables were evaluated with regards to the average diameter of the punty scar, the average height of the punty scar, and the general shape of the scar. The factors recorded and analyzed included the difference in temperature between the punty and vessel upon their attachment, the thickness of the base of the vessel, the area of the jackline, the mass of the vessel, the approximate size of the punty, and the temperature of the punty when the vessel was removed. The data suggests that a smaller punty corresponds to a smaller diameter and height in the punty scar. While increasing the delta T and jackline area correlated with a slightly smaller height of punty scar, it also correlated to an increasing diameter of the punty scar. An increase in the thickness of the bottom of the vessel correlated with a smaller diameter of the punty scar but was unrelated to the height of the scar. The greater the mass of the vessel correlated with an added height to the punty scar.

1. INTRODUCTION

1.1 THE GLASSBLOWING PROCESS

Punties are used in glassblowing to transfer glass pieces and parts while working molten glass. The term punty can be used as one of two nouns or a verb. 1) The punty is a solid metal rod[A]. 2) A small blob of glass that is gathered on the end of a punty rod and shaped for transfer is called a punty. 3) The act of transferring a glass piece onto a punty is called puntying, i.e. to punty the piece over. In general the actual meaning must be inferred by the context.

Glassblowers often follow a specific series of steps to produce vessels as outlined in Figure 1.[B] First, they gather a blob of molten hot glass onto the end of a hollow metal blowpipe[C]. They then blow through the pipe to create a bubble in the molten glass. A constriction, called a jackline, is put in the bubble near the pipe. The sides and tip of the bubble are then formed to the desired final shape. A punty is attached to the tip of the bubble, in the center

[A] A punty *rod* is a solid metal rod that is used to gather glass. It is solid and therefore unable to be blown through.

[B] Figure 1 reviews the normal glassblowing process. In the design of this experiment, three deviations from this process were necessary. 1) Small colored bits of glass were attached to the bubble after step 2 as sample labels. 2) A blow-mold was used to perform the additional shaping at step 4 to ensure consistent shape among all the samples 3) The process ended shortly after step 9 (skipping step 10) to preserve the fracture area of the jackline for analysis.

[C] The blow*pipe* is a hollow metal pipe that can be blown through to inflate a glass bubble. Not to be confused with a rod, which is solid and cannot be blown through.

of what will become the bottom of the vessel, to support the piece once the blowpipe is separated. The glassblower then removes the piece from the blowpipe by breaking it off of the pipe at the jackline. The pipe is discarded and the piece is kept on the punty until it is finished. The transferred piece, now fixed to the punty, is able to have the previously unworked, top-side of the piece exposed for shaping. Once finished the vessel is broken off of the punty and placed in an annealer[D] to be slowly cooled to room temperature.

[D] An annealer is a furnace used to slowly cool the glass from its working temperature to room temperature, over a period of a few hours to a few days, depending on the size of the pieces. This slow cooling keeps the glass from cracking or shattering due to thermal stress.

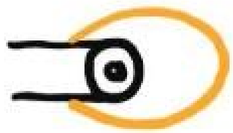
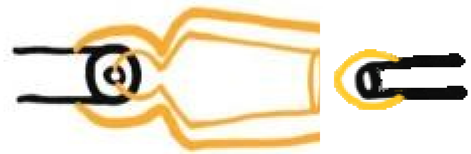
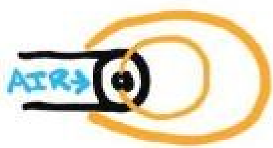
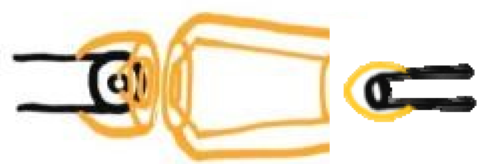
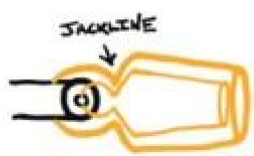
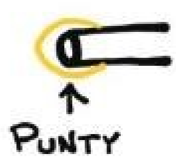
1. A gather of glass on the end of a preheated blowpipe		6. Attach the punty to the bottom of the vessel. (tip of the bubble)	
2. Blow through pipe to start a bubble		7. Thermally shock the jackline	
3. Constrict the bubble near the pipe to make a jackline		8. Break the piece off of the blowpipe	
4. Additional shaping of the tip of the bubble		9 Discard the blowpipe	
5. Form a punty on a solid rod		10. Final shaping of vessel on punty	

Figure 1. Overview of the glassblowing process. Once all the steps outlined below are completed the vessel is broken off of the punty and placed in an annealer.

Punties are made in a large variety of shapes and sizes to suit specific needs of the glass piece being puntied. Puntying a piece involves making a temporary connection to a piece of glass typically to shape the opposite end of the piece. They are (almost) always made on a solid punty rod and consist of a blob of hot glass. Hot glass makes a very strong connection with other glass, given the correct temperature control. This project focuses on dome-style punties shaped like a cotton swap as illustrated in **Error! Not a valid bookmark self-reference.**.

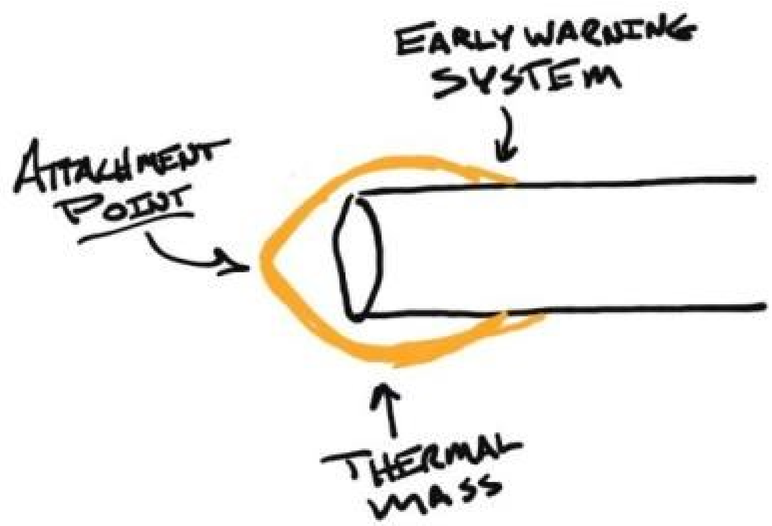


Figure 2. Features of a standard dome punty

Although subject to personal preference in many ways, three main aspects of the punty shape serve a purpose to the glassblower. The thin glass at the back of the punty serves as an early warning system for glassblowers as cracks will begin here, where the glass is thinnest and farthest from the heat, if the punty is getting too cold. The thermal mass helps the rest of the punty maintain its heat. The point at the tip allows the glassblower to control exactly how much of the punty they want to adhere to their piece when they attach the punty. The viscosity of the point as it is attached can also serve as a temperature gauge.

Punties are designed to be temporary connection points and are often very difficult for beginner glassblowers to properly learn and use. Punties may fail in several ways. In some cases the puny will fracture before they are supposed to, causing the piece to crash to the ground. Or, if the punty is attached too strongly to the vessel, the vessel will break before the punty does. Glassblowing instructional guides will often recommend that the only real way to become proficient at using a punty is by practicing, although they have a lot of advice for the beginning glassblower detailed as follows.[12]

1.2 OVERVIEW OF THE “BREAK-OFF” PROCESS

Strategic fracture is common in glassblowing. Although the nuances of succeeding are tricky to convey, the basic procedure entails chilling the glass (either with water or a cold tool) where the break is desired to induce thermal shock and striking the rod/blowpipe to initiate a fracture as demonstrated in **Error! Reference source not found.**. Strategic fracture has varying levels of difficulty. Some thick jacklines need to be drenched with water before they will fracture; while others require a delicate approach that may not even need the application of a chill to break. Applying a chill can risk damaging the vessel, especially later in the process when the heat is kept at a minimum to prevent deformation. (It is safer for the piece to avoid water if one is practiced enough to not need it.)

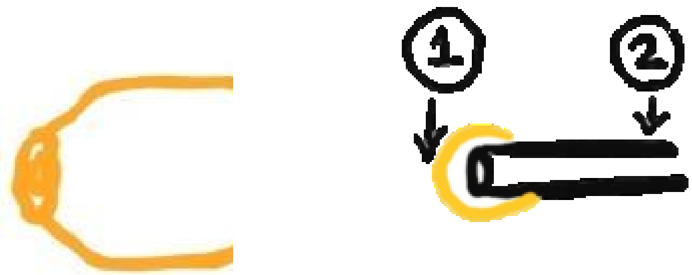


Figure 3. To break the piece off of the punty, apply a chill at the junction between the punty and piece (1) then impact the rod at (2).

1.3 THE PUNTY SCAR

In an ideal scenario, the punty may be fractured and separated from the vessel at the original interface and leave no defect. However, almost every punty leaves a defect called a punty scar on the bottom of the vessel where the punty was fractured and separated from the vessel, as shown in Figure 4. A portion of the punty may remain on the vessel and protrude from the surface causing it to no longer sit flat, or part of the vessel may chip off with the punty. For the purpose of this thesis the ideal punty was identified as being the punty with the smallest punty scar, indicating the least amount of damage to the vessel and therefore the least amount of polishing that must be done to the piece later.

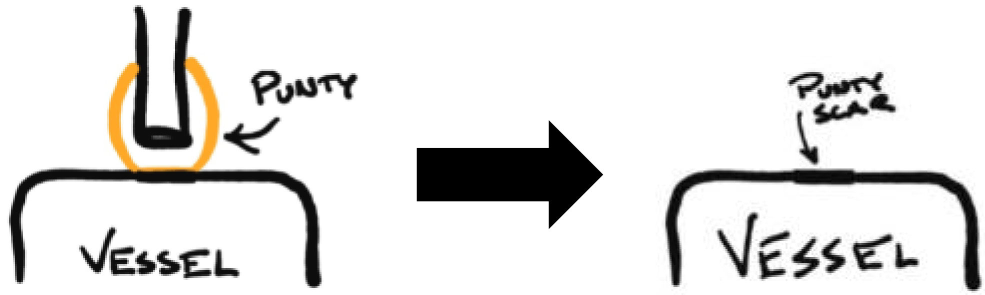


Figure 4. The location and formation of a punty scar.

Each glassblower makes their own variety of punty and, when asked, can point out different features they search for to ensure their piece does not fail. (Many of these will be explained shortly.) Clear failure is when a piece breaks, either falling to the ground or cracking, when the punty is broken off. Some glassblowers discard pieces that require extra polishing work. But often if a piece does not break in the making, the punty is considered successful. This definition of success is too broad to draw specific conclusions from, so it is necessary to define a more restrictive definition of success. The focus of this work is to identify the characteristics of the ideal dome punty: one that holds the piece until it is supposed to be broken off, and leaves minimal punty scarring.

1.4 WHAT THE GLASSBLOWING COMMUNITY HAS TO SAY

Glass blowing manuals have a lot of advice about how to correctly punty a piece, including: the temperature of the punty and the vessel as they are attached, the thickness of the vessel's base, the jackline, the weight of the vessel, the size of the punty, and the temperature of the punty when the vessel is removed from it (breakoff).

1.4.1 ATTACHMENT TEMPERATURE

Glass instructions caution about what temperature to attach a punty. If the punty is too cold it won't stick at all or the connection may fail with the slightest of jarring. Or if a punty is far too hot (and therefore the glass too fluid) it will smear or be unable to support the weight of the vessel which will ooze off of the punty. Slightly less hot, but still too hot to work properly would permanently weld the punty to the piece. In this case if a punty "get[s] stuck on too hot, you'll have no choice but take out a big chunk of the bottom [of the vessel]."[2] One manual describes a good punty temperature as being kept at a "dull glow" with the tip "the consistency of chewing gum," which is almost a helpful qualitative viscosity reference (but even chewing gum has various viscosities.)[1]

It is recommended that the vessel being puntied be warm but not moving.[13] Although Art of Fire elaborates that the vessel ought not be "so cold that it can't withstand the minute long process of attaching the punty"[1] In a similar vein Art of Fire warns against waiting too long after attaching the punty to the vessel and actually breaking the vessel from the blowpipe, recommending that "once the punty starts to stiffen up, it's time to break the piece off at the jackline. Many beginners ruin their pieces by spending too much time jacking and cooling the jackline while the punty gets cold. Once this happens you are doomed."[1] The piece (and punty) might otherwise be chilled by the extensive delay, and the introduction of the gloryhole[E] heat could cause it to thermally shock and break. It is also difficult to introduce heat specifically to the punty, "The main source of heat for the punty is the gloryhole… [which means that] there is no way to apply heat to the punty without applying an equivalent or greater amount of heat to the whole piece."[1] If too much heat is applied too quickly the piece may deform before the punty gets warm.

1.4.2 JACKLINE AREA

Advanced Glass lists jacklines as one of the physical features of the vessel that is highly influential on how successfully the vessel is transferred onto and released from the punty.[4] The jackline is the constriction placed in the bubble near the blowpipe where the vessel breaks off of the blowpipe (after it is attached to the punty.) The jackline both cools and narrows the glass where it is applied, such that, with the addition of a drop of water (or application of a cold tool) to the jackline and a solid tap to the blowpipe, a crack will initiate that transverses the jackline. The important thing to remember is that the vessel is broken at the jackline *after* the punty is applied, if the jackline does not break easily the punty may break instead.

[E] The gloryhole is a reheating chamber.

Once the crack is started though, it will "follow the path of least resistance. Hopefully this path is the jack marks that you put in your piece, but this is not always the case. More than anything else, temperature affects the way your piece breaks off of the blowpipe. The glass will crack where it is the coldest."[1] Following the coldest path means that the crack forms where the glass is most brittle.

1.4.3 VESSEL BOTTOM THICKNESS

Advanced Glass claims that the geometry of the glass piece itself may be most influential in terms of successful transfer to, and subsequent release from, the punty.[4] One feature mentioned is the thickness of the vessel's bottom. Art of Fire claims that the size of a punty can be tailored to the vessel's needs: a smaller mass punty will both heat and cool more quickly, which is ideal if the piece has a bottom that cannot take a lot of heat without deforming.[1]

1.4.4 MASS OF VESSEL

Advanced Glass indicates the weight of the vessel is one of the vessel's physical characteristics that influence the transfer and subsequent release from the punty.[4] The mass of the vessel translates into the strain placed on the punty, the entire weight of the piece is held by the small connection to the punty. Hot glass makes a very strong connection with other glass, given the correct temperature control. "A circular piece of glass with a diameter of half an inch is more than enough to support ten pounds of hot glass."[1]

1.4.5 COMPARATIVE PUNTY SIZE

According to Beginning Glass the size of the vessel determines the size of the punty that should be used.[2] The use of a blow-mold[F] was intended to remove the size and shape of the vessel as a variable; thus minimize variations in the size and shape of the punties.

1.4.6 BREAK-OFF TEMPERATURE

"If the only challenge were keeping the punty firmly attached to the piece, you would simply make a giant punty and keep it hot the whole time… in practice you want a punty that is just a chill and a tap away from letting go."[1] The break-off is when the punty-vessel connection is broken. In theory, "A good punty can be removed by a single tap on the punty rod. [Thus, rough handling of a punty] can lead to premature depuntification."[1] However this is not always the case and many glassblowers apply a thermal shock to ensure the piece breaks where (and when) it ought to break. It is common to err on the side of caution and stick a punty on a bit too well, rather than risk the vessel falling, but this necessitates extra removal effort.

[F] A blow-mold is a mold designed to allow a bubble to be blown to the interior shape, they are often used in production work.

1.5 LITERATURE REVIEW: WHAT THE SCIENCE SAYS

A glass is traditionally defined as a solid material that lacks long-range molecular order. This absence of long-range order is responsible for the various properties which enable glass to be used in glassblowing. At sufficiently high temperatures the glass-forming molecular groups possess enough energy to rearrange relative to one another allowing the glass to flow like a viscous fluid. This viscous behavior enables hot glass to be worked and processed into unique forms.

However, due to the absence of long-range molecular order, as the glass temperature decreases the glass-forming molecular groups gradually loose the energy needed to rearrange, resulting in increasing viscosity and a gradual transition from fluid to solid. Cooling also coincides with an increase in density (decrease in volume) due to rearrangement of the glass structure into a more optimum packing structure (albeit a non-crystalline one) and a decrease in bond length associated with thermal expansion. Once the glass becomes solid and the structure frozen, further relaxation of the structure becomes essentially impossible. Stresses present in the glass due to uneven shrinkage (most dramatically exemplified by thermal shock), or the application of external forces, cannot be relaxed which may result in failure of the bulk glass due to brittle fracture. The relationship between viscosity, density, and temperature are given in Figure 5 and Figure 6.

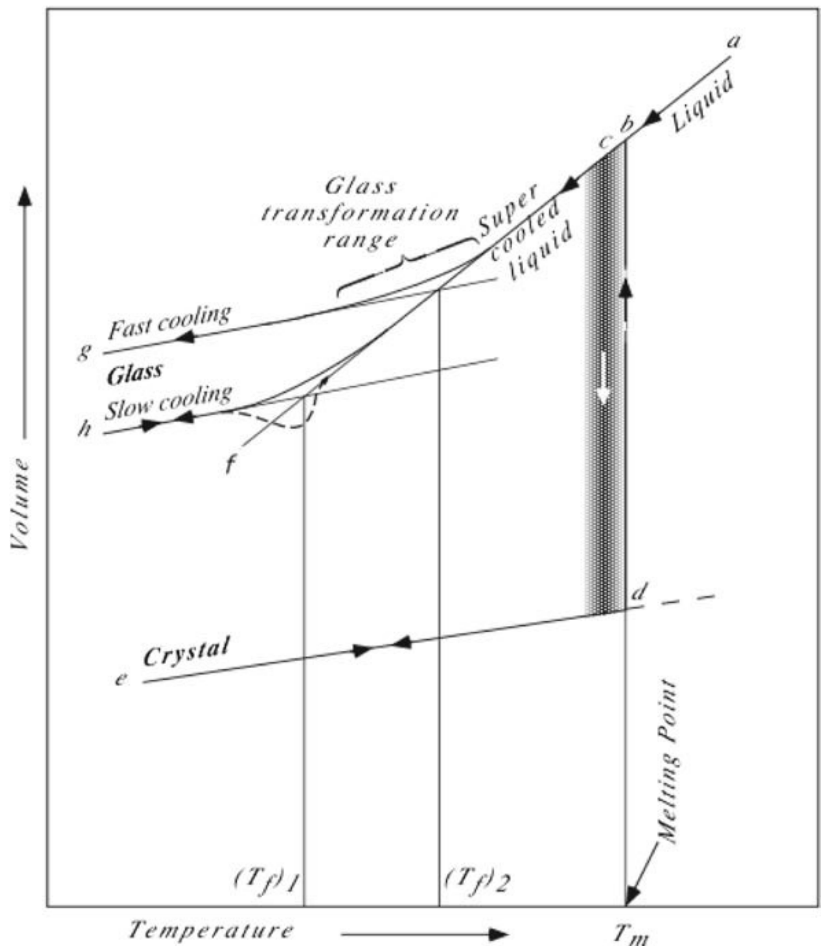


Figure 5. Volume temperature graph reproduced from Varshneya. If a material cooling from the liquid state (a to b), is given enough time to relax completely, it will form a crystalline structure (following the path from c to d and ultimately reaching e.) However, if the liquid material cools past the traditional melting point into the supercooled liquid temperature until it "solidifies" at the glass transformation range (the point as the property curve deviates from the straight line extrapolation towards g or h) it forms an amorphous glass structure.[5]

Name of reference temperature	*Viscosity* (Pa s)
Practical melting temperature	≈ 1–10
Working point	10^3
Littleton softening point	$10^{6.6}$
Dilatometric softening temperature	10^8–10^9
Glass transformation temperature	$\approx 10^{11.3}$
Annealing point	10^{12} or $10^{12.4}$
Strain point	$10^{13.5}$

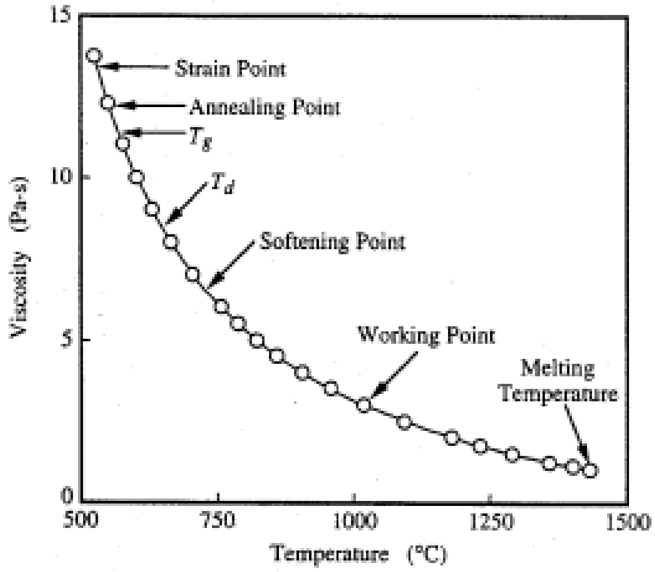


Figure 6. Viscosity versus temperature from Shelby 1997. The glass transformation temperature range denoted in Figure 5 corresponds to viscosities near Tg.[6]

In glassblowing, puntying is performed above the minimum temperature at which the glass may deform and flow, as puntying requires that a semi-permanent interface be formed between the punty and the vessel. If the punty is too hot a highly cohesive interface will form as it fuses to the vessel. If it fuses, the punty-vessel junction may not necessarily be the path of least resistance for the fracture. In this case the fracture may occur further along the punty (resulting in a protrusion on the base of the vessel) or into the bulk of the vessel (resulting in chipping from the vessel) depending on stresses present. Viscous flow behavior therefore suggests that puntying occur at just the right temperature above the glass transformation range to allow viscous flow of the punty and limited cohesion. Break-off must be performed once the glass has been chilled below the glass transition temperature so that brittle fracture may occur.

As shown in Figure 5, the thermal history (in other words, the heating and cooling applied to both the vessel and the punty) affects the resulting shrinkage, indicated by the slow and fast cooling lines. If the vessel and punty shrink at different rates, either from handling or their thermal mass, then a stress gradient will form between the two as the system cools through the glass transformation range and becomes solid. In the relatively short timescales involved in glassblowing, such stresses cannot be relaxed once the glass has cooled until the vessel is annealed after break-off. That is, stresses present near the interface between the vessel and the punty may contribute to the behavior of brittle fracture and induce fracture to occur elsewhere. The application of the cold tool or the water causes rapid cooling in thermal shock, concentrating stresses at the point of application.

2 EXPERIMENTAL PROCEDURE (EXPERIMENTAL DESIGN)

Standard blowpipes, a hollow metal pipe 134.6 cm long and 2.2 cm diameter, and standard (but well used) solid metal punty rods that ranged in diameter from 12.7 mm to 7.6 mm were used in the glassblowing shop at Alfred University. The diameter of a punty rod affects the average size of the glass punty itself. In this experiment 12.7 mm (½ inch) punty rods were used for all punties, although variations in punty diameter were likely due to wear.

The punties were made by several different individuals, three amateurs (glassblowers who rarely break the vessel but are inconsistent in punty making) tried to make a selection of data by simply trying any punty that worked (data sets 1._, 2._, and 3._), and one professional glassblower who made their accustomed and consistent punties (data set 4._)

Specific details of the following process are illustrated in Figure 7. Initially a small blob of molten glass was gathered from the glass furnace onto the end of a preheated hollow blowpipe. To provide ample bulk glass to fill the blow-mold, a second gather was acquired. A bubble was started by blowing through the pipe and the glass was shaped to approximately a bullet shape. Small pieces of colored glass (frit) were stuck to the glass to identify the sample. These frit indicators were applied by laying out the frit on the marvering table[G] and rolling the glass on the end of the blowpipe over them picking them up with the hot glass bubble. The process of attaching the frit cooled the glass where it touched the marver, so the frit indicators were added to the sides of the bubble and not the bottom where the punty could be affected.

[G] A marver is a metal table used for cooling and shaping glass, originally made of marble.

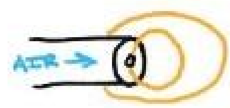
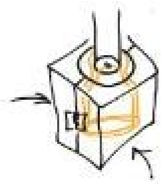
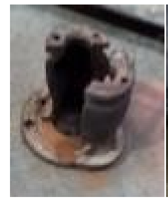
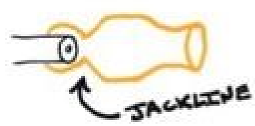
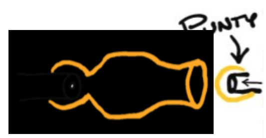
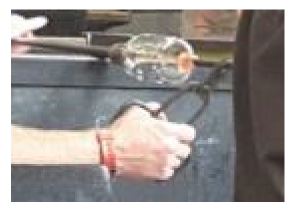
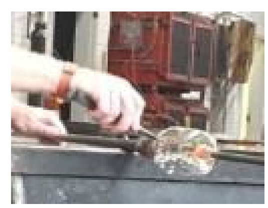
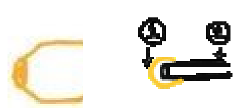
Start the bubble in the gather at the end of the blowpipe.		
The bubble is formed to its final vessel form by enclosing it in a blow-mold and inflating it to fill the space.		 
The bubble is constricted near the pipe to form a jackline, the intended location of a crack when the vessel is transferred onto a punty.		
The punty is attached to the tip of the bubble, in the center of what will ultimately be the base of the vessel.		
The jackline is cooled with water and the blowpipe impacted to break the vessel off of the blowpipe (while leaving it attached to the punty.)		
To break the vessel off of the punty, apply a chill at the junction between the punty and vessel (1) then impact the rod at (2).		

Figure 7. Visual overview of the process for making a glass vessel.

The bubble was reheated (to ensure the frit was fused to the bubble) before being blown into a cork lined blow-mold. The mold was used to ensure a consistent size and shape of the glass vessel. According to Beginning Glass the size of the vessel determines the size of the punty that should be used.[2] Thus using a blow-mold was theorized to minimize variations in the size and shape of the punties. The mold was sprayed with water between each trial to prevent the cork lining from burning out. Both the temperature of the mold and the duration of the time the glass was in the mold were not controlled. The piece was taken out of the blow-mold. Jacks[H] were used to tighten the neck of the vessel into a jackline to ensure it would break at that point.

A preheated solid metal punty rod was used to gather a small amount of glass that was then shaped into a punty on a marvering table. Once shaped, the punty was photographed. After a reheat, the punty was attached to the bottom of the vessel. A video record was made of the temperature of both the punty and vessel as they were attached. The temperature was obtained from a thermal imaging camera (ISG Infrasys X380, ISG Infrasys, Lawrenceville, GA). The temperatures were recorded on the video feed.

[H] Jacks resemble tweezers with the blades rotated 90°, they are waxed to avoid sticking to the glass as they shape it in a wide variety of ways.

Once "puntied over" the vessel was reheated to equalize the temperature before being broken off from the punty and placed into an annealer. This reheat served to thermally stabilize the piece to reduce thermal shock and subsequent cracking.

The amateurs used a drop of water at the punty-vessel connection to thermally shock the vessels when impacted. The professional simply knocked the pipe to break the vessels off without the addition of water. Sample 4.10 specifically was a demonstration of a production punty style characterized by a flat, square-shaped tip, higher usage temperatures, and the application of water for break-off. This style of punty is used particularly by glassybaby™.

In all the samples produced during this study the back end of a pair of glassblowing tweezers was used to impact the rod/pipe. This provided a much harsher impact than wood would have. Tweezers are a more accessible tool in most glassblowing studios. They also tend to be used for the chilling process, either as a water applicator or to provide a cold steel chill, so they are already in the glassblower's hand for break-off.

The temperature at break-off was video recorded as well. Vessels were not completed and left unopened in an attempt to minimize variables and to provide accurate jackline data.

3 RESULTS AND DISCUSSION

3.1 PUNTY SHAPE

The professionally-made punties were very consistent in temperature 722-797°C (75°C difference) [1329-1467°F (138°F difference)]. The amateur punties were much cooler and more varied, ranging in temperature from 599-754°C (155°C difference) [1110-1389°F (279°F difference)]. All the punties used in the amateur trials were photographed, and are shown in Figure 8 along with a few key images of the professional punties. (The professional worked too fast for punty pictures to be taken during data collection, however an image of three punties were taken.)

For the sake of study only punties that successfully puntied over a vessel (that survived the entire process) were studied. The samples which failed are indicated by an (*) after the sample number in Figure 8.

Figure 8. Portraits of the punties made during this study. The pipe in each image is ½ inch in diameter. The punties are not shown at the temperature at which they were attached. They were made, photographed, and reheated before attaching.

3.2 VISUAL IDENDIFICATION OF GLASS TEMPERATURE

For the purposes of application, knowing the precise temperature of the glass is unhelpful for glassblowers as they are working in the glass studio, unless they have a thermal imaging device on hand and an assistant designated for reading off the temperature. The visual characteristics of the punties in the video recording during this experiment are summarized in Table I where the approximate color and visual cues for various glass temperatures are recorded. Art of Fire recommended that punties be kept at a “dull glow” with the tip “the consistency of chewing gum” presumably referring to the 628-703°C range where the glass loses its glow. Experimentally the punties in this study ranged from 599-797°C [1110-1467°F].

Table I. Apparent temperature characteristics of punties.

Temperature Range (°C)	**Temperature Range (°F)**	**Visual characteristics of the punty**
802-825	1475-1517	Glass is a glowing yellow while the pipe near the glass is an orange red
628-703	1163-1297	Glass appears to lose its glow, it now is a dull warm orange
571-612	1059-1133	External pipe has lost all color and the glass is a dull red
482-523	899-973	Glass is clear with a slight redness in the pipe it encapsulates
459-488	858-910	All redness has disappeared

3.3 FRACTURE FEATURES

A punty scar is the mark left on the bottom of a completed glass vessel where the punty is broken off. For the purpose of this thesis the ideal punty was identified as being the punty with the smallest punty scar, indicating the least amount of damage to the vessel and therefore the least amount of polishing that must be done to the vessel later. Each punty scar was analyzed in three different ways.

3.3.1 GENERAL RANKING SYSTEM

In an attempt to codify the contour of the punty scar, a basic rating system was established. **Error! Reference source not found.** shows how the punty scars were assigned a rank from 1 to 4 to qualitatively describe how much additional polishing effort they would likely require.

The rank of 1 (most ideal) was given to punties that broke off flush to the sample bottom. There was no risk to the vessel's integrity nor was there any need for extra labor to finish the vessel.

Rank 2 was given to punties that took a chip out of the sample as they broke off. If the chip was too large for the thickness of the bottom it may ultimately affect the vessel's integrity. However, extra polishing work is usually necessary as sharp edges from the chip may require polishing to ensure safe usage.

Rank 3 punties have part of the punty attached to the bottom of the vessel, as well as a section broken out from the bottom of the vessel. They have less material to polish off and are therefore not as bad as rank 4 punties.

Rank 4, the worst punties broke off onto the samples, creating a bump that would need to be polished off in order for the vessel to sit flat. More experienced glassblowers tend to throw out vessels that the punty breaks in this way because it will take them less time to make a new vessel from scratch than it would to polish it flat.

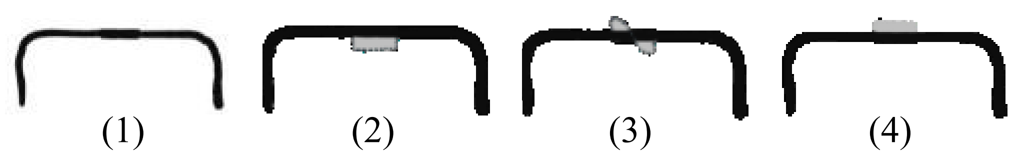


Figure 9. Numerical ranking of punty scar contour.

3.3.2 AVERAGE DIAMETER RANKING SYSTEM

The largest and smallest dimension of each punty scar was measured with calipers, the average of which provided an average punty scar diameter. A large punty scar implies the punty-to-vessel connection was stronger and more stable, although it may be more so than necessary. An ideal punty would hold the vessel securely but release easily leaving a smaller diameter scar, causing less damage to the vessel.

The professionally made vessels tended to break-off cleanly or left wide flat chips that contributed significantly to this measurement. The amateur punties broke off in a myriad of ways, too varied to draw any specific trends from. The amateur punties provide a range within which the professional punties provide a precise variant, or rather two variants.

Figure 10 shows the smallest diameter punty scars; sample 3.6 (9.3mm) and 1.9 (9.95mm). The widest punty scars were 4.10, 4.3, and 1.2, which were an average diameter of 21.3mm, 20.5mm, and 18.3mm respectively, show in Figure 11.

Figure 10. The smallest diameter punty scars, sample 3.6 (left) and sample 1.9 (right). The black bar in each image is 1 cm in length.

Figure 11. The widest punty scars were on sample 4.10 (left), 4.3 (center), and 1.2 (right). The black bar in each image measures 1 cm in length.

3.3.3 GREATEST HEIGHT RANKING SYSTEM

Figure 12 shows the samples with the greatest punty scar height, measured in samples 3.3 and 3.9, at heights of 5.16 and 5.35 mm, respectively. Finally, the shallowest punty scars are shown in Figure 13 with measured heights of at 0.8, 0.87, and 0.89 mm. The height of each punty scar was measured using depth calipers, finding the sum of the punty scar height that recessed into the vessel and protruded from it. A smaller total height indicates a smaller punty scar and less polishing required later.

Figure 12. Fractures for sample 3.3 (left) and 3.4 (center) the black bar is 1cm in length. A profile of sample 3.9 (right) is included for context.

Figure 13. The most shallow punty scars: sample 1.2 (left), sample 21. (center), and sample 4.9 (right). The black bar in each image is 1cm in length.

3.4 ANALYSIS

3.4.1 ATTACHMENT TEMPERATURE (ΔT)

Most of the punties were significantly hotter than the vessel they were attaching to, a positive value in this analysis. The temperature difference of the professional punties was significantly higher than those of the amateurs. The temperature difference between the vessel and the punty for the professional's samples were 180-303°C [324-545°F] while the amateur punties-vessel-temperature-difference ranged from -74-124°C [-133-224°F]. The smallest delta T (-74°C) occurred with sample 3.6, while the greatest delta T (303°C) occurred with sample 4.9.

The difference in the temperature between the punty and the vessel suggests a slight correlation to the diameter of the punty scar. Figure 14 indicates that as the temperature difference of the vessel and punty increased, the punty was much hotter than the vessel, the average diameter of the punty scar tended to increase as well. In the following images with two colors present, the red data points indicate the professional data, while the blue points indicate the amateur data.

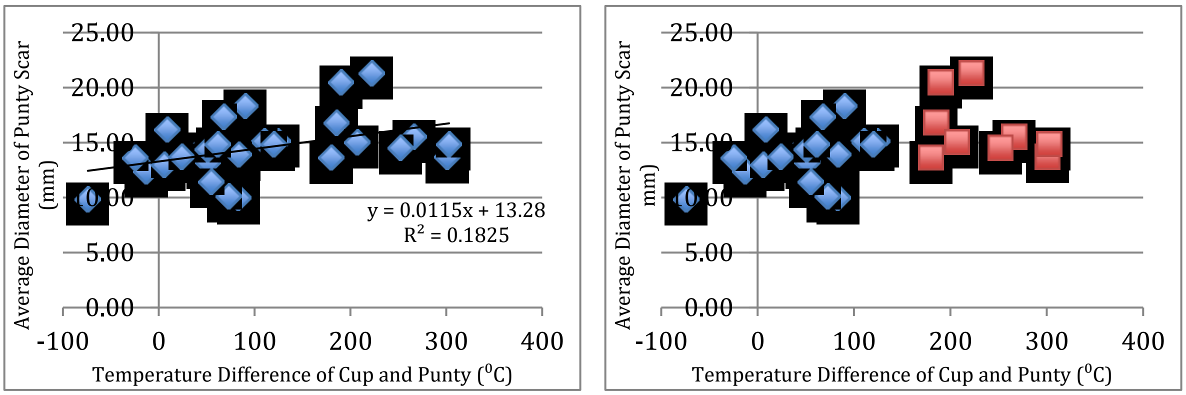


Figure 14. Punty scar diameter as a function of attachment delta T.

Figure 15 suggests a slight negative correlation is apparent between the temperature difference between the vessel and punty as they were connected, and the height of the punty scar.

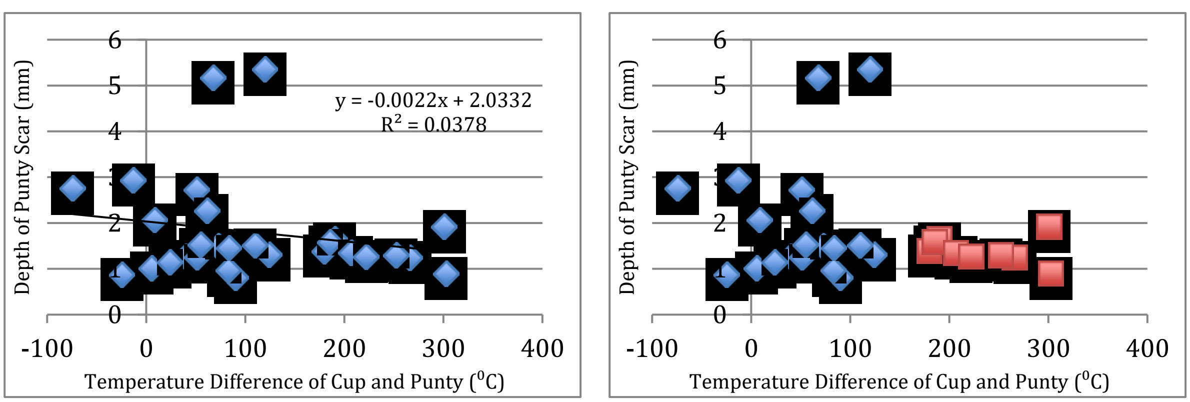


Figure 16 indicates that no clear shape trends arose in relation to the temperature difference

Figure 15. Height of punty scar as a function of attachment delta T.

between the vessel and the punty since the desirable contour of rank 1 was present across the range of delta T tested. However, all of the undesirable samples, rank 4, did have a delta T less than 110^{o}C.

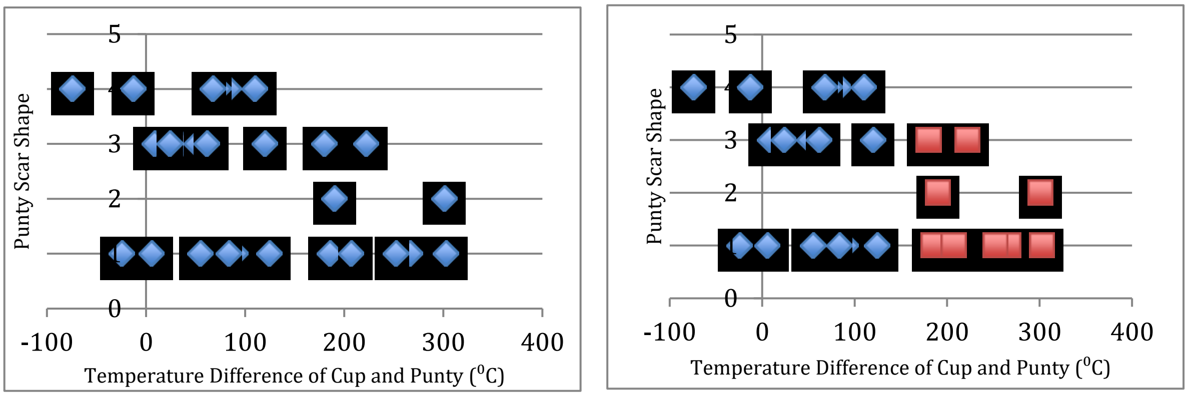


Figure 16. Punty scar shape as a function of attachment delta T.

While a significantly hotter punty attaching to a cooler vessel suggests to a slight increase in the diameter of the punty scars the height of those scars was diminished. The hotter, less viscous punties are able to squish onto the vessel, creating a greater diameter punty scar. The shape of the scars tended to be less desirable as the temperature of the punty and vessel becomes less extreme.

3.4.2 JACKLINE AREA

The jackline is the place where the vessel breaks off of the pipe, while remaining attached to the punty. The area of glass at the jackline is indicative of how much glass had to break without breaking the punty off of the other end. When the vessel was transferred to the punty it was heated minimally to preserve the fracture surface of the jackline as it was when it broke off. To identify the total area at the break the inner and outer diameters of the jackline surface were measured after the vessel was broken off of the punty and annealed. The location of the jackline area on a sample vessel is indicated in Figure 17.

Figure 17. The jackline area is highlighted here in red, the measurement was obtained using the inner and outer diameters of the highlighted portion.

The professional samples tended to have larger jackline areas ranging from 260-438mm^2. The amateur samples had a wide range of jackline areas, spanning 96-540mm^2. The smallest jackline area (96mm^2) occurred with sample 3.5, while the largest jackline (540mm^2) occurred with sample 2.0.

The data suggests a trend toward a greater diameter punty scar in conjunction with a larger jackline area as demonstrated in Figure 18.

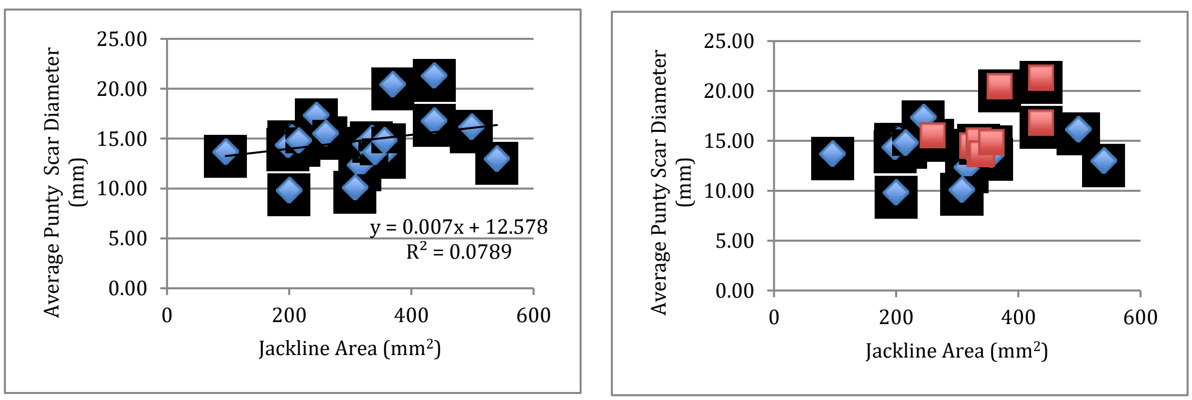


Figure 18. Punty diameter as a function of jackline area.

As the jackline area increased the height of the punty scar was diminished, as suggested in Figure 19.

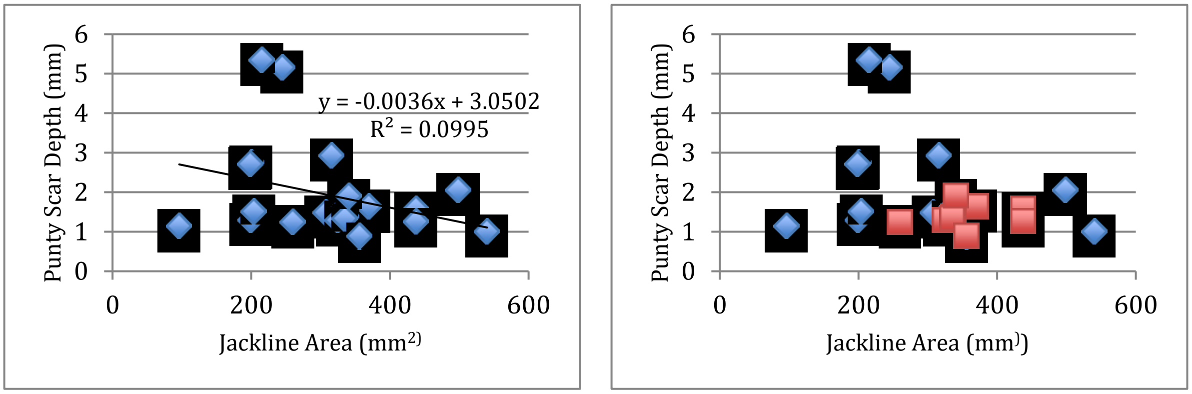


Figure 19. Punty scar height as a function of jackline area.

There are no apparent trends in punty scar shape as a function of jackline area as demonstrated by Figure 20 .

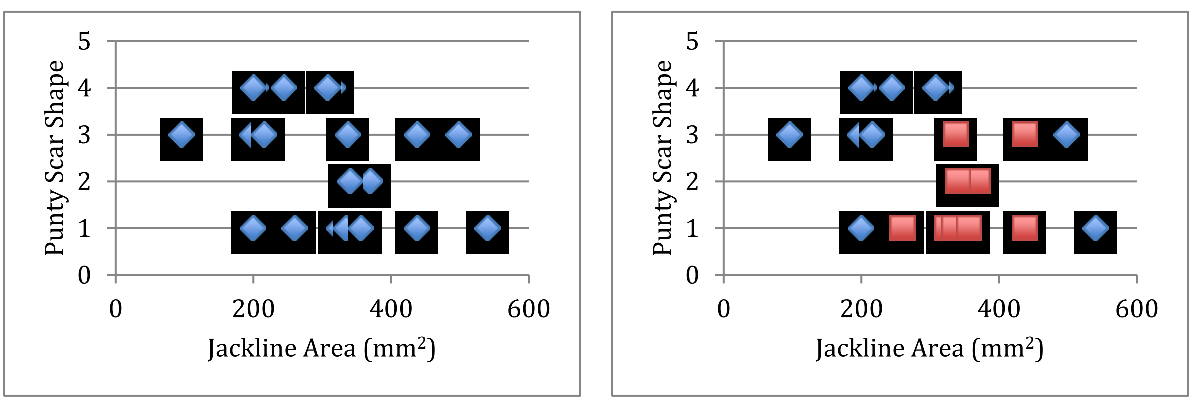


Figure 20. Punty scar shape as a function of jackline area

A greater jackline area correlates with a slightly greater punty scar diameter but a smaller punty scar height. The jackline area is indicative of the strength of the punty-vessel connection. (Note that the punty is at its hottest when its strength is being tested against the jackline's.) When dealing with a thicker jackline area the glassblowers tend to adjust their puntying, squishing the punty onto the piece with more force, to account for the additional force the punty will encounter as the jackline is broken. There were no apparent trends in punty scar shape in relation to the jackline of the sample.

3.4.3 VESSEL BOTTOM THICKNESS

An approximate vessel base thickness was measured using digital calipers from the outside of the vessel. The professional samples tended to have thinner bases, ranging from 2.0 mm to 9.8 mm; while the amateurs had thicker bases ranging from 5.6 mm to 22.6 mm. Sample 4.2 had the thinnest base (2.0 mm), while sample 2.0 had the thickest base (22.6 mm.)

Figure 21suggests that there is a slight negative correlation between vessel bottom thickness and the diameter of the punty scar was present in the data.

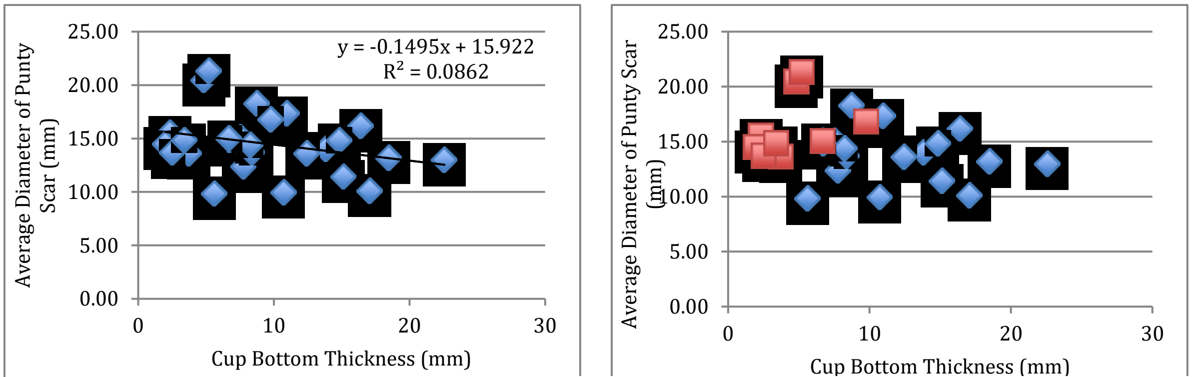


Figure 21. Diameter of punty scar as a function of thickness of vessel.

Figure 22 indicates that there was no correlation between vessel bottom thickness and the height of the punty scar.

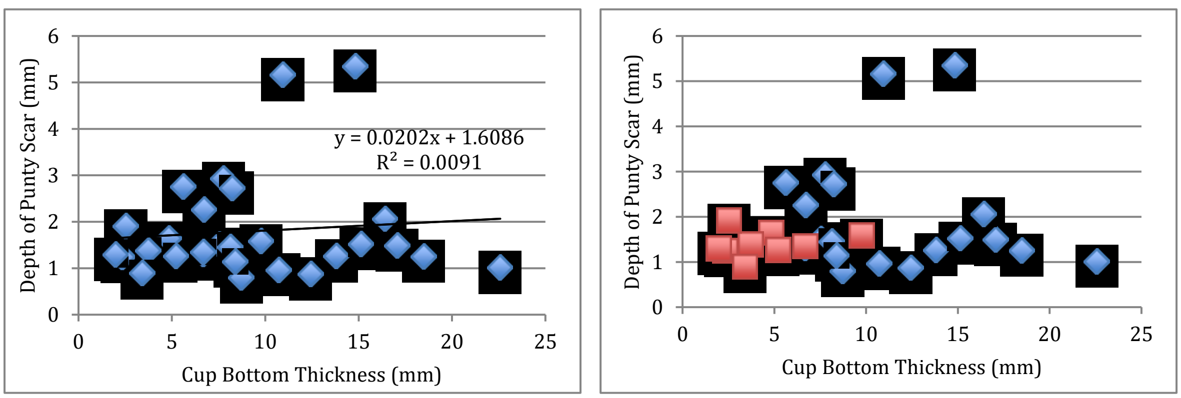


Figure 22. Punty scar height as a function of thickness of vessel's base.

No discernable trend appears in the contour rating system as a function of the vessel's base as indicated in Figure 23.

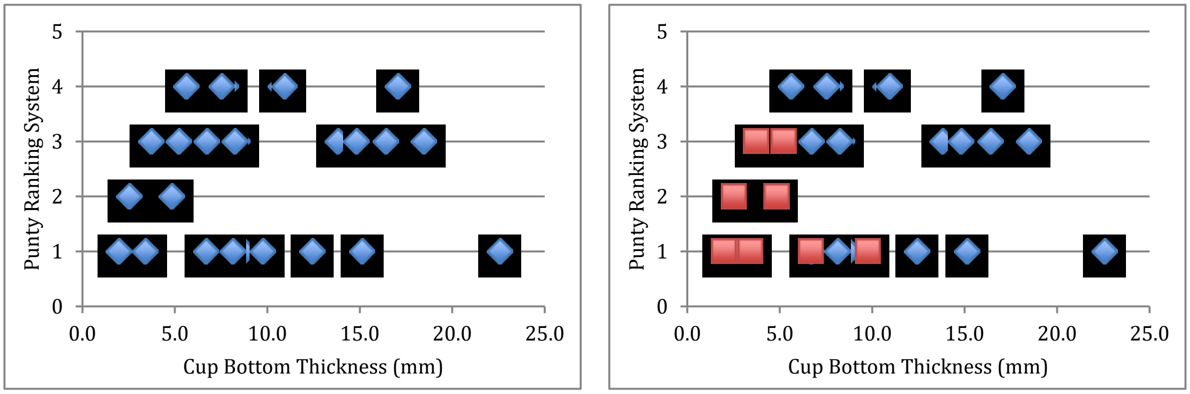


Figure 23. Punty contour ranking system as a function of thickness of vessel's base.

There is a slight tendency that the thicker the vessel’s base the smaller the diameter of the scaring. There was no apparent correlation between base thickness and the height of the punty scar. The thickness of the vessel base may have an effect on the thermal experiences of the punty. A thicker base would have a greater thermal mass and protect the punty-vessel junction from experiencing rapid thermal change. There is no apparent correlation between the size of the base of the vessel and the punty scar.

3.4.4 MASS OF VESSEL

The weight of the vessels indicates the amount of shear stress exerted on the punty at the attachment and the breakoff. When the vessel is being transferred to the punty, the punty needs to connect strongly enough that it can support the weight of the vessel, despite the shock applied to the blowpipe to break the jackline. (Otherwise the vessel may break off at both points and crash to the ground.) The mass of the vessel also provides a shear stress when the vessel is broken off from the punty itself.

The professional samples clustered in the center of the wide ranging amateur samples. The professional samples ranges from 177 g to 250 g in mass, while the amateur samples ranged from 155 g to 318 g. Sample 3.9 was the heaviest (318 g) while sample 1.7 was the lightest.

There are no apparent trends in the diameter of the punty scar and the mass of the vessel, as shown in Figure 24.

Figure 25 suggests that an increase in the mass of the vessel corresponded with an increase in the height of punty scar.

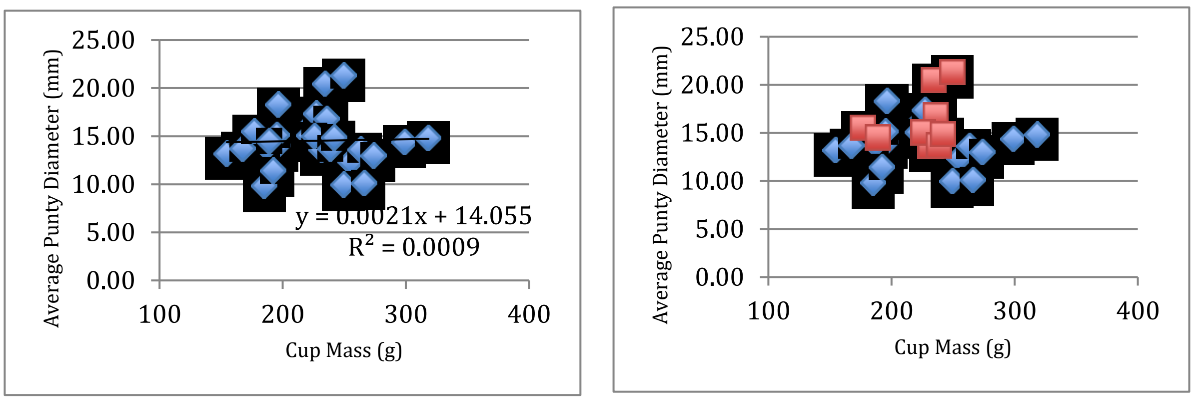


Figure 24. Punty diameter as a function of vessel mass.

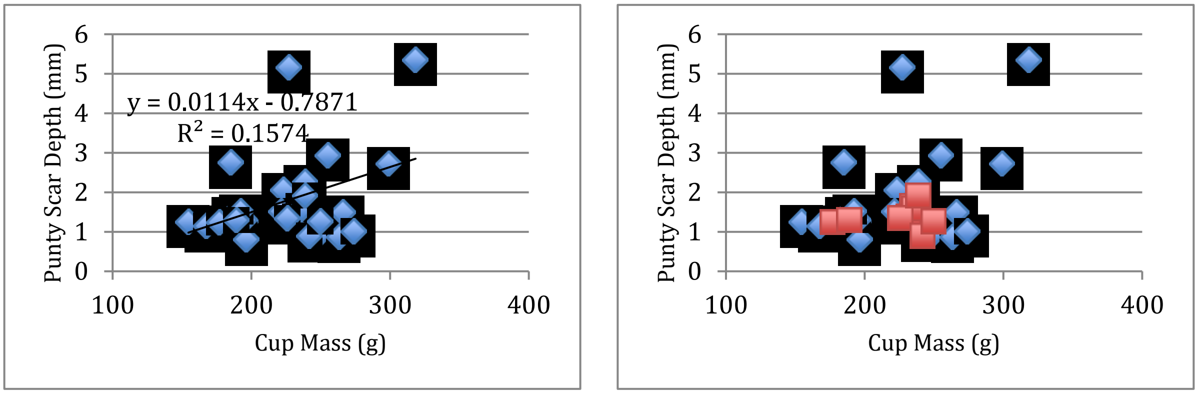


Figure 25. Punty scar height as a function of the mass of the vessel

There are no discernable trends in the contour of the punty scar to the mass of the vessel as demonstrated in Figure 26.

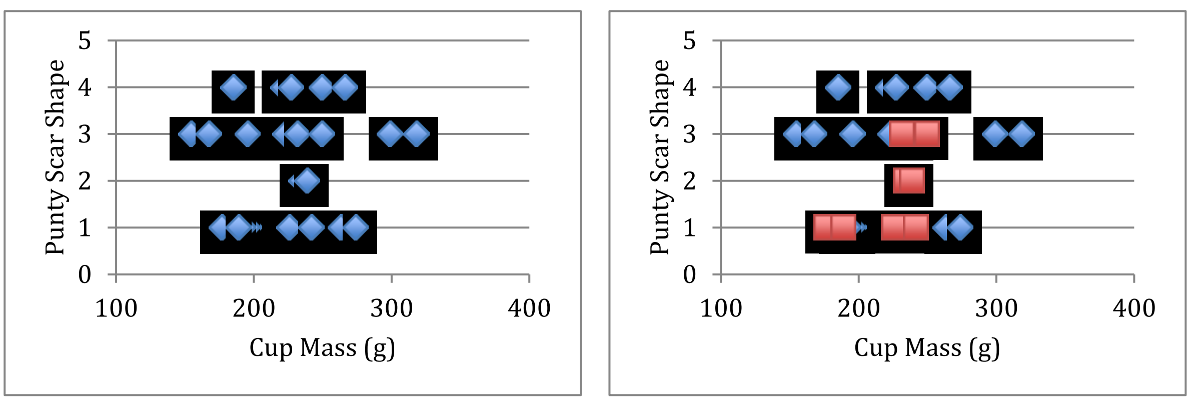


Figure 26. Punty scar shape as a function of vessel mass.

The mass of the vessel seems to have little effect on the diameter of the punty scar but a positive correlation can be found between the mass and height of the punty scar. The mass of the sample would have had little effect on the attachment of the punty to the vessel, hence the lack of effect on scar diameter. However, the mass provides a cantilever stress during break-off that may contribute to the greater height of punty scar with increasing mass of the vessel.

3.4.5 COMPARATIVE PUNTY SIZE

Using the punty portrait photos (Figure 8) and known rod sizes, the approximate comparable size of each amateur punty was calculated. An approximate size was identified as the area, using the largest dimensions (length and girth) of each punty once scaled to the punty rod diameter of ½".

The largest amateur punty was sample 3.3 (approximately 29.9 mm wide by 73.6 mm long) while the smallest was sample 3.8 (approximately 19.5 mm wide by 27.0 mm long)

A positive trend in the average diameter of the punty scar in relation to the comparative size of the punty is demonstrated in

Figure 27 .

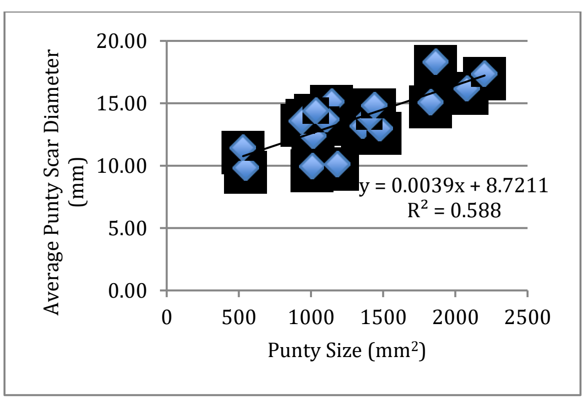


Figure 27. Punty scar diameter as a function of punty size.

A positive correlation between the size of the punty and the height of the scar is suggested in Figure 28.

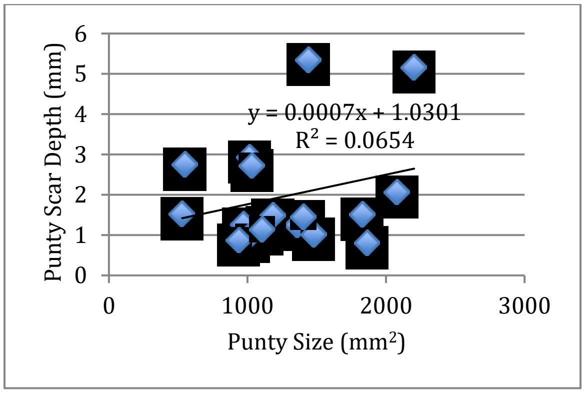


Figure 28. Punty scar height as a function of punty size.

Figure 29 shows there is no apparent correlation between punty scar shape and size of punty.

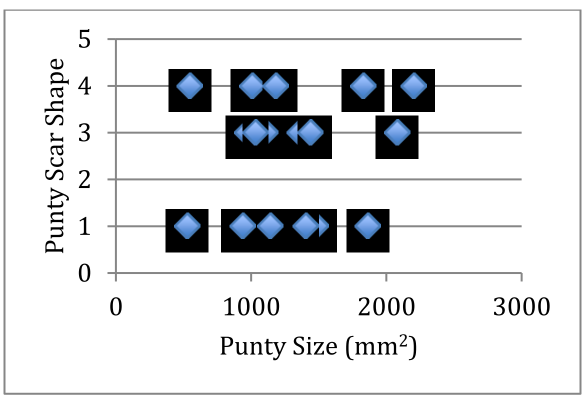


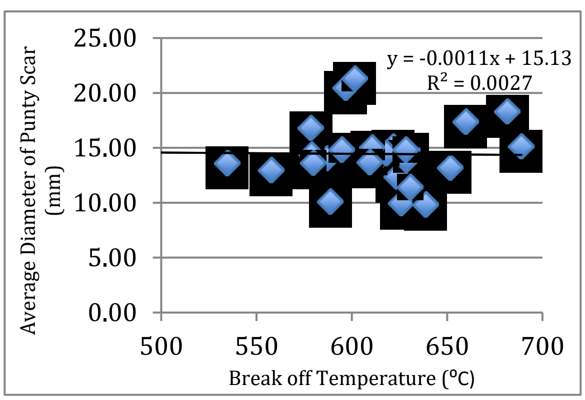
Figure 29. Punty scar shape as a function of punty size.

Both the diameter and the height of the punty scar increased as the size of the punty increased. Intuitively the larger punties left larger punty scars since they were in fact larger. There was no discernable pattern in the punty scar shape as a function of punty size.

3.4.6 BREAK-OFF TEMPERATURE

Break-off temperature gives a rough indication of the sample's thermal history. The temperature difference of the professional samples ranged from 579 °C – 628 °C. The amateur samples ranged in break-off temperature from 535 °C – 689 °C. Sample 2.1 was broken off at the lowest temperature (535 °C) and sample 1.5 was broken off at the highest temperature (689 °C).

Figure 30 shows that the temperature at which the vessel was broken off from the punty had no correlation with the diameter of the punty scar.



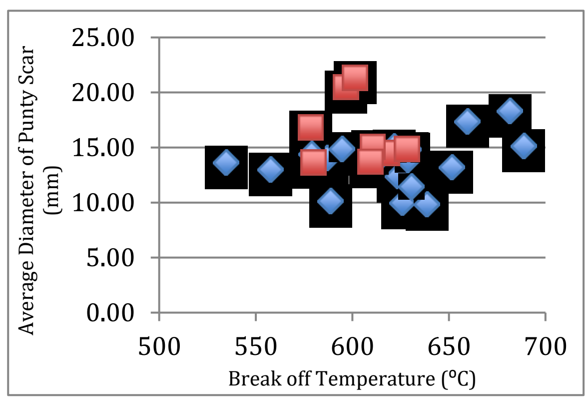


Figure 30. Diameter of punty scar as a function of break-off temperature.

Figure 31 demonstrates that the temperature at which the vessel was broken off from the punty had no correlation with the height of the punty scar.

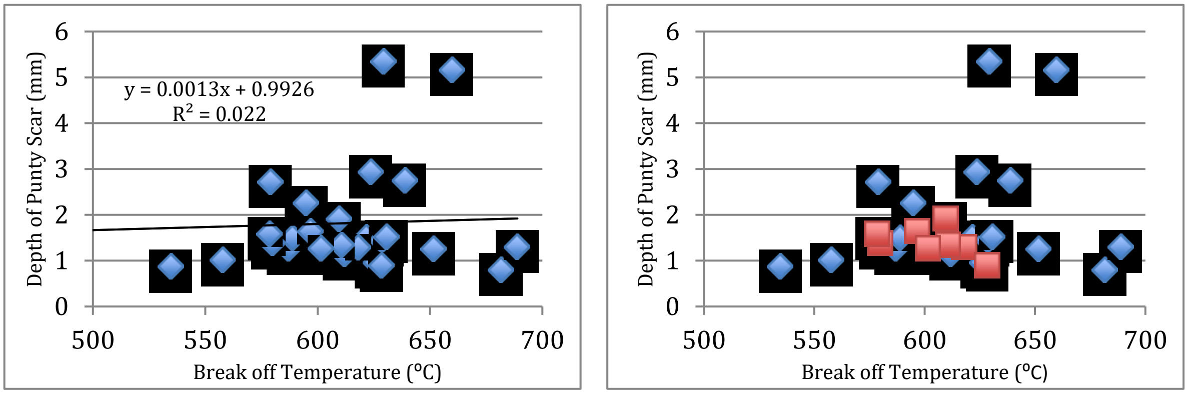
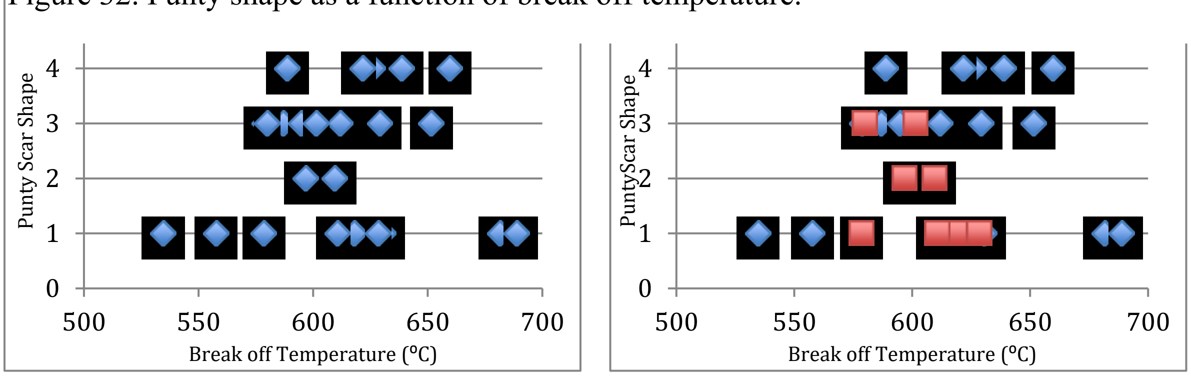


Figure 31. Punty scar height as a function of break off temperature.

No apparent trends in shape either, see Figure 32

Figure 32. Punty shape as a function of break off temperature.



It appears as though the break-off temperature is not related to the punty scar size or shape.

4 CONCLUSION

Glassblowing often requires the use of a glass feature called a punty to transfer the vessel off the blowpipe to a new rod. The punty is then broken off from the vessel once the vessel is finished being produced. What remains on the vessel is a defect called a punty scar. Although an essential component, punties are sensitive to various conditions and are difficult to master. Failure in the punty either results in irreversible damage to the vessel or may add significant finishing work to make the vessel usable. In general, it is ideal for the punty scar to be minimized to such an extent that it requires no finishing work at all. The glassblowing community indicates that the characteristics necessary for a successful punty and minimal scarring include the temperature at which the punty is attached to the vessel, area of the jackline, thickness of the vessel where the punty is attached, the mass of the vessel, size of the punty, and finally temperature at which the punty is broken-off. These characteristics were related to scientific concepts and explored to reveal how they affect punty quality and successful vessel production and related.

A heat gradient forms when a punty is attached to a vessel. When being attached the punty glass must be hot enough to deform and flow so that it can conform to the surface of the cooler glass, creating a semi-permanent interface. Unfortunately, if the temperature is too high a highly cohesive interface may form fusing the pieces together. This fusing means that the punty-vessel junction is not necessarily the path of least resistance for the fracture.[2] As the hot surface cools it contracts, causing tension in the cold side as it tries to pull it. These residual stresses from uneven shrinkage cannot be relaxed, so they may result in failure of the glass due to brittle fracture. The glass community agrees that, if a punty "get[s] stuck on too hot, you'll have no choice but take out a big chunk of the bottom [of the vessel]."[2] The shape of the scars tended to be less desirable as the temperature of the punty and vessel becomes less extreme (delta T less than 110ºC.) Viscous flow behavior suggests that puntying should occur at just the right temperature above the glass transformation range, to allow viscous flow of the punty and limited cohesion.

Most of the punties were significantly hotter than the vessel they were attaching to. The temperature difference of the professional punties was significantly higher than those of the amateurs. Empirical observations from the glass community indicate that the vessel being puntied be kept warm but not moving, to be relatively cold compared to the punty. [17] Punties were recommended to be kept at a "dull glow" presumably referring to the 628-703ºC range where the glass loses its glow. Experimentally the punties in this study ranged from 599-797ºC. Punties that were hotter than their vessels left larger diameter scars with less height. The greater diameter is understood to occur due to the lower viscosity of the hot punty that could press into the vessel.

The jackline area is indicative of the strength of the punty-vessel connection. The connection must be strong enough to withstand the breaking off process of the jackline break (without failing itself.) The punty is at its hottest temperature at this moment of break-off from the blowpipe, and thus more likely to stay connected and withstand the impact that causes brittle failure in the jackline. However, to ensure the safety of the punty-vessel connection, the jackline is thermally shocked. The chill concentrates stresses, caused by uneven shrinkage, at the point of application, the jackline. Glassblowing community warns that once the crack has started it will “follow the path of least resistance, [1] and following the stress means that the crack forms where the glass is most brittle.

The jackline area of the professional glassblower tended to be large, while the amateurs spanned a wide range of areas. A greater jackline area correlates with a slightly greater punty scar diameter, but a smaller punty scar height. When dealing with a thicker jackline area, glassblowers tend to adjust their puntying, squishing the punty onto the piece with more force, to account for the additional force the punty will encounter as the jackline is broken.

The thickness of the vessel base can have significantly more thermal mass than the punty attaching to it. If the vessel and punty shrink at different rates, given their thermal mass, then a stress gradient will form between the two as the system cools through the glass transformation range and becomes solid. In the relatively short timescales involved in glassblowing, such stresses cannot be relaxed once the glass has cooled. Those stresses present near the interface between the vessel and the punty may contribute to the behavior of brittle fracture and induce fracture to occur elsewhere.

Punties are attached directly to the base of a vessel. The thickness of the vessel base may have an effect on the thermal experiences of the punty. The mass of glass at the base may shield the punty from gaining or losing heat. A thick base may provide a thermal mass that would keep the punty-vessel junction at amiable temperatures more easily, but it also may prevent heat from reaching the punty. Additionally the glassblower will treat a piece differently depending on how thick it is; for example a thinner vessel will be kept at cooler working temperatures to avoid deformation.

The professional samples tended to have thinner bases, while the amateurs had thicker bases. There is a slight tendency that the thicker the vessels base, the smaller the diameter of the scarring; however, there was no trend with the height of the scaring.

The weight of the vessels indicates the amount of shear stress exerted on the punty at the attachment and the breakoff. When the vessel is being transferred to the punty, the punty needs to connect strongly enough that it can support the weight of the vessel, despite the shock applied to the blowpipe to break the jackline. (Otherwise the vessel may break off at both points and crash to the ground.) The mass of the vessel also provides a shear stress when the vessel is broken off from the punty itself.

The mass of the vessel seems to have little effect on the diameter of the punty scar, but a positive correlation can be found between the mass and height of the punty. The mass of the sample would have had little effect on how the attachment of the punty to the vessel occurred, hence the lack of effect on scar diameter. However, the mass provides a cantilever-like stress during break-off that may contribute to the greater height of punty scar with increasing mass of the vessel.

Since punties are tailored to the vessel, a blow-mold was used to provide a consistent shape of the vessel; thus minimize variations in the size and shape of the punties. The size of a punty will affect how much heat it retains between heating sessions.

Both the diameter and the height of the punty scar increased as the size of the punty increased. The larger punties left larger punty scars since they were in fact larger. There was no discernable pattern in the punty scar shape as a function of punty size.

Break-off in glass occurs at a constriction in the glass or at an interface which is then chilled. The chilled material is less elastic and more likely to break in brittle failure. The application of a chill causes the volume to shrink. This adds stress to the surrounding area. Break-off must be performed once the glass has been chilled below the glass transition temperature so that brittle fracture may occur. Break-off temperature gives a rough indication of the sample's thermal history. The professional punties were broken-off within a narrower temperature range than the amateur punties; however, both groups had approximately the same average break-off temperature. Results indicated that break-off temperature is not related to the punty scar size or shape.

Incorporating these guidelines will aid glassblowers in producing optimized punties for their needs, minimizing finishing work, and improving workflow.

6 RESOURCES CITED

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