目錄

圖目錄.....ii
表目錄.....v
中文摘要.....vi
Abstract.....vii
1. 前言.....1
2. 研究目的.....3
3. 文獻回顧.....3
4. 研究方法.....5
5. 結果與討論.....6
5.1 材料模型之取得與驗證.....6
5.2 光學玻璃透鏡熱壓實驗.....13
5.3 光學玻璃透鏡熱壓有限元素分析.....20
5.4 加熱爐之改善.....25
5.5 光學玻璃微熱壓實驗.....27
6. 總結.....33
7. 參考資料.....34
8. 計畫成果自評.....37
9. 附錄.....39
9.1 模仁加工方式.....39
9.2 模具補償最佳化分析系統測試結果.....42

圖目錄

圖 1 玻璃熱壓成形技術示意圖.....2
圖 2 玻璃熱壓成形溫度—時間關係圖.....2
圖 3 有限元素分析在各階段所需考慮之項目.....6
圖 4 玻璃熱膨脹曲線示意圖[15].....6
圖 5 L-BAL 42 熱膨脹曲線.....7
圖 6 S-FPL 51 熱膨脹曲線.....7
圖 7 S-FPL 52 熱膨脹曲線.....7
圖 8 S-FPL 53 熱膨脹曲線.....7
圖 9 光學玻璃黏度與溫度關係圖[17].....8
圖 10 黏塑性流變模型示意圖.....9
圖 11 黏彈性流變模型示意圖.....9
圖 12 2D 軸對稱玻璃試片有限元素分析模型.....10
圖 13 應變率 40%/min 模擬結果與實驗值應力—應變曲線比對.....11
圖 14 應變率 40%/min, 50%/min 及 60%/min 下模擬結果與實驗值力量—位移曲線比對.....11
圖 15 L-BAL42 在 Tg 點之.....12
圖 16 L-BAL42 在 Tg 點以上 50°C 之應力鬆弛曲線.....12
圖 17 L-BAL42 在 At 點以上 30°C 之應力鬆弛曲線.....12
圖 18 L-BAL42 應力鬆弛曲線平移關係圖.....12
圖 19 L-BAL42 應力鬆弛曲線預測與實驗結果比較.....13
圖 20 模仁設計圖.....14
圖 21 模仁-夾具組合圖.....14
圖 22 模仁加工成品圖.....15
圖 23 熱壓設備外觀圖.....15
圖 24 實驗編號 1 之透鏡成品圖.....16
圖 25 實驗編號 1 之實驗後上模仁圖.....16
圖 26 實驗編號 2 之透鏡成品圖.....17
圖 27 實驗編號 3 之透鏡成品圖.....17

圖 28 實驗編號 3 之實驗後上模仁圖.....17
圖 29 實驗編號 3 之實驗後下模仁圖.....17
圖 30 實驗編號 4 之透鏡成品圖.....18
圖 31 實驗編號 4 之實驗後下模仁干涉儀量測結果.....18
圖 32 實驗編號 5 之透鏡成品圖.....18
圖 33 實驗編號 5 之實驗後上模仁圖.....18
圖 34 模仁加熱實驗結果圖.....19
圖 35 熱壓成形分析模型.....20
圖 36 分析模型之溫度歷程.....20
圖 37 熱壓成形時力量—位移關係.....21
圖 38 熱壓實驗成品尺寸.....22
圖 39 熱壓實驗模擬結果尺寸.....22
圖 40 模型修正後之熱壓成形時力量—位移關係.....22
圖 41 模型修正後之熱壓實驗模擬結果尺寸.....22
圖 42 模具補償最佳化流程.....23
圖 43 最佳化用之有限元素分析模型.....23
圖 44 熱壓後與設計之透鏡曲線比較.....24
圖 45 非球面之形狀.....24
圖 46 設計變數.....24
圖 47 紅外線真空加熱爐示意圖.....25
圖 48 紅外線真空加熱爐外觀圖.....26
圖 49 新型實驗裝置初步實驗成品.....27
圖 50 模仁上之微結構.....27
圖 51 經熱壓成形後產生在光學玻璃上 KRS-5 之微結構.....28
圖 52 經熱壓成形後產生在光學玻璃 S-FPL53 上之微結構.....28
圖 53 Stavax 模仁.....28
圖 54 Stavax 模仁之 Fresnel 設計規格.....29
圖 55 實驗前 Ni-Co 模仁.....29
圖 56 實驗後 Ni-Co 模仁.....29
圖 57 玻璃熱壓成品.....30

圖 58 Ni-Co 模仁實驗前,左圖為結構中央處，右圖為 fresnel 溝槽結構部份.....30
圖 59 Ni-Co 模仁實驗後，左圖為結構中央處，中圖為模仁 fresnel 溝槽結構有接觸玻璃處，右圖為中圖為模仁 fresnel 溝槽結構無接觸玻璃處.....30
圖 60 玻璃熱壓成品，左圖為結構中央處，右圖為 fresnel 溝槽結構部分.....31
圖 61 實驗前 Ni-Co 模仁表面粗度輪廓儀量測.....31
圖 62 實驗後 Ni-Co 模仁表面粗度輪廓儀量測.....31
圖 63 玻璃熱壓成品表面粗度輪廓儀量測.....32
圖 64 表面粗度輪廓儀放大結果.....32
圖 65 模仁放電加工成品圖.....39
圖 66 成形機作業圖.....39
圖 67 模仁成形成品.....39
圖 68 模仁研磨作業圖.....40
圖 69 模仁拋光完成圖.....40
圖 70 模仁加工成品圖.....41
圖 71 模具外型 (R=10mm，球面).....42
圖 72 玻璃外型(R=10mm，球面).....42
圖 73 模具外型(R=10mm，拋物面).....43
圖 74 玻璃外型(R=10mm，拋物面).....43
圖 75 模具外型(R=10mm，雙曲面).....43
圖 76 玻璃外型(R=10mm，雙曲面).....43
圖 77 模具外型(R=15mm，球面).....44
圖 78 玻璃外型(R=15mm，球面).....44
圖 79 模具外型(R=15mm，拋物面).....45
圖 80 玻璃外型(R=15mm，拋物面).....45
圖 81 模具外型(R=15mm，雙曲面).....45
圖 82 玻璃外型(R=15mm，雙曲面).....45

表目錄

表 1 玻璃熱膨脹係數[15]....7
表 2 模仁材料性質....14
表 3 實驗參數....16
表 4 玻璃熱壓成形分析參數....21
表 5 新型實驗裝置測試實驗參數....26
表 6 玻璃微熱壓實驗參數....29
表 7 誤差修正結果比較(R=10mm)....44
表 8 誤差修正結果比較(R=15mm)....46

中文摘要

本計畫以全程三年之研究針對應用於光學玻璃熱壓之有限元素分析進行探討並對光學玻璃微結構熱壓成形進行初步研究討論。第一年藉由熱膨脹係數的量測、成形溫度下單軸壓縮實驗及應力鬆弛實驗的進行，取得熱壓製程分析所需之材料模型。並進行初步熱壓製程實驗探討實驗參數對玻璃成品的影響。第二年則依第一年的熱壓製程實驗參數建立有限元素分析模型，並將取得之材料模組代入分析，得到合理且可行的分析架構。另對成形時的模仁沾黏問題與模仁析出物狀況對實驗機台進行改善設計，以增進成品品質。第三年裡針對業界常遇到之模具預補償問題，以有限元素分析模型搭配最佳化分析，建立模具補償最佳化分析系統。另在光學玻璃微結構熱壓成形製程方面，分別以 V 型溝槽及 Fresnel 透鏡設計，使用改善後之新一代加熱爐實驗，確認其轉印性並對實驗參數組合進行探討。

藉由本計畫一系列的研究，已建立起一完整的光學玻璃熱壓成形之有限元素分析架構，除可對現階段業界會在製程時可能遭遇的問題提供解決方案，更是未來切入到表面具有微結構之光學玻璃元件的關鍵技術，後續發展無可限量。

關鍵字： 有限元素分析、光學玻璃、熱壓成形、最佳化分析系統、微結構。

Abstract

This three-year project focused not only on the application of FEA on the hot embossing of the optical glass material but also on the preliminary research of forming micro structure on the optical glass by hot embossing. In the first year, the material models were obtained by the experimental measurements of the thermal expansion coefficient, compression tests and the relaxation tests. Preliminary hot embossing tests were also performed within this year to investigate the influence of the forming parameters to the final products. In the second year, the FEA model was built according to the prior obtained material model and the hot embossing parameters and its feasibility was verified by comparing the simulation results to the hot embossing results. Owing to the sticking problem and the educt from the mold during embossing, the modification design of the hot embossing apparatus was also conducted in the second year to improve the quality of the products. In the third year, in addition to the construction of the die shape optimization system for the pre-compensation problem in industry, the research of forming micro structures on the optical glasses was performed with V-shape and Fresnel lens designs with the modified apparatus.

Throughout this project, the completed FEA model for the hot embossing of the optical glass can not only provide solution to the problems that the industry may encounter, but also be a critical technology to the forming process of the optical glass device with micro structures on the surface.

Keywords: FEA, optical glass, hot embossing, optimization system, micro structure.

1. 前言

近年來由於數位科技的發展，3C 產業快速成長，全球數位產品的需求量大增，應用於其中之光學鏡片供應量不足的窘境在此時即被凸顯出來；再加上目前國內亟欲提升產業技術，在此關鍵元件的成形製程上，更增添了高精度的要求，使成形後的光學鏡片不但可以用於相機鏡頭等一般消費性產品上，之後更可導入微影製程所需之設備中[1][2]。所以如何增進光學鏡片的產量及成形精度成為目前學界積極研究的重點之一。

光學鏡片依使用的材質可以區分為光學玻璃(Optical Glass)與高分子材料(Polymer Material)兩大類，目前光學用高分子材料尚不斷的開發，以降低材料與製程成本、提高光學性質(Optical Properties)為主要目標；玻璃鏡片的製造程序較繁複，且材料與製程成本較塑膠鏡片為高，但玻璃鏡片具有較佳的機械性質(Mechanical Properties)、熱穩定性(Thermal Stability)、光學性質等特性，所以在要求高精密度的光學儀器中，玻璃鏡片仍保有塑膠鏡片所無法完全取代的優勢。

傳統光學玻璃鏡片藉由研磨、拋光的方式加工成形，但耗時耗工，無法應付目前日益增大的產量需求；近年來有以單點鑽石(Single Point Diamond)為刀具，對玻璃進行超精密加工，即在成形機完成玻璃球面透鏡，然而超精密成形機的設備費用昂貴，且刀具成本高，目前尚未被廣泛用於鏡片加工。

玻璃熱壓成形技術，如圖 1 及圖 2 所示，具有材料流動距離短、成形精度高、設備簡單等特性，任何一種製程所製作出來的模仁皆能經由熱壓成形技術來達到批量複製的目的，因此被認為是光學鏡片製造中用以降低成本，提高產量之關鍵技術。然而，目前在玻璃熱壓成形技術上，仍有許多問題亟待克服，像是成形與冷卻過程中產生的殘留應力若過高，稍受外力或接觸時會在成形品表面或內部形成龜裂，造成元件損壞；鏡片中若含有殘留應力時更會導致散射中心的誤差，影響光學性質；以及在溫度、壓印力、持壓時間這些製程參數的設定上，現在仍須以試誤法進行多次的實驗才能得到較佳之設定，當胚料不同時，則需再重複試驗，耗費成本及時間。此時若以有限元素分析的方式對熱壓成形製程建立數值模型，不但可以縮短製程研發所需之時間，更可於接續的研究中引進最佳化分析，對製程參數進行優化的動作，進而達成降低製造成本，提高成形精度並增進產品品質之目的。

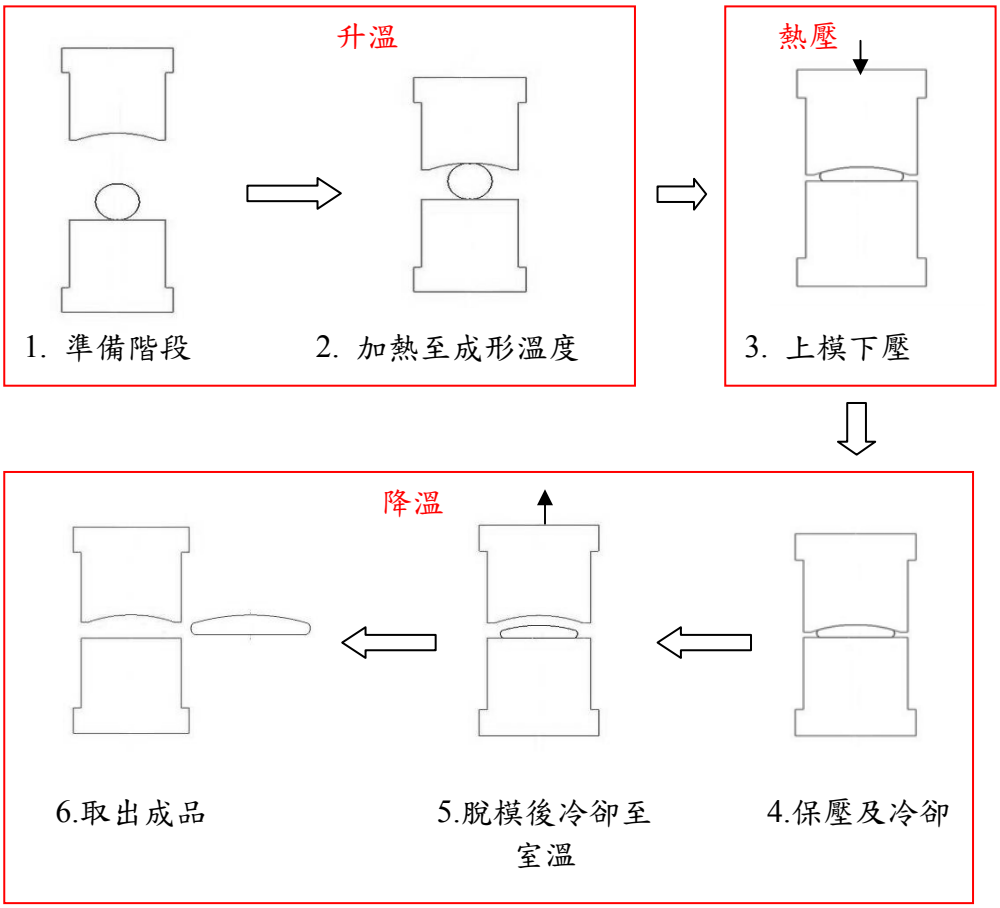

圖 1 玻璃熱壓成形技術示意圖

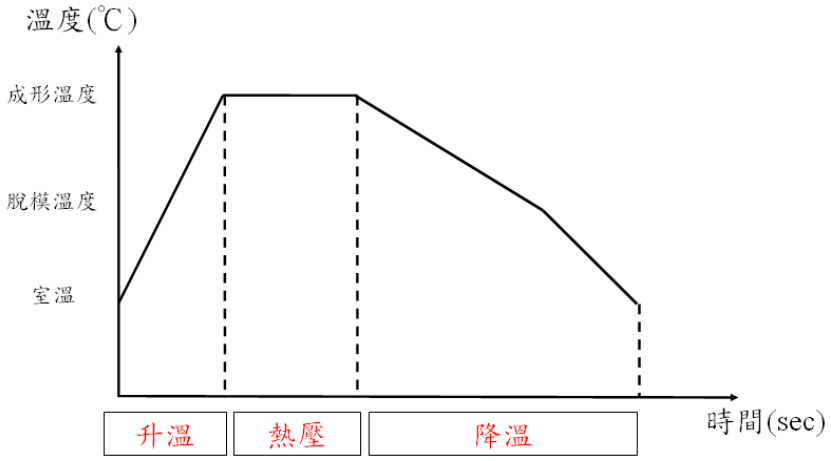

圖 2 玻璃熱壓成形溫度—時間關係圖

2. 研究目的

本研究的目的即是針對光學玻璃熱壓成形製程建立起一套有限元素分析的架構。根基於玻璃材料性質的探討，藉由成形條件的數值化模型模擬光學玻璃材料在熱壓成形製程中的變形行為，並對最終成品外型進行預測，探討製程參數對於元件成形性以及殘留應力之影響。研究中主要以開模熱壓製程作為載具進行數值分析以及實驗驗證，如此近程可供業界模造玻璃製程作為製程參數調整與模具設計之參考；遠程則將引入光學玻璃微熱壓成形分析。最終期能以本研究所建立之分析架構縮短製程研發所需之時間、降低製造成本、增進光學透鏡產品品質與競爭性。

3. 文獻回顧

在玻璃熱壓成形的相關文獻中，國外研究的部分有 Shishido[3]等針對玻璃熱壓時玻璃與模仁間之貼合程度進行研究，發現貼合程度將隨著玻璃表面張力的變化而改變，而貼合度的變化也會影響成形後的複製精度；Heckele[4]等人認為熱壓成形是適於光學元件微結構的理想技術，其優點是材料流動率低，可避免由內應力引起的散射中心（Scattering Centers）誤差，且熱壓成形是可製造出高精度、高品質、大面積的光學元件技術，由於成形步驟簡明，若能將熱壓成形過程更改為自動化成形製程，將有效的降低成本；Zhong 等[5]對於玻璃模造裡模仁進行熱機械特性的有限元素分析，探討模仁幾何形狀、材料，以及鍍膜層材料對於鍍膜模仁的影響；Saotome 等[6]對兩種光學玻璃在 Tg 點到 Tg 點以上 30 度的溫度範圍條件下進行壓縮實驗，得到不同溫度下真實應力與應變率的關係，證實了該溫度區間玻璃可視為牛頓黏滯流（Newtonian viscous flow）亦即表示黏度（Viscosity）為一常數； Hyre[7]以有限元素法對玻璃瓶的製程進行分析，並將玻璃的材料性質則視為黏塑性；Jain 等[8]以商用 FEM 軟體建立 2D 軸對稱模型進行分析，將成形時的玻璃視為牛頓流體（Newtonian fluid）且將黏度與溫度的相關性以及模仁與胚料介面的熱傳皆考慮進去，探討模造製程參數對成品品質的影響；Yi 等[9]使用有限元素模擬預估光學玻璃透鏡在熱壓成形製造中的變形行為，證實高精度非球面透鏡可利用模造方式來取得，且模仁的表面品質可以被轉印至透鏡上。國內與玻璃熱壓相關的討論有游[10]等人以電鑄鎳金屬模仁，熱壓成形於 PSK-100

玻璃材料上，成功地驗證了熱壓成形於玻璃材料之可行性；邱[11]以數值方法分析玻璃鏡片壓製成形整個製程中的溫度場；王[12]以陣列式 V 形槽結構分別對 FCD1 及 SF2 光學玻璃材料進行微熱壓印實驗，探討製程中各種參數對玻璃微熱壓成形特性的影響，且對成形中產生的缺陷探討其原因及改善方法，比較後得知 FCD1 材料較適合應用在微熱壓成形製程，適合的壓印溫度介於轉移點與軟化點之間而接近軟化點。

本實驗室的研究中，黃[12]自行設計與製造球面透鏡的模仁，並探討不同材質與鍍膜之模仁表面的品質；並以FCD1光學玻璃胚料製成平面透鏡，使用實驗室自行設計溫度可達600°C，壓印力可達2噸之熱壓設備，將平面透鏡壓印成球面透鏡，得到下述結論：

(1) 壓印時階段式升、降溫可以避免玻璃於升、降溫過程中破損。

(2) 在此製程上，除了壓印壓力會影響填充性，持壓時間亦會明顯的影響填充性。

(3) 此實驗壓印出之球面透鏡，其透鏡中心較外圍部分具有較低的殘留應力。

王[13]於後續的研究中以自行製作之S-FPL53光學玻璃材料預形體與L-BAL42商用預形體做為實驗材料，進行熱壓成形實驗，得到以下結論：

(1) 模仁在熱壓成形過程中，其轉印性良好，如能控制模仁表面品質，則可易於控制產品的精度。

(2) 預形體的形狀與表面精度將影響透鏡成品的精度。

(3) 硬膜層的技術將絕對影響壓印成品的結果，適當的製程參數將能提高模仁及硬膜層壽命並提升成品品質。

由於本研究旨在建立一套應用於光學玻璃熱壓成形的有限元素分析架構，所以研究中除參考上述所提及之相關文獻、技術討論，亦對於所使用的光學玻璃材料進行材料試驗以取得適用於本研究之材料模型；另對於熱壓設備進行改良並對模仁表面鍍膜層進行探討以達到更高品質的壓印成品。如此期能對目前業界在模造成形相關問題的解決上有所助益，更能針對後續光學玻璃微結構成形研究建立起一較完備的基礎架構。

4. 研究方法

本計畫之研究方法可分三個階段來說明。

第一階段：材料模型取得與驗證

以整個光學玻璃熱壓成形製程觀之，在有限元素分析模型建立之初，關於玻璃材料模型有以下幾個狀況需考慮：升溫時須考慮玻璃熱膨脹的行為，此時需要玻璃熱膨脹曲線的資訊；在熱壓時須考慮玻璃在成形溫度下的變形行為，此時需要進行單軸壓縮試驗以取得所需資料；而在降溫階段，不但有熱收縮的行為，此階段中還包含了玻璃材料內部應力鬆弛的行為，這部分則需進行應力鬆弛試驗進行探討。本研究首先參考以往之文獻，並針對研究中所使用之材料進行實驗，並以有限元素分析的方式驗證材料模組之可行性，以修正並取得最適當之材料模組。

第二階段：玻璃熱壓成形製程實驗及有限元素分析模型建構

在進行材料試驗的同時，利用本實驗室自行設計之熱壓機台進行初步光學玻璃熱壓實驗。參考實驗室曾採用的實驗參數，並搜尋業界目前在光學玻璃熱壓上的製程參數，以此兩種參數建立與模擬分析對照用之數據資料。接著以此熱壓實驗參數及設定，使用有限元素分析軟體 MSC.MARC 建立分析模型，將第一階段所取得之材料性質代入分析中，並與實驗作對照，找出合理的製程模擬方式。

另以模具預補償作為建構玻璃熱壓製程最佳化的載具，透過最佳化系統搭配有限元素分析，嘗試以數值運算方式對模具進行預補償，期能以此取得更高之產品精度。

第三階段：玻璃微熱壓成形

鑑於本研究為應用有限元素分析於光學玻璃熱壓成形技術之先行研究，除一般光學玻璃透鏡之成形為主要探討部分，在光學玻璃上成形微結構之可行性亦為本研究探討主題之一。在研究中選用了 V 型溝槽以及 Fresnel 結構進行為熱壓成形實驗，對其轉印性及後續為熱壓成形參數設定方面進行研究。

應用在光學玻璃熱壓製程的有限元素分析架構將經由上述三階段的一系列探討逐步建立起來，而此架構將會對未來在光學玻璃上壓印微結構的製程研究上提供相當的助益。

5. 結果與討論

5.1 材料模型之取得與驗證

光學玻璃熱壓成形製程有限元素分析可分為三階段：升溫、熱壓以及降溫，其中所需考慮的項目如圖 1 所示。研究一開始即針對這些所需的材料性質進行探討。初期所選用的材料為 OHARA 公司製造，Tg 點較低之四款光學玻璃進行測試，最後再選取適合之玻璃材料進行後續研究。

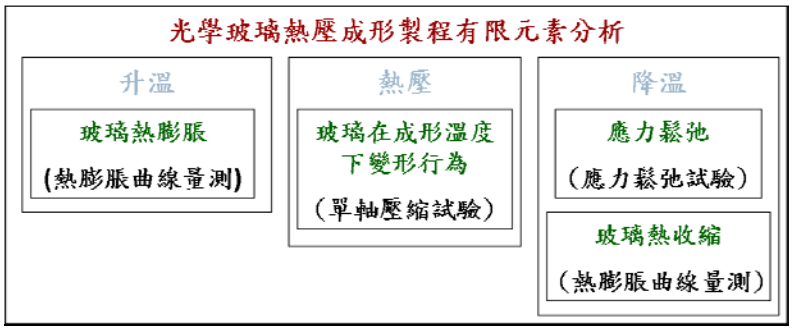

圖 3 有限元素分析在各階段所需考慮之項目

5.1.1 熱膨脹曲線量測

針對升、降溫過程時玻璃的熱膨脹行為部分，如圖 4 所示，由於玻璃製造商所提供的熱膨脹係數，如表 1，只有提供到 300°C，在 Tg 點之後的熱膨脹行為，廠商並無提供資料。為了取得可應用在有限元素分析裡的資訊，研究中委託台北科技大學奈米光電磁中心進行熱膨脹曲線量測實驗。

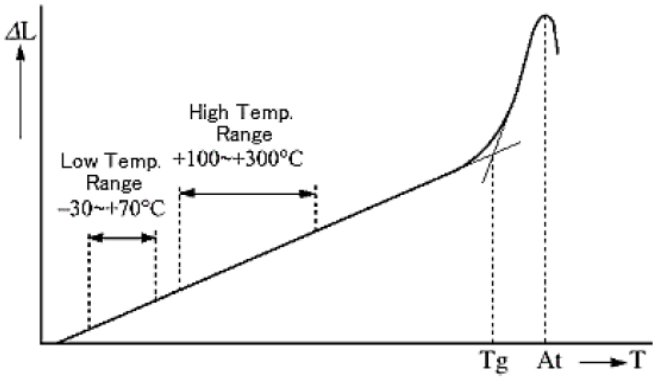

圖 4 玻璃熱膨脹曲線示意圖[15]

表 1 玻璃熱膨脹係數[15]

		L-BAL42	S-FPL51	S-FPL52	S-FPL53
熱膨脹係數 α (10^{-7}/˚C)	(-30~+70˚C)	72	131	133	145
	(+100~+300˚C)	88	155	158	169

以玻璃材料 L-BAL42 (Tg 點為 506°C)為例，實驗裡將玻璃裁切成圓柱形試片，直徑 8mm，高 25mm。在 100°C 以下升溫速率 2°C /min，100°C 以上升溫 4°C /min，升溫至 500°C 以上。另以上述設定對其餘三款玻璃 S-FPL51 (Tg 點為 458°C)、S-FPL52 (Tg 點為 445°C)及 S-FPL53 (Tg 點為 426°C)進行量測，熱膨脹量測結果如圖 5 至圖 8 所示。後續有限元素分析將依據此處所得之熱膨脹曲線進行相關模擬。

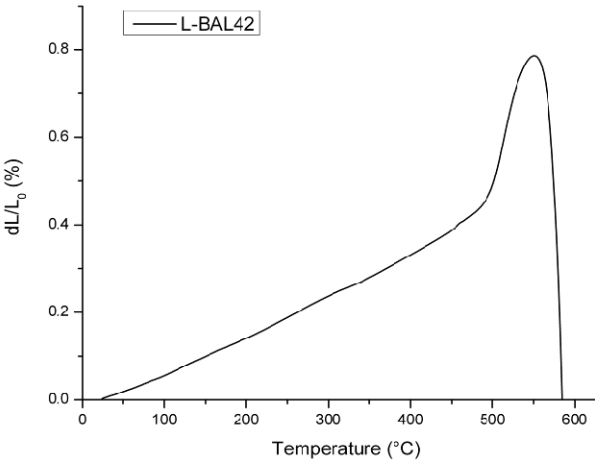

圖 5 L-BAL 42 熱膨脹曲線

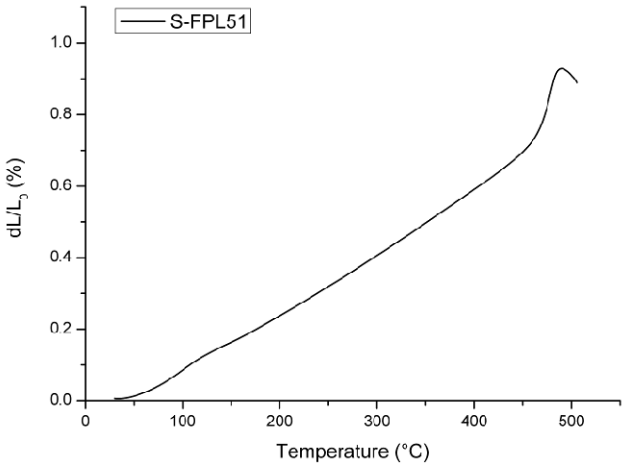

圖 6 S-FPL 51 熱膨脹曲線

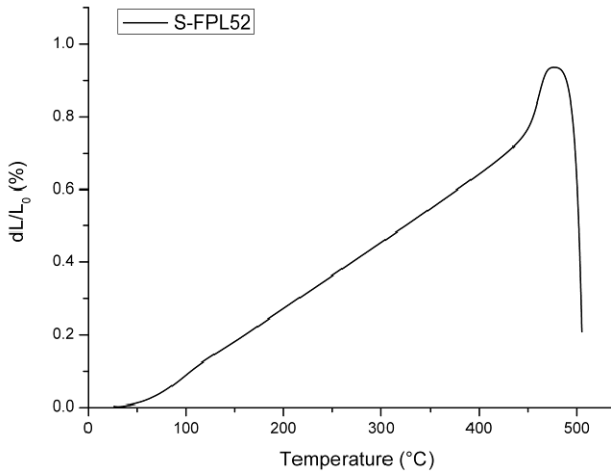

圖 7 S-FPL 52 熱膨脹曲線

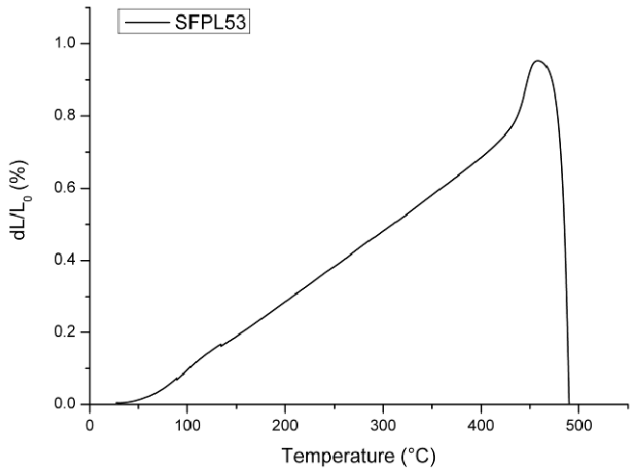

圖 8 S-FPL 53 熱膨脹曲線

5.1.2 成形溫度下之材料模型

在尋找光學玻璃熱壓成形溫度下的材料模型之前，需先瞭解光學玻璃本身的性質。光學玻璃是屬於非結晶材料，從製造過程中的高溫一路降到室溫取得成品為止，這一連串降溫過程皆由黏度(viscosity)主導讓玻璃逐漸硬化。其中黏度對溫度的關係可藉由示意圖 9 中觀察到。這種黏度對溫度的關係隨著玻璃成分的不同而有所差異，但大致上趨勢是相同的。玻璃製造商通常不會對各批號玻璃都提供這樣的關係圖，不過常會提供幾個對應到特定黏度的溫度資訊如下：

應力點（strain point）或下退火點（lower anneling point）：黏度為 $10^{14.5}\,dPa\cdot s$ 的溫度點。

退火點（annealing point）或上退火點（upper annealing point）：黏度為 $10^{13}\,dPa\cdot s$ 的溫度點。

軟化點（softening point）：黏度為 $10^{7.6}\,dPa\cdot s$ 的溫度點。

對於不同的光學玻璃，在 Tg 點以上黏度對溫度的關係以經驗公式 VFT 方程式[16]求得。VFT(Vogel-Fulcher-Tammann)方程式為：

$$\log\eta = A + \frac{B}{T - T_0} \qquad (式\ 1)$$

其中 T 為欲求得對應黏度之溫度點。A、B 及 T_0 這三個常數項則可藉由上述特定的黏度-溫度對應點代入取得。

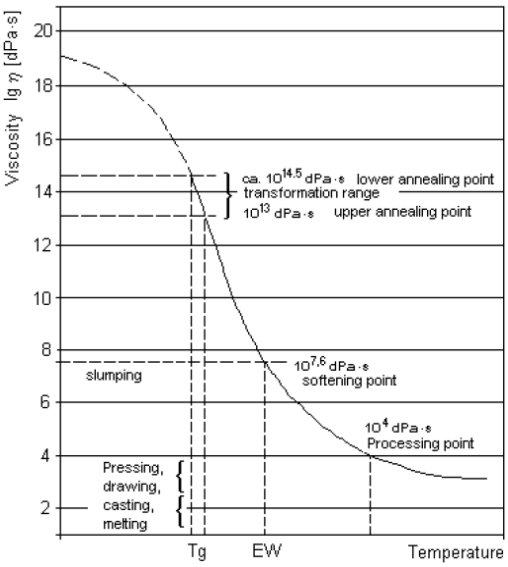

圖 9 光學玻璃黏度與溫度關係圖[17]

瞭解了光學玻璃黏度與溫度的關係後，便可切入光學玻璃熱壓成形部分。在先前相關文獻討論中，光學玻璃熱壓成形的溫度是介於 Tg 點與軟化點間，當玻璃在這溫度區間內受壓變形，此時變形行為的相關論述便從黏度延伸至兩種材料模型的假設：一種是黏塑性(Viscoplastic)，另一種為黏彈性(Viscoelastic)。

黏塑性材料的流變模型可視為摩擦滑塊與阻尼之組合，示意圖如圖 10。在材料流動未達塑流應力(flow stress)時材料視為未變形（摩擦滑塊部分）；當材料流動超過塑流應力時（$\sigma \geq \sigma_Y$），則將材料視為黏性流體（阻尼部分），此時材料塑流應力與應變率為正相關。

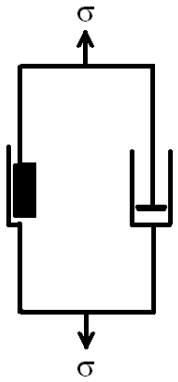

圖 10 黏塑性流變模型示意圖

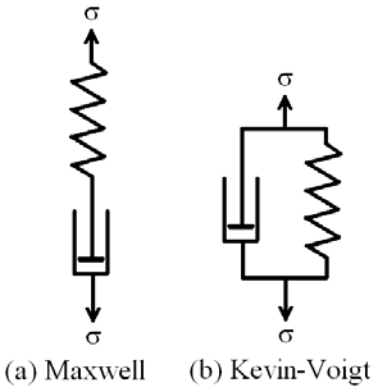

圖 11 黏彈性流變模型示意圖

黏彈性的流變模型為彈簧與阻尼之組合，如圖 11 所示。黏彈性材料的性質除黏性流動的特性外還包含了彈性回復的部分。但由於黏性流動（阻尼部分）為時間的函數，造成彈性變形（彈簧部分）無法在瞬間進行反應，所以在兩者交互作用下使得材料的變形行為出現潛變 (creep)或應力鬆弛(stress relaxation)的現象，而非單純的黏性流動或彈性回復。由於黏彈性模型對於描述材料在受到固定應力或固定應變的狀況下之變形行為略有不同，所以常以並聯方式組合的 Kevin-Voigt 模型描述潛變（固定應力）；以串聯方式組合的 Maxwell 模型描述應力鬆弛（固定應變）。

由於玻璃在熱壓成形時以何種材料模型完整描述在此溫度下的變形行為仍未定論，研究中乃針對這兩種材料模型進行研究，以尋找適用於整個製程分析之材料模型。

首先以黏塑性進行探討。黏塑性模型如下式：

$$\begin{cases} \sigma = 0 & \text{if} \quad \sigma < \sigma_Y \\ \sigma = 3\eta(T)\dot{\varepsilon} & \text{if} \quad \sigma \geq \sigma_Y \end{cases} \qquad (式\ 2)$$

其中 σ 為塑流應力，$\dot{\varepsilon}$ 是應變率(strain rate)，η 為黏度，為溫度的函數。亦即材料必須達到塑流應力後，才會表現出應變率相關(strain rate dependent)的材料行為，此時塑流應力會隨著應變率的不同而改變；而溫度的不同造成黏度改變，亦會造成塑流應力的變化。另由於光學玻璃鏡片對成品的尺寸精度要求較高，若能在成形中加入彈性部分的性質，則可對於熱壓製程中玻璃鏡片彈性回復的部分更進一步的研究；所以本研究在此處嘗試將式 2 的黏塑性模型調整成彈-黏塑性(elasto-viscoplastic)模型來探討玻璃材料在熱壓成形溫度下的行為，彈-黏塑性模型如下式：

$$\begin{cases} \sigma = \mathrm{E}\varepsilon & \text{if} \quad \sigma < \sigma_Y \\ \sigma = 3\eta(T)\dot{\varepsilon} & \text{if} \quad \sigma \geq \sigma_Y \end{cases} \qquad (式\ 3)$$

亦即在小於塑流應力前，材料呈現的是線彈性之行為，過了塑流應力後，行為表現與單純黏塑性模型相同；由於熱壓成形時是在一固定溫度下進行，所以本研究中將此時的黏度設為一定值。此部分先以玻璃材料 S-FPL52 在 Tg 點以上 30°C，固定真應變速率為 40%/min，未施加潤滑劑的條件下進行單軸壓縮試驗。由於廠商並無提供 S-FPL52 特定黏度對溫度點的資料，所以這部分必須先由模擬趨近實驗值的方式先取得在此溫度下的玻璃黏度才能進行後續探討。於是以商用軟體 MSC.MARC 建立有限元素模型，如圖 12 所示，將上下模仁設為剛體，玻璃採用彈-黏塑性的材料性質。接著將實驗條件代入有限元素分析中對實驗結果進行趨近，並可取得彈-黏塑性模型之係數項。此時楊氏係數為 1300MPa，黏度為 $10^{10}\,dPa\cdot s$。比對之應力—應變關係圖如圖 13 所示。

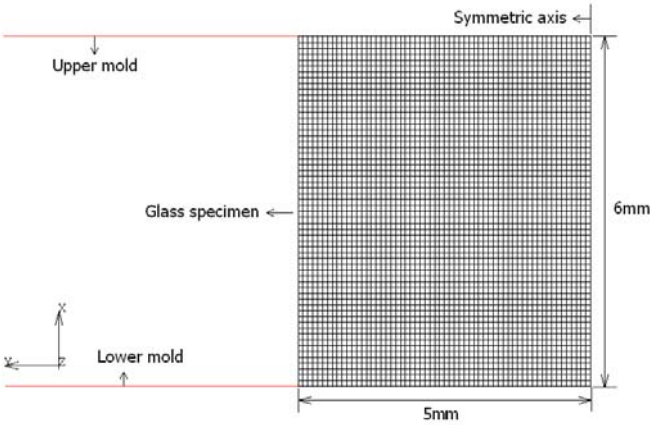

圖 12 2D 軸對稱玻璃試片有限元素分析模型

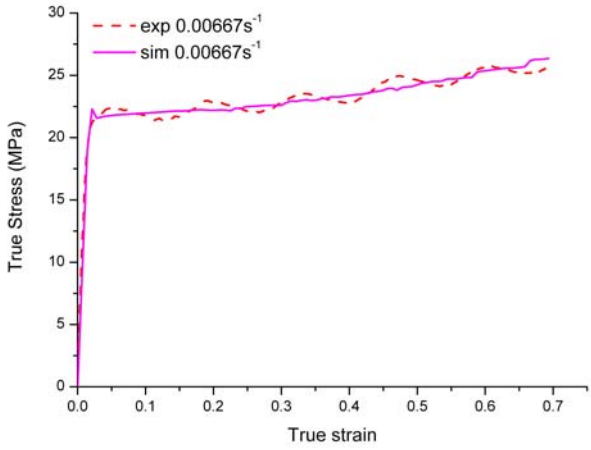

圖 13 應變率 40%/min 模擬結果與實驗值應力—應變曲線比對

觀察圖示可看到模擬趨近與實驗有相當程度的吻合，顯示材料模型在真應變速率為 40%/min 時採用此組參數是可行的。但在不同的應變速率下，則需再以不同應變速率下的單軸壓縮模擬與實驗對照後，依照此組參數建立的彈-黏塑性模型才可確立。

接著以真應變率為 50%/min 以及 60%/min 的壓縮條件，代入依上述參數組合建立的彈-黏塑性材料模型中，經計算得到塑流應力分別等於 24.9MPa 及 30MPa，並進行模擬以及實驗；模擬結果與實驗值的力量—位移及應力—應變圖如圖 14 所示。比較圖形後發現模擬結果與實驗值的趨勢相當吻合；由此可知，對於玻璃材料 S-FPL52，在 Tg 點上 30°C 的成形狀況下，依照此組參數建立的彈-黏塑性材料模型可以用來描述此時受力產生之變形行為，而此材料模型將可用在玻璃熱壓成形分析中。

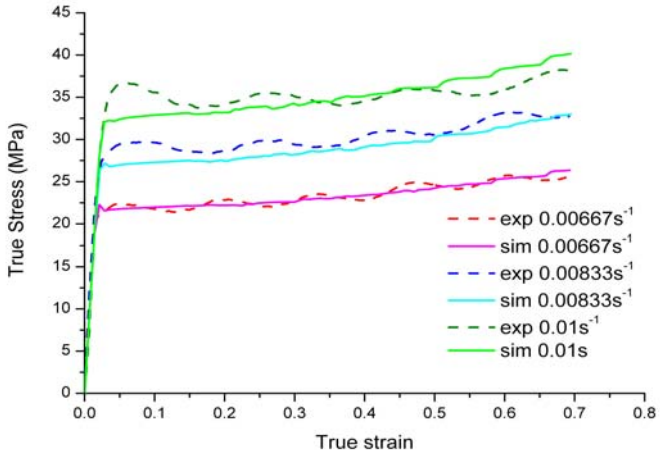

圖 14 應變率 40%/min, 50%/min 及 60%/min 下模擬結果與實驗值力量—位移曲線比對

5.1.3 應力鬆弛試驗

在探討玻璃黏彈性行為時，最能表現出此特性的莫過於應力鬆弛試驗。由於之前所使用的 S-FPL52 在黏度特性的掌握上只有 Tg 點以上 30°C 這個溫度點，要探討不同溫度點下的應力鬆弛行為則需要再進行多組實驗及模擬趨近，如此得耗費許多時間。所以在這部分中，採用廠商有提供特定黏度對應溫度資訊的玻璃材料 L-BAL42（Tg 點為 506°C）。將其裁切為直徑 8mm、高度 8mm 之圓柱型試片，分別以 Tg 點(506°C)、Tg 點以上 50°C (556°C)以及 At 點以上 30°C (568°C)進行單軸壓縮應力鬆弛實驗試驗，取得正規化應力(Normalized stress)對時間的關係，試驗結果如圖 15 至圖 17。

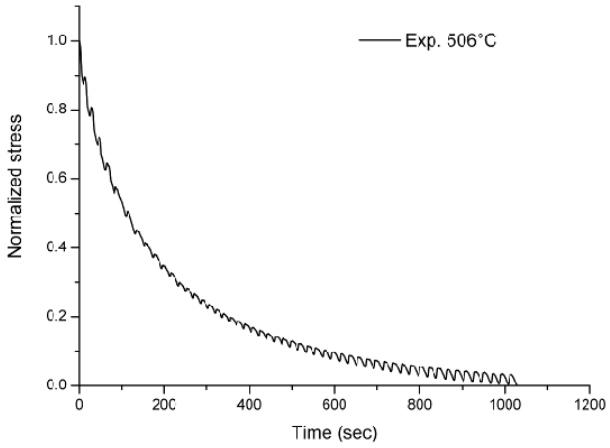

圖 15 L-BAL42 在 Tg 點之應力鬆弛曲線

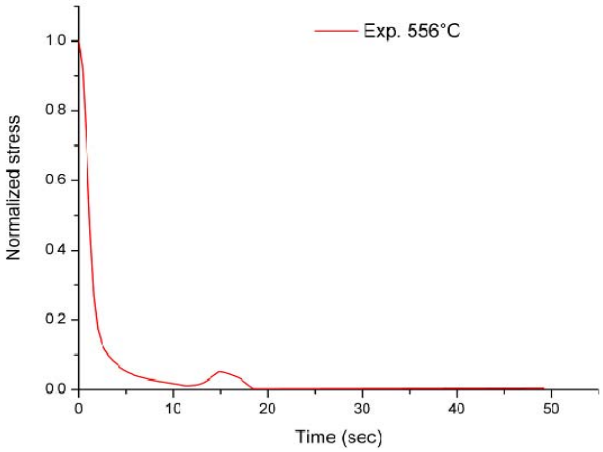

圖 16 L-BAL42 在 Tg 點以上 50°C 之應力鬆弛曲線

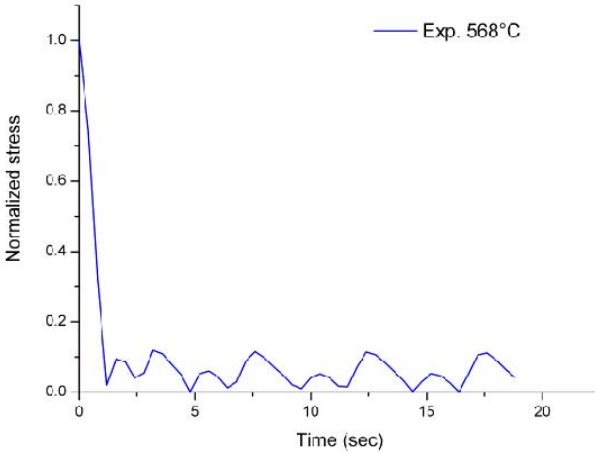

圖 17 L-BAL42 在 At 點以上 30°C 之應力鬆弛曲線

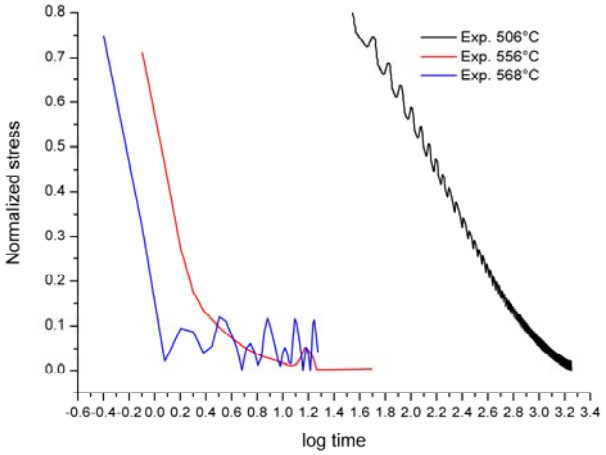

圖 18 L-BAL42 應力鬆弛曲線平移關係圖

將以上三個結果的時間軸取對數後發現應力鬆弛曲線有接近平移的關係，如圖 18 所示。此關係可以經驗公式 Williams-Landal-Ferry 方程式[18]來描述，方程式如下：

$$\log a_T = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \qquad (式\ 4)$$

方程式描述了在溫度 T 時，應力鬆弛曲線相對於參考溫度 T_r 具有一 $\log a_T$ 的平移量，其中 C_1 及 C_2 為係數項。為驗證此平移關係帶入到有限元素分析中的可行性，研究中另在 538°C 下進行驗證實驗，並以平移後之應力鬆弛曲線帶入模擬中，結果如圖 19 所示。從結果裡可以看到模擬結果與實驗值相當趨近，驗證了不同溫度下的應力鬆弛曲線可藉由經驗公式的計算取得以代入到有限元素分析中，對後續熱壓成形的模擬將有所助益。

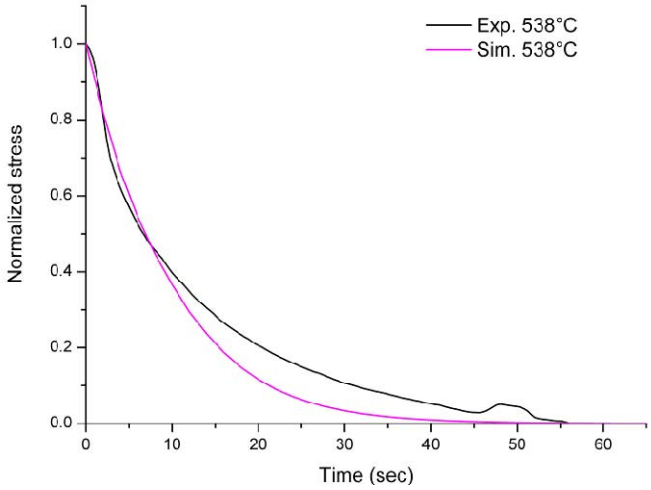

圖 19 L-BAL42 應力鬆弛曲線預測與實驗結果比較

藉由材料實驗的探討，對於光學玻璃透鏡熱壓時，有限元素分析模型中該採用哪些材料模型設定已建立初步的認知。但如何順利將材料模型設定代入玻璃熱壓製程分析中，則需藉由實際熱壓實驗加以確認，這部分將在下節中加以討論。

5.2 光學玻璃透鏡熱壓實驗

由於熱壓實驗的目的在於驗證玻璃材料模型之可行性及後續有限元素分析的正確性，為達成此目標，穩定的熱壓成形環境與耐用度高的模仁及鍍膜是不可或缺的。於是研究中首先以不同模仁材料進行嘗試，成形適合且形狀正確的模仁進行熱壓，確定適合進行後續研究之模仁；接著以本實驗室自行建構完成的熱壓

設備進行成形試驗，測試不同鍍膜材料以及成形參數的影響，尋找穩定且耐用的製程參數搭配以建立光學玻璃透鏡熱壓成形的完整流程。

5.2.1 模仁材料選用

模造玻璃用之模仁材料有以下幾點性質之要求：

1.模仁材料需可加工成高形狀精度。

2.模仁需在重複急速升降溫過程中，表面不易產生變形、裂痕與氧化作用。

3.模仁在高溫度工作範圍內，具有高剛性、耐衝壓強度與高硬度。

基於上述對模仁材料的要求，目前業界多採用碳化鎢作為模仁材料，研究中分別採用含鈷以及不含鈷之碳化鎢作為模仁材料進行嘗試，其材料性質如表 2 所示。

表 2 模仁材料性質

材料名稱 性質	碳化鎢(含鈷)（UM）	碳化鎢（不含鈷）（M78）
比重（g/cm^3）	13.9	15.4
硬度（HV）	1600	2600
抗折力（GPa）	2.5	1.47
壓縮強度（GPa）	5.9	4.8
熱膨脹係數（×10^{-7}/K）	60（20~150℃）	36（20~400℃）
熱傳導率（W/m・K）	67	42
含鈷成份	5.5%	無

由於碳化鎢為一種高硬度且具脆性的材料，在模仁設計上除了需考慮實驗試片尺寸、模仁夾治具及溫度感測（熱電偶）等因素外，更重要的是須考量加工上的難易度；研究裡所使用的模仁設計及模仁-夾具組合分別如圖 20 及圖 21 所示。

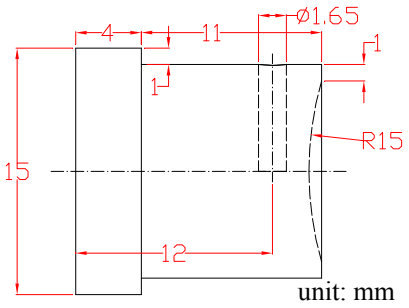

圖 20 模仁設計圖

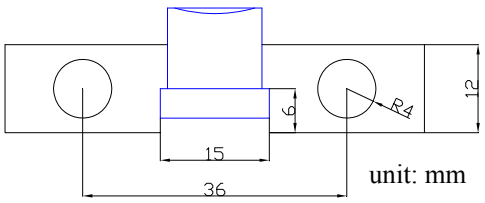

圖 21 模仁-夾具組合圖

而模仁的加工方式，與傳統光學玻璃透鏡的研磨拋光製程相似，藉由濕式拉磨法製作出模仁在模造實驗中之壓印面。模仁製作的流程依序為放電加工、成形、研磨、拋光到最後的定心，各階段的目的與過程詳見附錄 9.1。研究所使用的模仁便經由這一系列的流程製作完成，如圖 22 所示。

圖 22 模仁加工成品圖

5.2.2 不同材質鍍膜的比較與最佳製程參數的尋找

在完成模仁的製作後，接著便以本實驗室自行建構完成的熱壓設備進行熱壓成形試驗。設備最大施力可達兩噸，溫度可達 600℃，整體外觀如圖 23 所示。

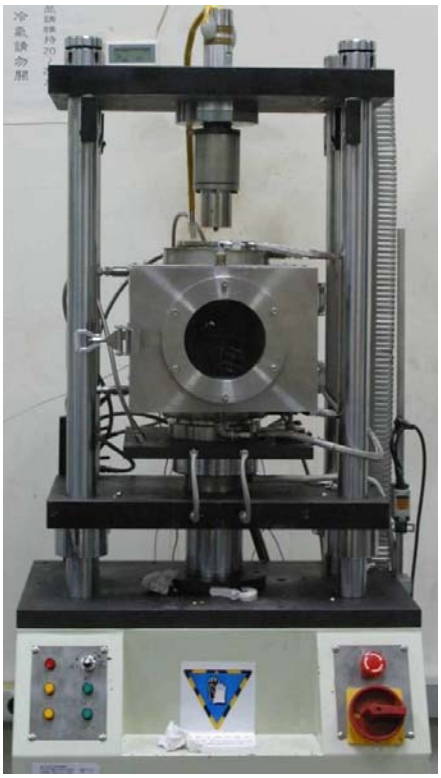

圖 23 熱壓設備外觀圖

參考現有熱壓成形文獻並且透過實驗室先前所進行的研究，研究裡以五組熱壓成形參數進行實驗，其中實驗所使用的玻璃材料為 OHARA 公司所生產之成形用光學玻璃，玻璃編號為 S-FPL53、S-FPL52 及 L-BAL42，玻璃轉移點溫度分別為 426℃、445℃及 506℃。相關實驗參數如表 3 所示。

表 3 實驗參數

實驗編號	1	2	3	4	5
玻璃材料	L-BAL42	S-FPL53	S-FPL52	L-BAL42	L-BAL42
上模仁材質（硬膜）	UM(TiN)	UM(TiN)	UM(TiN)	UM(CrN)	UM(CrN)
下模仁材質（硬膜）	M78(無)	M78(無)	M78(無)	UM(Pt-Ir)	UM(無)
溫度設定（℃）	556	476	503	556	556
升溫時間（min）	12	18	71	25	60
持溫時間（min）	15	15	5	20	0
荷重（N）	1960	980	980	1960	1960
荷重速率（N/min）	980	490	490	980	980
脫模溫度（℃）	456	376	403	456	456

實驗結果依實驗順序分述如下：

第一次實驗的結果如圖 24、圖 25 所示，從圖中可看出透鏡成品表面沾有黃色析出物的現象，以及上模仁 TiN 硬膜層高溫氧化及脫落的現象。

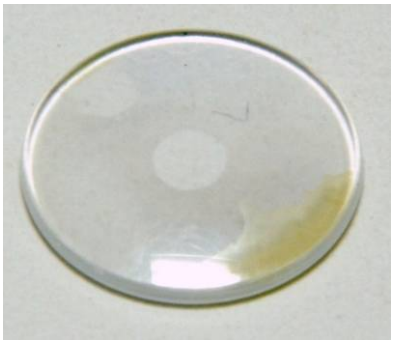

圖 24 實驗編號 1 之透鏡成品圖

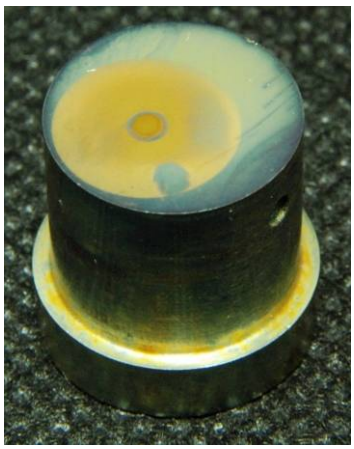

圖 25 實驗編號 1 之實驗後上模仁圖

S-FPL53 與 S-FPL52 的結果如圖 26、圖 27 所示，由於預形體尺寸較大，壓印完成後透鏡周圍留有餘料；由透鏡成品可看出表面並無沾附析出物的現象，且模仁在壓印完 S-FPL53 的材料試片後幾乎沒有變化的現象，但在之後 S-FPL52 的壓印實驗過後，由於實驗溫度較高，上模仁的 TiN 硬膜層可看出氧化現象，如圖 28 所示，而下模仁則因兩次的實驗之後開始產生沾黏的現象，如圖 29 所示。

圖 26 實驗編號 2 之透鏡成品圖

圖 27 實驗編號 3 之透鏡成品圖

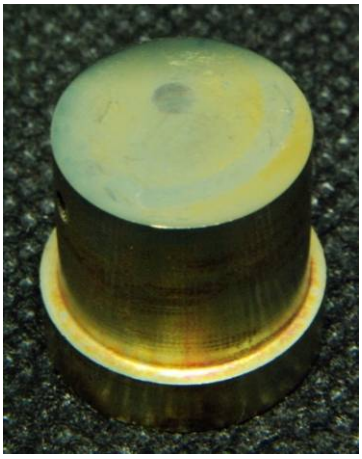

圖 28 實驗編號 3 之實驗後上模仁圖

圖 29 實驗編號 3 之實驗後下模仁圖

第四次的實驗下模仁使用的是貴金屬 Pt-Ir 硬膜層，透鏡成品如圖 30 所示，可看出 Pt-Ir 硬膜層脫落的情形嚴重，沾黏於透鏡上，下模仁實驗後經由干涉儀量測結果如圖 31 所示。

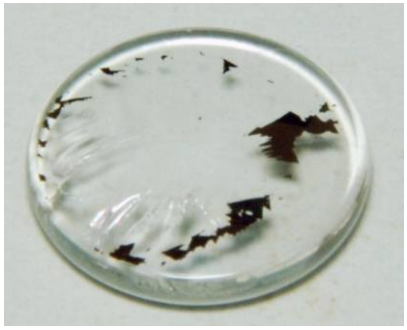

圖 30 實驗編號 4 之透鏡成品圖

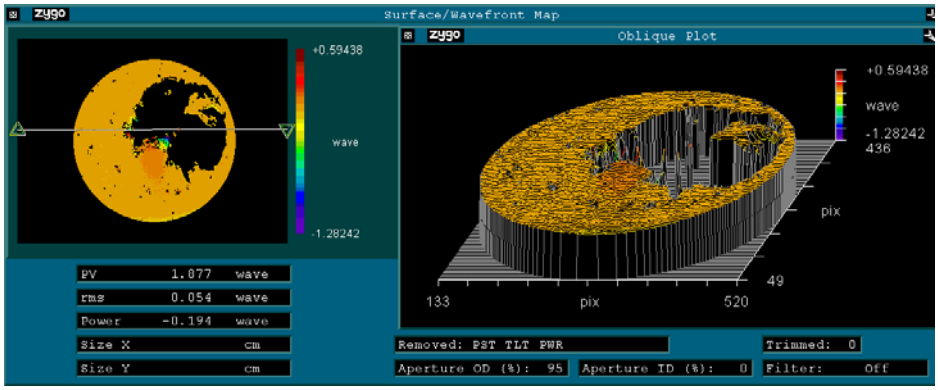

圖 31 實驗編號 4 之實驗後下模仁干涉儀量測結果

先前實驗所用之無硬膜層下模仁的材料為不含鈷成分之碳化鎢，其特色為高溫穩定性佳，可在無硬膜層的情形下直接進行壓印；而第五次實驗使用的無硬膜層模仁則為含有鈷成分之碳化鎢材料，目的在於比較這兩種材料在對高溫反應的差別。實驗結果如圖 32 所示，透鏡成品表面有大量的析出物沾附現象，而上模仁的 CrN 硬膜層也在兩次的實驗之後開始產生脫落現象，如圖 33。

圖 32 實驗編號 5 之透鏡成品圖

圖 33 實驗編號 5 之實驗後上模仁圖

模仁加熱實驗之溫度設定為 590℃，實驗結果如圖 34 所示，圖中左邊模仁為未經過實驗且未鍍硬膜的模仁，中間的模仁為 CrN 硬膜層模仁經加熱實驗後結果，右邊的模仁則為未鍍硬膜的模仁經加熱實驗後的結果。

圖 34 模仁加熱實驗結果圖

經由實驗結果分析歸納出下列幾點：

(1)TiN 硬膜層耐熱溫度低，高溫易氧化失效，以一次性實驗來看，476℃時尚無明顯變化，而 503℃與 556℃的實驗則是明顯出現氧化現象，如果是重複進行模造製程，則預估可耐之溫度將會更低。

(2)無硬膜層的無鈷成分碳化鎢模仁在幾次實驗之內會開始對玻璃產生沾黏的現象，且依實驗看來，壓印力越大、持壓時間越久的實驗越容易產生沾黏。

(3)貴金屬 Pt-Ir 硬膜雖在高溫下穩定性高，不易發生氧化現象，但是容易發生沾黏現象。

(4)CrN 硬膜層可耐溫度較高，在初步實驗的工作溫度下不易氧化，但也在幾次實驗之內開始發生沾黏現象。

(5)含鈷成分之碳化鎢模仁若無鍍硬膜層時，在高溫下其表面會有析出或反應的現象。

由實驗結果來看，模仁與硬膜層之壽命與氧化、沾黏、脫落等因素有很大的關係。氧化現象及含鈷成分之碳化鎢模仁析出現象推測是由於模仁在高溫中的大氣環境下實驗所發生，環境氣氛的改善是可能的解決方式。而沾黏與脫落的現象推測其原因為玻璃的溫度雖已到達轉移點，但其溫度下玻璃的黏性依然過大，亦即玻璃尚偏硬且黏，壓印時下壓力過大造成玻璃與模仁間的正向力與剪切力過大，若提高成形溫度此狀況亦可能抒解。

為解決上述問題，研究裡亦針對加熱爐的設備進行改善，藉由改變成形環境

氣氛以及提高成形溫度的嘗試對於成品品質增進與否進行探討。改善詳情將於 5.4 中敘述。下一節將先針對初步實驗結果與模擬作一驗證。

5.3 光學玻璃透鏡熱壓有限元素分析

在取得了材料模型，並進行過熱壓實驗的探討後，接著便可著手尋找合理的模擬方式將熱壓成形製程建立數值化模型。

5.3.1 合理的模擬方式

將有限元素模型依據光學透鏡開放式模具熱壓成形實驗的設定建立 2D 軸對稱模型，如圖 35 所示，其中所使用的玻璃珠直徑為 5.8mm，下模仁曲面之曲率半徑為 15mm。參考實驗參數，將成形溫度設定為 556℃。邊界條件設定為固定下模仁之底部，上模仁以 980N/min 向下壓印至力量到達 1960N 時停止。溫度歷程如所示，將分析模型在 30min 內從室溫 25˚C 升溫至 556˚C，接著維持 2min，壓印完後在 2hr 內從 556˚C 降溫至 25˚C。整個分析的溫度歷程如所示。為求先行建立起一合理的模擬方式，此處玻璃材料採黏塑性模型以加速分析模型的架構；碳化鎢模仁則為純彈性；玻璃與模仁接觸的介面設定為黏著，定剪摩擦因子為 1.0，參數設定如表 4。

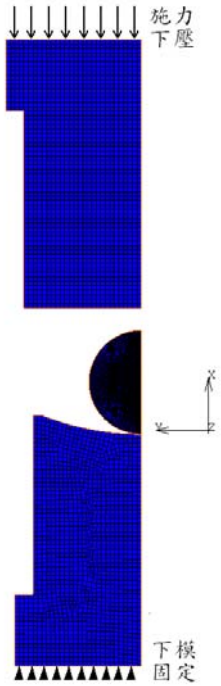

圖 35 熱壓成形分析模型

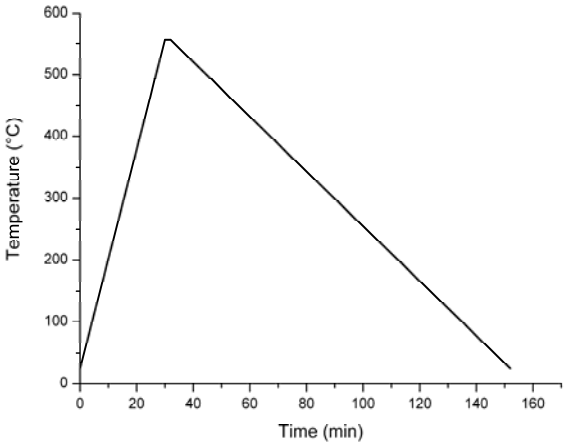

圖 36 分析模型之溫度歷程

表 4 玻璃熱壓成形分析參數

	L-BAL42 (玻璃)	UM (模仁)
材料模型	黏塑性	彈性
楊氏係數(GPa)	89.1	540
伯松比	0.247	0.23
密度 (g/cm3)	3.05	13.9
熱膨脹係數 α (10^{-7}/°C)	以熱膨脹曲線代入	60
比熱 (J/kg・K)	800	250.8

實驗與模擬的對照可以兩部分來看，一是成形時力量-位移的關係，另外是成形後透鏡的尺寸外觀。以成形時力量對位移的關係圖，如圖 37 所示，可以看到實驗與模擬雖然有差異存在，但在線型上的趨勢是一樣的。比較最終成品的尺寸外觀(圖 38)，則可看到在模擬成形完後的尺寸(圖 39)略有差異。這樣的狀況可能是分析中設定的溫度與實驗時真實溫度間有差異造成。溫度的差異會造成玻璃黏度不同，使得計算時塑流應力改變，造成預測的壓印力與實驗結果無法吻合。所以在研究裡嘗試以修正黏度項的部分對實驗結果進行趨近。從上述的分析結果觀察，實驗量得的壓印力比預測的結果來得高，推測是熱壓環境溫度的控制沒有達到欲進行實驗之溫度，造成壓印時玻璃材料表現出較黏稠的特性。所以在修正分析裡將材料模型的黏度項往更為黏稠的方向調整。修正分析的力量—位移結果如圖 40 所示，成品尺寸如圖 41 所示。可看到修正後的分析結果比起前先之預測更為趨近實驗值，驗證了前先實驗溫度未達到設定值的推測是合理的。未來將會以更精確之熱壓設備確立修正分析模型的正確性，並以更完整的彈-黏塑性模型代入分析中探討熱壓製程參數對成品尺寸及內部殘留應力的影響。

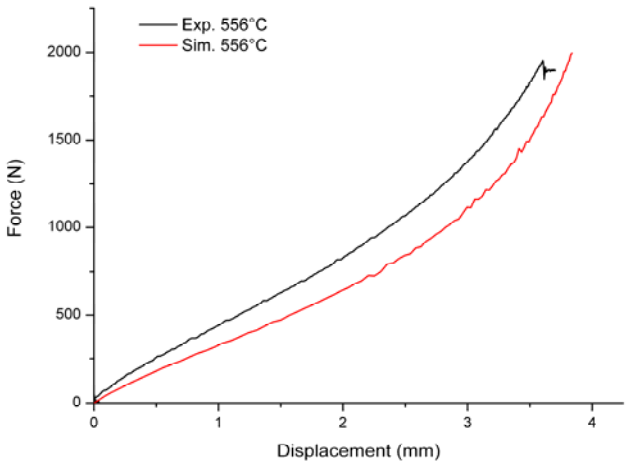

圖 37 熱壓成形時力量—位移關係

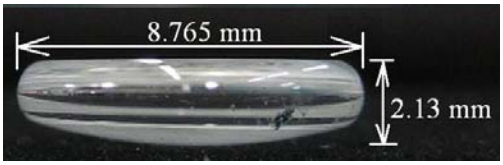

圖 38 熱壓實驗成品尺寸

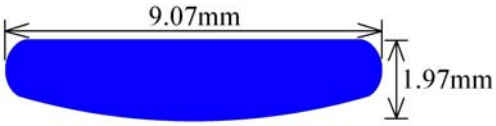

圖 39 熱壓實驗模擬結果尺寸

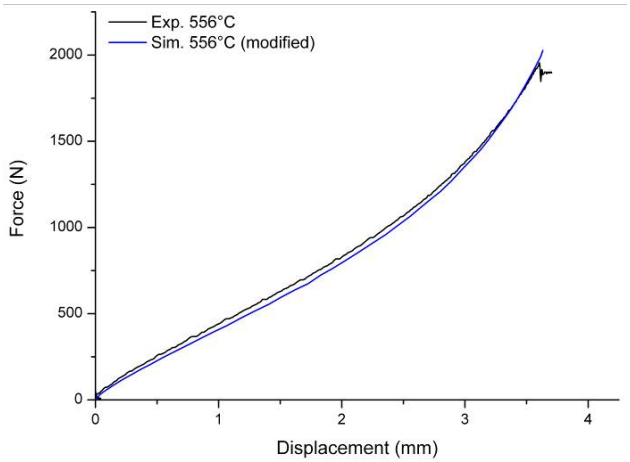

圖 40 模型修正後之熱壓成形時力量—位移關係

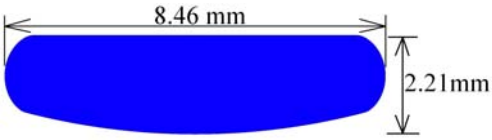

圖 41 模型修正後之熱壓實驗模擬結果尺寸

有限元素分析的應用除了可對熱壓製程參數進行探討，更可搭配最佳化分析對製程參數進行優化。在下節中將以建立模具外型設計之預補償最佳化分析系統作一展示。

5.3.2 模具補償最佳化系統建立

欲修正成形參數對於光學鏡片成品在尺寸外觀上的影響，對模具進行預補償是一相當普遍的方式。一般業界在修正模具方面會考慮材料的熱脹冷縮，針對成品與設計尺寸之間的誤差，依照經驗推估一收縮率，一般收縮率大約在 0.005～0.007 之間，以此一固定的收縮率在模具上預留尺寸。但是這種補償方式並無法解決誤差的問題，之後續仍需進行二次以上的誤差補償，這種方式對於時間以及成本都會造成一定程度的浪費。而透過最佳化系統搭配有限元素分析，則可有效率地進行模具預補償。

研究中以自行撰寫的連結程式將有限元素分析軟體(MSC. Marc)與最佳化程式(IMSL Fortran 程式庫中之最佳化副程式)串聯，建立一模具補償的最佳化流程。此流程如圖 42 所示。一開始先進行有限元素分析，根據有限元素分析的結果，將欲最小化之目標函數定義為透鏡成品跟原始設計尺寸之間的誤差，經由最佳化方法判斷目標函數是否滿足收斂條件，以修改有限元素分析輸入檔中模具曲線上的節點座標值，接著再回到有限元素分析中，如此反覆疊代至滿足最佳化系統中之收斂條件時，停止運算並輸出最佳化分析之結果。

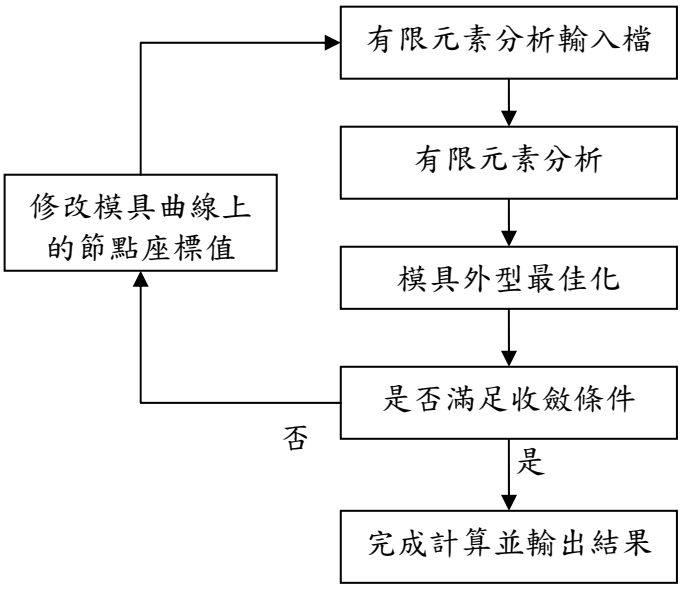

圖 42 模具補償最佳化流程

一開始以圖 43 之有限元素分析模型進行分析，觀察原始設計與熱壓後的曲線，如圖 44，可以看到成品與設計之間的差異。

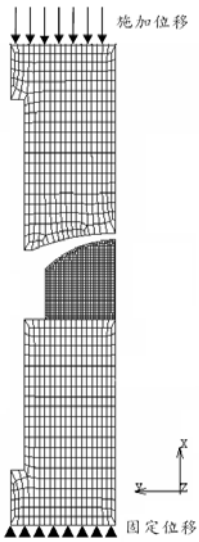

圖 43 最佳化用之有限元素分析模型

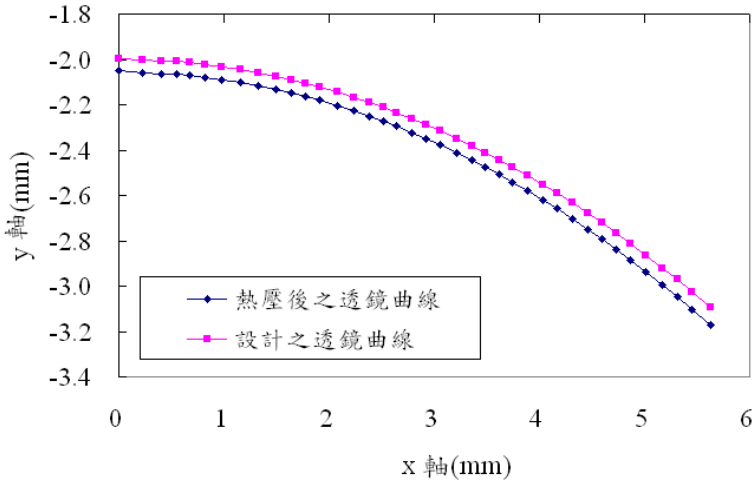

圖 44 熱壓後與設計之透鏡曲線比較

接著根據分析模型，將設計變數定義為模具曲線上的節點座標值，此模具曲線是根據非球面方程式(式 5-5)所繪出。R 為頂點之曲率半徑，k 為二次曲線常數，A4、A6 為高階非球面係數，而 k = 0 時為球面，－1< k < 0 時為以長軸為旋轉軸之橢圓面，k = -1 為拋物面，k < -1 時為雙曲面（如圖 45 所示）。

$$y = \frac{x^2}{R + \sqrt{R^2 - (1+k)x^2}} + A_4 x^4 + A_6 x^6 + \cdots\cdots \qquad (式\ 5)$$

x 代表到對稱軸之水平距離，也就是模具曲線上的節點橫座標值；y 所代表的則是 x 對應之透鏡厚度，也就是模具曲線上的節點縱座標值。設計變數為修改有限元素分析輸入檔中模具曲線之節點座標值，共使用了十六個節點來描述模具曲線，因此這十六個點將作為設計變數，如圖 46 所示，再以此配合適切之目標函數進行模具補償最佳化分析。

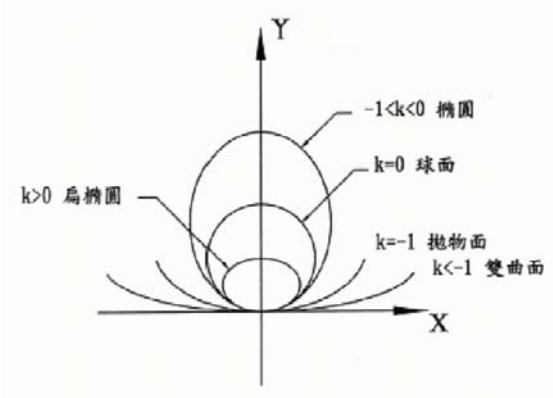

圖 45 非球面之形狀

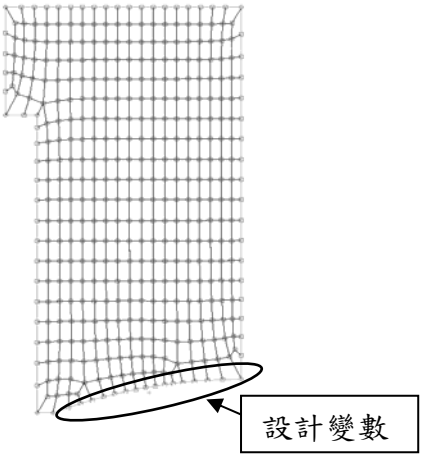

圖 46 設計變數

目標函數定義為玻璃成品上節點座標值與原始設計尺寸間誤差的方均根值：

$$\min \quad f=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(X_i-x_i)^2+(Y_i-y_i)^2\right]} \qquad (式\ 6)$$

其中（xi , yi）為根據所得到之原始設計尺寸值，而（Xi , Yi）為經過有限元素分析結果之玻璃成品幾何外型的座標值。

為了對建構完成的最佳化分析系統進行測試，以曲率半徑分別為 10mm 與 15mm 之初始模具外型，對形狀分別為球面、拋物面以及雙曲面之目標玻璃外型，進行模具補償最佳化取得最佳的模具形狀。詳細測試結果參見附錄 9.2。

由測試結果可得知當目標曲率半徑為 10mm 時，球面與不同非球面形狀下補償後之誤差與誤差修正值。透過經驗補償誤差消除約為 75.23%~80.35%，而透過模具補償最佳化系統，誤差的消除可達 94.60%~98.26%。在目標曲率半徑為 15mm 之情況下，透過經驗補償誤差消除約為 69.46%~79.59%，而透過模具補償最佳化系統，誤差的消除可達 94.76%~96.27%。

綜合以上結果可知，模具補償最佳化系統在各種目標形狀下，皆能有效地消除誤差，確實達到補償模具形狀之目的。未來將可以此系統應用到實際熱壓成形製程中對模具更有效率的進行預補償。

5.4 加熱爐之改善

為達成改變成形環境氣氛的以及提高成形溫度的需求，研究後期完成了新型紅外線真空加熱爐設備。其功能具有可做真空或特定氣體環境下的高溫實驗，並且具有快速升溫之功能。紅外線真空加熱爐示意圖如圖 47 所示。

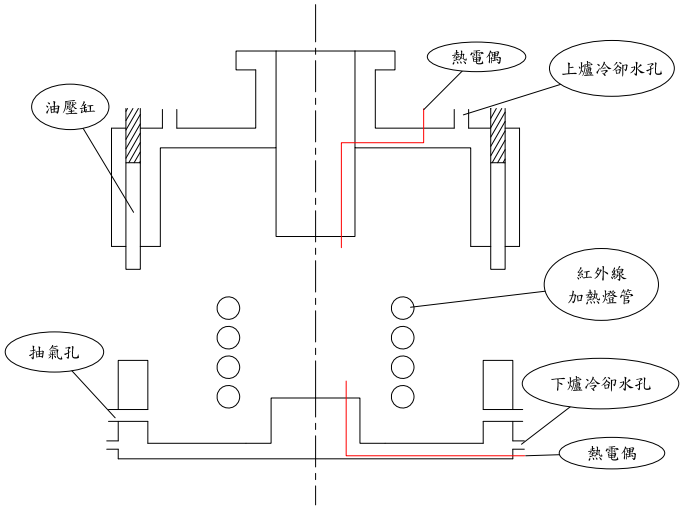

圖 47 紅外線真空加熱爐示意圖

加熱爐可分為上爐與下爐兩部份，下爐主要包含有紅外線加熱燈管及可供真空幫浦抽氣之抽氣孔；上爐部份則主要包含一具單向推動的油壓缸，此油壓缸的目的在於可使加熱爐密封作真空抽氣的動作，並可改變行程，使模仁在密封環境下得以做壓印的動作。上下加熱爐外圍均佈有冷卻管路。加熱爐外觀如圖 48 所示。

圖 48 紅外線真空加熱爐外觀圖

架設完成後利用此新型設備進行玻璃熱壓成形實驗，使用碳化鎢(含鈷)且無硬膜層之模仁材料，於真空抽氣的動作下升溫、持溫、壓印，待溫度降至脫模溫度後以充入氮氣的方式破真空，並持續通入氮氣直至室溫。此部份之相關實驗參數如表 5 所示。

表 5 新型實驗裝置測試實驗參數

玻璃材料	L-BAL42	升溫時間（min）	8
上模仁材質（硬膜）	UM(無)	持溫時間（min）	10
下模仁材質（硬膜）	UM(無)	荷重（N）	1960
溫度設定（℃）	556	荷重速率（N/min）	980
模造氣氛	真空	脫模溫度（℃）	456

實驗結果如圖 49 所示，此為碳化鎢無硬膜層模仁在真空中進行模造成形實驗所得之透鏡成品，圖中可看出透鏡成品比起在大氣環境下的成品在析出物沾附上已有明顯的改善。

圖 49 新型實驗裝置初步實驗成品

由測試結果可發現，改變加熱爐中的氣氛確實可改善模仁析出物附著的行為。之後將可以此設備進行後續微熱壓成形研究。

5.5 光學玻璃微熱壓實驗

在設備進行改善後便可著手切入至光學玻璃微結構熱壓成形製程研究的部分。本研究中嘗試以成形溫度較低之 KRS-5 以及 S-FPL53 之玻璃材料，分別在 365°C 以及 500°C 的溫度下成形微結構；模仁基底材料為鎳，微結構為連續之 V 型溝槽，其間隔為 50μm，高度及寬度皆為 50μm，模仁尺寸為 1cm×1cm，於其上鍍氮化鋁鈦(TiAlN)，模仁之微結構如圖 50 所示。成形後微結構如圖 51 與圖 52 所示，可看出玻璃可成功地成形 V 型微結構，也證明熱壓具有一定之轉印性。

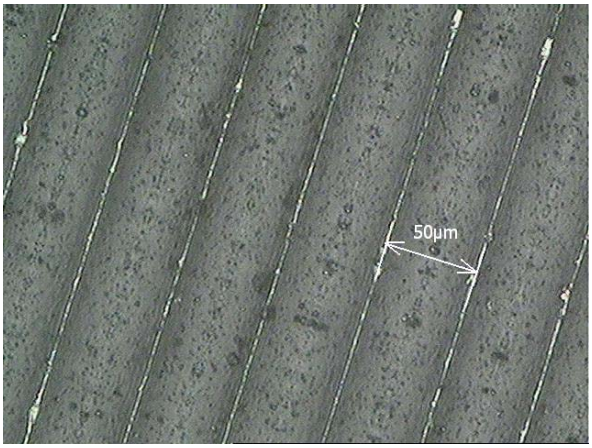

圖 50 模仁上之微結構

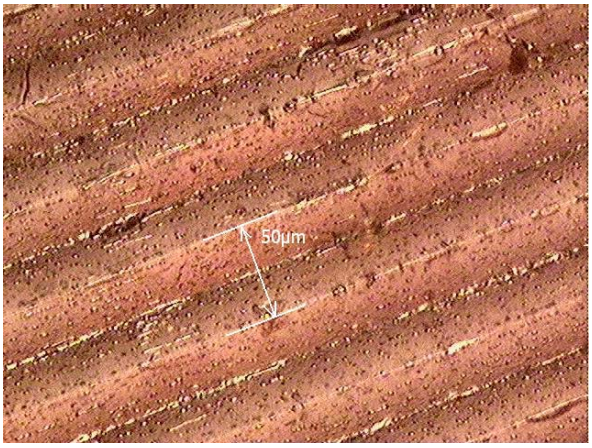

圖 51 經熱壓成形後產生在光學玻璃上 KRS-5 之微結構

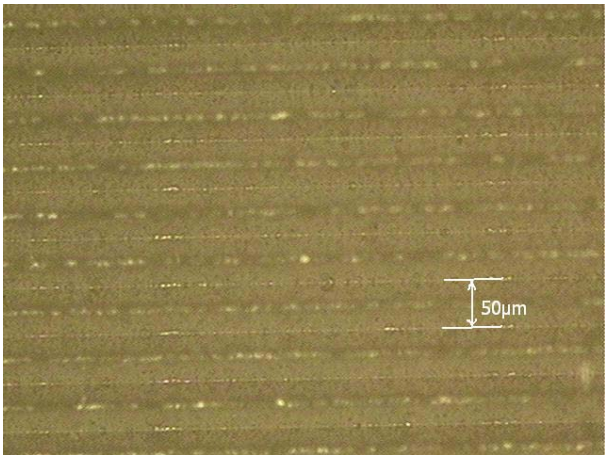

圖 52 經熱壓成形後產生在光學玻璃 S-FPL53 上之微結構

除 V 型結構轉印試驗之外，另利用了財團法人國家實驗研究院儀器科技研究中心提供之塑膠射出成型之 Stavax 模仁如圖 53，再由電鑄翻模之方式成型微結構模仁，電鑄材料為 Ni-Co 合金，微結構的設計尺寸如圖 54，為軸對稱的 Fresnel 透鏡設計。

圖 53 Stavax 模仁

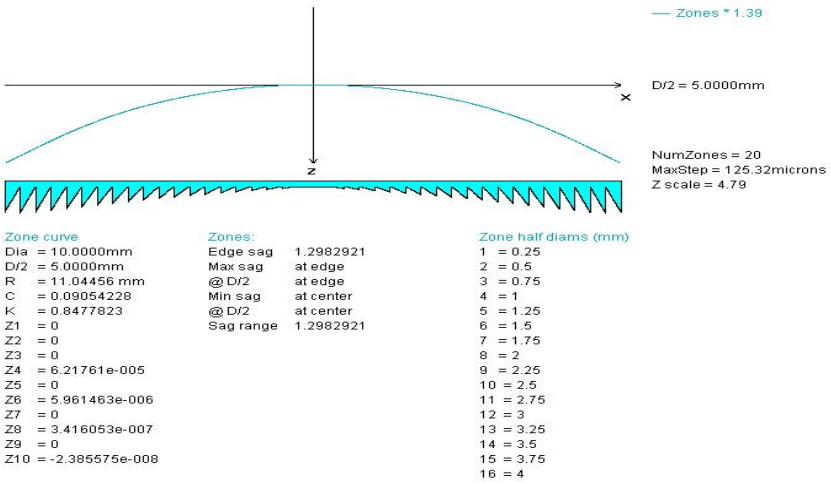

圖 54 Stavax 模仁之 Fresnel 設計規格

微熱壓實驗用玻璃為編號為 L-BAL42 的玻璃，玻璃轉移點溫度為 506℃。實驗相關參數如表 6。

表 6 玻璃微熱壓實驗參數

玻璃材料	L-BAL42	升溫時間	930sec
上模仁材質	UM	持溫時間	30min
下模仁材質	Ni-Co 合金	荷重(N)	1960
溫度設定（℃）	568	荷重速率 (N/min)	490
模造氣氛	真空	脫模溫度（℃）	568

實驗結果敘述如下：

圖 55、圖 56、圖 57 分別為實驗前 Ni-Co 模仁、實驗後 Ni-Co 模仁與玻璃熱壓成品，由圖中可看出 Ni-Co 模仁熱壓後有明顯表面劣化情形產生，熱壓期間模仁結構並無全部接觸到玻璃試片，圖 56 模仁中央較光亮部分為熱壓期間有接觸到玻璃試片部份，邊緣較暗淡部分為沒有接觸到玻璃試片部份，玻璃熱壓成品部分則在結構邊緣有破損碎裂之情形。

圖 55 實驗前 Ni-Co 模仁

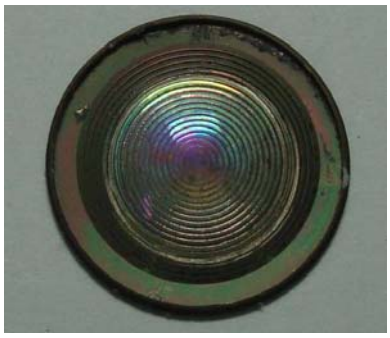

圖 56 實驗後 Ni-Co 模仁

圖 57 玻璃熱壓成品

配合光學顯微鏡與表面輪廓粗度儀之量測，光學顯微鏡拍攝如圖 58、圖 59、圖 60，可看出模仁 fresnel 結構在熱壓實驗後有變形與破損之情形，結構溝槽邊緣也比實驗前來得明顯不平整，在玻璃成品部分，fresnel 溝槽部分也如實驗後之 Ni-Co 模仁邊緣有凹凸不平之現象。

表面輪廓粗度儀量測如圖 61、圖 62、圖 63，Ni-Co 模仁熱壓實驗後中央有與玻璃試片接觸部份產生形變，結構向下凹陷之狀況，而玻璃成品部份可看出玻璃並無完全轉印模仁之結構，在形狀上與模仁並不完全相同。

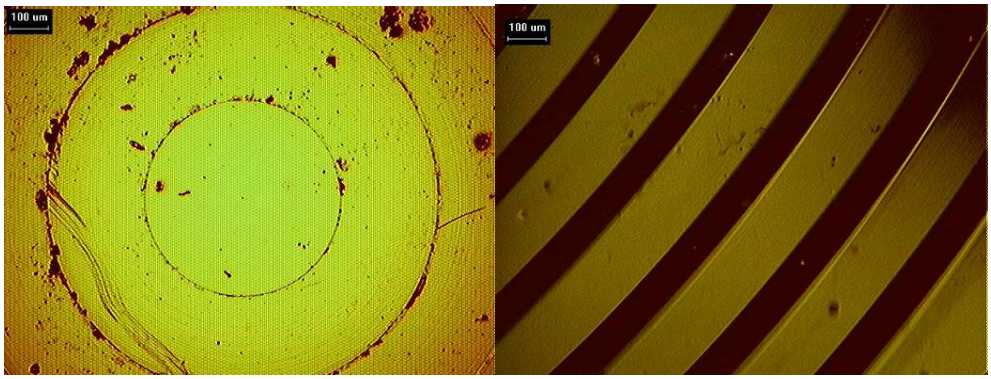

圖 58 Ni-Co 模仁實驗前,左圖為結構中央處，右圖為 fresnel 溝槽結構部份

圖 59 Ni-Co 模仁實驗後，左圖為結構中央處，中圖為模仁 fresnel 溝槽結構有接觸玻璃處，右圖為中圖為模仁 fresnel 溝槽結構無接觸玻璃處

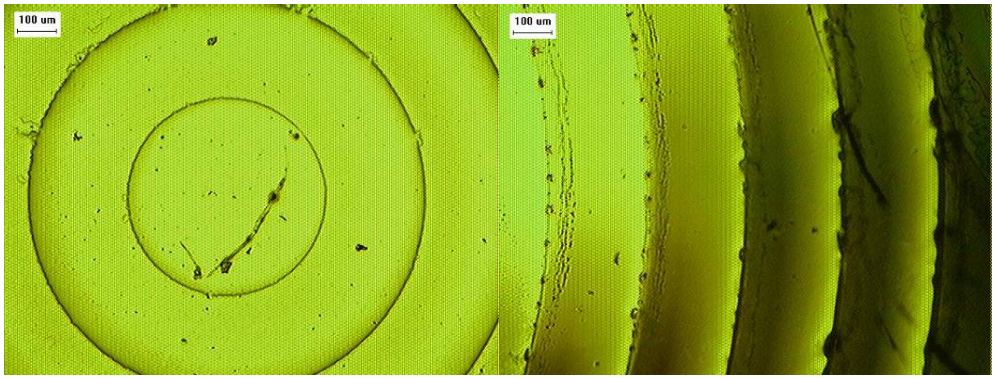

圖 60 玻璃熱壓成品，左圖為結構中央處，右圖為 fresnel 溝槽結構部分

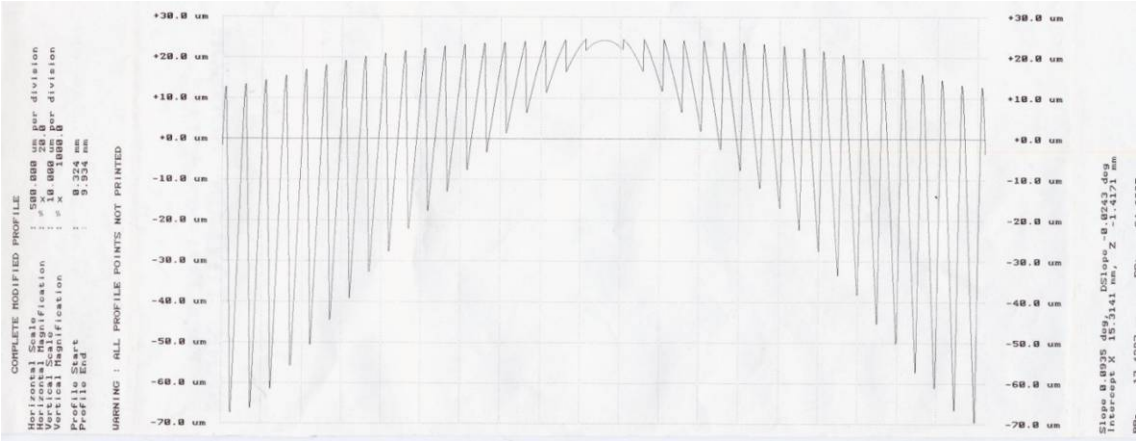

圖 61 實驗前 Ni-Co 模仁表面粗度輪廓儀量測

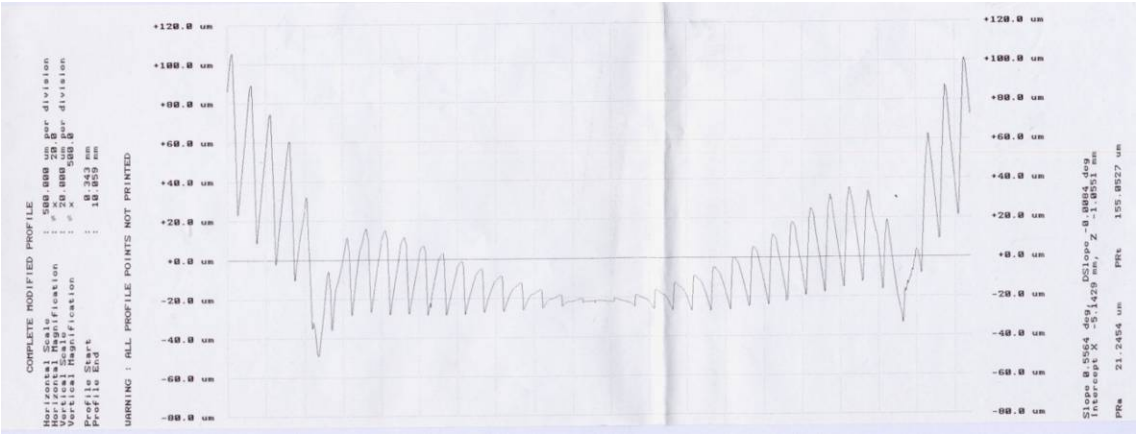

圖 62 實驗後 Ni-Co 模仁表面粗度輪廓儀量測

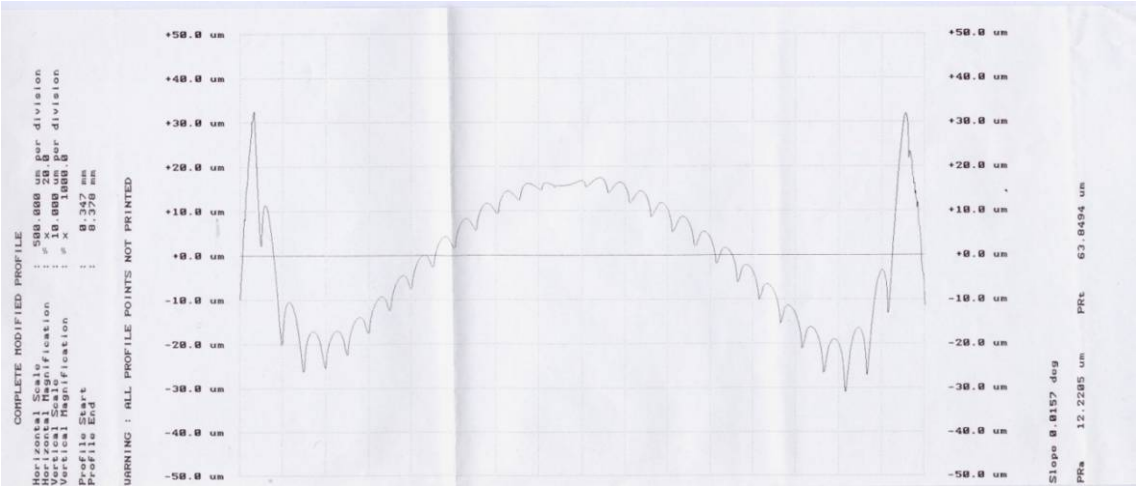

圖 63 玻璃熱壓成品表面粗度輪廓儀量測

再由表面粗度輪廓儀之結果放大觀察，如圖 64，由上而下三排圖為實驗前模仁、實驗後模仁與玻璃成品，其中最右之圖為結構中央處，圖依序向左為結構向外圈延伸之對照。可看出熱壓實驗後 Ni-Co 模仁有與玻璃接觸之結構高度有明顯下降，外圍沒有與玻璃接觸之高度無明顯之變化，在玻璃試片方面，轉印後結構之高度從中央至外圍，比起無論是實驗前或實驗後之 Ni-Co 模仁結構都來得小，並且尖端部分成圓弧形，與模仁尖端部分呈銳利形狀不同。

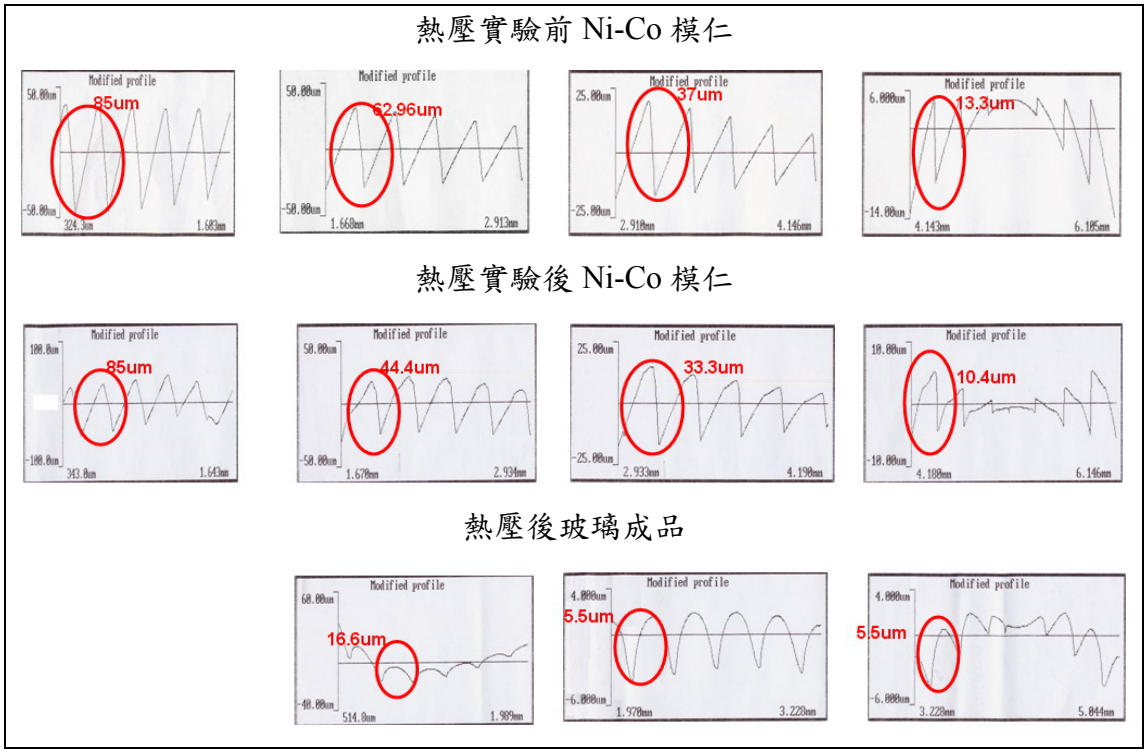

圖 64 表面粗度輪廓儀放大結果

經由實驗結果分析歸納出以下幾點：

(1)Ni-Co 模仁在熱壓實驗後表面有劣化情形產生，由本來光亮之表面在實驗後呈現黯淡情形。

(2)玻璃成品邊緣呈現破損缺片之情形，可能為加壓、脫模或冷卻時產生之情況，需改變實驗加壓、脫模或冷卻等參數來解決破損之情況。

(3)Ni-Co 模仁在熱壓實驗後結構幾何形狀發生明顯之形變，熱壓過程造成結構向下凹陷且邊緣溝槽呈現凹凸不平之情形，顯示 Ni-Co 合金模仁在 568℃溫度下做熱壓實驗，模仁會被玻璃試片擠壓產生不可恢復之變形，改善方法可在模仁表面鍍上耐熱硬膜層強化結構之強度，或者電鑄更厚之 Ni-Co 合金模仁加強其耐壓強度。

(4)玻璃轉印性方面，本實驗之實驗參數無法使玻璃在熱壓過程完全填充於模仁結構之間，使得玻璃成品結構填充性不足，未來需再改變實驗之如升溫溫度、持壓時間、荷重、荷重速率等參數來探討玻璃轉印性之情形。

6. 總結

本計畫經由此一系列的研究，可以歸納出以下幾個結論：

(1) 將有限元素分析應用在光學玻璃熱壓成形的基礎部分就是玻璃材料模型的掌握。研究裡對選用的材料進行了熱膨脹實驗以取得較完整的熱膨脹曲線、單軸壓縮試驗以確定玻璃在熱壓溫度下的變形行為以及應力鬆弛試驗以取得玻璃材料的黏彈性行為。由於玻璃製造商所能提供的資訊有限，所以當熱壓材料更換時，以上的試驗皆需再進行一次，如此才能用較準確的材料模型進行分析。

(2) 研究中建立了光學玻璃熱壓有限元素成形分析模型，並對其中的玻璃部分進行材料模型修正，得到了相當接近實驗值的分析結果。雖然修正模型的準確性在未來仍須以溫控更精確的熱壓設備進行實驗來確認，但以目前所建立的分析模型而言，現階段的架構是合理且可行的。

(3) 最佳化搭配有限元素分析對製程參數進行優化的可行性在研究中以模具補償最佳化分析系統的建立得到確認。但由於在進行完模具補償最佳化後，最終仍須進行實驗驗證最佳化結果優劣與否。這部分將可在未來對最佳化預補償後之模具外型實際製作模具，並以此模具進行成形製程，接著對成品以干涉儀檢測其表面品質與形狀精度，量測成品是否達到要求之形狀、尺寸精度與表面品質，將這

些資訊回歸到最佳化分析系統中進行修正，使系統更為完整。

(4) 由熱壓成型實驗可得出以下數點結論：在大氣氣氛下之實驗，TiN 硬膜層耐熱溫度低，高溫易氧化失效；無硬膜層的無鈷成分碳化鎢模仁對玻璃有沾黏的現象，壓印力越大、持壓時間越久越容易產生沾黏；貴金屬 Pt-Ir 硬膜雖在高溫下穩定性高，不易發生氧化現象，但是容易發生沾黏現象；CrN 硬膜層可耐溫度較高，在大氣氣氛實驗的工作溫度下不易氧化，但也會發生沾黏現象；含鈷成分之碳化鎢模仁若無鍍硬膜層時，在高溫下其表面會有析出或反應的現象。經由研究後期加熱設備的改善，模仁析出物與沾黏的問題已獲得解決。

(5) 由光學玻璃微結構熱壓成形製程可行性實驗可知，Ni-Co 模仁在熱壓實驗後表面有劣化情形產生，由本來光亮之表面在實驗後呈現黯淡情形；玻璃成品邊緣呈現破損缺片之情形；模仁在熱壓實驗後結構幾何形狀發生明顯之形變；熱壓過程造成結構向下凹陷且邊緣溝槽呈現凹凸不平之情形。顯示 Ni-Co 合金模仁在 568℃溫度下做熱壓實驗，模仁會被玻璃試片擠壓產生不可恢復之變形。在玻璃轉印性方面，由於本實驗參數下之無法使玻璃在熱壓過程完全填充於模仁結構之間，使得玻璃成品結構填充性不足，未來將以更硬、耐熱溫度更高之模仁進行微熱壓實驗，並將本研究建立的有限元素分析架構有效率地探討微結構熱壓參數對成型性、轉印性及尺寸精確度的影響。

7. 參考資料

[1] T. Matsuyama, Y. Shibazaki, Y. Ohmura, T. Suzuki, “High NA and low residual aberration projection lens for DUV scanner”, Optical Microlithography XV, Proc. of SPIE, 4691, pp.687-695, 2002.

[2] T.Matsuyama, Y. Ohmura, D. M. Williamson, “The Lithographic Lens: its history and evolution”, Optical Microlithography XIX, Proc. of SPIE, 6154, 2006.

[3] K. Shishido, M. Sugiura, and T. Shoji,“Aspect of glass softening by master mold”, Proceedings of SPIE, 2536, pp. 421-433, 1995.

[4] M. Heckele, “Hot embossing – The molding technique for plastic microstructures”, Microsystem Technologies, 4, pp.122–124, 1998.

[5] D. Zhong, G.G.W Mustoe, J.J. Moore, J. Disam, “Finite element analysis of a coating architecture for glass-molding dies”, Surface and Coatings Technology,

146-147, pp.312-317, 2001.

[6] Y. Saotome, “Microformability of optical glasses for precision molding”, Journal of Materials Processing Technology, 140, pp. 379-384, 2003.

[7] M. Hyre, “Numerical Modeling of glass forming and conditioning”, Journal of American Ceramic Society, 85, 1047-56, 2002

[8] A. Jain, A. Y. Yi, “Numerical Simulation of Compression Molding of Aspherical Glass Lenses”, AIP Conference Proceedings, 712, 239-244, 2004.

[9] A.Y. Yi and A. Jain “Compression molding of aspherical glass lenses-a combined experimental and numerical analysis” Journal of the American Ceramic Society, 88, pp. 579-586, 2005.

[10] 游智勝，*玻璃基材微流道之熱壓成形製程*，2002 奈米工程暨微系統技術研討會/國科會微機電系統成果發表會。

[11] 邱志宏，*玻璃鏡片壓製成形過程之傳熱分析*，國立清華大學動力機械工程研究所碩士論文，1995 年 6 月。

[12] 王興邦，*玻璃微熱壓之成形特性研究*，國立交通大學機械工程研究所碩士論文，2002 年 6 月。

[13] 黃建溢，*光學玻璃球面透鏡熱壓成形研究*，國立交通大學機械工程研究所碩士論文，2004 年 6 月。

[14] 王嘉偉，*光學玻璃透鏡之熱壓成形研究*，國立交通大學機械工程學系碩士論文，2006 年 6 月。

[15] OHARA Technical Information.

[16] H. Scholze, *Glass: Nature, Structure, and Properties*, Springer, 1991.

[17] SCHOTT Technical Information.

[18] MSC 2005, *MSC.Marc User’s Guide*, MSC Software.

[19] S. Rekhson, *Glass Science and Technology*, edited by D. R. Uhlmann and N. J. Kreidl, Academic Press Inc., pp.1-115, Florida, USA, 1986.

[20] Y. Taniguchi, “Mold for molding optical element”, US Patent 5855641, 1999.

[21] G. C. Firestone, A. Jain, and A. Y. Yi, “Precision laboratory apparatus for high temperature compression molding of glass lenses“, Review of Scientific Instruments, 76, 063101, 2005.

[22] A. Y. Yi, C. Huang, F. Klocke, C. Brecher, G. Pongs, M. Winterschladen, A. Demmer, S. Lange, T. Bergs, M. Merz, and F. Niehaus, “Development of a

ompression molding process for three-dimensional tailored free-form glass optics", Applied Optics, 45, pp.6511-6518, 2006.

[23] G. W. Scherer, *Relaxation in Glass and Composites*, Wiley, New York, pp.1–94, 1986.

[24] A. Jain, G. C. Firestone, and A. Y. Yi, "Viscosity Measurement by Cylindrical Compression for Numerical Modeling of Precision Lens Molding Process", Journal of the American Ceramic Society, 88, pp.2409–2414, 2005.

[25] M. Hyre, "Numerical Modeling of glass forming and conditioning", Journal of the American Ceramic Society, 85, 1047-1056, 2002.

[26] http://www.schott.com/optics_devices/german/download/tie-40_optical_glass_for_precision_molding.pdf

[27] N. Cristescu and I. Suliciu, *Viscoplasticity,* Martinus Nijhoff, 1982.

[28] G. A. A. Meden-Pielinger, J. H. P. Van de Heuvel, Precision pressed optical components made of glass and glass suitable modeling, US Patent 4391915, 1983.

8. 計畫成果自評

本計畫以為期三年之研究，從第一年材料物性及數學模型之驗證和製程模組之建立；到第二年則以所建模組進行光學玻璃透鏡實際製程之模擬，研究製程參數對成品之影響；最後於第三年對光學玻璃透鏡微熱壓成形之可行性進行探討，為後續微熱壓成形製程研究做準備。計畫中所預期之目標均已完成，整個研究所達成之成果敘述如下：

光學玻璃材料模型：

1. 藉由熱膨脹實驗取得正確之熱膨脹曲線。
2. 由單軸壓縮實驗取得玻璃在成形溫度下的光學玻璃彈-黏塑性行為。
3. 以應力鬆弛試驗瞭解玻璃在不同溫度下的光學玻璃黏彈性行為。

光學玻璃熱壓實驗：

1. 藉光學玻璃透鏡熱壓實驗對找出適合的模仁與玻璃材料組合。
2. 以熱壓實驗及模仁加熱實驗確認環境氣氛與熱壓溫度對沾黏狀況和析出物的影響。
3. 完成新一代加熱爐以改善環境氣氛，解決實驗時沾黏和析出物的影響。
4. 提供光學玻璃熱壓製程模擬參數之參考。

光學玻璃熱壓之有限元素分析：

1. 參考熱壓製程實驗參數，並將自行試驗之材料模型帶入模擬中，配合驗證實驗修正分析模型，建立起整個有限元素分析架構。
2. 以有限元素模擬搭配最佳化分析，針對業界現行之模具補償方式建構完成模具補償最佳化分析系統。

光學玻璃微熱壓成形：

1. 分別以 V 型結構及目前常見的 Fresnel 結構進行初步光學玻璃微熱壓成形實驗並確認其轉印性。
2. 提供後續玻璃微熱壓成形在材料與模仁搭配以及實驗參數組合之建議。

計畫裡經由上述一系列的研究逐步建立起光學玻璃熱壓製程的有限元素分析架構，後續將可導入現階段業界所採用的玻璃模造成形製程中，幫助解決目前所遇到的問題，在未來亦可應用到光學玻璃上壓印微結構的製程研究裡，提升光學元件之製造技術。

本研究目前已發表一篇國際期刊及一篇研討會論文，置於附錄最後。

國際期刊：

1. Yu-Chung Tsai, Chinghua Hung, Jung-Chung Hung, “Glass material model for the forming stage of the glass molding process”, Journal of Materials Processing Technology, Vol. 201, 2008, pp. 751-754.

研討會論文：

1. Tsung-Chun Wu, Yu-Chung Tsai and Chinghua Hung, Jung-Chung Hung, “Die shape optimization on molding processs of optical lens”, 中國機械工程學會第二十四屆學術研討會.

9. 附錄

9.1 模仁加工方式

模仁的加工方式，與傳統光學玻璃透鏡的研磨拋光製程相似，藉由濕式拉磨法製作出模仁在模造實驗中之壓印面。模仁製作的流程依序為放電加工、成形、研磨、拋光、定心等，各階段的目的與過程簡述如下：

(1) 放電加工（Electrical Discharge Machining，EDM）：由於碳化鎢為高硬度材質，無法用一般鑽孔的方式在模仁材料上鑽出小孔，因此在加工熱電偶欲放置的小孔時，便藉由放電加工的方法來達成，如圖 65 所示。

圖 65 模仁放電加工成品圖

(2) 成形（Curvature Generation，CG）：其目的在於對模仁表面加工出欲壓印之曲面，即一預定曲率之曲面；使用之機器為成形機，成形原理為利用杯狀鑽石砂輪對工件表面進行輪磨，如圖 66 所示，成形成品如圖 67 所示。

圖 66 成形機作業圖

圖 67 模仁成形成品

(3) 研磨（Lapping）：模仁成形完成後，在成形表面可清楚看見鑽石砂輪輪磨時所產生的刀痕，因此必須經由研磨的動作將刀痕除去，並使表面粗糙度降低，直到可以進行拋光的階段。過程中使用一相對曲率（曲率相同凹口相反）之

公模與模仁進行對磨，使用磨料為碳化矽磨砂，粒度由＃280、＃500、＃800、＃1200、＃2000、＃3000、＃6000 循序漸進，研磨過程中，如圖 68 所示，磨料粒度、擺動幅度、擺動與旋轉速度、偏心程度、接觸壓力等皆為影響因素，除了理論的根據外，經驗亦相當重要。

圖 68 模仁研磨作業圖

(4) 拋光（Polishing）：拋光的原理與研磨類似，目的在於使工件的表面粗糙度再次提升至鏡面程度，拋光模表面的料有絨布、羊毛氈、拋光皮（Polyurethane）和拋光瀝青等，通常要達到高精度的拋光面，最常使用的材料為拋光瀝青，而拋光液則因工件的硬度而有所不同，在此所使用的拋光液為水性鑽石漿，拋光完成之模仁如圖 69 所示。

圖 69 模仁拋光完成圖

(5) 定心：定心的動作在解決工件幾何中心軸與曲面（光學）中心軸不一致的問題，偏心可分為兩種誤差型式，一種是光軸與幾何中心軸平行，另一種則是光軸與幾何中心軸交叉，而實際上工件的偏心是這兩種誤差的綜合。除了使光軸與幾何中心軸對齊之外，經由定心的動作還可以成形出工件最後軸對稱的外形部分，本研究的模仁為一軸對稱外形，因此在經由定心的程序之後便完成模仁的加工製作，模仁成品如圖 70 所示。

圖 70 模仁加工成品圖

9.2 模具補償最佳化分析系統測試結果

為了對建構完成的最佳化分析系統進行測試，以曲率半徑分別為 10mm 與 15mm 之初始模具外型，對形狀分別為球面、拋物面以及雙曲面之目標玻璃外型，進行模具補償最佳化取得最佳的模具形狀。圖 71 表示目標為曲率半徑 10mm 之球面透鏡時，圖 72 比較模具的初始形狀，以及分別透過經驗補償與最佳化補償之結果；則比較玻璃未受補償之熱壓結果，透過經驗補償、最佳化補償後之結果，以及期望之理想形狀。圖 73 至圖 76 則是不同非球面目標形狀下，對於模具、玻璃進行與前述相同方式之比較。透過以上結果將誤差整理於表 7。

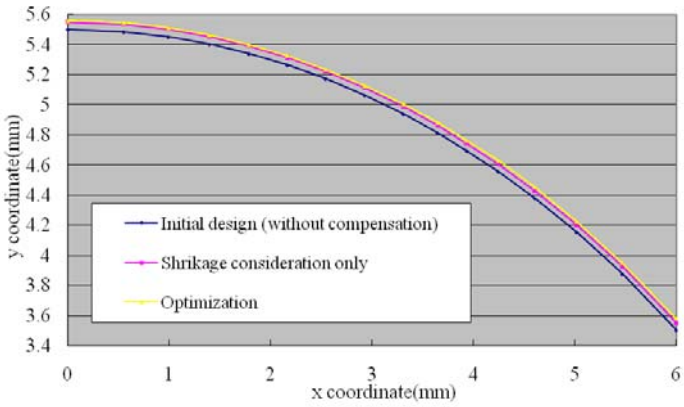

圖 71 模具外型 (R=10mm，球面)

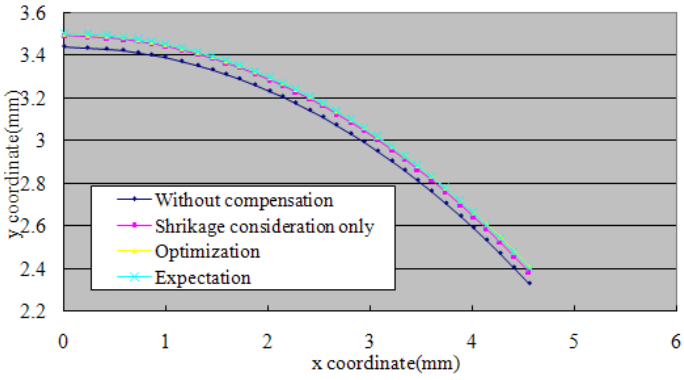

圖 72 玻璃外型(R=10mm，球面)

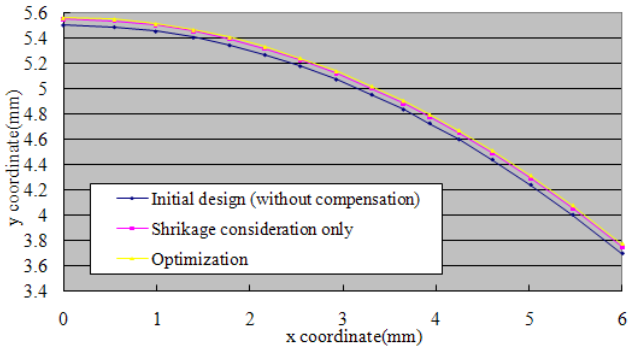

圖 73 模具外型(R=10mm，拋物面)

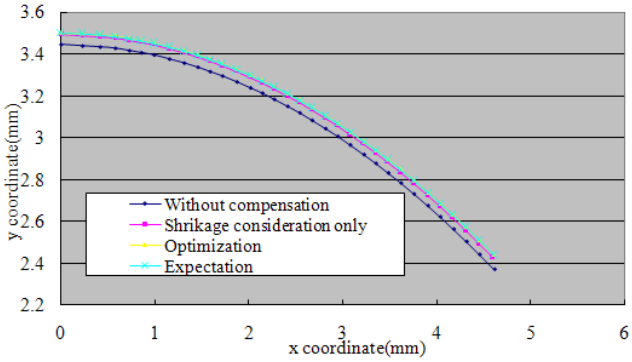

圖 74 玻璃外型(R=10mm，拋物面)

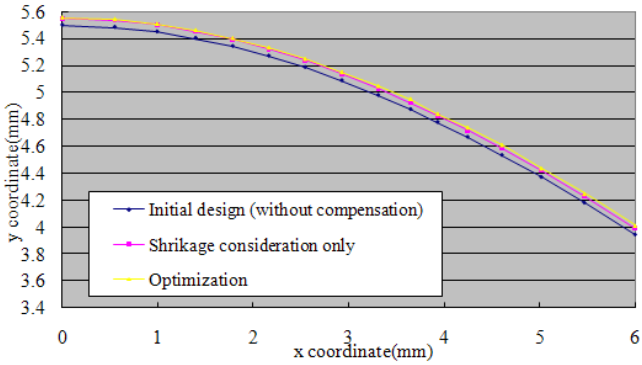

圖 75 模具外型(R=10mm，雙曲面)

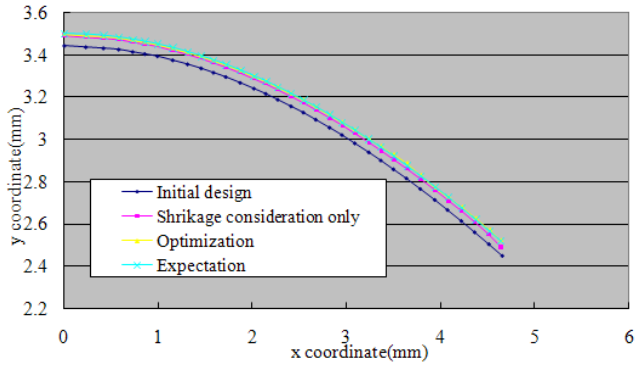

圖 76 玻璃外型(R=10mm，雙曲面)

表 7 誤差修正結果比較(R=10mm)

球面(k=0)		
	誤差(mm)	誤差消除(%)
未補償	0.06425	0.00
經驗補償	0.01479	76.98
模具補償最佳化系統	0.00214	96.67
拋物面(k=-1)		
	誤差(mm)	誤差消除(%)
未補償	0.06194	0.00
經驗補償	0.01217	80.35
模具補償最佳化系統	0.00108	98.26
雙曲面(k=-3)		
	誤差(mm)	誤差消除(%)
未補償	0.06144	0.00
經驗補償	0.01522	75.23
模具補償最佳化系統	0.00332	94.60

表示目標曲率半徑為 10mm 時，球面與不同非球面形狀下補償後之誤差與誤差修正值。透過經驗補償誤差消除約為 75.23%~80.35%，而透過模具補償最佳化系統，誤差的消除可達 94.60%~98.26%。

圖 77 至圖 82 表示目標曲率半徑 15mm，球面與不同非球面形狀下，對模具與玻璃進行前述相同之比較結果。計算以上結果將誤差整理於表 8。

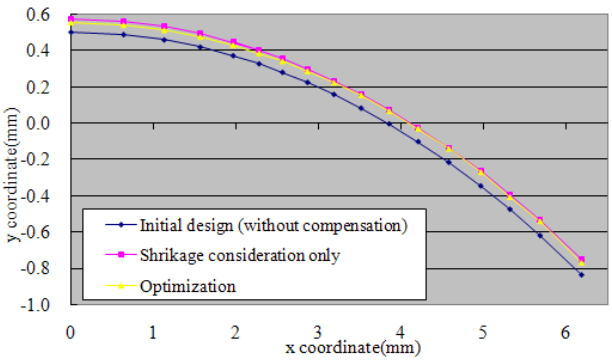

圖 77 模具外型(R=15mm，球面)

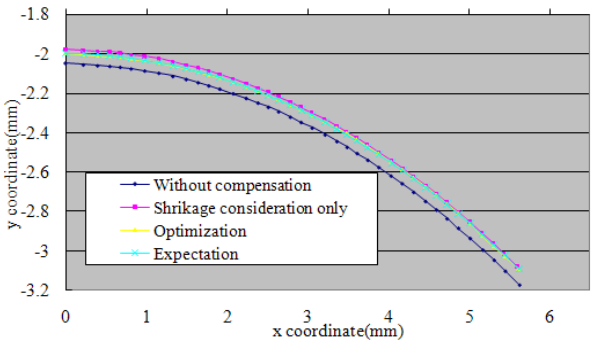

圖 78 玻璃外型(R=15mm，球面)

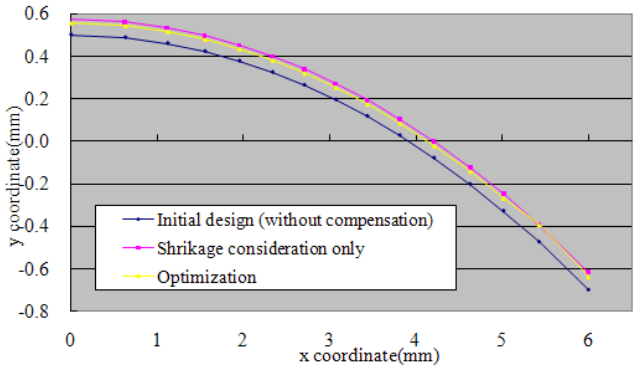

圖 79 模具外型(R=15mm，拋物面)

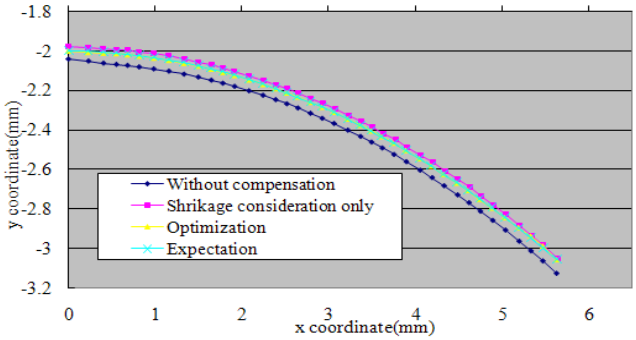

圖 80 玻璃外型(R=15mm，拋物面)

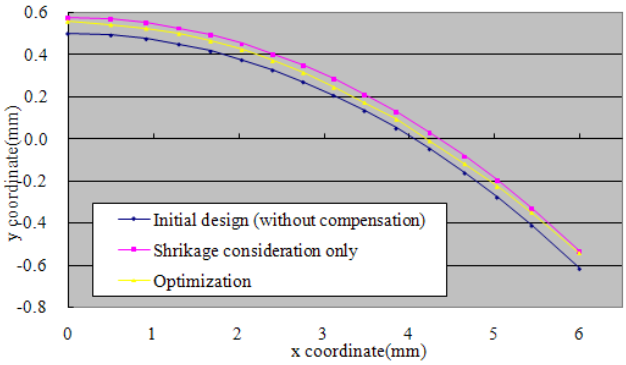

圖 81 模具外型(R=15mm，雙曲面)

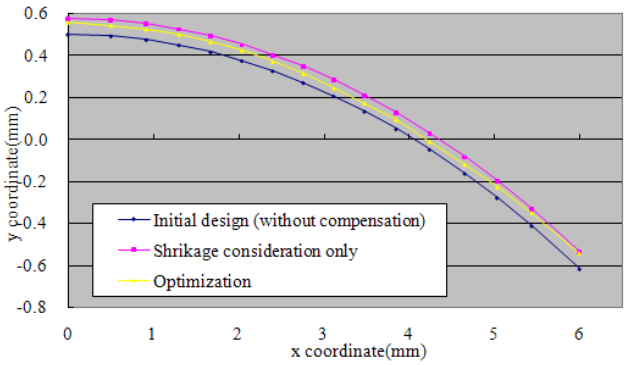

圖 82 玻璃外型(R=15mm，雙曲面)

表 8 誤差修正結果比較(R=15mm)

球面(k=0)		
	誤差(mm)	誤差消除(%)
未補償	0.06542	0.00
經驗補償	0.01335	79.59
模具補償最佳化系統	0.00343	94.76
拋物面(k=-1)		
	誤差(mm)	誤差消除(%)
未補償	0.06461	0.00
經驗補償	0.01976	69.46
模具補償最佳化系統	0.00244	96.27
雙曲面(k=-3)		
	誤差(mm)	誤差消除(%)
未補償	0.04910	0.00
經驗補償	0.01289	73.74
模具補償最佳化系統	0.00185	96.22

表示在目標曲率半徑為 15mm 之情況下，透過經驗補償誤差消除約為 69.46%~79.59%，而透過模具補償最佳化系統，誤差的消除可達 94.76%~96.27%。

JOURNAL OF MATERIALS PROCESSING TECHNOLOGY 201 (2008) 751–754

journal homepage: www.elsevier.com/locate/jmatprotec

Glass material model for the forming stage of the glass molding process

Yu-Chung Tsai[a], Chinghua Hung[a,*], Jung-Chung Hung[b]

[a] Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30010, Taiwan, ROC

[b] Department of Mechanical Engineering, National Chin-Yi Institute of Technology, 35 Lane 215, Section 1, Chung-Shan Road, Taiping City, Taichung, Taiwan, ROC

ARTICLE INFO

Keywords:
Glass molding process
Elasto-viscoplastic
FE

ABSTRACT

The aim of this research is to obtain an accurate material model for glass that can be used in finite element (FE) analysis of the glass molding process. A thorough understanding of the deformation behavior of the glass specimens was acquired by performing uniaxial compression tests. The elasto-viscoplastic model was utilized for the glass material at the molding temperature to construct the FE model, and a suitable set of parameters for this material model was verified by comparing the simulation results to the experimental data. As a result, the feasibility of the elasto-viscoplastic model for glass at the molding temperature was confirmed; this material model can be used in FE analysis of the prediction and modification of properties of the final lens products.

© 2008 Published by Elsevier B.V.

1. Introduction

In recent years, glass molding technology has been widely used to produce the small scale optical lenses used in 3C products. A feature of this technology is that glasses are heated to a temperature above the glass transition temperature (Tg) or even the yield point (At) and are formed by replication from the same mold in high numbers (Meden-Pielinger, 1983; Taniguchi, 1999; Firestone et al., 2005; Yi et al., 2006). The ability to produce large numbers of replicas and the imprint characteristic make this glass molding technology an ideal choice, more preferable to the conventional glass grinding/polishing technology used to make aspherical lenses.

There are three stages of the glass molding process: heating, molding and annealing. During the heating stage, both molds and glass are heated to the molding temperature, and a fixed displacement is then applied in order to proceed with open/closed die forming in the forming stage. In the subsequent annealing stage, the molds are held in the final position of the forming stage and cooled along with the glass until the mold-releasing temperature is reached; the glass is then separated from the molds.

Glass is a temperature-sensitive material, and both the forming and annealing stages, in which the glass undergoes high temperature variation, will greatly affect the precise shape and dimensions of glass lenses. Consequently, defects in the optical properties of glass lenses will be affected by the deviations in shape and dimension. In addition, the lifetime of the molds used in the forming stage is another critical problem that is encountered in mass production. Therefore, this study focuses on the forming stage of the glass molding process.

It is known that low temperature processes help to lengthen the operating lifetime of the mold material (SCHOTT, in press). In the molding stage, the higher the molding tem-

* *Corresponding author*. Tel.: +886 3 5712121x5516; fax: +886 3 5720634.
E-mail addresses: Victor@twntsai.com (Y.-C. Tsai), chhung.mail@nctu.edu.tw (C. Hung).
0924-0136/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.jmatprotec.2007.11.294

perature, the lower the pressure, and vice versa. The molding temperature currently used by the industry is between 30 °C and 40 °C above At, i.e., the molding temperature is high, and the operating lifetime of the molds is shortened. If the molding temperature is lowered, the pressure increases, which also shortens the operating lifetime of the molds. In order to retain a good operating lifetime for the molds, a compromise between temperature and pressure was made in this study, with the molding temperature set to 30–50 °C above Tg. Uniaxial compression tests were performed at this molding temperature and the stress–strain relationships were observed in the first part of this study. A finite element (FE) model of the uniaxial compression tests was then constructed; analyses were performed and the simulation results were compared to the experimental data. Attempts were made to find an accurate material model for the FE analysis. After the feasibility of the material model was verified, it could then be introduced into the FE analysis of the glass molding process.

2. Material model

Several studies have regarded glass as a viscoelastic material and have focused on its stress relaxation behavior (Scherer, 1986; Rekhson, 1986; Gy et al., 1994; Duffre'ne et al., 1997; Duffre'ne and Gy, 1997). Jain et al. (2005) not only focused on the measurement of the viscosity of glass at the molding temperature but also utilized FE analysis for the glass molding process; this study regarded glass as a viscoelastic material (Jain and Yi, 2005; Jain et al., 2006). When discussing the bottle formation of glass at a high temperature, glass is regarded as behaving as a Newtonian fluid, where the viscosity is temperature-dependent, and the material model is rigid-viscoplastic (Hyre, 2002; MSC, 2005). Yi and Jain (2005) also attempted to utilize the rigid-viscoplastic model in FE analysis of the glass molding process.

In order to fully understand the material behavior of glass in the forming stage, and to develop an accurate material model which not only can be used in FE analysis of the glass molding process, but also in the microstructure imprinting procedure, the elastic properties of glass should be considered. In this research, the elasto-viscoplastic model (Cristescu and Suliciu, 1982) was introduced to investigate the deformed behavior of glass in the molding stage. This model is described by

$$\begin{cases} \sigma = E\varepsilon, & \text{if } \sigma < \sigma_Y \\ \sigma = 3\eta(T)\dot{\varepsilon}, & \text{if } \sigma \geq \sigma_Y \end{cases} \tag{1}$$

where σ is the stress, $\eta(T)$ the temperature (T) dependent viscosity, and $\dot{\varepsilon}$ is the strain rate. This function shows that the material behaves as a linear elastic material before the flow stress (σ_Y) is reached, and as a strain rate-dependent viscoplastic material after the flow stress is reached. Although the viscosity varies with temperature, it will be regarded as constant during this analysis because the temperature is fixed in the molding stage.

3. Experiments

In order to find a material property of the glass that can be used in FE analysis of the glass molding process, uniaxial compression tests on the glass material S-FPL52 (with Tg equal to 445 °C), fabricated by the OHARA company, were performed at the chosen molding temperature (475 °C). The strain rate was held at 0.00667 s^{-1}, and the experiments were conducted without lubricant. Cylindrical specimens of 10 mm in diameter and 6 mm in height were used. The FE model of the uniaxial compression test at the molding temperature was then built using a commercial FE program, MSC.MARC, as shown in Fig. 1. Both the upper and lower molds were set as rigid bodies, and the glass specimen was set as an elasto-viscoplastic material. The parameters of the material model were adjusted using the trial and error method to achieve the best-fitting simulation results in comparison with the experimental data.

The friction model, used to model the interfacial friction conditions between the glass and molds, is described by

$$\tau = mk_m \tag{2}$$

where τ is the frictional stress of the interface, m the shear factor ($0 < m < 1$), and k_m is the shear yield stress of the glass near the interface. A shear friction factor of 1.0 was used, which assumes complete sticking between the glass and molds (Yi and Jain, 2005).

4. Results and discussion

The comparison results of the experiment and simulation are shown in Figs. 2 and 3. A set of parameters for the material model was obtained from these trial and error attempts such that Young's modulus was equal to 1300 MPa and viscosity was equal to 10^{10} P (1000 MPa s). The simulation results fitted with the experimental data quite well, and show that this set of parameters is feasible under the condition of a strain rate of 0.00667 s^{-1}.

To verify whether or not the elasto-viscoplastic model consisting of this set of parameters is feasible for FE analysis under different strain rates, further comparisons between simulation results and experimental data were made. Uniaxial compression tests with strain rates of 0.00833 s^{-1} and

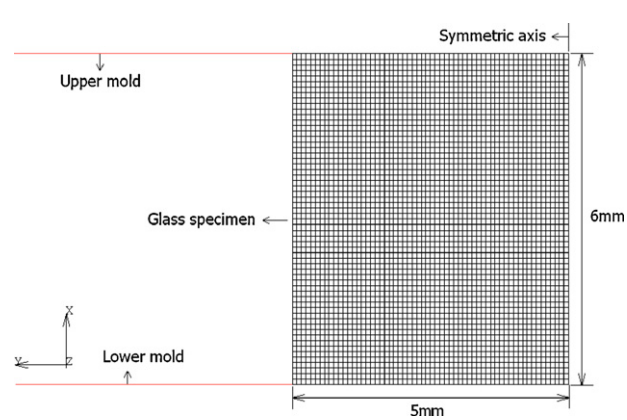

Fig. 1 – 2D axisymmetric model of a glass specimen.

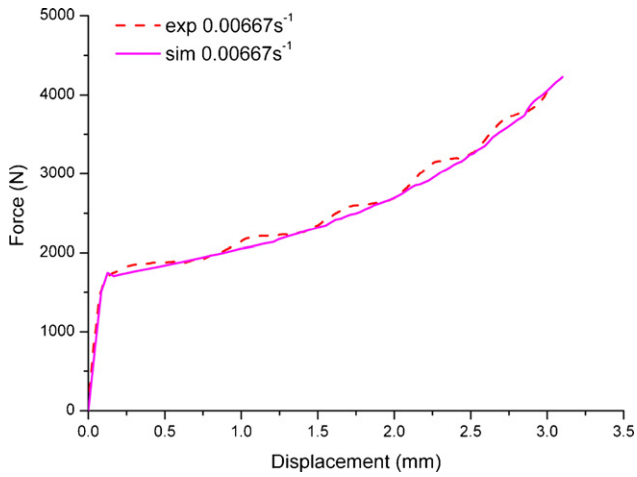

Fig. 2 – Comparison of force–displacement curves between experimental and simulation results at a strain rate of 0.00667 s^{-1}.

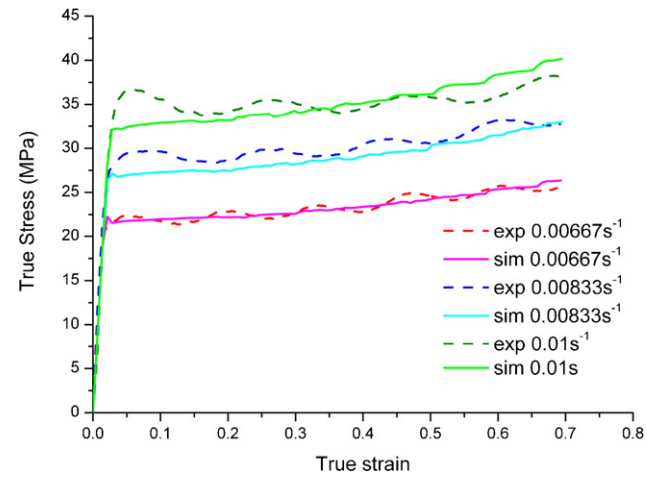

Fig. 4 – Comparison of force–displacement curves between experimental and simulation results at strain rates of 0.00667 s^{-1}, 0.00833 s^{-1} and 0.01 s^{-1}.

0.01 s^{-1} were performed, and the flow stresses under each strain rate were found to be 24.9 MPa and 30 MPa, respectively. Comparisons of the simulation results and experimental data are shown in Figs. 4 and 5, from which it can be seen that the simulation results using the previously obtained material parameters fitted to the experimental data quite well. Therefore, the elasto-viscoplastic model is feasible for describing the deformation behavior of the glass in the molding stage with different strain rates.

The final shape of the glass specimen after compression is shown in Fig. 6 and the simulation result is shown in Fig. 7. Due to the limitations of the apparatus, some parallel deviations exist between the upper and the lower molds, which may cause the nonuniform deformation of the glass specimen; temperature control of the environment and both molds also have some discrepancies. For glass material, a small difference in temperature or pressure could change the final shape of the product. It can be seen from these two figures that

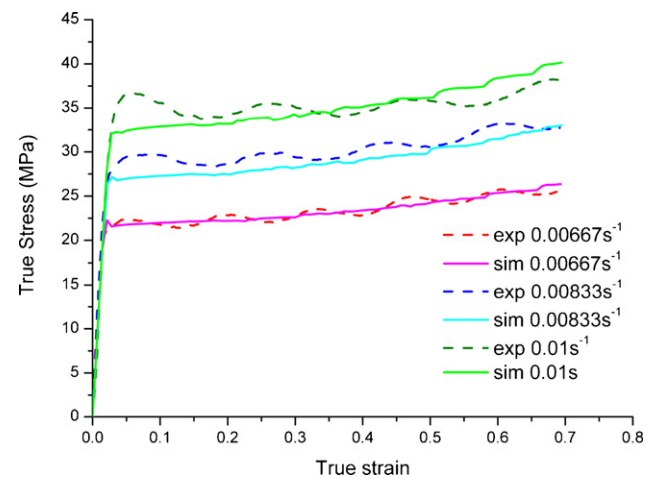

Fig. 5 – Comparison of stress–strain curves between experimental and simulation results at strain rates of 0.00667 s^{-1}, 0.00833 s^{-1} and 0.01 s^{-1}.

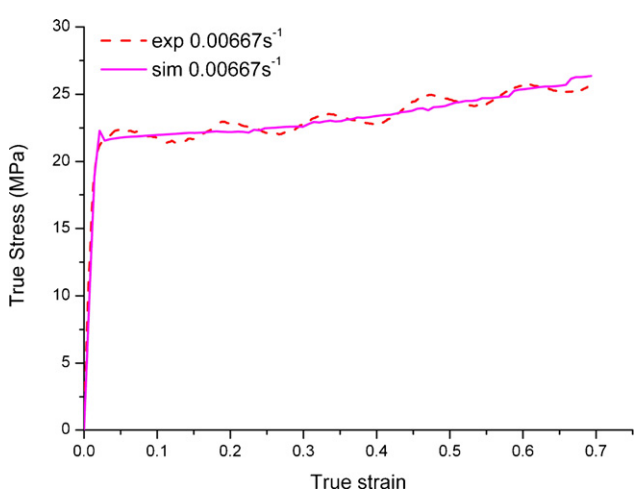

Fig. 3 – Comparison of stress–strain curves between experimental and simulation results at a strain rate of 0.00667 s^{-1}.

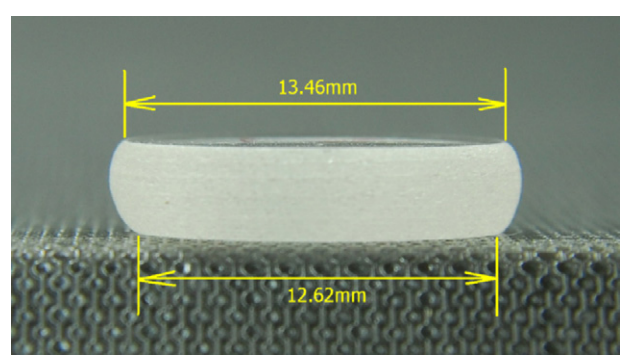

Fig. 6 – Final shape of the glass specimen.

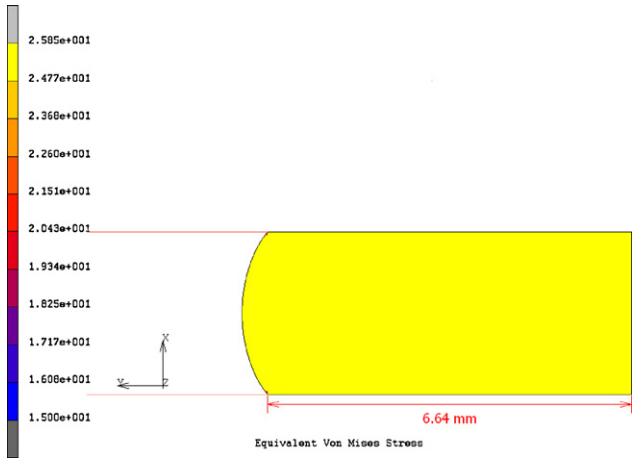

Fig. 7 – Simulation results of the final shape of the glass specimen.

the glass ends were not deformed as evenly as was shown in the simulation results. Nevertheless, this study can still provide a reference for a material model that can be used in FE analysis of glass molding. More precise investigations will be performed when the precision of the apparatus is improved.

5. Conclusion

Research on the deformation behavior of glass at a specific molding temperature (30 °C above Tg) was performed in this work, and the feasibility of the elasto-viscoplastic model for glass material in the molding stage was verified by comparing the simulation results to the experimental data. Some conclusions from this work can be made as follows:

(1) The elasto-viscoplastic model can be introduced into FE analysis of the glass molding process during the molding stage.
(2) The investigations performed in this work are within the molding stage. However, annealing is also a key stage in the glass molding process and will also affect the precision of the final product shape. In order to perform FE analysis more precisely, and to reduce the residual stress of the products to improve the optical properties, the stress relaxation characteristic of the viscoelastic property of the glass material should be considered in the annealing stage. Also, thermal properties in the annealing stage such as heat conduction between the molds and glass, convection between the environment and the glass and molds, and change in the thermal expansion coefficient should be considered thoroughly.
(3) Molds were assumed to be rigid bodies in this work, but in the glass molding process, elastic recovery of the molds will affect the prediction of the final product shape. Therefore, consideration of the elastic property of the molds should be included in the FE analysis in order to pre-compensate for the molds in advance and to predict the final shape of the glass lens more precisely.

Acknowledgements

The authors would like to thank the National Science Council of Taiwan, ROC for the grant NSC 95-2221-E-009-176, under which the investigation was undertaken. The authors would also like to thank the National Center for High-Performance Computing for its facility support.

REFERENCES

Cristescu, N., Suliciu, I., 1982. Viscoplasticity. Martinus Nijhoff.
Duffre'ne, L., Gy, R., 1997. Viscoelastic constants of a soda-lime-silica glass. J. Non-Cryst. Solids 211, 30–38.
Duffre'ne, L., Gy, R., Burlet, H., Piques, R., 1997. Viscoelastic behavior of a soda-lime-silica glass: inadequacy of the KWW function. J. Non-Cryst. Solids 215, 208–217.
Firestone, G.C., Jain, A., Yi, A.Y., 2005. Precision laboratory apparatus for high temperature compression molding of glass lenses. Rev. Sci. Instrum. 76.
Gy, R., Duffre'ne, L., Labrot, M., 1994. New insights into the viscoelasticity of glass. J. Non-Cryst. Solids 175, 103–117.
Hyre, M., 2002. Numerical modeling of glass forming and conditioning. J. Am. Ceram. Soc. 85, 1047–1056.
Jain, A., Yi, A.Y., 2005. Numerical modeling of viscoelastic stress relaxation during glass lens forming process. J. Am. Ceram. Soc. 88, 530–535.
Jain, A., Firestone, G.C., Yi, A.Y., 2005. Viscosity measurement by cylindrical compression for numerical modeling of precision lens molding process. J. Am. Ceram. Soc. 88, 2409–2414.
Jain, A., Yi, A.Y., Xie, X., Sooryakumar, R., 2006. Finite element modeling of stress relaxation in glass lens moulding using measured temperature-dependent elastic modulus and viscosity data of glass. Model. Simul. Mater. Sci. Eng. 14, 465–477.
Meden-Pielinger, G.A.A., Van de Heuvel, J.H.P., 1983. Precision pressed optical components made of glass and glass suitable modeling, US Patent 4,391,915.
MSC, 2005. MSC. Marc User's Guide. MSC Software.
Rekhson, S., 1986. In: Uhlmann, D.R., Kreidl, N.J. (Eds.), Glass Science and Technology. Academic Press Inc., Florida, USA.
Scherer, G.W., 1986. Relaxation in Glass and Composites. Wiley, New York.
SCHOTT Technical Information, Optical glass for precision molding, SCHOTT, in press.
Y. Taniguchi, 1999. Mold for molding optical element, US Patent 5,855,641.
Yi, A.Y., Jain, A., 2005. Compression molding of aspherical glass lenses–a combined experimental and numerical analysis. J. Am. Ceram. Soc. 88, 579–586.
Yi, A.Y., Huang, C., Klocke, F., Brecher, C., Pongs, G., Winterschladen, M., Demmer, A., Lange, S., Bergs, T., Merz, M., Niehaus, F., 2006. Development of a compression molding process for three-dimensional tailored free-form glass optics. Appl. Optics 45, 6511–6518.

Die Shape Optimization on Molding Process of Optical Glass Lens

Tsung-Chun Wu, Yu-Chung Tsai, Chinghua Hung

Department of Mechanical Engineering, National Chiao Tung University
NSC Project No.: NSC-95-2221-E-009-176

Abstract

Demand of optical glass lens is progressively increasing with the development of optical and electrical products. As far as the optical glass material is concerned, lens molding technique, compared with the conventional glass lens grinding and polishing process, has lots of advantages, like much simplified manufacture process and dramatically reduction of cost and waste. However, there still exist several difficulties needed to be overcome, such as the shape deviations of the final lens products that may influence the qualities of optical image. This paper utilized FEA on the glass lens molding process and constructed a die shape optimization design system in order to compensate the shape deviations of the lens products so that the errors can be reduced efficiently. Once the deviations of the lens products have been minimized, the aim of mass production for lens molding of optical glass can be accomplished.

Keywords：glass molding, optimization, FEA.

1. Introduction

The fabrication processes of optical lenses comprise casting, hot embossing forming, injection molding, grind-polishing and so on. But as far as optical glass material is concerned, grind-polishing and glass molding are the only two ways to manufacture optical glass lenses for the time being.

Compared with the grind-polishing fabrication process of optical glass lens, glass molding serves as a more economical one. Glass molding is also called hot embossing forming of optical glass lens since the quality of the die surface can be translated onto the lens surface. There are several merits of glass molding, like easiness for mass production, cost reduction of labor and time, and simplified steps of process. Fabrication process of glass lens molding can be generalized to three stages:

(1) Heating: After the dies and glass gob were put into the hot forming working machine, both the top and bottom dies and the glass gob were then heated to the desired temperature (the forming temperature) which is slightly higher than the transition temperature (Tg) of the used optical glass material.

(2) Forming: The top die moved downward with a constant velocity in order to press the glass gob to the designed curvature while the glass material became soft.

(3) Cooling: Afterwards, the dies and the glass lens were cooled to a preset temperature (below the Tg) and at the same time the top die was released. In the end, the dies as well as the glass lens were cooled to the room temperature and the glass lens became a finished product.

It can be seen from several international publications that feasibility of the glass molding process is beyond all doubt [1]-[4].

Glass is a temperature-sensitive material, and the whole molding process, in which the glass undergoes high temperature variation, will greatly affect the precise shape and dimensions of glass lenses. Consequently, defects in the optical properties of glass lenses will be affected by the deviations in shape and dimension. Therefore, the aim of this research is to construct a die shape optimization system in order to compensate the geometrical deviations to the original designed curvature for the final lens products.

2. Research method

At first, commercial FEA software, MARC was utilized to perform thermo-mechanically coupled analysis on the lens molding process of optical lens. According to the results of FEA, a die shape optimization was conducted subsequently by a linking program between MARC and the optimization module in IMSL Fortran library. The die shape optimization procedure is shown in Figure 1.

3. Finite Element Analysis (FEA)

The detailed settings of finite element analysis are described as follows:

3.1 Process of Glass Lens Molding

The glass lens molding process in the work can be seen in Figure 2. In the heating stage, the dies and the glass gob were heated to the temperature about 475℃, which was 30℃ higher than the transition temperature (445℃) of glass S-FPL52, fabricated by OHARA Corporation. In forming stage, while the dies and the glass were hold at the constant temperature 475℃, the top die moved downward with a constant velocity of 0.0483 mm/s. Then, in the final cooling stage, both the dies and the glass were cooled to around 200℃, the top die moves back to its original position and eventually they were cooled together to room temperature.

3.2 Geometrical Model

Because the external appearances of dies and glass gob were symmetric with the central axis, the molding processes were therefore treated as an axisymmetric problem. A glass gob with plan-convex geometry with radius in 7 mm on the top end was formed into a lens with radius in 15 mm. Four-node axisymmetric, thermo-mechanical coupled, quadrilateral elements were used to model the glass and both dies.

3.3 Material Properties

Because the flow stress of the glass material varies with strain rate during the forming stages at high temperature. Material properties modeling of glasses are typically regarded as viscoplastic by many researches [5]. Considering the requirement of the geometrical accuracy of the optical lens products, the elastic deformation behavior of the glass lens during the cooling cycle should be taken into account. Therefore, elasto-viscoplastic is used to model the glass material in this paper.

The description of the elasto-viscoplastic material model is shown below:

$$\begin{cases} \sigma = \mathrm{E(T)}\varepsilon \ , & \text{if } \sigma < \sigma_{\mathrm{Y}} \\ \sigma = 3\eta(\mathrm{T})\dot{\varepsilon} \ , & \text{if } \sigma \geq \sigma_{\mathrm{Y}} \end{cases} \quad (1)$$

, where E is the temperature-dependent Young's modulus, σ is the stress, $\eta(\mathrm{T})$ is the temperature (T) dependent viscosity, and $\dot{\varepsilon}$ is the strain rate. This function shows that the material behaves as a linear elastic material before the flow stress (σ_{Y}) is reached, and as a strain rate-dependent viscoplastic material after the flow stress is reached.

Flow stress (σ_{Y}) had been calculated through the parametric material model in accordance with the compression experiments conducted in our laboratory (shown in Figure 3). While the forming temperature is set to 475℃ and the specified strain rate is 0.0083 (1/s), the viscosity and the flow stress of the glass material used are 1000MPa·s and 24.9MPa respectively.

In addition, the Young's modulus of glass material is temperature-dependent during the heating and cooling stages [6][7] and can be expressed by the following empirical equation [6],

$$\mathrm{E_t = E_0 - At - Bt^2} \quad (2)$$

, where E_t is the Young's modulus at temperature t and E_0 is the Young's modulus at room temperature. A and B are the constants depending on the particular glass. Based on the experiments done in our laboratory, Young's modulus of the glass material S-FPL52 used in this simulation had been measured, which is 1300MPa at forming temperature 475℃. And the Young's modulus of the glass material at room temperature is 71700MPa, provided by OHARA Corporation [8]. With equation (2) the constant coefficients *A* and *B* are found to be -8.234 and 0.3294 respectively. The relationship between the Young's modulus and temperature of the glass material, S-FPL52, can be plotted in Figure 4.

Other detailed mechanical and thermal material properties of the dies and glass used in this analysis are listed in Table 1.

3.4 Boundary Conditions

Figure 5 shows the two-dimensional axisymmetric model of lens molding process with the displacement and thermal boundary condition applied to it. The lowest part of the bottom die is fixed in axial direction and the movement of top die is given a displacement boundary condition of 2.5mm downward. For this simulation, it is assumed that conduction and convection are the primary modes of heat transfer mechanism in thermal-mechanical coupled analysis. A convective heat transfer coefficient of 200 $\mathrm{W\cdot(m\cdot℃)^{-1}}$ and a constant value of the interface heat transfer coefficient of 2800 $\mathrm{W\cdot(m\cdot℃)^{-1}}$ are used to simulate the heat exchange at the contact surfaces between the glass and dies [9].

The friction model, used to model the interfacial friction conditions between the glass and dies, is described by

$$\tau = \mathrm{mk_m} \quad (2)$$

where τ is the shear stress of the interface, m is the shear factor (0<m<1), and k_m is the shear yield stress of the glass near the interface. A shear friction factor of 1.0 was used, which assumes complete sticking between glass and dies [5].

4. Die Shape Optimization

In glass lens molding process, there exist several factors which cause the geometrical errors of the final products. In order to overcome such problems, a die shape optimization process with FEA was conducted to compensate these deviations.

4.1 The Optimization Implement

The optimization algorithm adopted in this research is the Sequential Quadratic Programming (SQP) method. SQP method is often selected as a single objective optimizer with continuous variables for accuracy, reliability and efficiency [10].

The implement selected to perform the optimization is the optimization module form IMSL Fortran library. "NNLPF" subroutine is selected to perform the optimization because this subroutine is coded on the basis of the SQP method. The users need to define the design variables, the objective function and the constraints in the optimization system. Instead of giving their gradient functions, the gradient functions of the objective and constraints are calculated automatically by program during the numerical process.

4.2 Formulation of Optimization System

4.2.1 Design Variables

For the die shape optimization, the designed geometry of the die shape is treated as the design

variable. In finite element analysis, the positions of the die nodes, which might contact the glass, are therefore served as the design variables in the die shape optimization. The node coordinates of the die shape can be presented by the following equation

$$y = \frac{x^2}{R + \sqrt{R^2 - (1+k)x^2}} + A_4 x^4 + \cdots \quad (4)$$

Equation (4) is the general formulation of the aspherical curve, where R is the radius of the curve and k is the conic parameter that stands for the variation of the conic section. While k is equal to 0, it is a spherical curve. When k is smaller than 0 but greater than -1, it is an elliptic curve. k = -1 and k < -1 are parabolic and hyperbolic curves respectively. A_4 and others are the high-order modified coefficients of the aspheric curve.

As for a local minimum problem, the initial guess of the design variable is important for looking for the optimal solution of the objective function. Therefore, the initial guess of the design variable in this optimization was regarded as the values considering the shrinkage ratio because the size error of the design with the shrinkage consideration only is less than that without any compensation. Shrinkage consideration means that if we want to get a lens product with radius in 15 mm, the traditional design will set the radius of the dies in 15.075 mm considering the shrinkage ratio 0.005. Hence, the initial guess of the design variables are then calculated through equation (5),

$$y_{ini} = \frac{x_{ini}^{\ 2}}{R_c + \sqrt{R_c^{\ 2} - (1+k)x_{ini}^{\ 2}}} + er_c \quad (5)$$

, where x_{inl} and y_{inl} are the radial and axial coordinates of the nodes in the die shape curves. R_c stands for the radius considering the shrinkage ratio 0.005. er_c is the error between the original design and that with shrinkage consideration only, which is calculated by root mean square function.

The method is to modify the specified node coordinates at the die shape geometry in the input file of the FEA. While the design variables had been changed, the linking program will calculate value of the objective function by calling the analysis solver.

4.2.2 Objective Function

The choice of objective function of the optimization system is to minimize the difference between the original die design and the finished shape of the lens. A root mean square function is used to define the object function f as in the following equation:

$$f = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(X_i - x_i)^2 + (Y_i - y_i)^2\right]} \quad (6)$$

In equation (6), (X_i, Y_i) refer to the node coordinates of the final lens product at the top surface calculated through the FEA and (x_i, y_i) are the node coordinates of the expectative designed lens curve calculated from equation (4). The minimized function f is the target of the optimization.

5. Results and discussions

Figure 6 displays the axial displacement distribution in the beginning of the cooling cycle with the temperature drop from 475℃ to 300℃. At 300℃, a profile difference can be seen between the top die and the glass lens. Figure 7 plots the differences between the designed and the formed lens curves and uneven errors are found. The error increases slightly with the distance from the center axis.

The Optimization system was constructed and the numbers of design variables were set from sixteen to eighteen depended on the curves of die shapes. Three kinds of aspherical lenses including spherical, parabolic, and hyperbolic lenses that were selected to perform the die shape optimization. The optimization results were compared to the error of the lens products without any compensation. Table 2 lists the optimization results of aspherical lens with radius of 15 mm. The results show that error reductions of Optimization results of these kinds of lenses can reach 94.76%~96.27% error reductions.

It can be seen in Figure 8 and Figure 9 that the final lens curve formed by the optimized die shape is conformed to the expectation. The average error of the lens curve is reduced from 0.058468 to 0.01617 and the maximum error is reduced from 0.071757 to 0.00339. Therefore the optimization system is useful and efficient to compensate the deviations.

6. Conclusions

FEA on the molding process of optical glass was performed and die shape optimization system was constructed in this work. Some conclusions can be made as followings.

(1) Lens molding process had been simulated using the FEA while the elasto-viscoplastic model was used to model the optical glass material and the temperature-dependent Young's modulus of the glass material had been incorporated into the material model. Thermal-mechanically coupled analysis was selected as the analysis type in which the mechanical and thermal effects were both taken into consideration. This research shows that it is feasible to apply the FEA to predict the performance of the lens molding process.

(2) Compensation for the deviations of the finished lens product can be obtained by the optimization system. Regardless of the reasons leading to the deviations of dies or the glass occurred in the fabrication process. Three different kinds of aspherical lenses had been used to perform the die shape optimization and the results show that error reductions could reached 94.76% or above. On the other hand, the compensation using optimization system can efficiently eliminate the uneven deviations at the lens surfaces. The phenomenon of the unevenness is significant in aspherical lenses. Hence, the optimization system is especially useful for aspherical lenses.

(3) This research was mainly focused on the compensation of the die shape and found that the results obtained from the optimization system were closer to the ideal lens design in comparison to that of the industrial compensation method which only adopting the thermal expansion of the glass. To make this optimization system more convincible, verified experiments of the optimization results should be performed in the future works.

7. Acknowledgements

The authors would like to thank the National Science Council of Taiwan, ROC for the grant NSC 95-2221-E-009-176, under which the investigation was undertaken. The authors would also like to thank the National Center for High-Performance Computing for its facility support.

8. References

[1] G. A. A. Meden-Pielinger, J. H. P. Van de Heuvel, “Precision pressed optical components made of glass and glass suitable modeling ”, US Patent 4391915, 1983.
[2] Y. Taniguchi, “Mold for molding optical element”, US Patent 5855641, 1999.
[3] Shishido, K., Sugiura, M., and Shoji, T., “Aspect of glass softening by master mold”, Proceedings of SPIE, v. 2536, pp. 421-433, 1995.
[4] G. C. Firestone, A. Jain, and A. Y. Yi, “Precision laboratory apparatus for high temperature compression molding of glass lenses“, Rev. Sci. Instrum., **76**, 063101, 2005.
[5] Yi, A. Y., and Jain, A., “Compression molding of aspherical glass lenses-a combined experimental and numerical analysis”, Journal of the American Ceramic Society, pp. 579-586, 2005.
[6] Spinner, S., “Elastic Moduli of Glasses at Elevated Temperatures by a Dynamic Method”, Journal of the American Ceramic Society, pp. 113-118, 1956.
[7] Jain, A., Yi, A. Y., Xie, X., and Sooryakumar, R., “Finite element modeling of stress relaxation in glass lens moulding using measured, temperature-dependent elastic modulus and viscosity data of glass.”, Modeling and Simulation in Materials Science and Engineering, pp. 465-477, 2006.
[8] Ohara Glass Catalog, Ohara Corporation, 2006.
[9] Jain, A., and Yi, A. Y., “Numerical Modeling of Viscoelastic Stress Relaxation During Glass Lens Forming Process”, Journal of the American Ceramic Society, pp. 530-535, 2005.
[10] Arora, J. S., Introduction to Optimum Design, 2nd edition, ELSEVIER academic press.

9. Figures and Tables

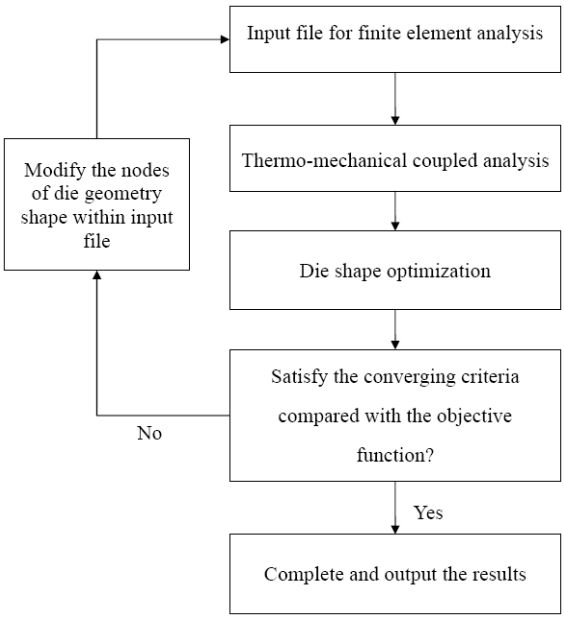

Figure 1 Die shape optimization procedure

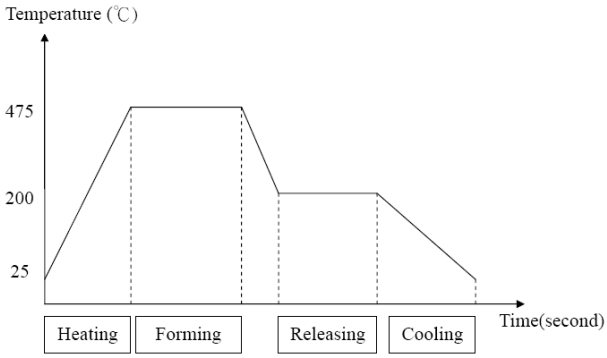

Figure 2 Temperature history diagram

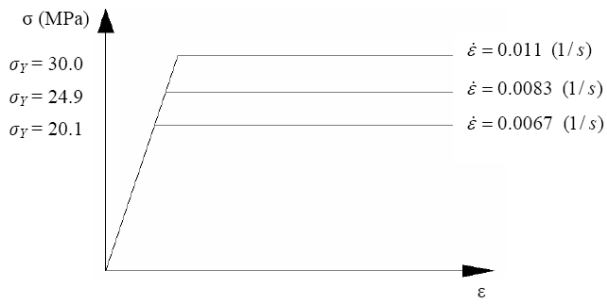

Figure 3 Relations between stress and strain with different strain rate at 475℃

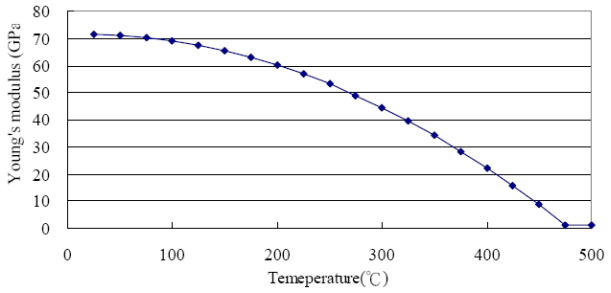

Figure 4 Young's modulus as a function of the temperature

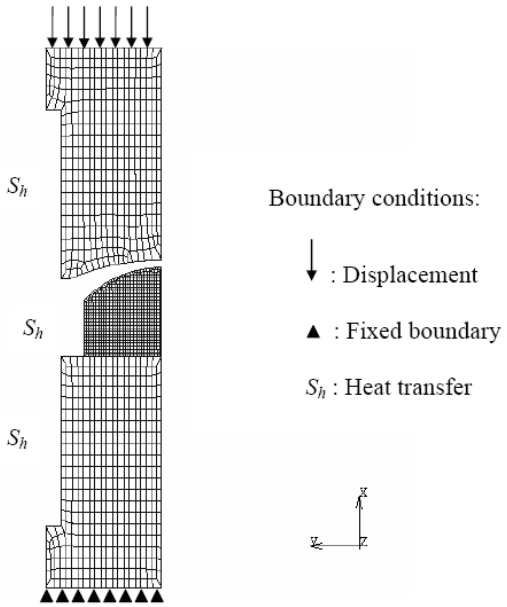

Figure 5 Boundary conditions in axisymmetric analysis model

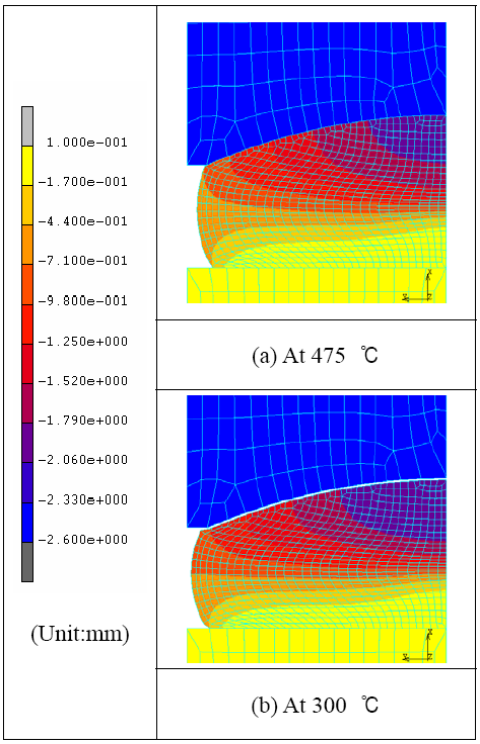

Figure 6 Axial displacement of glass formed lens

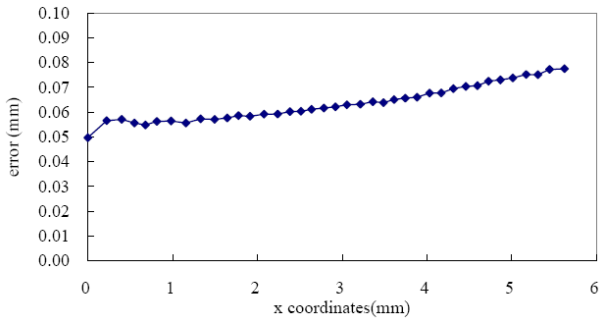

Figure 7 Error between the designed and formed lens

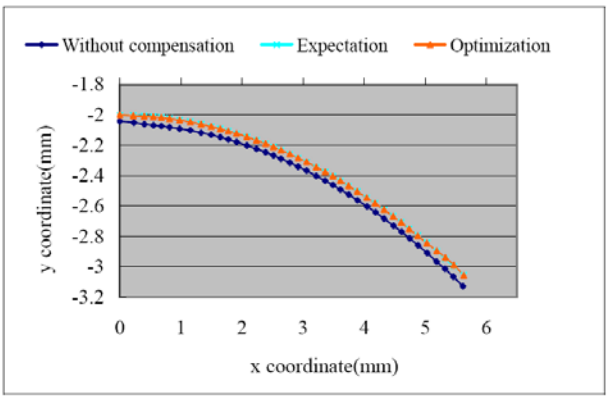

Figure 8 Glass formed lens curve with R =15mm (parabolic)

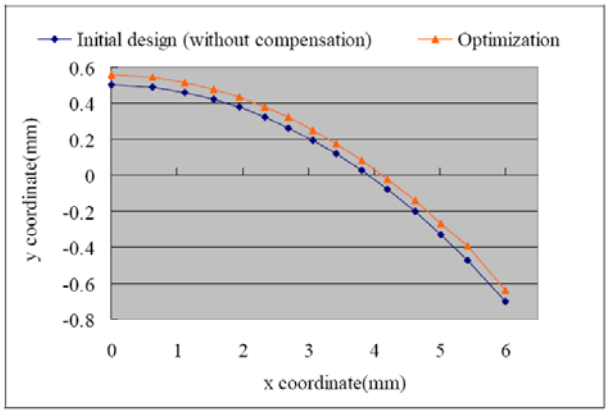

Figure 9 Die shape curve with R =15mm (parabolic)

Table 1 Material properties of dies and glass

	Dies	Glass
Material type	Elastic	Elasto-viscoplastic
Young modulus (GPa)	610	See Figure 4
Poison ratio	0.299	0.21
Density (kg/m^3)	14900	3550
Thermal conductivity (W·(m·℃)$^{-1}$)	82	0.849
Coefficient of thermal expansion (×10^{-6}/℃)	5	18 (≤445℃) 100.4 (>445℃)
Specific heat (J·(kg·℃)$^{-1}$)	300	800
Transition temperature		445℃

Table 2 Comparison with optimization results (R=15 mm)

Spherical(k=0)		
	error(mm)	error reduction(%)
without compensation	0.06542	0.00
Optimization	0.00343	94.76
Parabolic(k=-1)		
	error(mm)	error reduction(%)
without compensation	0.06461	0.00
Optimization	0.00244	96.27
Hyperbolic(k=-3)		
	error(mm)	error reduction(%)
without compensation	0.04910	0.00
Optimization	0.00185	96.22

模造光學玻璃透鏡之模仁最佳化

吳宗駿、蔡宇中、洪景華
國立交通大學機械工程學系
國科會計畫編號：NSC-95-2221-E-009-176

摘要

近來光學玻璃透鏡的需求隨著光電產品的發展大幅度的提升，以光學玻璃材料而言，模造技術相對於傳統的研磨拋光技術有著如簡潔的製造流程以及降低成本、料耗等的優勢。然而像透鏡成品的外型差異會影響成像品質這類的問題仍須克服。本研究嘗試對光學玻璃模造製程進行有限元素分析，並建立一模仁外型最佳化系統對模仁進行預補償，使透鏡成品在形狀精度上可以有效的消除誤差，提升模造玻璃的量產性。

關鍵字：玻璃模造，最佳化，有限元素分析。