Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1483~1490

# A CFD-aided experimental study on bending of micro glass pipettes

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(Manuscript Received May 31, 2007; Revised August 30, 2007; Accepted September 30, 2007)

**Abstract**

This paper presents a study on the temperature profile in the bending process of glass pipettes. To prevent undesirable deformation of the pipette at its bending section, such as kink and constriction, several factors influencing the bending quality are investigated, including the width and temperature of the heating element, heating and bending time. Taguchi method is used to study the key factors and to identify an optimal parameter combination. ANSYS is also employed to study the heat transfer and temperature distribution in the heating zone. It is concluded that the temperature distribution in the bending area is critical to the bending quality, and the width of the heating element decisively determines the temperature distribution.

*Keywords*: Glass pipette; Bending; Taguchi method; CFD

## 1. Introduction

Processing quality control is critical for the fabrication of micro-components, especially for micro glass pipettes used for medical applications. The deformation of these pipettes normally involves heating and then bending.

Deformation of glass materials is quite different from metal ones that have distinctive elastic and plastic deformation regions. While comprehensive studies on metal materials have been carried out using experimental, constitutive and computational methods, the properties and deformation of glass materials are not well understood largely due to the complexity of constitutive models in the viscoelastic region.

To study these viscoelastic materials, the experimental method is the most popularly used means. For example, Tordjeman et al, Lu et al, and Xian et al [1-3] studied the temperature effects on the viscoelastic behaviours of glass by experiments and found that temperature is one of the most critical factors in the glass processing, such as glass fibre drawing and impregnation.

Computational fluid dynamics (CFD) is another powerful and cost effective way [4], particularly for the prediction of the temperature distribution and complex industrial glass processes where physical measurement cannot be easily realised. This method has been applied to predict the glass surface temperature in the laser-induced chemical vapour deposition (LCVD) process [5], heat transfer profile in glass tempering process [6] and temperature variations in the creep forming process of automotive windscreens [4]. The accurate prediction of temperature profiles has significantly improved the processing quality in an economical way.

According to [7, 8], the key for making a good bend is to heat the glass sufficiently and evenly. For example, windscreens in the automotive industry are heated uniformly and deformed in an oven or furnace at a constant temperature [4, 9]. In contrast, the heating of a pipette is localized at the bending point, where a serious imbalanced temperature distribution

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is naturally expected.

This study investigates the main factors involved in the heating and bending processes to counter the imbalance and to identify an optimal parameter setting with the application of Taguchi method. ANSYS software is also used to study the temperature distribution in the heating zone for better understanding the relationship between the temperature distribution and the bending quality.

## 2. Materials and glass bending

### *2.1 Materials*

The pipette used in this study is made of borosilicate glass, with an outer diameter (OD) of 1 mm and an inner diameter (ID) 0.58 mm. It is very sensitive to heating due to its thin wall thickness (0.21 mm). Overheating melts the material, leading to the collapse of the glass, whereas insufficient heating results in crack or breakage in the bending process.

The bending device used in the experiment employs electrical Nichrome ribbon as a heating source to soften the pipette at the bending point. A fully enclosing heating element in square or round shape is commonly used for pipette pulling machines but it is not feasible for this application due to an opening being required for the bending. A long U-shaped Ni80Cr20 electrical ribbon with a thickness of 0.15 mm is selected for the bending device based on previous study [10].

### *2.2 Bending of glass pipette*

A good bend of a pipette should be smooth without any kink or constriction. Insufficient heating tends to cause crease at the inside and overstretching at the outside of the bend, which results in the diminution of the inner diameter of the pipette. On the other hand, overheating causes another quality issue, i.e. collapse. Fig. 1 illustrates some sample bends from [7]. Fig. (a) presents a good and smooth bend. (b), with crease and constriction, is caused by heating up only a small portion of the pipette. The glass is softened and bent at a very narrow zone. (c) demonstrates a collapse at the bending cross section due to overheating.

Both the poor quality bends result in the diminution of inner diameter. It is a critical quality issue that affects the smoothness of flow or even blocks the flow way inside the pipette during the application procedures.

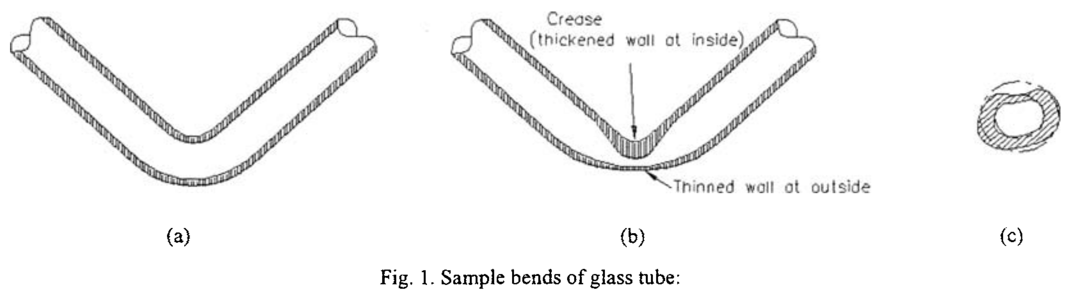
In the following section, Taguchi method is employed to investigate the influential factors on the heating and bending of the glass pipette in order to identify an optimal parameter combination.

## 3. Experiment

### *3.1 Taguchi method*

Taguchi method [11-13] is a robust design technique. By applying statistical method, it uses representative fractional factorial experiments (FFEs) to determine optimal parameters, and fully investigate the variability, especially the sensitivity of the system specification to the causal factors of variability. In FFEs design, an orthogonal array (OA) uses only a portion of the total possible combinations to estimate the main factor effects and some of the interactions. Certain representative treatment conditions are chosen to maintain the orthogonal relationship among the various factors and interactions. For instance, a L9 ($3^4$) OA has nine trial conditions, which is applicable for four factors with three levels of setting.

Taguchi method uses signal-to-nose (S/N) ratio to quantitatively analyse the variations of the performance indicator. In general, the S/N should be maximised to achieve a robust design. Three major S/N ratios are applicable to a wide range of response




(a) (b) (c)

Fig. 1. Sample bends of glass tube:
(a) Good bend, (b) Poor bend (crease/constriction), and (c) Poor bend (collapse).

variables, depending on particular analytical characteristics, which includes 'nominal is better' ($S/N_N$), 'smaller is better' ($S/N_S$), and 'bigger is better' ($S/N_B$). For example, $S/N_B$ stands for characteristics that must be made big, such as strength or durability. The equation for $S/N_B$ ratio is given by

$$S/N_B = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

where $n$ is the number of trial repetitions under the same condition and $y_i$ the result of each measurement.

### 3.2 Experimental design

The ID of the pipette in the bending zone is regarded as a performance indicator of the bending quality. The objective of the experiment is to minimize the kinks and constriction, namely to maximize the inner diameter.

The configuration of the pipette and the heating ribbon are illustrated in Fig. 2. The pipette is heated continuously during the heating and bending process. The opening of the U-shaped ribbon is for the pipette to pass through while bending.

### 3.3 Experimental parameters

The factors influencing the heating and bending process are shown in the cause-effect diagram (Fig. 3), including the width and the surface temperature of the ribbon, heating and bending time, the gap between ribbon and pipette, ambience temperature and air flow. Bending time is the time required for the bending action.

Since the bending process is performed in a clean room with constant temperature, the effects of the environment are not considered in this study to simplify the analysis. The gap between the ribbon and the pipette was set as 0.3 mm based on preliminary studies, which is the smallest possible gap so that the pipette does not contact the ribbon during the heating and bending process. Four principal factors are, therefore, determined for the experiment. Three levels are set for each factor based on previous experiments (Table 1). The L9 OA is selected accordingly. The experimental condition for each trial is shown in Table 2.

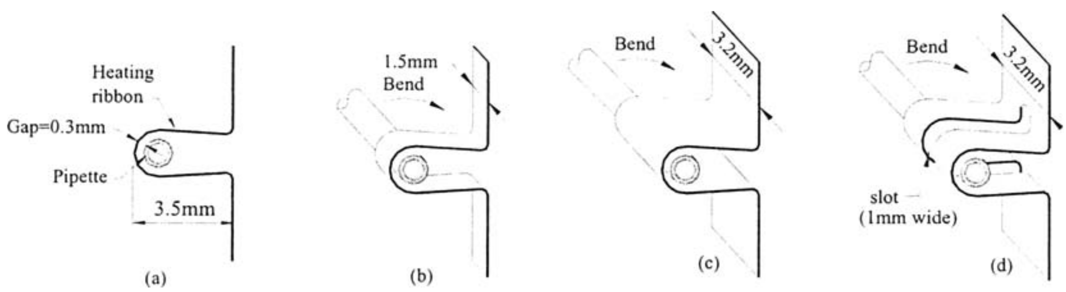



Fig. 2. Sketch of pipette heating configuration:
(a) Front view, (b) 1.5 mm ribbon-R15, (c) 3.2 mm ribbon-R32, and (d) 3.2 mm ribbon with slot-R32s.

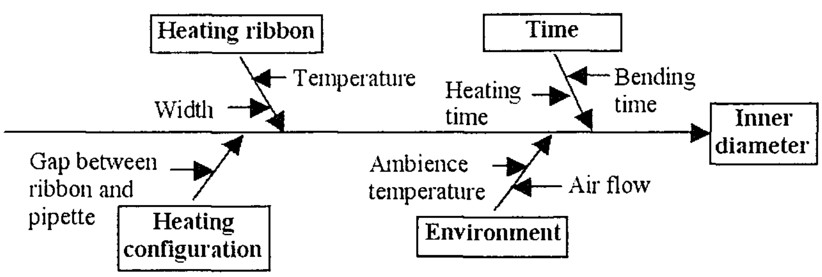



Fig. 3. Cause-effect diagram of bending quality.

Table 1. Design factors and levels.

| Factors | Description | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | Ribbon width | 1.5 mm (R15) | 3.2 mm with slot (R32s) | 3.2 mm (R32) |
| B | Ribbon temperature | 1050°C | 1100°C | 1150°C |
| C | Heating time | 7sec | 10sec | 12sec |
| D | Bending time | 3sec | 5sec | 7sec |

Table 2. Experimental layout and data collection.

| Trial no. | Factors | | | | | | | | Samples (ID) | | | | | | Mean (ID) | $S/N_B$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | | B | | C | | D | | y1 | y2 | y3 | y4 | y5 | y6 | | |
| 1 | 1 | (1.5) | 1 | (1050) | 1 | (7) | 1 | (3) | 304 | 288 | 282 | 304 | 295 | 290 | 294 | 49.35 |
| 2 | 1 | (1.5) | 2 | (1100) | 2 | (10) | 2 | (5) | 349 | 366 | 348 | 357 | 340 | 349 | 352 | 50.91 |
| 3 | 1 | (1.5) | 3 | (1150) | 3 | (12) | 3 | (7) | 370 | 366 | 375 | 376 | 394 | 390 | 379 | 51.55 |
| 4 | 2 | (3.2s) | 1 | (1050) | 2 | (10) | 3 | (7) | 472 | 475 | 473 | 453 | 456 | 464 | 466 | 53.35 |
| 5 | 2 | (3.2s) | 2 | (1100) | 3 | (12) | 1 | (3) | 444 | 467 | 470 | 441 | 449 | 450 | 454 | 53.12 |
| 6 | 2 | (3.2s) | 3 | (1150) | 1 | (7) | 2 | (5) | 460 | 489 | 460 | 472 | 470 | 484 | 473 | 53.48 |
| 7 | 3 | (3.2) | 1 | (1050) | 3 | (12) | 2 | (5) | 438 | 451 | 458 | 465 | 459 | 453 | 454 | 53.14 |
| 8 | 3 | (3.2) | 2 | (1100) | 1 | (7) | 3 | (7) | 460 | 448 | 465 | 459 | 452 | 444 | 455 | 53.15 |
| 9 | 3 | (3.2) | 3 | (1150) | 2 | (10) | 1 | (3) | 422 | 420 | 439 | 412 | 425 | 420 | 423 | 52.52 |

Table 3. Factors / S/N ratio response table.

| Factors | A | | | B | | | C | | | D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Levels | A1 | A2 | A3 | B1 | B2 | B3 | C1 | C2 | C3 | D1 | D2 | D3 |
| $S/N_B$ | 50.6 | 53.3 | 52.9 | 51.9 | 52.4 | 52.5 | 52.0 | 52.3 | 52.6 | 51.7 | 52.5 | 52.7 |

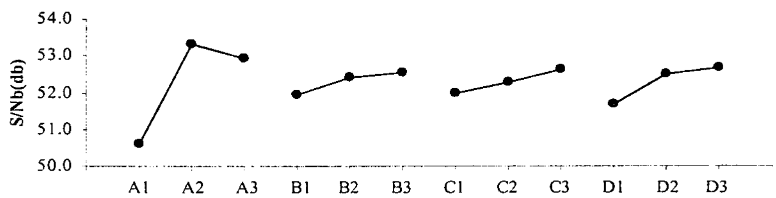



Fig. 4. Influential factors vs S/N ratio.

### 3.4 Experiment

The experiment was conducted in a constant temperature laboratory at 23°C. There are nine trial conditions. Six repetitions are made for each trial to ensure the accuracy of the results.

The temperature of the heating ribbon is measured by Cambridge disappearing ribbon pyrometer. Le-Croy-LC334AM oscilloscope is used to monitor the current and voltage of the ribbon. The ID at the bending point of each sample is measured by Nikon profile projector-6CT2 and recorded in Table 2.

## 4. Results and discussion

### 4.1 Experiment results

Since the larger value of the inner diameter is desired, Eq. (1) is used to calculate the $S/N_B$ ratio. The mean of ID values and the corresponding $S/N_B$ ratio are shown in Table 2 as well.

Based on Table 2, the relationship between the levels of each design factor and the corresponding S/N ratio is depicted in Table 3 and Fig. 4.

Table 3 and Fig. 4 reveal that the ribbon type (factor A) is the most influential factor with the maximum difference of S/N of 2.7 among the levels. The second influential factor is the bending time (D) with a S/N difference of 1.0. The effects of level 2 and 3 of the factor D are quite similar, and both are much better than level 1. The influence of the ribbon temperature (B) and heating time (C) are similar.

According to the principles of the Taguchi method, the level with the highest S/N ratio gives the minium variation around the mean value. Therefore, the best design of the levels of each factor can be obtained from Fig. 4 as A2B3C3D3, i.e. 3.2 mm wide ribbon with slot cut, ribbon temperature of 1150 °C, 12 seconds heating time, and 7 seconds bending time.

### *4.2 Confirmation experiment and discussions*

Since the proposed best parameter combination is obtained from the FFEs instead of a full factorial design, a confirmation experiment is necessary for the optimal parameter combination. If the result from the experiment does not satisfy the desired specifications, the experiment process will be redeveloped until the specified criteria can be met.

The experiment is conducted using the proposed optimal parameters A2B3C3D3. The results revealed that the mean value of the minimum inner diameter of the pipette at the bending point is 0.487 mm, with a S/N ratio of 53.75. Both are the best over the results of all the trial conditions shown in Table 2. For the bend under the worst parameter combination (A1B1C1D1), the mean value of the ID of the pipette is only 0.294 mm and the S/N ratio is 49.35. The difference of ID values between the best and the worst bends is significant, with 65.6 % bigger for the best, as shown in Fig. 5. This positively verifies the proposed optimal parameter combination.

### *4.3 Discussion on computational simulation of the heating profile*

Due to the small diameter and transparent material of the micro glass pipette, no commercially available thermometer can be used for the measurement of glass temperature in the heating zone. Therefore, CFD is applied to study the temperature profile in the heating area of the pipette.

A heating model is constructed (Fig. 6), which is similar to that presented previously in [10].

Three types of ribbon R15, R32, and R32s are compared with their respective heating profile. The surface temperature of the ribbon is set to be 1150 °C. Fig. 7(a), (c) and (e) illustrate the temperature distribution on the symmetry plane for three ribbons respectively. Fig. 7(b), (d) and (f) show the corresponding temperature distribution on the YZ-plane crossing the axis of the pipette. The figures reveal that the temperature distributes evenly on the pipette cross section plane for all the three ribbons.

Fig. 8 presents the temperature variation at the middle of the pipette wall along the pipette axis.

Based on the properties of the borosilicate glass and the bending temperature measured with SEM 103C-F366 oven and a thermal couple, it is found that the threshold temperature for bending is 640-660 °C.

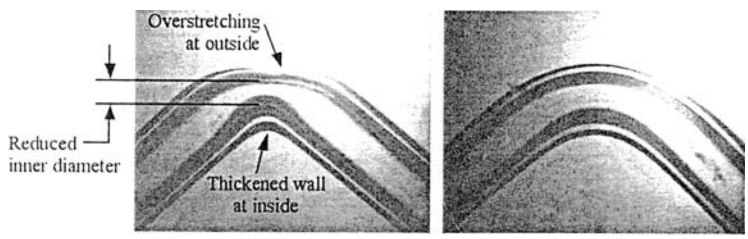



Fig. 5. Comparison of bends under the worst and best conditions:
(a) Poor bend with crease and constriction, and (b) Good and smooth bend.

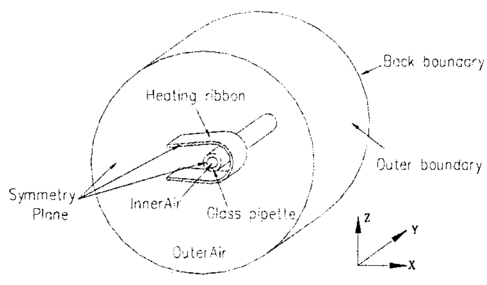



Fig. 6. Model construction.

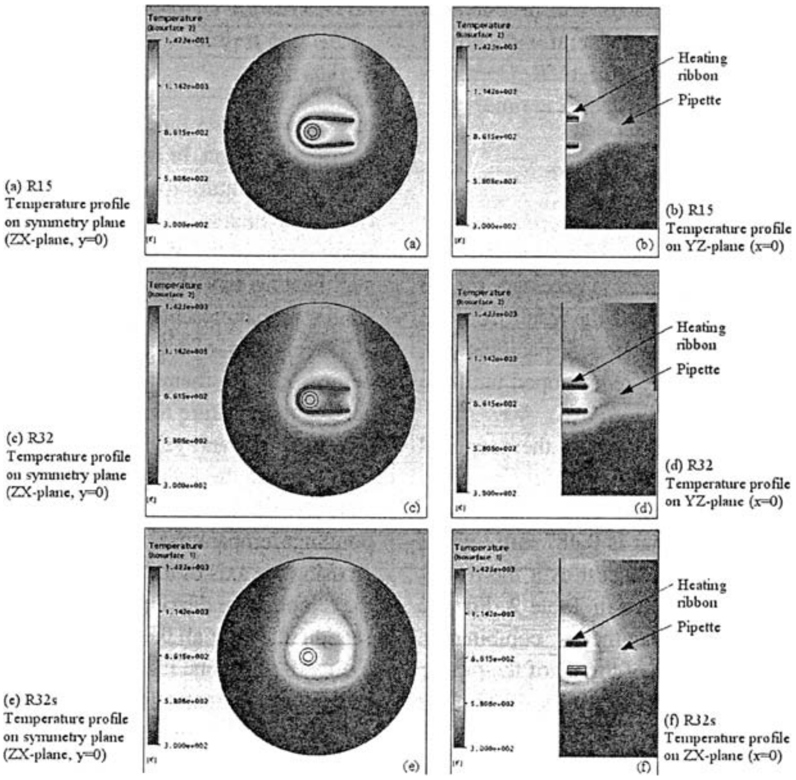



Fig. 7. Temperature profile of heating process.

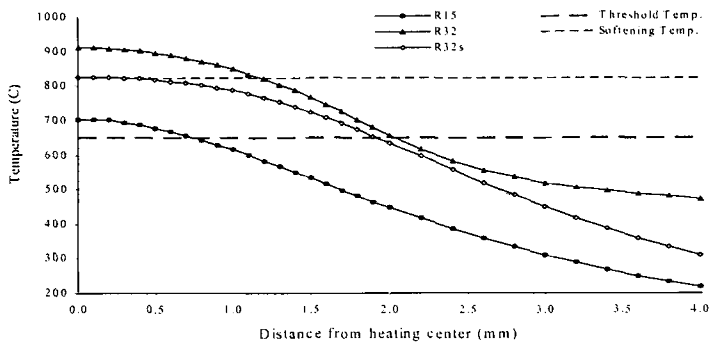



Fig. 8. Temperature variations along the pipette axis.

Figs. 7 and 8 demonstrate that the wider ribbons (R32, R32s) provide a wider heating zone than the narrow one (R15). The length of the softened glass suitable for bending are 3.85 mm and 4.08 mm respectively for ribbon R32s and R32, while only 1.5 mm for R15.

According to [7, 8], the length of heating zone needs to be two full diameters of the tube for a right-angle bend, which means that the length of the softened pipette must be at least 2 mm. The crease and constriction occurring as shown in Fig. 5(a) can then be attributed to the use of R15 ribbon. Since only 1.5 mm length of the pipette is softened, the deformation is produced in a narrow area, leading to over-stretching at the outside and over-squeezing at the inside of the bend. Comparatively, the bending heated by R32 and R32s has much better performance.

Further comparing R32 and R32s in Fig. 8, R32s produces a smoother temperature distribution than R32. The highest temperature of the pipette at the heating centre is 826 °C for R32s and 911 °C for R32. The softening temperature of the borosilicate glass is 821 °C at which the glass starts to deform under gravity [14]. For R32 the length of which the pipette temperature over 821 °C is 2.4 mm. In this section, glass deforms under gravity, resulting in a collapse and in turn causes a reduction of the ID at the bend. This explains why the slotted 3.2 mm ribbon (R32s) produces the best bend among the three types of ribbons in the experiment of Section 3.

## 6. Conclusion

In the bending process of glass tube, kink and constriction are common defects. For the bending of a pipette with an OD of 1.0 mm and ID 0.58 mm, these defects are a disastrous quality issue, especially for pipettes used for medical application since it may cause a blockage to the liquid flow.

To prevent this issue from happening, the study employed Taguchi method to investigate the influential factors, including the width and temperature of the heating ribbon, heating and bending time, and to finally determine a set of desired process parameters for the bending of the pipette.

An optimal parameter combination has been obtained, namely a ribbon width of 3.2 mm with slot, ribbon temperature of 1150 °C, 12 seconds heating time, and 7 seconds bending time. The testing results indicate that the inner diameter at the bending point is outstanding under the optimal parameter setting over those under other combinations.

CFD simulation is conducted by using ANSYS software to study the heating profile and the temperature distribution in the heating zone of the pipette. The results reveal that a uniformly distributed heating zone with sufficient width is very important for a quality bend. In this study, the 3.2 mm wide ribbon with slot produces the best heating profile for the bending of a pipette. The simulation further confirms the conclusions drawn upon the experiment results.

## Acknowledgement

The authors wish to express their gratitude to Australian Research Council (LP0454190) and The Pipette Company of Australia for supporting this research.

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