Final Report
for
DAAK70-79-C-0138

# Manufacturing Methods and Technology for Production Hot Forging of Alkali Halide Lenses

PERIOD COVERED: 7 September 1979 - 7 April 1983

WRITTEN BY: James D. Weigner, Project Engineer and
William B. Harrison, Program Manager

PREPARED FOR: U.S. Army Electronics and Development Command
Night Vision and Electro Optic Laboratory
Fort Belvoir, VA

BY: Honeywell Ceramics Center
5121 Winnetka Ave. North
New Hope, Minnesota 55428

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (WHEN DATA ENTERED)

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOV'T ACCESSION NUMBER: AD-A130 813

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (AND SUBTITLE)
MANUFACTURING METHODS AND TECHNOLOGY FOR PRODUCTION HOT FORGING OF ALKALI HALIDE LENSES

5. TYPE OF REPORT/PERIOD COVERED
Final Report
7 Sept 1979 - 31 March 1983

6. PERFORMING ORG. REPORT NUMBER
D42061

7. AUTHOR(S)
William B. Harrison
James D. Weigner

8. CONTRACT OR GRANT NUMBER(S)
DAAK70-79-C-0138

9. PERFORMING ORGANIZATIONS NAME/ADDRESS
Defense Electronics Division
Ceramics Center
Golden Valley, Minnesota 55422

10. PROGRAM ELEMENT,PROJECT,TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME/ADDRESS
USAECOM Night Vision and Electro Optic Laboratory Fort Belvoir, VA

12. REPORT DATE
May 1983

13. NUMBER OF PAGES
120

14. MONITORING AGENCY NAME/ADDRESS (IF DIFFERENT FROM CONT. OFF.)

15. SECURITY CLASSIFICATION (OF THIS REPORT)
UNCLASSIFIED

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (OF THIS REPORT)

Approval for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (OF THE ABSTRACT ENTERED IN BLOCK 20. IF DIFFERENT FROM REPORT)



18. SUPPLEMENTARY NOTES

19. KEY WORDS ( CONTINUE ON REVERSE SIDE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

IR Optics, Optical Fabrication, Lens Forging, Alkali-Halide Lenses, Form-to-Shape Optics, FLIR Systems, Optical Testing

20. ABSTRACT (CONTINUE ON REVERSE SIDE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

All of the objectives of the Manufacturing Methods and Technology Program were met. Low cost, readily available KBr single crystals were hot forged-to-shape with tooling and equipment which can modestly produce 100 lenses in one, eight-hour production shift. This rate is at least six times the original goal of 300 per month. A semi-automatic, computer process control system designed and built by Honeywell was used for this purpose. No optical finishing operations were required to meet the optical specifications established for this lens design. In addition, the visible light transmission of KBr should make its optical alignment in the IR-imager easier. It is estimated that the lower cost of this lens would save the government about $300,000 per year over that where a ZnSe lens is used.

HD-168 REV 11/74

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 55 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (WHEN DATA ENTERED)

The optical test equipment established and procured as a deliverable contract requirement for evaluating the KBr lens is unique and a breakthrough technique. It is a computer automated test procedure which is not only suitable for the forged optical surfaces of the KBr lens but one which will have wide usage for quickly evaluating optical flats, spherical and most aspherical optical surfaces.

It is indeed unfortunate that development for a suitable, MIL-STD coating for the humidity sensitivity of KBr (beyond the scope of this MM&T program) has not proceeded to the point where KBr lenses can be deployed in the IR-imager system. We do believe that the capabilities established by this program will find eventual DOD applications for low cost IR optical components which have short duration exposure to humid atmospheres—such as in IR-guided munitions and bomblets.

# TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (Concluded)

# LIST OF TABLES

# PREFACE

This final report on Contract No. DAAK70-79-C-0138 has been prepared for work sponsored by the Systems Integration Division, Night Vision and Electro Optics Laboratory, U.S. Army Electronics Research and Development Command. The contract covered experimental work extending over two periods: 7 September 1979—7 August 1981 and 7 April 1982—31 May 1983. Mr. William M. Johnson, NV&EOL, was the Contracting Officer's Representative.

Honeywell Inc. personnel who directly contributed to this study include: Regis J. Betsch, Lead Project Engineer, 1 September 1979—1 September 1980; James D. Weigner, Lead Project Engineer, 1 September 1980—31 May 1983; Gilbert O. Hendrickson, Maurice P. Murphy and Joseph E. Starling, Ceramic Engineers; Clark Olson, Walter Polgrin, M.R. Sandberg and R.B. Luhmann, Technicians; Rogers H. Anderson and Francis M. Schmit, Research Scientist; Joseph Koteles, Quality Engineer; Earl F.E. Burandt, Production Engineering Supervisor; and William B. Harrison, Program Manager.

The authors gratefully acknowledge the Honeywell Corporate Technology Center group who developed the hot forge-to-optical figure technique; the many suggestions offered by William M. Johnson, Robert Dockery and Robert A. Spande of NV&EOL in the guidance and redirection of this program; Irv Able, Honeywell Electro Optic Division for the KBr Optical Designs; Dave Stoltzmann from Honeywell Systems and Research Center for identifying the interferometric testing approach; and N. Balasubramanian of Digital Optics, Corp. for providing the white light interferometer



The reverse of this page is blank.

# SECTION 1
# INTRODUCTION

## 1.1 SCOPE

This final report on Contract No. DAAK70-79C-0138 fulfills the requirement for line number CLIN 0001 item number A010 for the "Manufacturing Methods and Technology for Production Hot Forging of Alkali Halide Lenses."

## 1.2 BACKGROUND

In an earlier Honeywell Contract, DAAR70-72-C-0218, it was demonstrated that a plano-concaved potassium bromide (KBr) lens could be used to replace the zinc selenide (ZnS) color correcting lens used in the SU-103/UA, common module IR imager. This KBr lens met all of the imager's optical specifications. Furthermore, it was demonstrated that a hot forged-to-shape process could be used to generate the plano-concaved optical surfaces where no optical polishing operations were required to finish the optical surfaces of this lens.

## 1.3 APPROACH

This Manufacturing Methods and Technology (MM&T) Program was initiated and performed to establish the manufacturing processes required to produce a minimum of 300 KBr plano-concaved lenses per month. The forge-to-shape process originally developed at Honeywell[1,2,3] was refined and made compatible for this production requirement goal. All manufacturing processes, equipment, tooling and production controls were then established, defined and demonstrated with a pilot run of 12 lenses. All incoming material specifications as well as final optical characterization procedures for the final lens were also defined with the test equipment required.

## 1.4 SUMMARY

All of the objectives of the Manufacturing Methods and Technology Program were met. Low cost, readily available KBr single crystals were hot forged-to-shape with tooling and equipment which can modestly produce 100 lenses in one, eight-hour production shift. This rate is at least six times the original goal of 300 per month. A semi-automatic, computer process control system designed and built by Honeywell was used for this purpose. No optical finishing operations were required to meet the optical specifications established for this lens design. In addition, the visible light transmission of KBr should make its optical alignment in the IR-imager easier. It is estimated that the lower cost of this lens would save the government about $300,000 per year over that where a ZnSe lens is used.

The optical test equipment established and procured as a deliverable contract requirement for evaluating the KBr lens is unique and a breakthrough technique. It is a computer automated test procedure which is not only suitable for the forged optical surfaces of the KBr lens but one which will have wide usage for quickly evaluating optical flats, spherical and most aspherical optical surfaces.

It is indeed unfortunate that development for a suitable, MIL-STD coating for the humidity sensitivity of KBr (beyond the scope of this MM&T program) has not proceeded to the point where KBr lenses can be deployed in the IR-imager system. We do believe that the capabilities established by this program will find eventual DOD applications for low cost IR optical components which have short duration exposure to humid atmospheres—such as in IR-guided munitions and bomblets.

# SECTION 2
# ENGINEERING APPROACH

## 2.1 INTRODUCTION AND BACKGROUND

This Manufacturing Methods and Technology (MM&T) program was established to demonstrate that the hot forged-to-shape process originally developed on Contract DAAR70-72-C-0218[1] could be adapted for producing a minimum of 300 KBr plano-concaved lenses per month. Such a lens would be a suitable replacement for the ZnSe color connecting lens used in the large IR-imager module (SU-103/UA) of a forward looking infrared (FLIR) system.

The wide transmission spectrum (visible to 14$\mu$m) of potassium bromide (KBr) and other alkali halides makes them particularly attractive for IR systems. These materials are readily available from several domestic sources and they are much lower in cost than zinc selenide (ZnSe). The hot forged-to-shape process allows certain of the alkali halides to be formed directly to the final optical figure and finish. Thus, the expensive optical polishing operations commonly used on all optical elements can be eliminated. Substantial cost reductions can be achieved where it is feasible to use alkali halide lenses in place of germanium, ZnSe, silicon, etc. IR optical elements.

Single crystal alkali halides have yield strengths of only 150-300 psi and cracks readily propogate through single crystals. However, the hot forging operation recrystalizes these materials into 10 to 20$\mu$m grain size structures that have yield strengths in excess of 2500 psi and which can plastically deform rather than crack like brittle single crystals. Some of the alkali halides have a relatively high sensitivity to moisture; however, two types of optical coatings have been established to greatly improve their moisture resistance.

A plasma-polymerized ethane coating for KBr has been developed[1,2,3] which offers moisture resistance at 71°C and 95 percent relative humidity. This coating is the best-to-date for low energy FLIR type of applications. A second system which uses thallium iodide[4] has been developed which is satisfactory for high-energy transmissive radiations at 40°C and 45 percent relative humidity.

The KBr plano-concave lens which is the subject of this program was designed to replace the ZnSe color correcting lens currently being used in the SU-103/UA, large common module IR imager. Figure 1 shows the general position of the IR-imager in a FLIR system. This figure also shows that three lenses and a 90° turning mirror are used in the imager. Figure 2 shows the detail of imager-optics with the KBr lens used in place of the normally used ZnSe color correcting lens. Figure 3 shows the KBr lens requirement. The dimensions of the KBr lens are 2.45 inches in diameter and 0.28-inch center thickness. The lens has a 0.15-inch thick flange and a clear

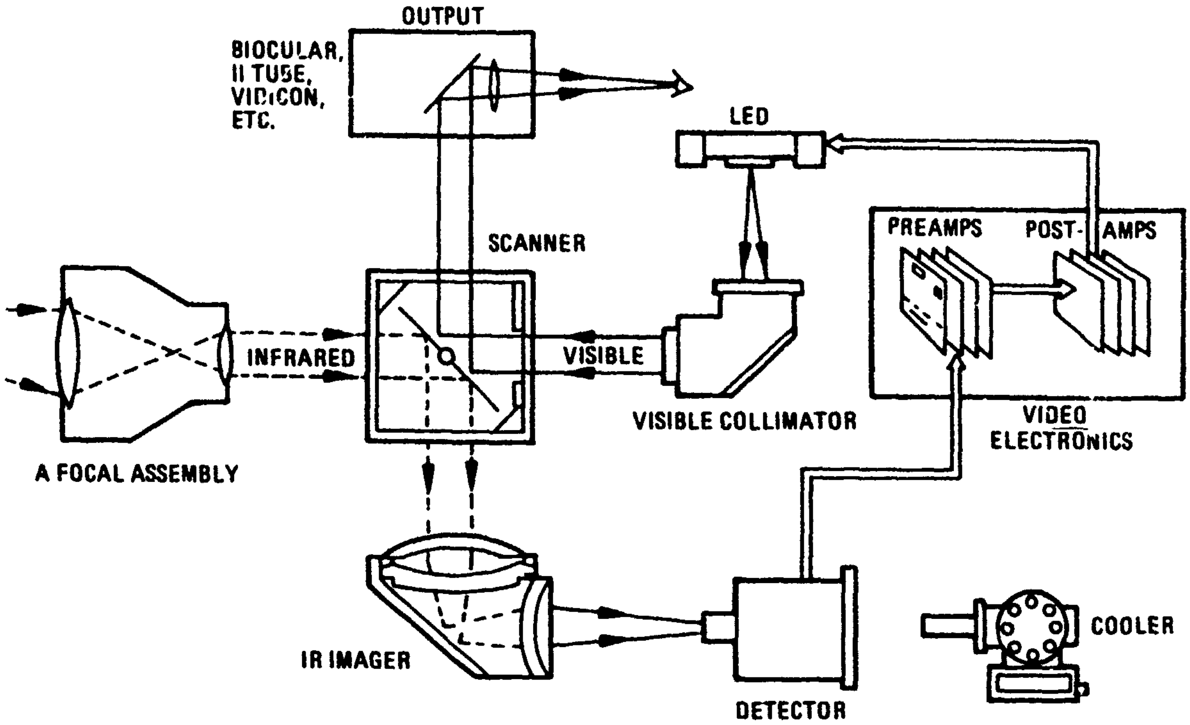



*Figure 1. FLIR system and common modules.*

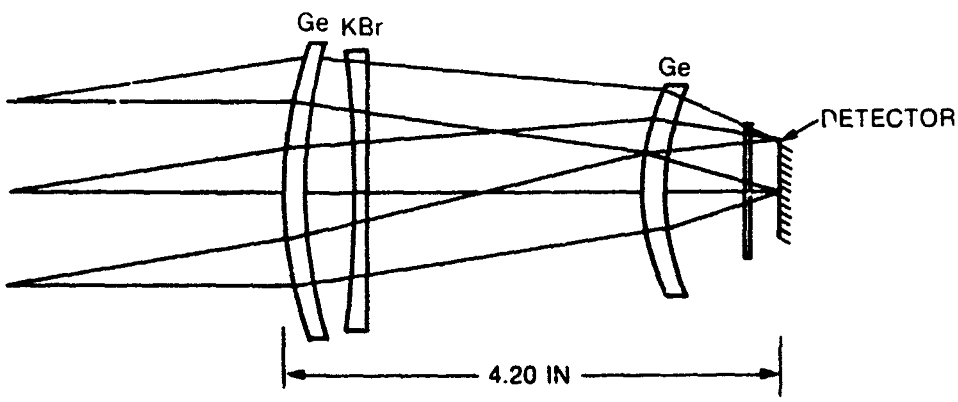
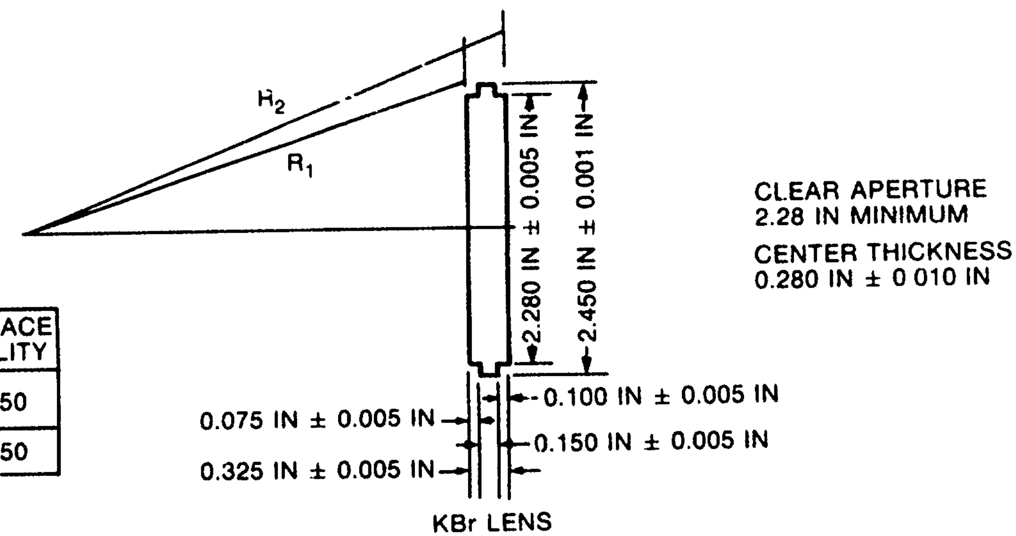



*Figure 2. Ray tracing of SU-103/UA imager with KBr lens.*




| | RADII | SURFACE QUALITY |
|---|---|---|
| $R_1$ | 17.25 IN ± 0.25 IN | 80/50 |
| $R_2$ | ∞ | 80/50 |

***Figure 3. Drawing requirements for KBr lens.***

aperture of 2.28 inches. The radius of curvature of the concave side is 17.25 inches. This KBr lens module meets all of the imager's optical specifications which are: %MTF on axis 74%, %MTF off axis 66%, flange focal length (FFL) 17.86 ± .25mm, and effective focal length (EFL) 67.8 ± .7mm.

## 2.2 REFINEMENT OF DEVELOPMENTAL PROCESSES

In the initial part of this MM&T program the developmental KBr hot forged-to-shape processes were studied and refined to produce improved optical quality in the final forged lens, while at the same time simplifying the process and reducing the manufacturing cost. There were four significant parts to the refinement study. These are discussed in the following subsections.

### 2.2.1 One-Step Forging Process

In an attempt to make a major cost reduction and process simplification, a single crystal was forged on Pyrex dies to final figure, complete with flange. The resultant lens had a completely formed flange (obtained using steel inserts in the forging sleeve) and the optical surfaces appeared to be completely defect and haze free. However, the optic axis was not within tolerances, and experiments with forging single crystals two-high on pyrex dies ended in die failure. The crystals tend to slip to one side during forging creating severe wedging and failure of the dies. It is feasible in a two-step forging process to obtain a flanged lens. This would completely eliminate the final matching step. However, the difficulties in perfecting this process were not investigated further in this contract.

In the first step of the two-step forging process, the KBr single crystal is hot forged into a strengthened, polycrystalline blank which is preshaped to the diameter required for the second-step forging operation. The second step forges the first-stage blank between optically polished dies to the final lens specifications. The refinements made on these two processes follow.

### 2.2.2 First-Stage Forging

Table 1 summarizes the various processing parameters which were studied in this MM&T program for the first-stage forging operations.

The first-stage forging step is a critical operation in producing the hot forged-to-shape KBr plano-concaved lens. The optical properties of the final lens depend upon the optical quality of the original KBr single crystal. Its weight, size, internal stresses and crystal orientation with respect to the forging direction are all important and need to be controlled.

Throughout the program, reductions in the starting weights of the single crystals were made until a minimum practical weight was obtained. The final process used crystals weighing only 105 grams as opposed to the former 125-gram crystals. This 16-percent reduction in weight significantly reduced the cost of starting material.

TABLE 1. *FIRST-STAGE FORGING PARAMETERS*

| Parameter | Recommendation | Condition | |
|---|---|---|---|
| | | Developmental | Options Studied |
| Isostatic Pressure | 1 Atmosphere Air | 1 Atmosphere Air | 4K psi He |
| End Forging Load | 35,000 lb/3-in forging | 35,000 lb/3-in forging | 5,000 lb/3-in forging |
| Temperature | 250°C | 250°C | 275°C, 300°C |
| Forging Directions | <100> | <100> | <110>, <111> |
| Input Shape | Cylinder | Cylinder | Cube |
| Lubrication | Spray Fluorcarbon | Sheet Teflon | Silicon oil, no lubrication |
| Aspect Ratio | 0.8-1.0 height-diameter | 1.0 | 0.77, 0.60 |
| Die Shape | Conical/Flat | Flat | Conical |
| Die Material | 420-F Stainless Steel | Brass | |
| Sleeve Material | 4140 Hardened Steel | Steel | Brass, 420-F Stainless Steel |
| Forging Speed | 6.4-percent constant strain | 50 mils/min | Constant strain to 50 percent, ram speeds of 20 and 30 mils/min |
| Parallel | 6 parallel | | |
| Series | 1 High | 1 High | 1 High |
| Water Polish | Conical ends, rounded corners | Rounded corners | No water polish |
| Weight Before/After Polish | 105/88g | ~125/92g | |

The aspect ratio (height:diameter) was originally thought to have an influence on the residual strain produced in the forged blank. However, crystals with aspect ratios as low as 0.75 were forged with excellent results and no obvious differences could be seen between these lenses and ones having an aspect ratio of 1.0.

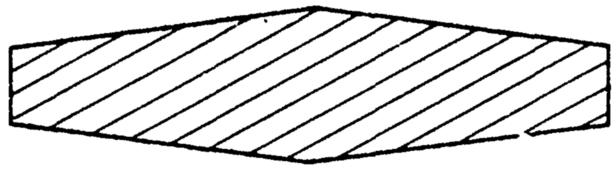
It is important that the ratio of the first-stage forging blank thickness to the height of the starting crystal be at least 0.5, i.e., the height must be reduced by at least 50 percent of the starting crystal. This is necessary to ensure adequate strengthening by producing a fine-grained polycrystalline structure.

Various lubrication approaches were examined as well as no lubrication on finely sanded brass, 420-F stainless and 4140 tool steel dies. In all non-lubricated trials the KBr adhered to the die surfaces.

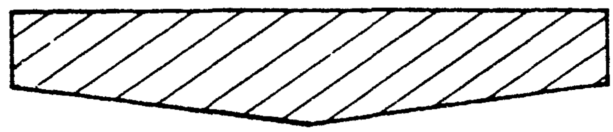
Sheet Teflon, successfully used with flat dies, tended to bunch up and cause a considerable amount of relief in the surface of the first-stage forging. This required a machining step to be performed prior to second-stage forging. This was self-defeating since shaped dies were intended to remove this machining step which was necessary for forgings produced between flat dies. Silicone oil, which was the first choice of substitute lubricant, produced very highly strained material. Also, there is a major concern that silicone oil remaining on the len surface would affect subsequent coating processes.

A fluorocarbon mold-release spray, MS-122 (Miller Stephenson), was found to be stable at 250°C and was inert when in contact with the 420-F stainless dies. It was found that MS-122 does react chemically with brass at 250°C, but does not affect the forging when steel dies are used in a brass sleeve. The use of lubrication in the first stage forging has eliminated the need for a premachining step for second-stage forging, although a water polish must be used to remove the lubricant.

Another refinement in the process involved a change in the configuration of the first stage forging. The previous configuration was a double-conical blank, Figure 4. The double cone configuration was used to ensure point contact during the second-stage forging process and thereby prevent air entrapment. However, after the first-stage forging has undergone preparation for final forging, the cones may not be exactly concentric on the blank. When forging against the convex pyrex die in the second-stage process, any offset tends to wedge the dies. When two sets of dies are stacked on top of each other as in the 2 $\times$ 3 process, the wedging is compounded. The additional tolerances caused by the expansion of the steel sleeves at forging temperature also contribute to the problem. In an attempt to alleviate the problem, one of the cones on the first stage forging was eliminated. Figure 4 shows a cross section of the past and final configurations. When the flat side of the forging is placed against the convex Pyrex die, a point contact is still achieved, and the wedging problem is eliminated.



**a) DEVELOPMENTAL DOUBLE–CONICAL FORGING**



**b) FINAL PLANO-CONICAL FORGING**

*Figure 4. Cross sections of past and final first stage forging configurations.*

During the program it was observed that the KBr cylinders did not deform uniformly during forging. There are four directions which allow easier plastic flow of the material perpendicular to the <100> forging axis. This results in the forging acquiring an almost square projection normal to the die motion direction during forging. When the corners of this square make contact with the restraining sleeve, the material is forced to flow along the difficult plastic deformation directions (i.e., normal to the edge of the square) until uniform contact is made at the restraining sleeve. A cleaved <100> cube was partially forged to verify the direction of easiest plastic deformation. The deformation of the sample, Figure 5, distinctly shows that easy direction is 45° to the <100> faces; thus it is along the <110> direction. This data suggested a simple but elegant technique to reduce the amount of residual strain due to first stage forging. Cubes were obtained with their x and y axis parallel to the <110> and z parallel to <100>. This configuration retains the <100> forge direction while using a shape which allows less movement of the KBr along the hard deformation direction (i.e., the cube's corners).

However, examination of the forged <110> cubes indicated that no reduction in strain was obtained and that the strain was much more aligned than with <100> cylindrical crystals. Also, no benefit is seen in using <100> cubes as opposed to cylinders; therefore, cylinders remain the best starting configuration.

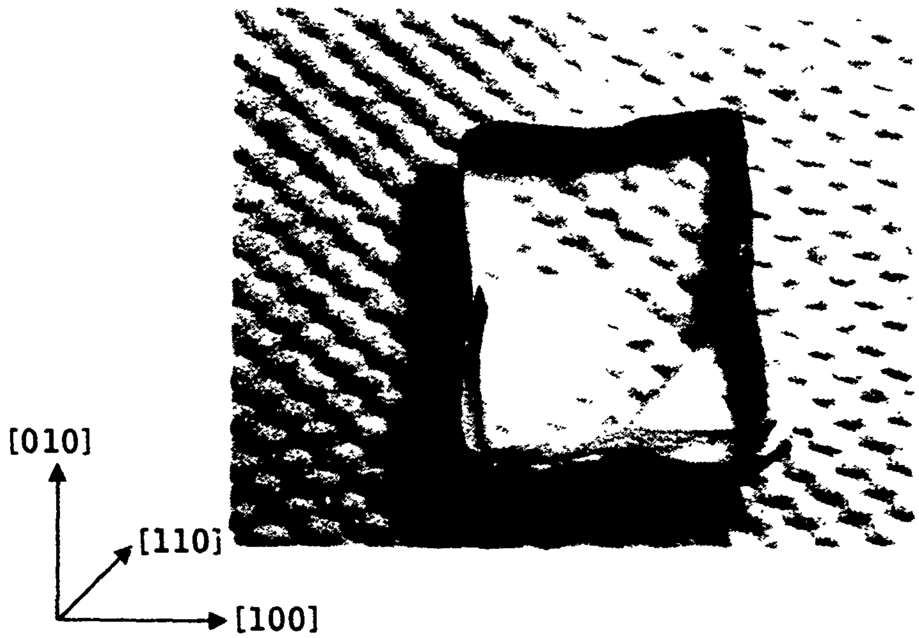



*Figure 5. Forged cube of KBr demonstrating hard and soft plastic flow directions.*

To a first approximation, the strain generated within the crystal will be proportional to the strain-rate used in the first-stage forging. If a 10%/minute-strain is used, then a 1mm slice of material will decrease by .1mm in one minute regardless of the total height of the crystal. Thus, a constant strain-rate relates to the constant amount of strain imparted to a given constant volume of material per unit time. This implies that strain-rate and not ram speed should be the controlled parameter during forging.

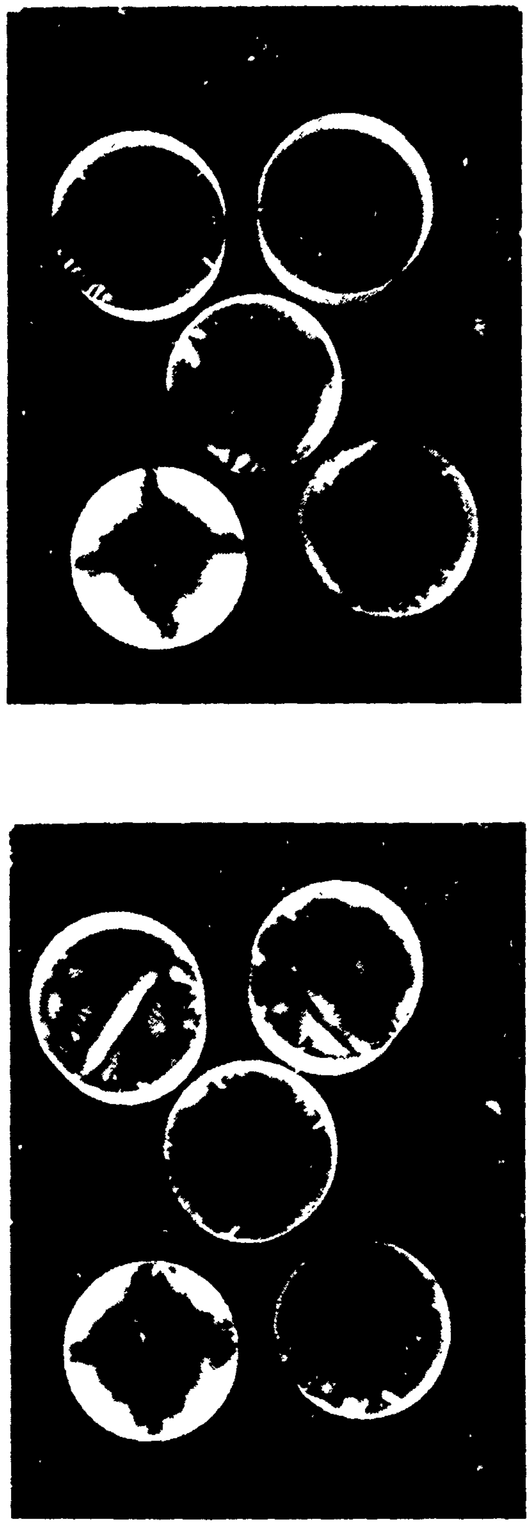
By using a 6%/minute-strain rate the final ram speed was .8mm/minute instead of the 1.25mm/minute originally used. The total forging time time was only 17 minutes instead of 20 minutes. By using a constant strain rate the final strain rate was less than when a constant ram speed was used. This also resulted in lower residual strain in the forging while using less forging time.

In an attempt to speed up the production of first-stage forgings, hot loading of the single crystals was examined. It was shown that a crystal could be heated independently and transferred to the hot dies without thermal shocking the crystal. However, it is important that lubrication of the dies is maintained. The dies cannot be sprayed while hot, but the crystal can be sprayed before heating. This has been shown to provide adequate lubricant; however, care must be taken in transferring the crystals so as to not wear off any lubricant. It has also been shown that a forged crystal can be removed while hot and placed in a heated environment for slow cooling. Because of the extra time required and the extreme care with which these methods must be employed so as to prevent thermal shock to the KBr, another approach was adapted to speed up the process.

It was originally thought that the amount of strain in the starting crystal would reflect the amount of strain in the forged lens, but our findings indicate that this may not always be the case. The forging rate does however, have an important bearing on the residual strain in the forging. Figure 6 shows the polariscopic strain photographs of 10 KBr starting crystals. The forging identification numbers are indicated in the margins. Figure 7 shows the polariscopic strain photographs for five of the first-stage forgings. These five (forging numbers 084, 085. 091, 092 and 093) were all loaded into dies and heated in the press at the same time. Upon reaching a temperature of 250°C, numbers 084, 085 and 091 were forged at the same time to 80 percent of final pressure. They were then pressed individually to a final pressure (35,000 pounds/3 inch-forging) while maintaining the 6.4-percent per minute strain rate. The last two numbers 092 and 093, were forged individually for the entire forging and at a faster rate (about 10-percent per minute) then the previous three forgings. Both 092 and 093 exhibited high strain after forging, Figure 7, while 084, 085 and 091 showed low strain after forging. When comparing this to the starting crystals, number 092 had high strain before and after forging, while number 093 had low strain initially but high strain after forging. This dramatically illustrates the effect of high strain rate on residual strains.

Figure 8 shows strain photographs of the remaining five forgings. These were all loaded into dies and heated at once. They were then forged one at a time at 6.4 percent per minute strain rate. None of the forgings showed apparent high strain but several of the starting crystals showed significant strain (numbers 089, 090, and very high strain in 087). These results seem to indicate that the initial apparent strain in the starting crystal may actually be relieved in the forging process.

Polariscopic inspection of the crystals is still important as a means of characterizing the crystals and spotting inclusions or flaws in the crystal that may not be visible otherwise. It should also be kept in mind that these conclusions are based on a small sample and that some of the apparent strain reduction is due to the thickness reductions of the crystal. What is more important is the evidence that the constant, lower strain-rate does produce very low strain forgings. It should also be realized that lightly strained single crystals are very susceptable to thermal shock, which may cause cracking in the single crystal upon heating. If forgings occur with small cracks in the forged blank, the initial strain in the crystal should be investigated as a possible cause. Therefore, polarscopic inspection of the crystals is an important means of characterizing the crystals and spotting inclusions and flaws which may not be apparent to the naked eye.



084 085 086 087 088

089 090 091 092 093

***Figure 6. Polariscopic strain photographs of 10 KBr starting crystals.***

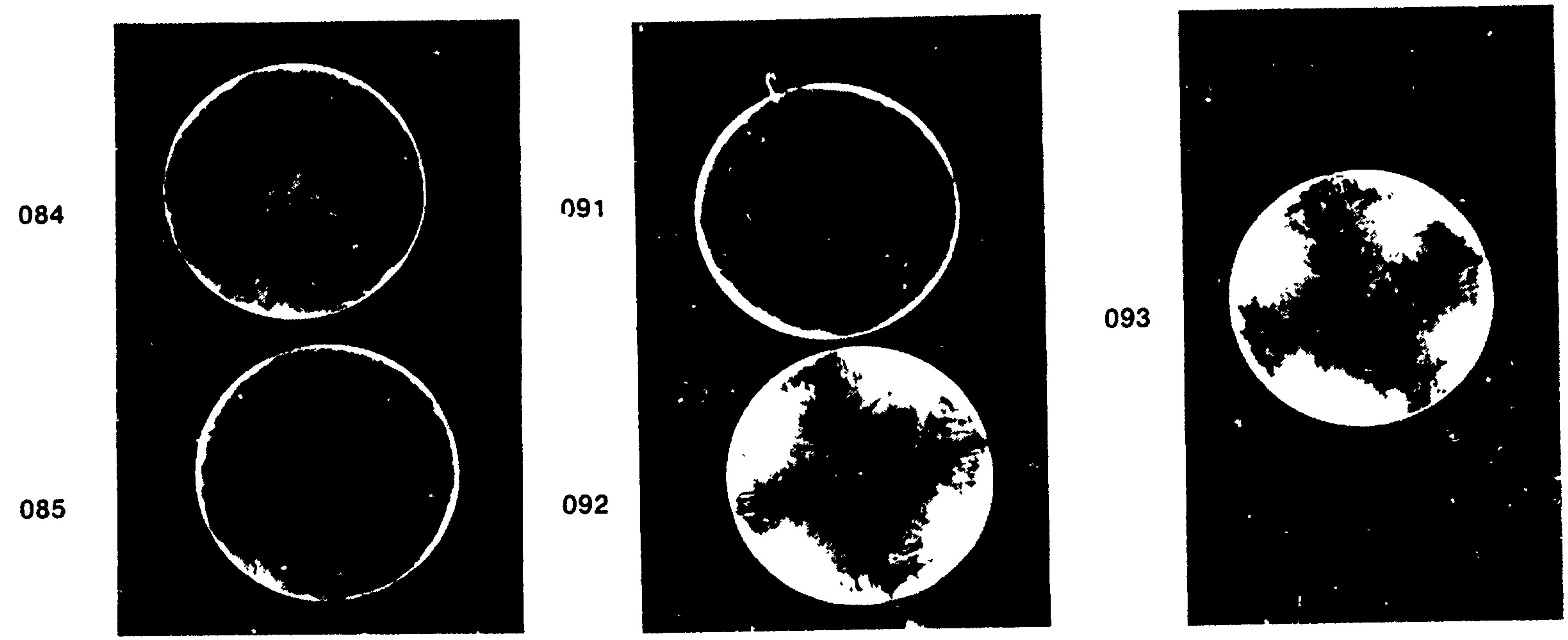



*Figure 7. Polariscopic strain photographs of first stage forging numbers 084, 085, 091, 092 and 093.*

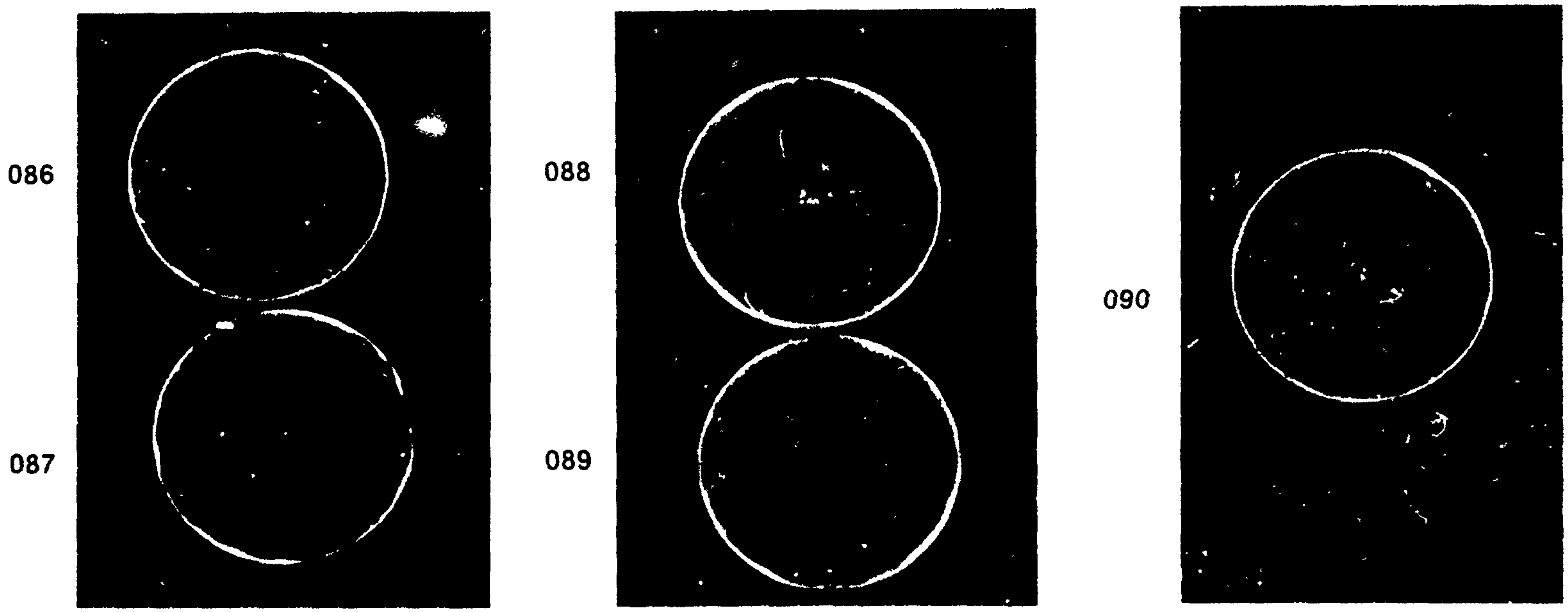



*Figure 8. Polariscopic strain photographs of first stage forging numbers 086, 087, 088, 089 and 090.*

### 2.2.3 Second-Stage Forging

Table 2 summarized the second-stage forging parameters which were studied in the initial process refinement portion of the MM&T program. Only a small amount of reduction occurs during the second-stage forging operation. However, this stage is very critical in producing the final optical figure and surface finish of each lens.

Perhaps the most significant breakthrough was the elimination of the 4000 psi helium isostatic pressure requirement for this second-stage operation. The final lenses are forged in air at normal atmospheric pressure. High cost, potentially dangerous high pressure tooling which would have been difficult to adapt for high volume production was avoided. Not only has this been a substantial cost saving, but it also made it feasible to use low cost tooling in a type of heated press which is commonly available in many domestic production facilities. The cost for a complete set of tooling was estimated to be about $5000.

In order to obtain optimum results, several criteria must be met. This includes complete removal of the lubricant from first-stage forging: slow, controlled forging rate to ensure accurate and complete die replication and lower forging temperature (225°C) to minimize secondary recrystalization.

The water polishing step was very critical to ensure good quality lenses. Its purpose was two fold, first to remove the flurocarbon lubricant and second to finalize the weight to 85 ± 0.5 grams. It was the weight of the forging that ultimately determined the final lens thickness. The weight as optimized at 85 ± 0.5 grams ensured a final lens thickness well within the 0.280" ± 0.010 " center thickness requirement.

The developmental process produced only one lens at a time and at best the process would produce only three lenses per day with a full-time operator controlling the process. After determining that the 4000 psi isopress operation could be eliminated, four other significant process changes were studied.

The first eliminated the press operator by using a computer process controller for controlling the forging cycle of a press (400 ton capacity) with two heated platens. This press was automated and modified with a Honeywell investment. Figure 9 shows an overall view of the automated press. The following parameters were controlled or monitored:

(1) The temperature of the upper and lower platens was controlled and recorded
(2) Pressure was recorded and over pressure at any point in the pressing cycle caused a system shut-down
(3) The ram-rate was continuously varied and recorded to produce a constant strain-rate for the forged lenses.

*TABLE 2. SECOND-STAGE FORGING PARAMETERS PAST AND PRESENT*

| Parameters | Recommendations | Conditions | |
|---|---|---|---|
| | | Developmental | Options, Studied |
| Isostatic Pressure | 1 Atmosphere Air | 4K psi He | 2K psi He, 100 psi He |
| End Forging Load | 31,000 lb/3-in lens | 35,000 lb/3-in lense | |
| Temperature | 225°C | 225°C | |
| Pre-machining | None | Machine to conical shape | |
| Water Polish | Remove fluorcarbon and material to 85 ± 0.5gms | Remove damage from machining and 10g of material | Remove fluor-carbon and 10g of material |
| Methonal/Dry Polish | Removal of surface haze | Removal of surface haze | |
| Die Lubrication | None | None | |
| Sleeve and Ram Lubrication | MS-122 | | |
| Die Material | Pyrex | Pyrex | Soda-Lime, Cervit |
| Convex Die Radius | 17.25" | 15.07 | 17.25 |
| Sleeve Material | Steel | Steel | |
| Series/Parallel Forging | 2 high/3 parallel | 1 high/1 parallel | |
| Hot Transfer | Yes | None | Yes |
| Forging Speed | 0.006 in/min/lens in series (0.012 in/min for 2 high × 3 parallel) | 0.006 in/min/lens | |

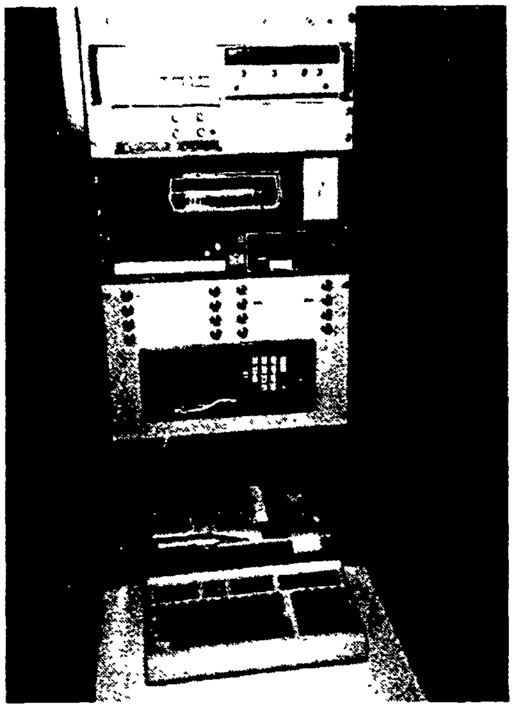


*Figure 9. Console containing electronic controls for press automation.*

Secondly, the type of die material was varied from Pyrex to determine the influence of using a higher thermal expansion soda-lime glass and a lower thermal expansion Cervit glass. It was expected that thermal expansion of the replicating surfaces may be critical to the optical figure achieved; however, no significant difference was observed for the plano-concave KBr lenses produced from these different dies. Therefore, the original Pyrex die material was used. One adjustment in the radius of the convex Pyrex die was made to bring the effective focal length (E.F.L.) of the lens closer to the specified value of 67.8 ± 0.77mm. An adjustment in the radius of curvature of the convex Pyrex die surface from a 15.07 inch to 17.25 inch changed the E.F.L. of the KBr lens in the IR-imager from 68.3 to 67.2mm.

The third area studied series and parallel forging of multiple lenses. Initially three die sets (each containing a single first-stage forging) were forged at one time. While satisfactory lenses were produced, small differences in the overall length of the die parts produced inconsistant die fill. Next, two lenses were forged in series, Figure 10. Successful lenses were also achieved; therefore, a 2×3 process was studied where three die sets (Figure 11) were forged in parallel.

Before a 2×3 assembly was used, the rams and dies had to be coordinated in order to have equal heights. The rams and dies were measured and grouped in such a way that the heights were as close as possible and then shimmed to the same height. When loading with the KBr blanks, the blanks were chosen by weight so that the

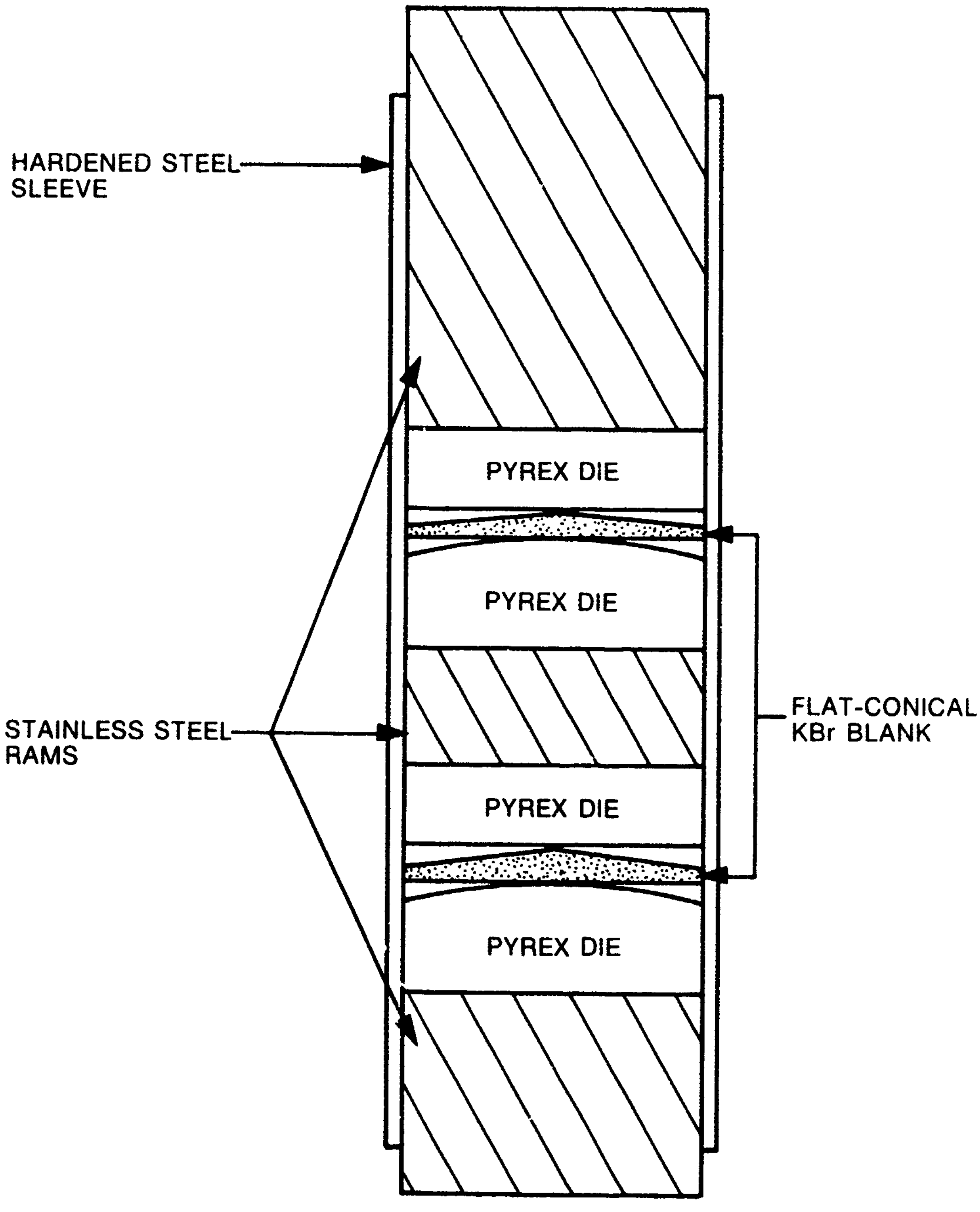



*Figure 10. Two-high forging configuration.*

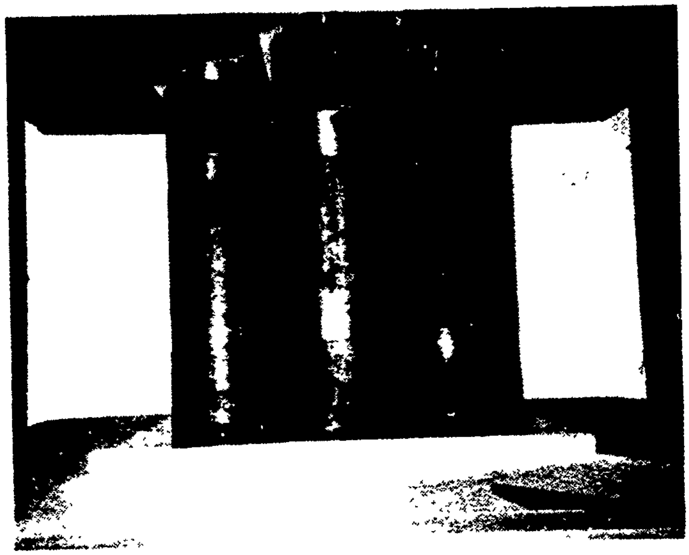


*Figure 11. Complete 2x3 array before forging.*

combined weights of both blanks in each sleeve were approximately equal. The sleeve, die ram, and shim matching was maintained so that it was not necessary to remeasure each assembly before use.

All of these minor adjustments which were used would be eliminated in production with more precision tooling and closer weight first-stage forgings.

The last area examined was the use of hot-transfer techniques to eliminate the need for long heating and cooling schedules (about three hours) in the automatic forging press. Some thought was given to hot-transfer, first-stage blanks into preheated dies. This would minimize the number of die sets needed for forging. However, the problems involved in handling hot KBr, coupled with maintaining a clean environment, were too prohibitive for this type of hot-transfer. Another difficulty arose in maintaining lubrication between the steel rams and sleeve. The lubricant could not be applied to hot surfaces. Therefore, the best alternative was to use enough preheated die sets so that a semi-continuous process would meet the production rates.

Techniques were established for hot handling die sets to and from the press. In our pilot production case, six die assemblies (depends on production rate desired) were loaded in a clean, humidity controlled (<35% RH) area and then transferred to a heating chamber near the press. These were heated to 225°C and held at this temperature a minimum of 30 minutes. They were then transferred three at a time to the press and the automatic pressing cycle was started. After about 10 minutes the reduction process at about 31,000 pounds/die assembly (previously about 35,000 pounds) was completed, the pressure released, and hot die assemblies were removed and allowed to cool in air. Due to the large thermal mass of the assemblies, cool-down was slow enough to avoid a thermal shock problem.

Figure 12 shows polariscopic strain photographs of six lenses produced in a 2×3 forging using the present process. The strain in each lens was fairly uniform and not excessive.

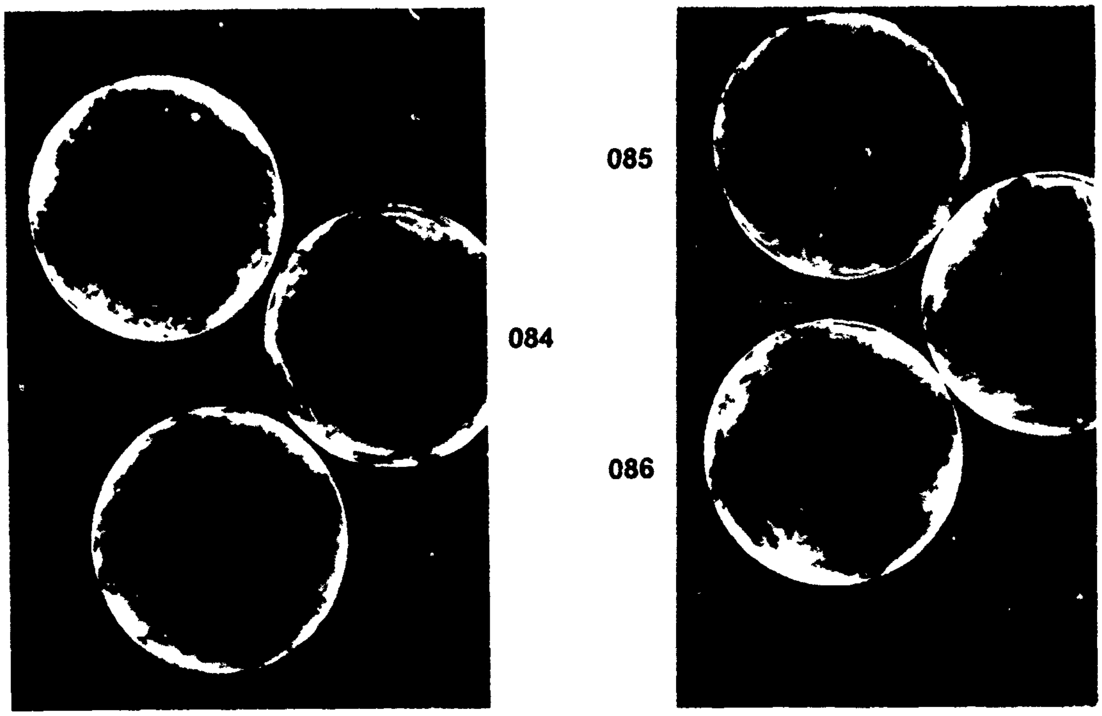



*Figure 12. Strain photographs of second stage forging numbers 084 through 089.*

In summary, it has been shown that the high pressure, helium isostatic pressure system is not necessary. Instead, low cost tooling in a readily available heated platen press can be used for the second-stage forging of plano-concave KBr lenses. The resulting lenses were of exceptional optical quality and relatively free of internal strain.

### 2.2.4 Optical Testing

In Honeywell's initial effort[1,2,3] at direct forging of alkali halide lenses, it was assumed that it would be necessary to meet optical figure requirements within a few fringes for each lens surface, similar to conventional lens making. However, our results indicated that this was not the case. Testing the MTF performance of the imager with the hot forge-to-shape KBr lens in the IR imager showed that it performed within the imager specifications. The MTF test, however, is too costly and time consuming to use for each KBr lens to be mounted in the imager.

Therefore, alternate techniques for optical characterization of the lenses were studied in a DARPA/NVL funded program[1,2,3] for transfer to this MM&T program. These include:

- A double pass transmission wavefront distortion test performed on the interferometer (at 6328Å) using a concave mirror positioned about 3 inches above the KBr lens. This mirror, with a radius of 30 inches, returns the beam through the lens (hence, "double pass") and is interfaced with the reference beam, Figure 13.

- A lateral shearing technique in a single-pass configuration was also investigated to correlate the interferometric results with the MTF test. To implement this interferometric measurement, the lateral shearing interferometer shown in Figure 14 was designed specifically for the KBr lens used in the IR imager. A lateral shear of 0.3 inch was necessary to correlate the MTF performance to the shear. To provide such a shear, an optically flat parallel plate of 4-inch diameter by 0.625-inch thickness was used as shown in Figure 14. The tilt angle of the parallel plate is about 40 degrees. A compensating lens with relatively good quality was used to balance the divergence of the KBr lens. In general, a fringe pattern is seen reflected from the parallel plate when a 1.5-inch clear-aperture is used. Interferograms of any lens with less than 4 fringes deviation indicate acceptable optical performance of the lens. An excellent correlation between lateral shear fringe deviation and MTF data for typical forged KBr lenses was obtained. This technique can be used for quality control of the forged KBr lens[1,2,3].

MTF performance has shown that forged lenses have the same performance virtually every time. While the surface optical figure has not been consistent, the MTF of the total imager has been within specifications. This shows that forging both sides of a lens simultaneously replicates both of the desired surfaces in the dies. When the thermal contraction takes place during cooling and changes one of the figures, then it changes the other side in an identical but opposite fashion with complete compensation. This was substantiated in the double-pass transmission wavefront distortion test which showed a lens, no. 597, that has optical figures (on both sides) that are no closer to spherical than 7-8 visible fringes does in fact have a wavefront distortion on a transmitted beam of only 0.063 wave at 10μm. This measurement substantiated our analysis that the forged lens performs as predicated by the surfaces of the forging dies.

However, both of these tests had several common difficulties:

1) Time consuming
2) Required much judgement by the operator
3) Beyond the skills required for normal inspection personnel.

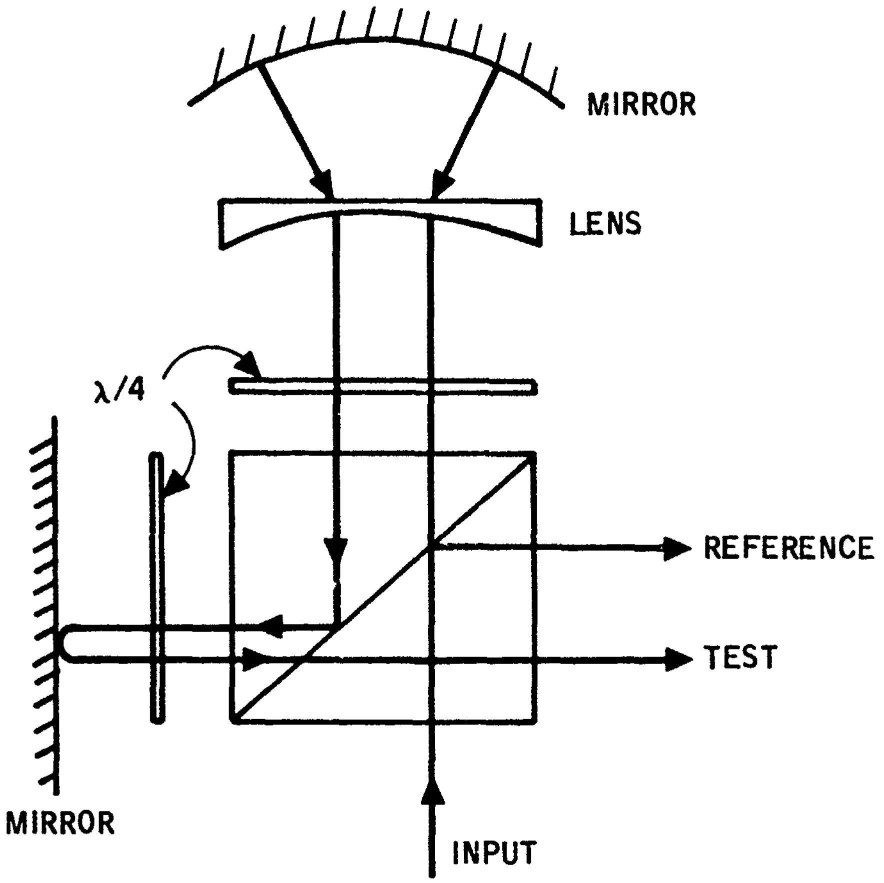



*Figure 13. Double pass transmission wavefront distortion test.*

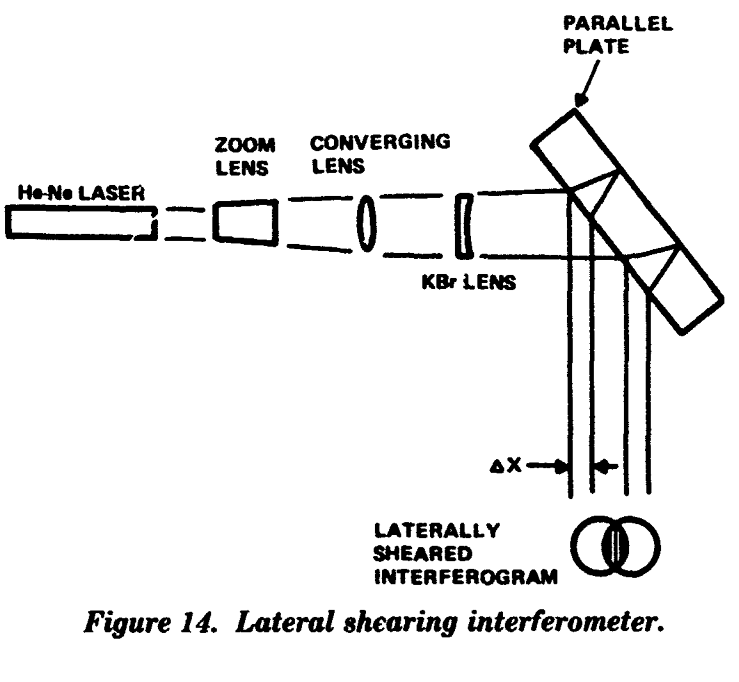



*Figure 14. Lateral shearing interferometer.*

Several techniques were combined to determine the quality of the lenses for this study. Figure 15 shows the polariscope photographs of lenses from F/N 018 and 049. (Note the distinct striations in the strain and a cross pattern for F/N 018, neither of which are discernable for F/N 049.) Figure 16 shows the effect of the residual strain on the surface. The fringes on F/N 018 show the overlaid form of a cross corresponding to the strain observed under the polariscope. Figure 16 also includes the double pass transmission interferograms of F/N 018 and 049. It is obvious that they are superior to the interferograms from the surface figure. This is direct evidence of the self-compensation which has been thought to occur when mutual distortion of top and bottom surfaces occurs. The % MTF was measured for F/N 018 and was found to be well within specifications, Table 3.

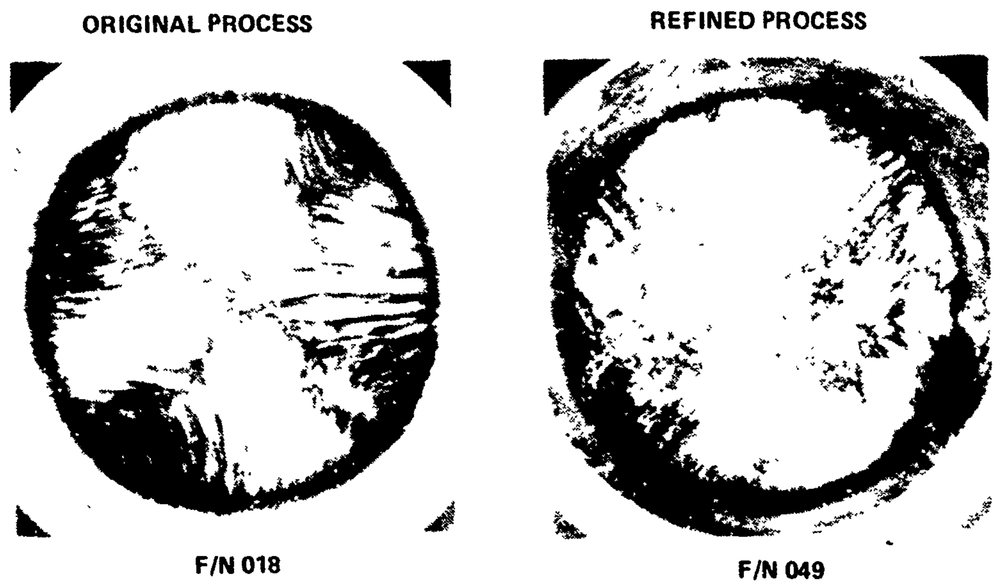



*Figure 15. Polariscopic photographs of KBr lenses as produced by the old and new processes.*

During this MM&T Program much consideration was given to the area of optical evaluation of the lenses. The surface figure, transmission distortion, and % MTF are the desirable parameters to measure on the lens. However, the % MTF measurements were extremely time consuming, which makes the technique unsuitable for production testing. Therefore, it was desirable to compare other measurements on the individual lens to tolerance standards which have been correlated back to the % MTF measurements. This would eliminate the need for the time consuming % MTF measurements on each lens.

We obtained a device manufactured by Digital Optics Corporation in Sunnyvale, California to achieve the required testing. This device is a surface interferometer which compares the lens surface to a standard reference surface and uses novel software and evaluation techniques. The device can compare the surface deviation of the

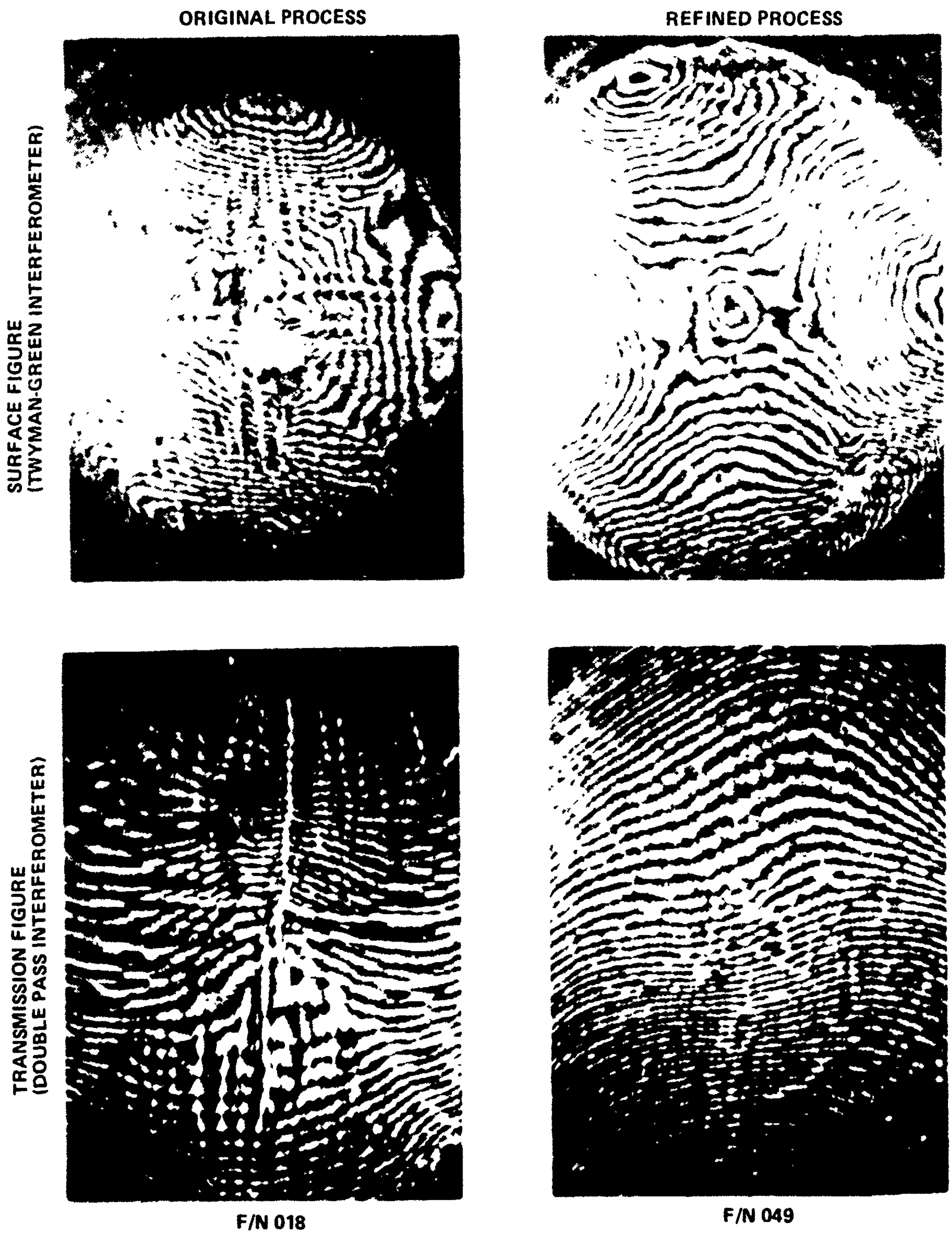



*Figure 16. Sample optical figures of KBr lenses as produced using the old and new processes.*

*TABLE 3. RESULTS OF %MTF MEASUREMENTS AT 10 LINE PAIRS/MM FOR SELECTED KBr LENSES*

| Forging No. | On Axis | 5mm Off Axis | Effective Focal Length | Flange Focal Length |
|---|---|---|---|---|
| Specification | >74% | >66% | 67.8 ± .7mm | 17.86 ±.25mm |
| -597* | 75.48% | | 69.26 | 17.62 |
| -018 | 77.29% | 72.84% | 67.23 | 17.76 |
| -014 | 74.69% | 71.04% | 67.08 | 17.69 |
| -038 | 74.98% | 68.69% | 67.16 | 17.71 |

*Contract DAAK70-77-C-0218.

lens from the desired surface by comparing the lens to the radius of curvature for a reference surface. The deviation of the front and back surfaces can be subtracted out to determine the transmission wavefront distortion due to the lens surfaces.

Initially, tests were performed on the concave surfaces of two lenses, using the Digital Optics equipment. One lens was supplied by NV&EOL, which had been produced during the first few months of the contract. The other was a lens from the optimized 2 × 3 process (F/N 084). The lenses were compared to a test plate with radius of curvature of 17.2835 inches. The forging die had a radius of curvature of 17.2805 inches. When the comparison was done,, the old lens had a deviation of about 3-1/2 wavelengths of visible light over the central 20-millimeter diameter while the new lens had a deviation of only 1/2 wave. This showed the excellent progress which was made through optimization of the process parameters.

Figure 17 shows the raw test data output for F/N 084. The numbers indicate deviations of the lens from the reference surface (no. 9999 indicates pixels outside of the aperture area). The numbers represent 0.01 micron units of deviation in the sagitta. The data can then be displayed on a graphics CRT as a fringe pattern, stored for future use, or otherwise processed. Figures 18 and 19 are contour plots of the deviation (with tilt removed) for F/N 084. This illustrates just one of the possibilities for processing the data to visually display areas of high deviation.

Further tests were done on several lenses representing the best and worst lenses fabricated during the program. MTF measurements were taken as well as evaluation on the Digital Optics Equipment and wavefront distortion analysis. From these tests guidelines were developed for complete optical testing, using the Digital Optics Equipment (see Section 2.4). A go/no-go set of parameters was established to optically test the lenses using this equipment. Assuming proper forging techniques and the use of optical grade KBr single crystals, it was not necessary to do transmission testing on the lenses. Lenses passing the requirements on the Digital Optics interferometer also pass the %MTF requirements.

RUN2.DAT

DO YOU WANT TO NORMALIZE THE DATA (1=YES, 0=NO):

FIT A PLANE TO THE DATA? (1=YES,0=NO): 0

J →

I ↓

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 2 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 3 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 4 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 45 | 52 | 57 | 57 | 74 | 67 | 72 | 82 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 5 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 26 | 40 | 46 | 49 | 52 | 53 | 57 | 63 | 63 | 62 | 66 | 69 | 70 | 75 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 6 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 21 | 27 | 37 | 40 | 44 | 46 | 51 | 52 | 54 | 59 | 59 | 60 | 67 | 71 | 72 | 69 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 7 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 30 | 25 | 26 | 28 | 34 | 34 | 40 | 51 | 47 | 51 | 56 | 52 | 57 | 59 | 61 | 62 | 66 | 69 | 67 | 81 | 999 | 999 | 999 | 999 | 999 |
| 8 | 999 | 999 | 999 | 999 | 999 | 999 | 29 | 26 | 25 | 14 | [illegible] | 29 | 24 | 35 | 40 | 41 | 42 | [illegible] | 52 | 52 | 51 | 52 | 58 | 63 | 62 | 62 | 61 | 59 | 999 | 999 | 999 | 999 |
| 9 | 999 | 999 | 999 | 999 | 999 | 12 | 19 | 26 | 21 | 21 | 26 | 22 | 32 | [illegible] | 27 | 40 | 47 | 47 | 51 | 51 | 51 | 53 | 55 | 55 | 58 | 56 | 56 | 58 | 62 | 999 | 999 | 999 |
| 10 | 999 | 999 | 999 | 999 | 999 | 17 | 19 | 21 | 20 | 25 | 24 | 28 | 27 | [illegible] | 24 | 32 | 42 | 40 | 47 | 49 | 46 | 47 | 48 | 51 | 56 | 58 | 51 | 54 | 52 | 999 | 999 | 999 |
| 11 | 999 | 999 | 999 | 999 | 22 | 18 | 22 | 19 | 23 | 22 | 28 | 30 | 31 | 36 | 40 | 35 | 42 | 47 | 39 | 42 | 44 | 48 | 47 | 50 | 47 | 53 | 51 | 51 | 45 | 54 | 999 | 999 |
| 12 | 999 | 999 | 999 | 22 | 21 | 21 | 23 | 28 | 21 | 26 | 28 | 36 | 31 | 35 | 36 | 40 | 35 | 41 | 44 | 42 | 44 | 43 | 43 | 45 | 45 | 50 | 51 | 50 | 48 | 44 | 999 | 999 |
| 13 | 999 | 999 | 999 | 27 | 23 | 26 | 26 | 29 | 33 | 31 | 23 | 31 | 31 | 38 | 38 | 38 | 40 | 40 | 38 | 40 | 41 | 41 | 45 | 45 | 44 | 48 | 46 | 44 | 44 | 44 | 42 | 999 |
| 14 | 999 | 999 | 999 | 27 | 27 | 29 | 28 | 33 | 22 | 22 | 33 | 27 | 22 | 35 | 37 | 37 | 27 | 40 | 41 | 41 | 40 | 42 | 42 | 44 | 46 | 42 | 47 | 45 | 41 | 41 | 34 | 999 |
| 15 | 999 | 999 | 29 | 27 | 30 | 31 | 33 | 33 | 34 | 35 | 37 | 36 | 33 | 34 | 34 | 22 | 39 | 40 | 39 | [illegible] | 41 | 41 | 41 | 43 | 42 | 45 | 42 | 41 | 38 | 34 | 32 | 999 |
| 16 | 999 | 999 | 999 | 27 | 31 | 25 | 34 | 36 | 28 | 27 | 27 | 25 | 36 | 32 | 34 | 27 | 40 | 42 | 38 | 40 | 40 | 40 | 45 | 40 | 38 | 38 | 42 | 38 | 32 | 34 | 31 | 34 |
| 17 | 999 | 999 | 29 | 27 | 31 | 33 | 36 | 36 | 35 | 37 | 39 | 38 | 35 | 39 | 36 | 41 | 42 | 39 | 39 | 40 | 39 | 39 | 35 | 40 | 37 | 37 | 38 | 35 | 32 | 28 | 29 | 28 |
| 18 | 999 | 999 | 31 | 28 | 30 | 34 | 39 | 36 | 39 | 40 | 41 | 38 | 37 | 37 | 40 | 41 | 36 | 41 | 40 | 38 | 37 | 38 | 35 | 36 | 36 | 35 | 35 | 33 | 31 | 30 | 27 | 30 |
| 19 | 999 | 999 | 26 | 30 | 30 | 34 | 29 | 39 | 37 | 40 | 39 | 37 | 37 | 41 | 38 | 39 | 39 | 35 | 41 | 40 | 35 | 37 | 35 | 36 | 31 | 34 | 29 | 30 | 27 | 28 | 26 | 999 |
| 20 | 999 | 999 | 31 | 30 | 30 | 32 | 37 | 38 | 37 | 39 | 40 | 38 | 33 | 42 | 42 | 41 | 41 | 41 | 39 | 36 | 34 | 34 | 32 | 32 | 29 | 29 | 26 | 26 | 28 | 25 | 26 | 999 |
| 21 | 999 | 999 | 25 | 25 | 28 | 30 | 34 | 35 | 28 | 29 | [illegible] | 37 | 39 | 42 | 40 | 41 | 40 | 40 | 40 | 37 | 38 | 35 | 31 | 32 | 28 | 27 | 26 | 23 | 26 | 24 | 22 | 999 |
| 22 | 999 | 999 | 999 | 21 | 22 | 26 | 20 | 34 | 35 | 23 | 37 | 28 | 41 | 41 | 40 | 39 | 39 | 39 | 42 | 42 | 34 | 35 | 31 | 27 | 27 | 23 | 26 | 26 | 21 | 22 | 18 | 999 |
| 23 | 999 | 999 | 999 | 20 | 20 | 23 | 25 | 31 | 31 | 34 | 34 | 36 | 37 | 40 | 39 | 39 | 38 | 35 | 35 | 35 | 32 | 34 | 31 | 27 | 16 | 23 | 23 | 23 | 18 | 19 | 22 | 999 |
| 24 | 999 | 999 | 999 | 12 | 18 | 19 | 20 | 22 | 26 | 34 | 31 | 35 | 36 | 36 | 38 | 38 | 37 | 34 | 36 | 35 | 32 | 32 | 28 | 25 | 26 | 23 | 20 | 17 | 18 | 16 | 999 | 999 |
| 25 | 999 | 999 | 999 | 999 | 11 | 11 | 16 | 19 | 23 | 27 | 29 | 29 | 33 | 31 | 33 | 34 | 37 | 33 | 33 | 33 | 32 | 29 | 27 | 23 | 21 | 21 | 20 | 18 | 16 | 11 | 999 | 999 |
| 26 | 999 | 999 | 999 | 999 | 2 | 7 | 13 | 14 | 16 | 21 | 26 | 29 | 29 | 32 | 30 | 32 | 30 | 32 | 33 | 29 | 33 | 26 | 23 | 21 | 19 | 17 | 18 | 15 | 17 | 999 | 999 | 999 |
| 27 | 999 | 999 | 999 | 999 | 999 | 4 | 8 | 11 | 18 | 21 | 24 | 24 | 21 | 20 | 25 | 28 | 26 | 30 | 30 | 27 | 26 | 25 | 21 | 19 | 16 | 18 | 16 | 10 | 999 | 999 | 999 | 999 |
| 28 | 999 | 999 | 999 | 999 | 999 | 999 | 2 | 6 | 6 | 11 | 18 | 19 | 23 | 24 | 22 | 21 | 22 | 27 | 28 | 25 | 23 | 24 | 22 | 18 | 15 | 10 | 10 | 10 | 999 | 999 | 999 | 999 |
| 29 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 2 | 2 | 7 | 9 | 14 | 19 | 21 | 20 | 21 | 19 | 22 | 26 | 22 | 20 | 19 | 18 | 13 | 8 | 8 | 999 | 999 | 999 | 999 | 999 | 999 |
| 30 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 0 | 5 | 6 | 11 | 13 | 17 | 18 | 17 | 21 | 19 | 20 | 19 | 18 | 11 | 11 | 10 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 31 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 5 | 7 | 7 | 6 | 13 | 14 | 10 | 13 | 11 | 10 | 13 | 6 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |
| 32 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 3 | 8 | 6 | 7 | 4 | 6 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 | 999 |

ENTER FILENAME:

Figure 17. Raw test data output for lens 084.

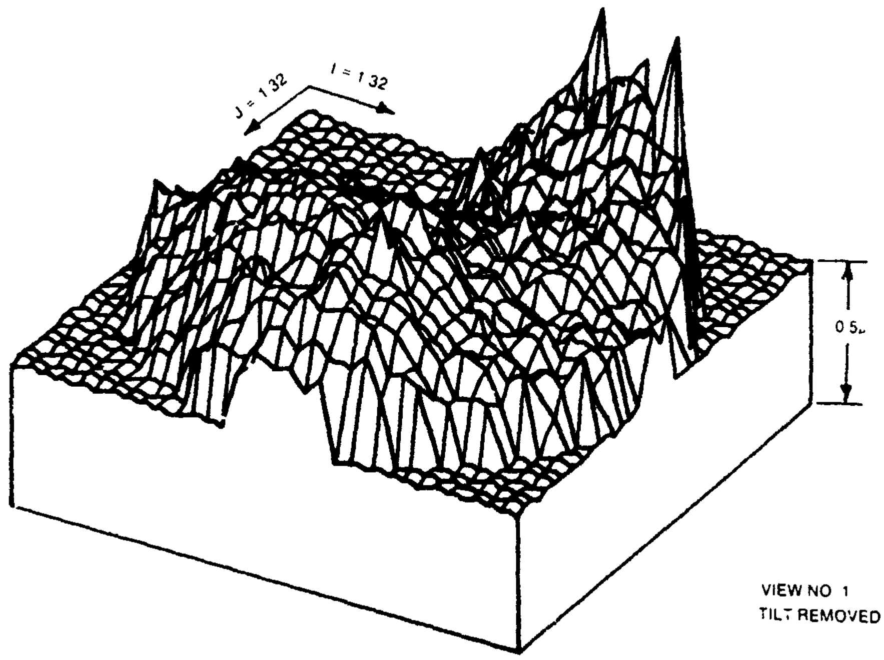



***Figure 18. Contour plot of concave surface deviation of lens 084.***

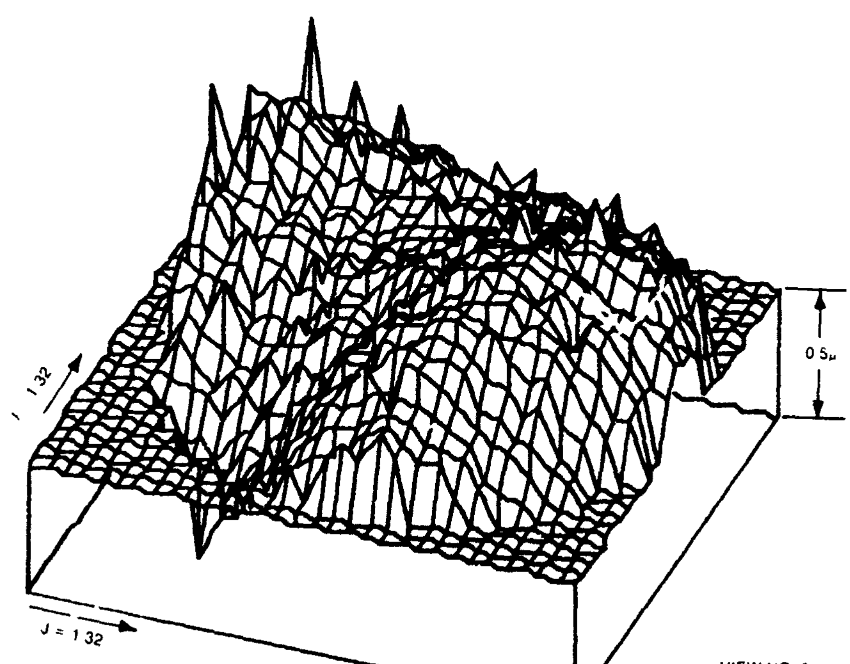



***Figure 19. Contour plot of concave surface deviation of lens 084 rotated 90 degrees.***

### 2.2.5 Summary of Process Refinements

In the process refinement portion of this program, exceptional progress was made in reducing the complexity and cost of the process while improving the lens quality. All process tooling, equipment and techniques for the first- and second-stage crystal and forging configurations were optimized as well as the forging parameters themselves. Series forging was successfully demonstrated for the second-stage forging process and attempted for first-stage forging, but has shown not to be the best approach for first-stage forgings. Hot transfer of the crystals to the first-stage forging operation was shown to be feasible but discarded in lieu of hot transfer of the assembled dies and forging in parallel. The hot transfer of assembled dies was also shown to be the best method for production of second-stage forgings, Section 2.3.

The optical testing approach was also optimized for inspection type personnel where only two pieces of test equipment were required. The Digital Optics Interferometer performed the surface distortion analysis and compared both surfaces of a lens to reference test surfaces.

The polariscopic examination of single crystals, first-stage and second-stage forgings assured that bulk optical uniformity and transmission were maintained. When these two tests were met, the %MTF, effective focal length and flange focal length requirements for the KBr in the IR-imager were met.

## 2.3 PROCESS DOCUMENTATIONN

The refined process as developed for the production forging of the lenses is described in the following sections. The overall process flow is presented, followed by the actual material and equipment required to perform the described process.

### 2.3.1 Final Processing Flow Diagram

Figure 20 shows the production process flow. The process is divided into four major areas:

1) Initial crystal inspection
2) First-stage forging
3) Second-stage forging
4) Final processing.

The incoming KBr crystals are examined for flaws, inclusions and the proper orientation, after which they are examined polariscopically for strain.

The crystals are then water polished and loaded into the lubricated dies. The dies are heated in the oven and then transferred in lots of six to the press to be forged. After forging the dies are removed, cooled and the blanks removed. The dies are reloaded and returned to the heating oven.

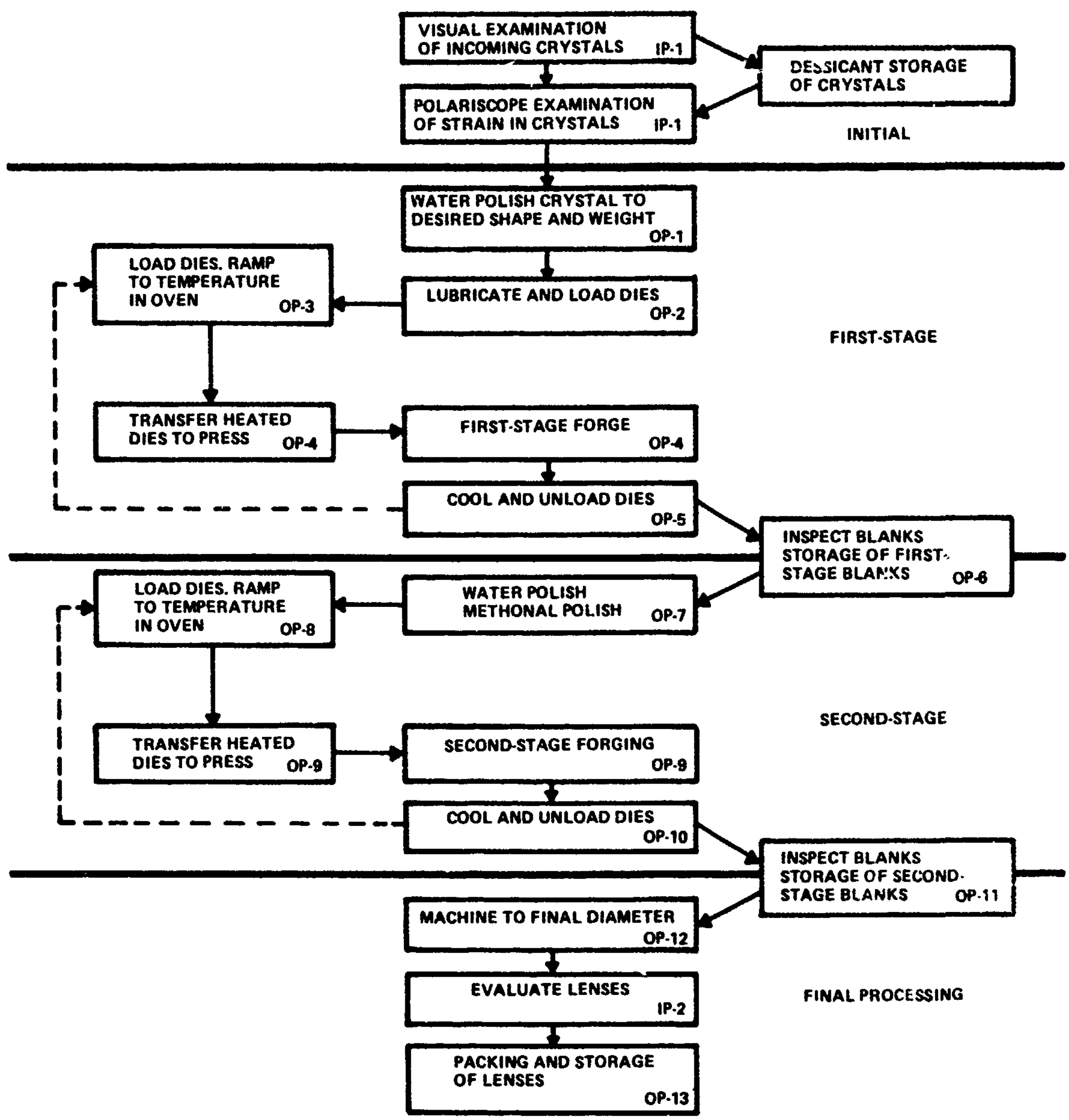



*Figure 20. Block diagram of forging process.*

For second-stage forging the first-stage blanks are water polished, methanol polished and loaded into the two-high forging assemblies for preheating in an oven. The heated assemblies are transferred into the press, forged, removed and cooled. The lenses are unloaded and the dies reloaded for heating in the oven.

The flange and final diameter is then machined on the lens, followed by optical evaluation, packaging and shipping the lenses. The details of the process are presented in the following subsection.

### 2.3.2 Processing Material, Equipment, Tooling and Procedures

The format for this section is as follows: Each operation is numerically identified, followed by the required materials, equipment and tooling. The procedure is then described for performing the operation. The equipment specifications and tooling drawings are referenced and presented in Appendix A and B.

- Operation No. 01—Single Crystal Polish

| | |
|---|---|
| Material: | Inspected KBr single crystals, Dwg. No. 27062<br>Distilled water<br>Rubber gloves (surgical, non-powdered)<br>Paper toweling<br>Methanol, special analytical grade, $H_2O$ content $<0.03\%$ |
| Equipment: | Rotating lapping station<br>Polarization light box |
| Tooling: | N[illegible] |
| Procedure: | Turn on the water feed (10-30drops/min) to the rotating lap. Wearing rubber gloves, round the faces and sharp edge of the cylindrical crystals Then polish the sides of the crystal by holding them horizontally on the lap and slowly rotating the crystal. Periodically dry off the crystal with a paper towel and weight. Continue water polish until the crystal weighs $89+1,-0$ grams. When the desired weight is obtained, wet cheesecloth with methanol and rub all surfaces of the crystal until all residual haze is gone. Check final polished crystal under polarized light to make sure all surface damage has been removed. |

- Operation No. 02—Preparation and Loading of First-Stage Dies

| | |
|---|---|
| Material: | Polished KBr crystals<br>MS-122 (Miller-Stephenson) Fluorocarbon spray or equivalent<br>Dry nitrogen gas supply, 15 psi minimum, with ionizing nozzle<br>Rubber gloves (surgical, non-powdered)<br>Face masks |
| Equipment: | Filtered air-flow bench<br>Humidity controlled environment, 35% RH maximum |

Tooling: First-stage forging sleeve (Dwg. No. 28100608)
First-stage dies (Dwg.No. 28100608)

Procedure: Perform this operation in a humidity controlled area on a flow bench with dust filtered air flow.

Wear rubber gloves and face masks to prevent moisture and skin oil contamination of the crystals. Inspect all tooling and die surfaces for wear and damage. Repair as necessary. Spray all surfaces of the dies and inside surface of the forging sleeve with the fluorocarbon lubricant. Spray die and crystal surfaces with dry nitrogen to remove dust. Place the conical die in the forging sleeve, conical surface up. Place the crystal in the center of the conical die and insert the flat die, forging surface down, as shown in Dwg. No. 28100608.

- Operation No. 03—Preheat First-Stage Die Assemblies

Material: Assembled First-Stage Dies (Dwg. No. 28100608)

Equipment: Heating oven, 250°C minimum

Tooling: None

Procedure: Place the assembled dies into the oven for heating. From a cold start, place the temperature set point at 250°C and turn on the oven. When loading dies into a heated oven, allow the oven to cool to 125±5°C. Allow assemblies to soak at 250°±5°C for four hours before forging.

- Operation No. 04—First-Stage Forging

Materials: Asbestos gloves
Metal carrying tray
Six heated forging assemblies

Equipment: Heated press for forging
Computer controls

Tooling: Tape cassette (Forging Program Software)

Procedure: Remove six heated assemblies from the oven and place in press at 250°C. Close the press until almost in contact with the dies. Continue forging at a constant strain rate of 6.4%/minute. This can be done manually by changing the current to the metering valve via the computer keyboard, or automatically by programming the computer for a constant 6.4% strain rate. When 80% of the final forging pressure is reached (28,000 lb/crystal, or 168,000 lb. for six assemblies) discontinue combined forging and perform individual forging to a final pressure of 35,000 lb/crystal.

The automated process controls consist of a current-driven metering valve to control the ram speed, pressure transducer to monitor oil pressure, Accurate distance meter (0.0001-inch resolution), and thermocouple to monitor temperature. These devices are tied into a computer with a real-time clock. The computer calculates distance traveled per time interval and adjusts the oil flow accordingly. When the proper pressure is reached the computer shuts down the forging operation. Should temperature or pressure problems arise, the computer stops the process and alerts the operator visually and audibly. A constant display of temperature, pressure and distance traveled is maintained on the computer display, and once a minute the computer prints an update on the status of the forging. This tape serves as a record for process control.

- Operation No. 05—Cool and Unload First-Stage Forging

| | |
|---|---|
| Materials: | Rubber gloves<br>Identified polyethylene bags<br>Forged assemblies<br>Asbestos gloves<br>Asbestos-tipped tongs<br>Metal trays, with fiberglass insulated lining |
| Equipment: | Cooling oven<br>Low humidity storage area (< 35% RH) |
| Tooling: | Aluminum cooling plate with metal spacers (Dwg. No. 28100617) |
| Procedure: | Preheat oven and trays to 100°C. Place the aluminum cooling plate with metal spacers to allow 1 inch of air space beneath the plate. Using the asbestos gloves, transfer the forged assemblies from the hot press to the cooling plate. After 15 minutes, remove the sleeve and top die. Use the asbestos-tipped tongs to transfer the forgings to a pre-heated, insulated tray and place immediately in the oven. Be sure to maintain the identity of each forging. When the oven is full of forgings (or at the end of the work day), turn the oven off and allow to cool. When cool, remove the forgings and place in a polyethylene bag with an identifying label corresponding to the proper traveller sheet for that forging. Store in low (< 35% R.H.) humidity area. |

- Operation No. 06—Inspection of First Stage Forgings

| | |
|---|---|
| Materials: | KBr First-Stage Forgings<br>Rubber gloves, (surgical non-powdered) |
| Equipment: | Polarization light box |
| Tooling: | Polariscopic Strain Standards (Dwg. No. 28100618) |
| Procedure: | Wearing rubber gloves, remove the first-stage forging, from the polyethylene bags. Inspect visually for complete die filling, cracks and chips. The forgings must have replicated the steel dies to within 1/4" of the edge. The forging must have made contact with the forging sleeve over the entire circumference. Forgings with incomplete replication or wall contact can be reforged providing |

there are no cracks in the forging. Inspect all forgings under the polariscope for excessive strain. Indicate on the traveller sheets the degree of strain (i.e., low, high, average) as compared to strain standards. Return forgings to their identified bags and return to storage.

- Operation No. 07—Preparation of Blanks for Second-Stage Forging

Materials:

Inspected first-stage forgings
Rubber gloves (surgical non-powdered)
Cheesecloth
Methanol, special analytical grade, $H_2O$ content $<0.03\%$
Face masks
Polyethylene bags

Equipment:

Vacuum pump
High pressure dry nitrogen blow-off station
Triple beam balance

Tooling:

Vacuum chuck (Dwg. No. 28100613)

Procedure:

This process removes all traces of the fluorocarbon lubricant and reduces the forging weight to 85 $\pm$ 0.5 grams. Wear rubber gloves and face masks during this operation.

Place the forging in the vacuum chuck and engage vacuum. Wet the cheesecloth under cool running tap water. Wring cloth slightly, but leave fairly wet during removal of lubricant. Rub the wet cloth briskly over the entire forging surface for 5-10 seconds. Immediately after removing the wet cloth, release a one-second burst of 1000 psi dry nitrogen across the forging surface. Rinse the cloth thoroughly and repeat, gradually reducing the rubbing time as the lubricant is removed. Concentrate on heavy lubricanted areas. When all lubricant is removed, do the same with the opposite surface. When all lubricant is removed weigh the forging. Return forging to vacuum chuck and wipe with a well-rinsed, thoroughly wrung cloth for 1-2 second swipes. Rinse cloth and wring thoroughly after each swipe. Upon completion of a swipe, blow off with a dry nitrogen blast. Weigh forging as required and polish until within the 85 $\pm$ 0.5 gram tolerance. The residual haze must be removed by either dry or methanol polishing with cheesecloth. If the haze is moderate to low, and there are no water spots or streaks, dry polish vigorously with cheesecloth. If there is excessive haze, water spots or streaks, wet the cheesecloth with ethanol and polish until clear. Place the polished forgings in clean, polyethylene identified storage bags.

- Operation No. 08—Load and Preheat Second-Stage Forging Assemblies

Materials:

Polished first-stage forgings
Rubber gloves (surgical non-powdered)
Face masks
MS-122 fluorocarbon lubricant
Liquid detergent

Equipment: Low-pressure (10-15 psi) dry nitrogen supply with ionizing spray nozzle
Filtered flow bench in low humidity environment (< 35% RH)
Heating oven

Tooling: Convex and flat polished Pyrex dies (Dwg. No. 28100609)
Spacing rams (Dwg. No. 28100609)
Forging sleeve (Dwg. No. 28100609)

Procedure: Spray the inside of the forging sleeve and sides of the forging rams with fluorocarbon lubricant, wash and dry the Pyrex dies using a mild, non-abrasive liquid detergent. While wearing rubber gloves and face mask, remove polished forgings from the storage bags. Blow off the faces of the Pyrex dies and the first-stage forgings with the ionized, dry nitrogen to remove dust.

Insert into the top of the forging sleeve the following: the three-inch bottom spacer, convex Pyrex die, first-stage forging (flat side down), flat Pyrex die, 1-1/2" spacer, convex Pyrex die, first-stage forging (flat side down), flat Pyrex die and 4" spacer. (See Dwg. No. 28100609.) After assembly, place the assemblies in a preheated 225 ± 5°C oven. Assemblies must soak in oven a minimum of 6 hours before forging.

- Operation No. 09—Transfer and Forging of Second-Stage Assemblies

Materials: Asbestos gloves
Loaded and preheated forging assemblies (3) (Dwg. No. 28100609)
Teflon sheets, 0.010" × 3" × 3" (3)

Equipment: Heated press for forging
Computer controls

Tooling: Tape cassette (forging program software)

Procedure: Wear asbestos gloves to transfer three preheated assemblies to the preheated press (225 ± 3,0°C). Place a sheet of 0.010" teflon on the top of each assembly and begin forging using the constant speed software program. Perform the forging at a rate of 0.012"/minute to a final pressure of 35,000 pounds for the three assemblies. Hold at pressure for 5 minutes and release to starting position. (Refer to Operation No. 04 procedure for a description of the computer controls.)

- Operation No. 10—Cool and Unload Second-Stage Dies

Materials: Forged second-stage assemblies
Asbestos gloves
Plastic boxes with cover; 2-1/2 × 2-1/2 square × 3-5" long
Rubber gloves (surgical non-powdered)
Face masks

Equipment: Humidity controlled room (< 35% R.H.)
6" vernier caliperes

Tooling: Aluminum cooling table (Dwg. No. 28100617)

Procedure: Remove the forged assemblies from the heated press and place on aluminum cooling table. Allow to cool to 35°C or less. Transfer the cooled assemblies to the humidity controlled (<35% R.H.) area. Wearing rubber gloves and face mask disassemble the dies. Keep the forged lens sandwiched between the Pyrex dies and measure the height of the lens/die assembly with vernier calipers. The Pyrex dies are identified with their height. Substract the die height from the measured die/lens thickness to determine the lens center thickness. Record this thickness on the traveler sheet. Place the lens in a plastic box in such a manner that the surfaces of the lens do not touch the box (concave surface down). Mark the I.D. number of the lens on the cover of the box and store for next operation.

- Operation No. 11—Inspection and Storage of Second-Stage Forgings

Materials: Rubber gloves (surgical non-powdered)
Face masks
Forged lens blanks in plastic boxes

Equipment: Polariscopic light box
Desiccated storage cabinet

Tooling: Strain standards, Dwg. No. 28100620

Procedure: Visually examine the lens for chips, cracks and inclusions. Any lenses possessing defects within the clear aperture 2.280" gage are to be rejected. Lenses which have incomplete die replication within the clear aperture can be saved for repeat forging, provided there are no other defects, Examine the forgings in the polariscopic light box for strain evaluation and compare to go/no-go strain standards. Indicate on the traveler sheet the relative amount of strain (i.e., low, high, excessive-rejected, etc.). Return the lenses to the storage boxes and return to a desiccated storage cabinet.

- Operation No. 12—Flange Machining

Materials: Inspected second-stage forged blanks
Rubber gloves (surgical non-powdered)
Face masks
Razor blades (single edged)
Low-pressure (10-15 psi) dry nitrogen with ionizing spray nozzle

Equipment: Machining lathe (Dwg. No. 28100611)
HeNe laser (5 mW or less)

Tooling: Machining fixture (Dwg. No. 28100610)

Procedure: While wearing gloves and face mask, carefully remove any edge flashing around the forging with a razor blade. Insert the lens into the machining fixture with the concave surface out. The HeNe laser is aligned along the lathe axis as shown in drawing. The beam passes through a pinhole in the screen, reflects oft the front and back surfaces of the lens and appears on the front of the cardboard screen. With the room lights off, turn the alignment screws and rotate the fixture so as to superimpose the surface reflections and center them on the pinhole. This ensures that tilt has been removed and the optic axis of the lens coincides with the lathe axis. Using a lathe speed of 500-600 rpm and a maximum cut of 0.030", machine the O.D. to 2.450" as deep as possible. Then machine the 2.280" minor diameter to 0.075" deep from the concave face. (Machine all the lenses in a lot in this manner.) Remove the alignment fixture. Use a collet to hold the machined minor diameter on the concave side. Finish machining the major diameter, then machine the minor diameter 0.100" deep from the flat side. Blow off excess machining dust from each side of lens with low pressure dry nitrogen.

- Operation No. 13—Packing and Shipping

Materials:
Rubber gloves (surgical non-powdered)
Face masks
Packing containers—2.5" diameter fluoroware type H22-25 with plastic springs and covers
Identification labels
Nylon packing tape
Desiccant
Packing material—bubble pack
Poly-lined aluminum foil bags—MIL-B-131F; Class 1
Shipping box

Equipment: Heat Sealer

Tooling: None

Procedure: Wearing rubber gloves and face masks, place the lens in the bottom packing container with the flat side down so only the edges of the lens are in contact with the container. Place one concave retaining spring with concave side against the concave lens surface. Depress springs with covers and screw in place. Tape around the circumference of the package to prevent the cover from popping off. Place the lens identification label on the top cover of the package. Place six containers in a polyethylene coated aluminum foil bag with six capsules of desiccant, deair and heat seal the bag. Place identification label on bag and place 1 to 10 bags in a cardboard shipping box using bubble pack around inside surface of box and between bags of lenses. Close and tape box, add packing slip and shipping labels to box.

## 2.4 QUALITY ASSURANCE

To ensure that the hot-forge-to-shape plano-concave KBr lenses produced by the processed defined in Section 2.3 meet the requirements for the drawings and specifications given in Appendix B, a quality test plan has been established for the program. This Quality Assurance Program is presented below and would be coordinated by our Quality Department. An approved system is in place which meets MIL-STD-45208A "Inspection System Requirements."

### 2.4.1 Material Control

Single crystal starting material for the hot-forge-to-shape process is essential to producing a consistent, reliable lens. The KBr cyrstals required are available from two domestic sources (Optovac, Inc. in North Brookfield, Mass. and Harshaw Chemical Co. Solon, Ohio). These would be procured against Honeywell Material Specification No. 27062 as described in Appendix A. Each shipment of KBr single crystals shall be inspected by the procedure given below.

- Inspection Procedure No. 01—Incoming Single Crystal Acceptance

| | |
|---|---|
| Material: | Incoming optical grade KBr, (100) orientation<br>Single edge razor blade<br>Polaroid film<br>Small mallet (4-6 ounce)<br>Identification labels and traveler sheets<br>Storage bags, polyethelene, 5″ × 6″<br>Metal trays |
| Equipment: | Polarization Light Box<br>Polaroid Camera<br>Dessicated storage container |
| Tooling: | Strain Standards—Single Crystals (Dwg. No. 28100619) |
| Procedure: | Remove packing material from crystals and place them on a tray. Avoid breathing on crystals as well as excessive (65%) humidity. Generate a traveler sheet for each crystal similar to the one shown in Figure 21. A set of labels must show a forging I.D. number, a place for the date and lot number. For each crystal, three labels are needed with the above information. One label is marked "bag," one is marked "container" and one is marked "run data" for the traveler sheet. A fourth label (marked "polariscopic photos") is required for those crystals which are photographed. Visually examine the crystals for chips and cracks. Small surface chips and scratches are acceptable as these will be removed during subsequent processing. Internal flaws, however, are not acceptable. Record the results of the visual examination on the traveler (i.e., no chips or cracks; small edge chips; rejected-internal cracks). The weight and dimensions are then taken and the crystal placed in the plastic bag, being careful that the bag number corresponds to the traveler number. |

## 2.4 QUALITY ASSURANCE

To ensure that the hot-forge-to-shape plano-concave KBr lenses produced by the processed defined in Section 2.3 meet the requirements for the drawings and specifications given in Appendix B, a quality test plan has been established for the program. This Quality Assurance Program is presented below and would be coordinated by our Quality Department. An approved system is in place which meets MIL-STD-45208A "Inspection System Requirements."

### 2.4.1 Material Control

Single crystal starting material for the hot-forge-to-shape process is essential to producing a consistent, reliable lens. The KBr cyrstals required are available from two domestic sources (Optovac, Inc. in North Brookfield, Mass. and Harshaw Chemical Co. Solon, Ohio). These would be procured against Honeywell Material Specification No. 27062 as described in Appendix A. Each shipment of KBr single crystals shall be inspected by the procedure given below.

- Inspection Procedure No. 01—Incoming Single Crystal Acceptance

| | |
|---|---|
| Material: | Incoming optical grade KBr, (100) orientation<br>Single edge razor blade<br>Polaroid film<br>Small mallet (4-6 ounce)<br>Identification labels and traveler sheets<br>Storage bags, polyethelene, 5″ × 6″<br>Metal trays |
| Equipment: | Polarization Light Box<br>Polaroid Camera<br>Dessicated storage container |
| Tooling: | Strain Standards—Single Crystals (Dwg. No. 28100619) |
| Procedure: | Remove packing material from crystals and place them on a tray. Avoid breathing on crystals as well as excessive (65%) humidity. Generate a traveler sheet for each crystal similar to the one shown in Figure 21. A set of labels must show a forging I.D. number, a place for the date and lot number. For each crystal, three labels are needed with the above information. One label is marked "bag," one is marked "container" and one is marked "run data" for the traveler sheet. A fourth label (marked "polariscopic photos") is required for those crystals which are photographed. Visually examine the crystals for chips and cracks. Small surface chips and scratches are acceptable as these will be removed during subsequent processing. Internal flaws, however, are not acceptable. Record the results of the visual examination on the traveler (i.e., no chips or cracks; small edge chips; rejected-internal cracks). The weight and dimensions are then taken and the crystal placed in the plastic bag, being careful that the bag number corresponds to the traveler number. |

HONEYWELL CERAMICS CENTER
OPTICAL LENS BLANK PROCESSING DATA SHEET
CONTRACT NO. ______

A MATERIAL IDENTIFICATION — BLANK ID ____________

VENDOR DATA

MATERIAL TYPE ____________

INGOT NO. ____________

DATE RECEIVED ____________

INSPECTOR ________ DATE ________

HONEYWELL DATA

P.O. ________ INSHIP NO. ________

ITEM NO. ____________

WEIGHT ____________

DIMENSIONS ______ "TH X ______ " DIA.

B. INCOMING INSPECTION

VISUAL ____________

POLARISCOPIC ____________

ORIENTATION ____________ INSPECTOR ________ DATE ______

C. HOT FORGING:

FIRST STAGE

CORE: PREPARATION ____________

DIMENSIONS ________ X ________ ________
THICK DIAMETER WEIGHT

DIE SET: ID ________ TYPE ________

PARAMETERS: TEMP ______ RAM RATE ______ REDUCTION ______ STRAIN RATE ______

FINAL DIMENSION: ________ X ________
THICK EFF. DIA.

REMARKS: ____________

SECOND STAGE:

CORE: PREPARATION ____________

DIMENSIONS ________ X ________ ________
THICK DIAMETER WEIGHT

DIE SET: ID ________ TYPE ________

PARAMETERS: TEMP ______ RAM RATE ______ REDUCTION ______ STRAIN RATE ______

EVACUATE: ________ ISOSTAT. PRESS ________

FINAL DIMENSION: ________ X ________
THICK EFF. DIA.

REMARKS: ____________

EVALUATION:

VISUAL ________ INSPECTOR ________ DATE ______

POLARISCOPIC ____________

SPHERICITY ________ FLATNESS ________

MACHINING

PROCESS ________ INSPECTOR ________ DATE ______

FLANGE DIMENSION ________ X ________ X ________
THICK MINOR DIA. MAJOR DIA.

*Figure 21. Lens traveler sheet.*

After visual examination, polariscopically examine the strain in each crystal. Place the crystal between the polarizer plates and rotate to obtain the maximum strain pattern. Rank the crystals in a lot for high, low or average strain. Photograph one each of the highest, lowest and average strain crystals. Record on the traveler sheets the qualitative strain for each crystal (i.e., high, low, average based on strain standard).

If the crystal was one which was photographed, record this on the traveler. Attach the photo to a backing sheet, identify with the "Polariscopic Photo" label, and attach to the traveler. Save the tag marked "container label" for identifying the packing container of the finished lens.

The vendor should certify that the cylinder faces are (100) faces. No x-ray diffraction is required by the customer. However, leave one crystal per lot as a verification of (100) orientation. To do this, take the tallest crystal of the lot and lay it on its side on a clean, hard surface. Place a sharp, unused single-edged razor blade 1/8" or less from one of the faces, with the blade parallel to the face and perpendicular to the side of the crystal. (Drawing No. 28100614). To cleave, rap the razor blade sharply with a small mallet (four to six ounces). The crystal should cleave cleanly parallel to the face. It is imperative that the razor blade be parallel to within 3° of the crystal face. If the cleavage is not smooth or cracks propagate in other directions within the crystal, re-cleave the crystal. In the event the second cleavage is also bad, the lot should be investigated further for proper orientation. Cleave additional crystals if necessary, return the lot to the vendor. On the traveler sheet indicate the crystals that were cleaved.

After inspecting, return the crystals to the plastic bags and place in a dessicated storage container.

### 2.4.2 Process Controls

The Quality Department periodical will conduct a process audit to establish that all processing procedures are being adhered to by the production operators, that all equipment requiring calibration has been properly calibrated, and the individual process controls checks made by production are being performed properly. The process checks for each operation as described in Section 2.3 are itemized below:

| Operation No. | Process Control Points |
|---|---|
| 01 | Weight of polished KBr 89±0.5 gms; surface damage removal (Polariscopic) and visual examination shape |
| 02 | Tooling wear and damage-visual; dimensional, check with calipers |
| 03 | Oven temperatuure control 250 ± 5°C |

| | |
|---|---|
| 04 | The computer program controls the process. Forging status is printed out every minute.<br>T—Temperature is controlled at 250 ± 3°C. (Computer will not start until temperature is within range. Computer "alerts" if temperature leaves range during forging.)<br>P—Pressure, step-1 with six dies—168,000 lbs. maximum; step-2 with one die—35,000 lbs. maximum (computer stops at programmed pressure point, also stops if pressure rise rate is too high or if maximum pressure is exceeded.)<br>R—Forging rate, 0.065 inches/minute to 0.022 inches/minute (forging rate follows a prescribed non-linear decreasing rate to yield a constant strain rate). |
| 05 | (None) |
| 06 | Surface finish of first-stage forging-visual<br>Surface damage and internal strain-Polariscopic visual examination |
| 07 | Weight 85 ± 1/2 grams |
| 08 | Check tooling for wear and damage; periodically check Pyrex die surfaces for flatness and convex radius; oven temperature 225 ± 5°C |
| 09 | Computer data tape<br>T = 225 ± 3°C<br>P = 95,000 lb. for 2 × 3 assembly<br>R = 0.012"/min |
| 10 | Check overall thickness of Pyrex Dies and second-stage forging, calculate center thickness 0.280 ± 0.010" mark forging identity |
| 11 | Surface finish of second-stage forging 80/50<br>Surface damage and internal strain polariscopic-visual |
| 12 | Check drawing dimensions<br>Flange = 0.150 ± 0.005, located 0.075 ± 0.005 from concave surface.<br>minor dia: 2.280 ± 0.005—0.000<br>major dia: 2450 ± 0.001 |
| 13 | (None) |

### 2.4.3 Final Inspection of KBr Lens

After a production lot of lenses has been completed a 100-percent inspection shall be given all lenses to assure that all lenses meet the drawing requirements and the optical criteria which are described below:

- Inspection Procedure No. 02—Final Inspection

Material: Completed lenses and traveler sheets
Rubber gloves (surgical non-powdered)
Face mask
Polaroid film

| | |
|---|---|
| Equipment: | Vernier calipers<br>Humidity controlled room (35% RH maximum)<br>Polarization light box with Polaroid camera<br>White-light interferometer (Dwg. No. 2810015)<br>Namarski microscope |
| Tooling: | Thickness Calibrated Pyrex Die Set<br>Go/no-go strain standard (Dwg. No. 2810020)<br>80/50 scratch dig reference plate<br>Computer software program |
| Procedure: | Wearing rubber gloves and a face mask in a humidity controlled room, remove a lens from the shipping container. Use a vernier caliper to check the following dimensions: |

| | |
|---|---|
| Flange thickness: | $0.150 \pm 0.005$ inch |
| Flange location: | $0.075 \pm 0.005$ inch from concave surface |
| Major diameter: | $2.450 \pm 0.001$ inches |
| Minor diameter: | $2.280 \pm {}^{0.005}_{0.000}$ inches |

Place the lens between the thickness calibrated die set and measure the total thickness of the lens and die set. Subtract the calibrated die thickness to obtain center thickness of lens. Center thickness = $0.280 \pm 0.010''$.

With the Namarski Microscope, compare the surface finish of both the concave and flat surfaces to the 80/50 scratch/dig reference plate. (Surface finish must be better than 80/50 reference.) Perform optical testing on the Digital Optics Interferometer. Place the lens in the sample holding fixture with the lens number on top, the flat side facing beam splitter and with the flat reference plate in the reference holder.

Follow computer operating procedure. The point-to-point deviation shall not exceed 300 units (μm). The maximum surface departure shall not exceed 2000 units (20μm). Repeat procedure for concave surface and concave reference being careful to keep the lens reference mark (lens No.) up. Repeat measurements.

- The point-to-point deviation shall not exceed 300 units (3μm).
- The maximum surface departure shall not exceed 2000 units (20μm).

Determine the total wavefront distortion due to the two surfaces by subtraction (computer command).

- Maximum departure (tilt removed) = 300 Units (3$\mu$m)
- Maximum point-to-point deviation = 50 units (0.5$\mu$m)

Remove lens from interferometer and check under cross polarizers for handling damage and internal strain. Compare to go/no-go strain standard. If ok after obtaining 6 lenses, document strain with Polaroid photograph, then place lens in containers for shipment. Document all data on lens traveler sheets.

### 2.4.4 Other Quality Measures

The manufacturing process described in section 2.3 and the process control point outlined in section 2.4.2 both depend heavily on the accuracy of its instrumentation. The Quality Assurance Department maintains and calibrates the equipment used in manufacturing and testing of the KBr lenses. Calibration accuracies are traceable to the National Bureau of Standards. A material review board system is in place to review corrective actions to be taken for nonconforming materials. Quality Engineers and a Failure Analysis group are available to provide timely feedback and adjustment of errors when they arise in the process or product. Well established processes are also routinely audited to ensure that the processing steps are being followed correctly to produce satisfactory products.

## 2.5 PILOT RUN AND CAPABILITY DOCUMENTATION

After all manufacturing and testing methods were established and documented these methods were used on a pilot run of twelve (12) lenses. During this pilot run a 15-minute video tape was made to further document the processes established in this program. All of the materials, equipment, tooling and procedures discussed in Section 2.3 were used to produce these 12 lenses. The Quality Assurance measures given in Section 2.4 were also followed. Of the 12 lenses produced 10 were judged to be satisfactory against our optical acceptance criteria.

The video tapes with an explanatory sound-track were produced in three formats—1/2" Beta-max, 1/2" VHS and standard 3/4" track. NV&EOL has one copy of each format and Honeywell has the master on file and one copy—1/2" VHS and standard 3/4" formats available.

# SECTION 3
# TEST RESULTS AND DISCUSSION

This section discusses the results obtained on the hot forged-to-shape KBr lenses produced during each of the four major tasks performed for this MM&T program. The four tasks are process optimization, multiple forging, optical testing and the final pilot run.

## 3.1 PROCESS OPTIMIZATION

In the initial portion of this program the research process for producing KBr lenses was transferred to the Honeywell Ceramics Center and the process was optimized and made suitable for production. A total of 70 lenses was produced by the one-at-a-time process. Table 4 gives the process modification tried and indicates the condition of the forged lens obtained. Of these 59 were judged to be suitable for optical testing. Of the 11 lenses which were not satisfactory, 5 first-stage forgings stuck to the die during attempts to simplify or eliminate the lubrication of the dies; three lenses broke or cracked during first-stage forging; one lens contained internal flaws which related to the single crystal; and one lens broke during handling. Only one second-stage forging failure occurred when one of the glass dies failed.

The initial five forgings (F/N 001 to 005) were produced on research equipment by the standard 4000 psi helium isostatic technique which was used during the research phase. Ceramic Center technicians and engineers produced these after several preliminary training forgings were produced. During this phase the research process was fully documented. Figure 22 shows the typical results obtained by research (F/N 719) and the initial MM&T forging (F/N 001). Note that no measurable optical fringes were obtained for the concave surface on either of these forgings. However, the compensation obtained from the plano surface helped to produce total wave front distortion fringes which appear to be about 3λ at 6328Å

The remaining portion of this subsection will discuss the more significant process modifications which were studied to improve the optical quality of the KBr lenses produced as well as those which were more cost effective.

### 3.1.1 Reduced Isostatic Pressure

The hot isostatic pressure research process was performed at 4000 psi. To scale up this approach to an economical production process would have required very expensive tooling and safety equipments. Many forgings were therefore produced at lower pressures without any significant problems, Table 4. Figures 23, 24, 25 and 26 show some of the results obtained. Note that the radius of curvature increased slightly (from 16.9 to 17.2 inches) as the pressure was reduced from 4000 to 100 psi. The optical cross observed for the residual strain in these lenses also became less ap-

# *TABLE 4. TEST RESULTS FOR KBr LENSES FORGED INDIVIDUALLY*

| Forging Number | Single Crystal | | First Stage Forging | | Second Stage Forging | | Final Forged Lens | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | Strain | Special Conditions | Special | Conditions | Special | Conditions | Strain | Condition | |
| 001-005 | Low Med | – | Teflon sheet on flat dies | | Machined cones | | Medium | O K | |
| 006 | Low | – | | | Mach cones 100 psi He | | Medium | O K | |
| 007 009 | Low | – | | | Machined cones | | Med High | O K | |
| 010 | Med High | – | Silicone oil flat dies | | Machined cones | | Med | O K | |
| 011 | High | – | | | Machined cones | | Med | O K | |
| 012 | Med High | – | Silicone oil conical dies | | | * | – | * | First stage failure |
| 013 014 | Med | – | | | | | High | O K | |
| 015 | Med | – | | | 2000 psi helium | | Med High | O K | |
| 016 | Med High | – | | | 100 psi helium | | – | Failed | Second stage failure |
| 017 | Med | (100) cube | | | | * | | * | |
| 018 | Med High | (100) cube | | | 100 psi helium | | Med | O K | |
| 019 | Med High | (100) cube | Teflon & silicone oil | | | * | – | * | Internal defects |
| 020 | Med | (100) cube | Silicone oil | | 2000 psi helium | | Med High | O K | |
| 021 | Med | (100) cube | | | | | | O K | |
| 022 | Med | (100) cube | Teflon sheet | | | * | – | * | Broken during handling |
| 023 | Med | (100) cube | | | 2000 psi helium | | | O K | |
| 024 | Med | (100) cube | Flat & conical dies | | 100 psi helium | | | O K | |
| 025 | Med | (100) cube | Flat & conical dies | | | * | | | |
| 026 | Med High | | Flat dies | | Machined cones, 4 | | | O K | |
| 027 028 | Med High | | Double conical dies | | 5 machined cones | | | O K | |
| 029 | Med High | (110) cyl | | | | | | O K | |
| 030 | Med High | (111) cyl | | | | | | O K | |
| 031 | Med | | 300 °C | | | | | O K | |
| 032 | Low | (110) cyl | 300 C | | | | | O K | |
| 033 | Med | (111) cyl | 300 C | | | | | O K | |
| 034 037 | Med High | (100) cyl | | | | | | O K | |
| 038 | Med High | | | | 4 forged cones 2000 psi helium | | | O K | |
| 039 | Med | | | | | * | – | * | Thermal shock failure |
| 040 | Low | | Brass conical dies silicone | | | * | – | * | Cracked |
| 041 | Low | | Brass, no lubricant | | | * | – | * | Stuck to dies |
| 042 | Med | | | | | * | – | * | Stuck to dies |
| 043 | Med | | Steel dies, no lubricant | | | * | – | * | Stuck to dies |
| 044-046 | Low Med | | Spray teflon lubricant | | 100 psi helium | | – | O K | Some surface haze |
| 047 | Med | | | | 1000 psi forged at 1 atm | | | O K | |
| 048 | Med | | | | 1 atm He | | | O K | |
| 049 051 | Med 051 high | | Brass w/spray teflon | | 100 psi helium | | Med | O K | Slight 1st stage sticking |
| 052 | High | (100) cube | | | 100 psi He | | Med High | O K | |
| 053 | High | (100) cyl | Fast heat & cool | | | | Med High | O K | |
| 054 055 | Low | | T/D = 82, fast cool | | | | Med High | O K | |
| 056 057 | Low Med | | T/D = 56, fast cool | | | | Med High | O K | |
| 058-059 | Med | | T/D = 46, fast cool | | | | | O K | |
| 062 | High | | Burn off sp teflon | | | * | | * | Die stuck and cracked |
| 063-064 | Low Med | | C S R 064 | | | | | O K | |
| 065 | Low | | C S R 10 | | | | | O K | |
| 066 067 | Med High | | C S R 064 | | 250 °C | | | O K | |
| 070 | Med | | | | 250 C | | | O K | |
| 071,077,091 | Med | | | | | * | | * | |
| 072,073,076 | High | | | | | | | O K | For CTC coating work |
| 078-080 | Med | | No lubricant | | | * | | * | Stuck to die |
| 081 | Med | | | One step | | | | Failed | |

* No second stage lens produced
T = Thickness
D = Diameter
C S R = Constant strain rate

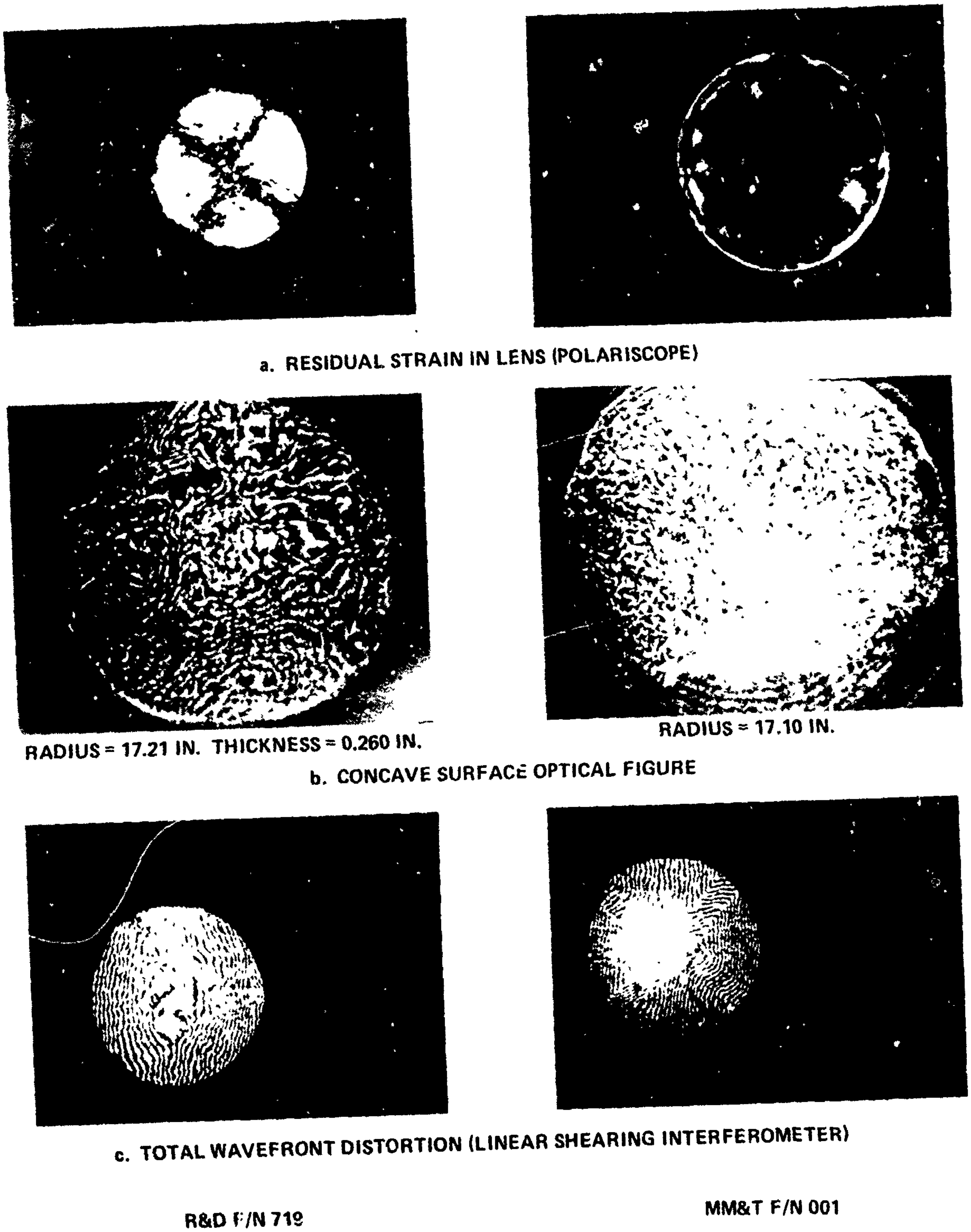
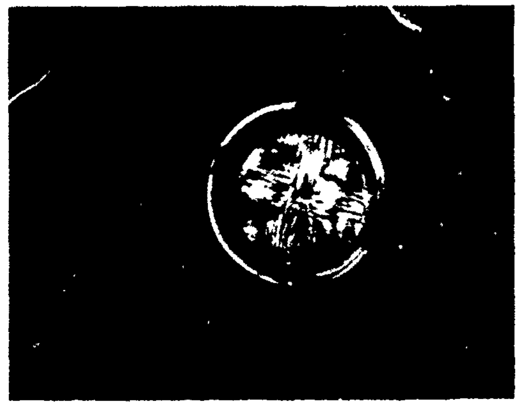



*Figure 22. R&D and initial MM&T forgings.*

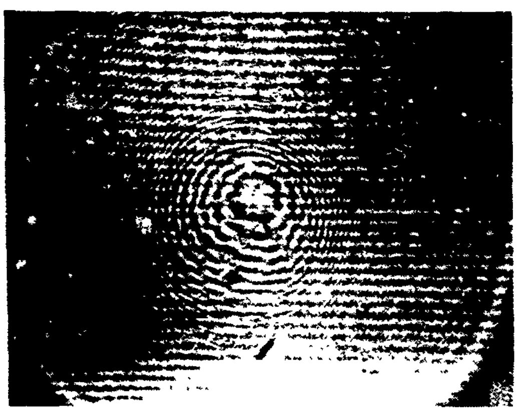


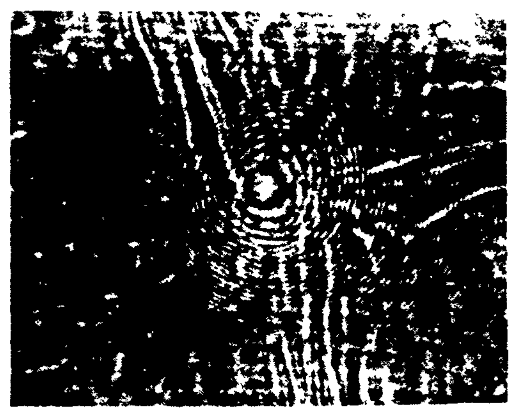
a. RESIDUAL STRESS IN LENS (POLARISCOPE)

RADIUS = 17.21 IN. THICKNESS = 0.256 IN.

RADIUS = 17.10 IN. THICKNESS = 0.270 IN.

b. CONCAVE SURFACE OPTICAL FIGURE



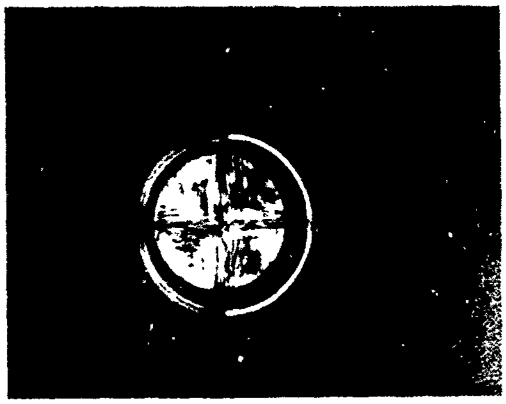


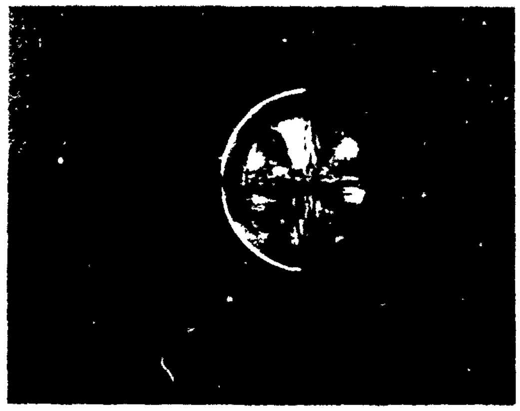
c. PLANO SURFACE OPTICAL

F/N 010 2000 psi ISOSTATIC

F/N 011 4000 psi ISOSTATIC

*Figure 23. Influence of reduced He isostatic pressure.*





a. RESIDUAL STRAIN IN LENS (POLARISCOPE)

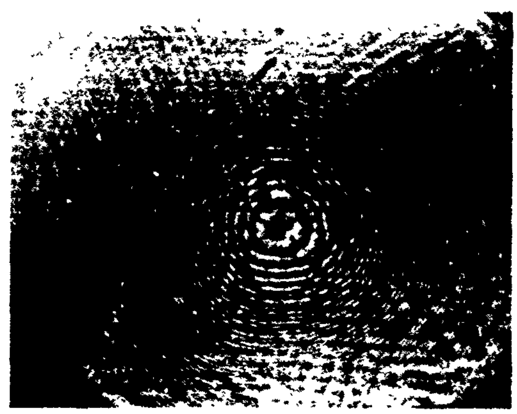
RADIUS = 16.97 IN. THICKNESS = 0.292

RADIU[illegible].90 IN. THICKNESS 0.0272 IN.

b. CONCAVE SURFACE OPTICAL FIGURE

c. TOTAL WAVEFRONT DISTORTION (SHEARING)

F/N 014 4000 psi ISOSTATIC



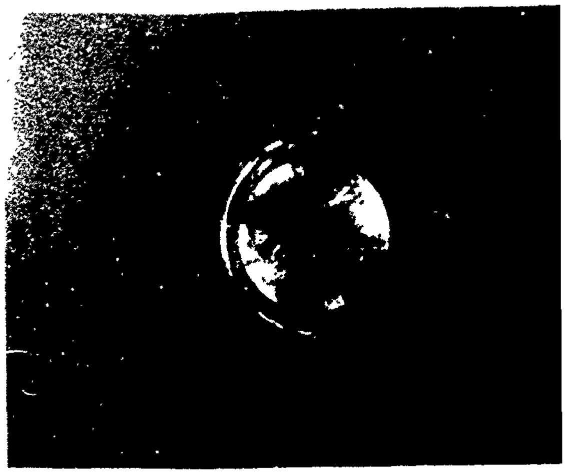
d. PLANO SURFACE OPTICAL FIGURE

F/N 015 2000 psi ISOSTATIC

*Figure 24. Influence of reduced He isostatic pressure and elimination of machining after first-stage forgings on optical properties of KBr lenses.*



The reverse of this page is blank.

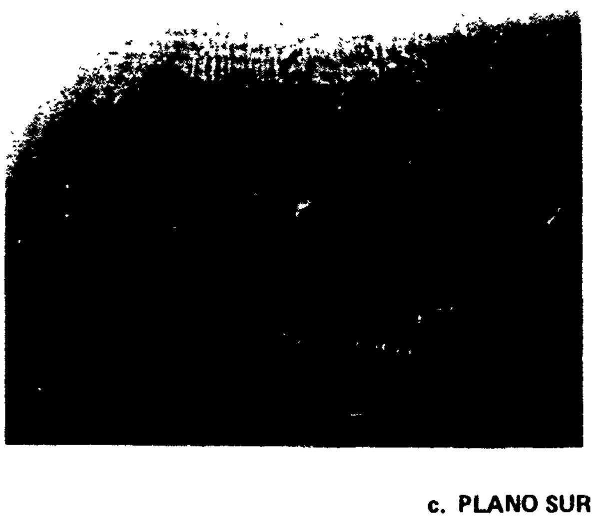


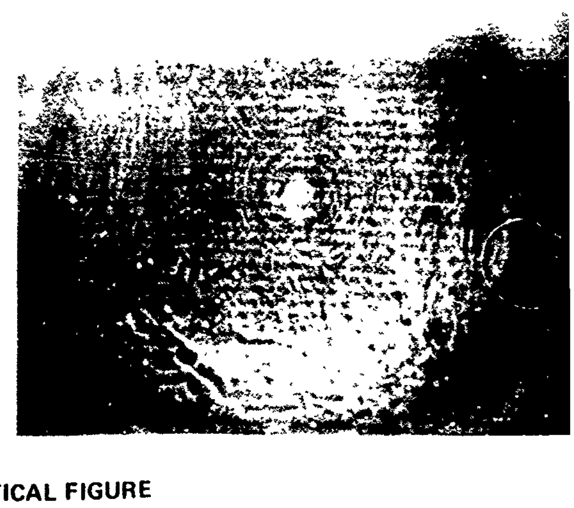
a. RESIDUAL STRESS IN LENS (POLARISCOPE)

RADIUS = 17.00 IN. THICKNESS = 0.259 IN.

RADIUS = 17.26 IN. THICKNESS = 0.262 IN.

b. CONCAVE SURFACE OPTICAL



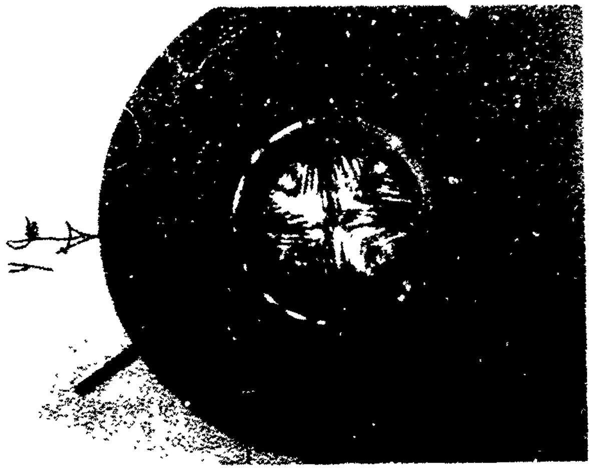


c. PLANO SURFACE OPTICAL FIGURE

F/N 021 4000 psi ISOSTATIC

F/N 023 2000 psi ISOSTATIC

*Figure 25. Influence of He isostatic pressure and the use single crystals on optical properties of KBr le*



:) ESIDUAL STRESS IN LENS (POLARISCOPE)

ADIUS = 17.26 IN. THICKNESS = 0.262 IN.

RADIUS = 17.20 IN. THICKNESS = 0.261 IN.

b. CONCAVE SURFACE OPTICAL

GURE

d. TOTAL WAVEFRONT DISTORTION (SHEARING)

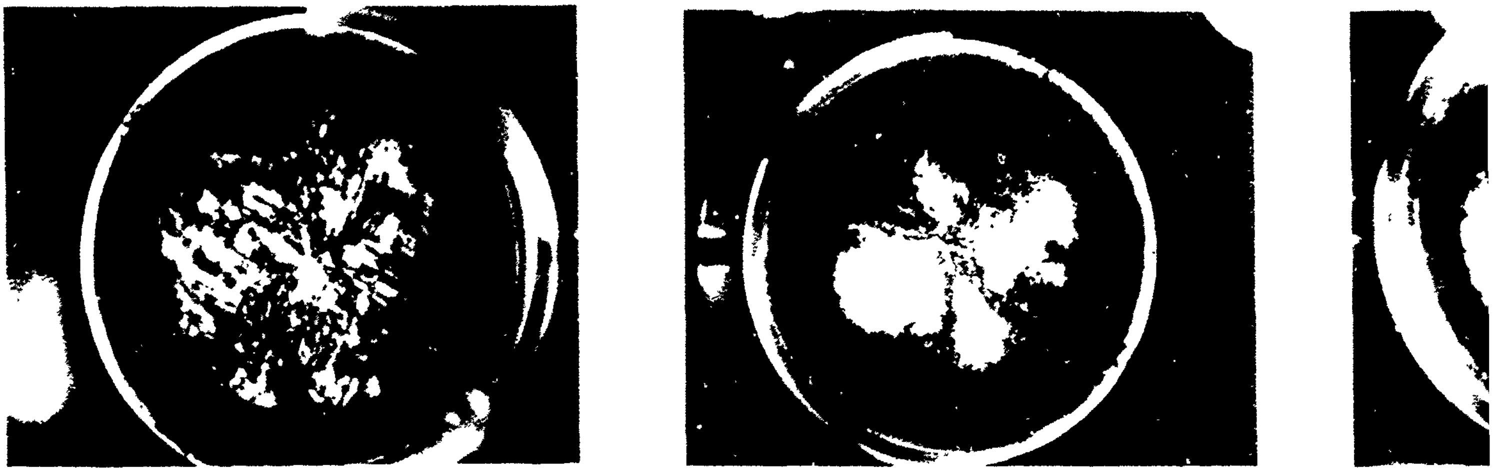
F/N 023 2000 psi ISOSTATIC

F/N 018 100 psi ISOSTATIC

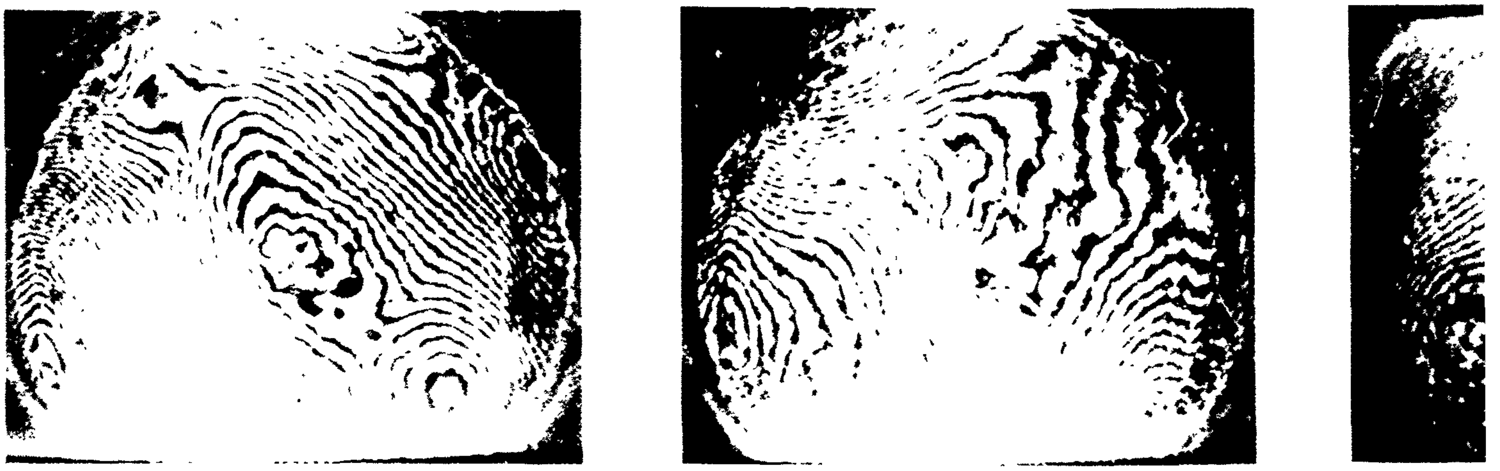
*se o… e of He isostatic pressure and the use of cubic shaped*
*len… ystals on optical properties of KBr lenses.*



The reverse of this page is blank



a. RESIDUAL STRAIN IN LENSES (POLA

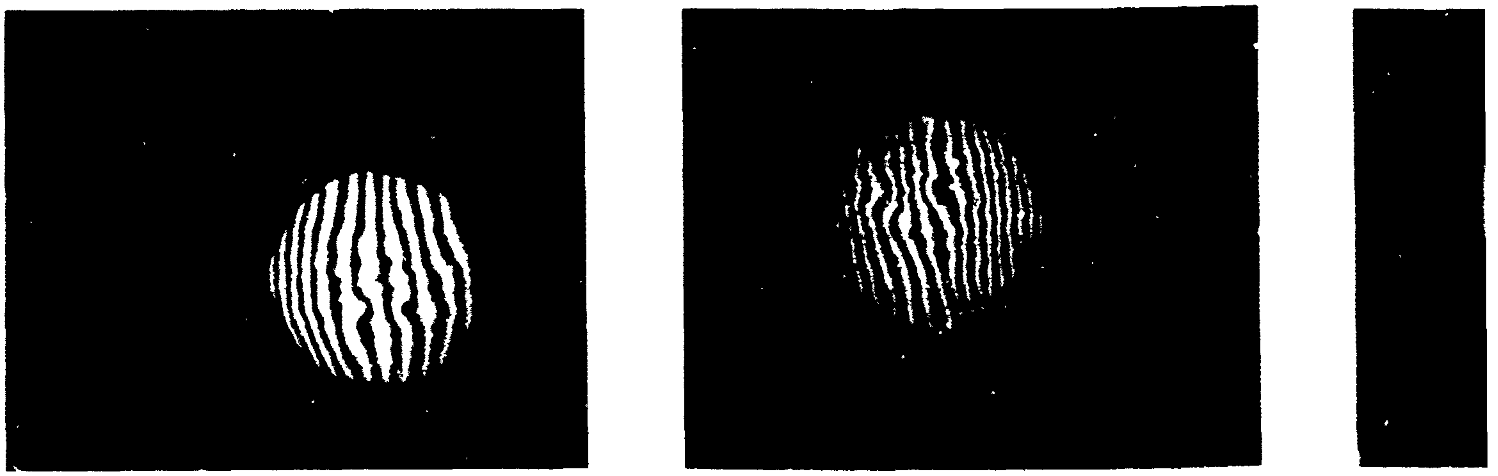


RADIUS = 17.17 IN. THICKNESS = 0.262 IN.

RADIUS = 17.18 IN. THICKNESS = 0.262 IN.

RADIUS =

b. CONCAVE SURFACE OPTICAL F



c. TOTAL WAVEFRONT DISTORTION (SHEA

F/N 050 100 psi

F/N 048 ATM. PRESS

*Figure 26. Low-pressure optimized forgin*

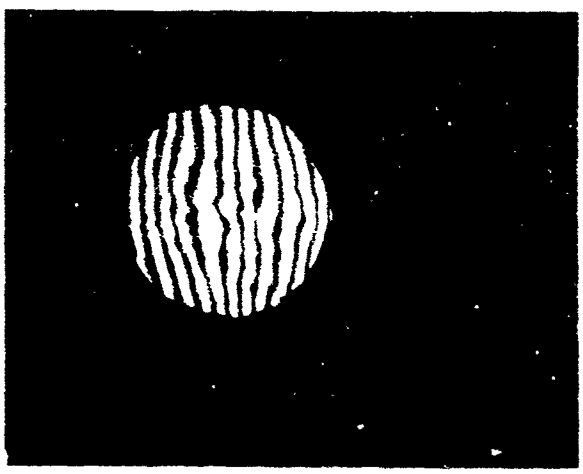
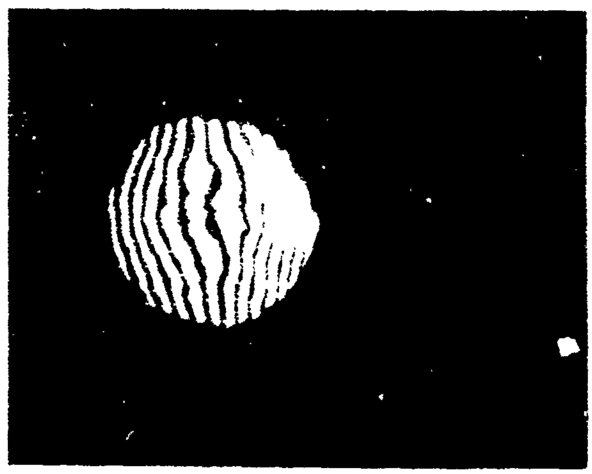


L STRAIN IN LENSES (POLARISCOPE)



IN. RADIUS = 17.20 IN. THICKNESS = 0.259 IN. RADIUS = 17.17 IN. THICKNESS = 0.257 IN.

CAVE SURFACE OPTICAL FIGURE

EFRONT DISTORTION (SHEARING)

F/N 051 100 psi F/N 049 100 psi

*essure optimized forging for KBr lenses.*



The reverse of this page is blank

parent. The complexity of the optical fringes observed on the concave surface and plano surfaces also decreased. As a result the total wavefront distortion also improved to about one-half to one $\lambda$. The 100-psi hot forgings were considered to be insignificant isostatic pressure and thus one desired objective of eliminating the hot isostatic chamber was achieved. Figure 26 shows that no significant difference was obtained when atmospheric pressure was used over 100-psi isostatic pressure. This then was the production technique which was established.

### 3.1.2 First-stage Preshaping

The first-stage forgings used in the research process were flat disc. These were then machined into a double cone, Figure 4. To eliminate this operation cone shaped brass or steel dies were produced and the first-stage forging preshaped the KBr for the second-stage forging operation. Several attempts were made to eliminate the other polishing and cleaning operation between these two forging operations but these were unsuccessful. By forging to shape less material was used and some slight improvements in the optical properties were obtained, Figure 24.

### 3.1.3 Single Crystal Shape

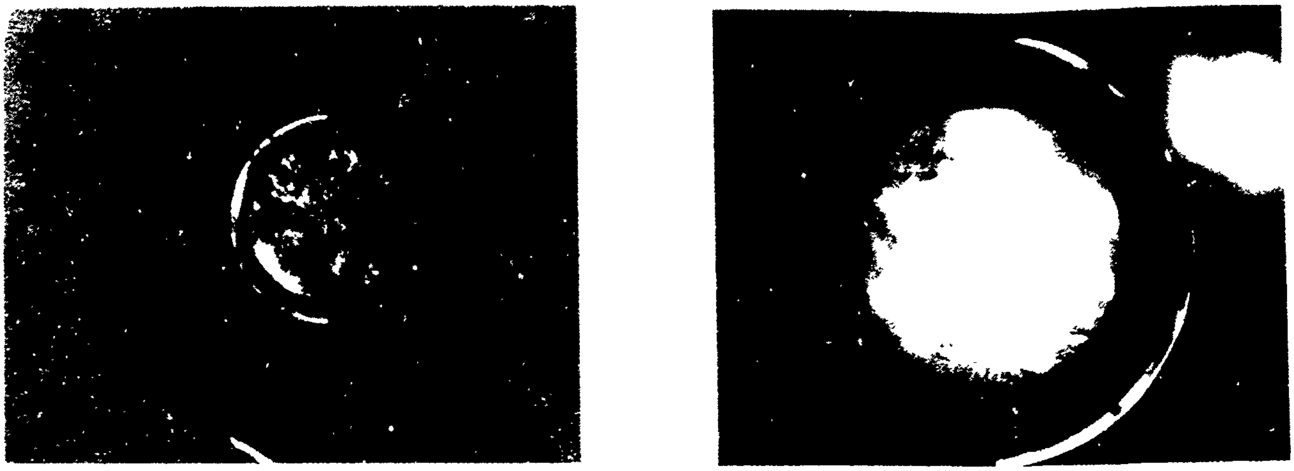
Since cleaved single crystals of KBr are the cheapest source of material, a limited number of these were obtained and a few were evaluated as cubes. Figure 25 shows that unique strain patterns are established particularly at higher pressures (2000-4000 psi) which influence the optical uniformity of the surfaces obtained by the hot forged-to-shape process. Therefore, the cylindrical crystal shape used in research was continued.

### 3.1.4 Crystallographic Orientation and Forging Temperature

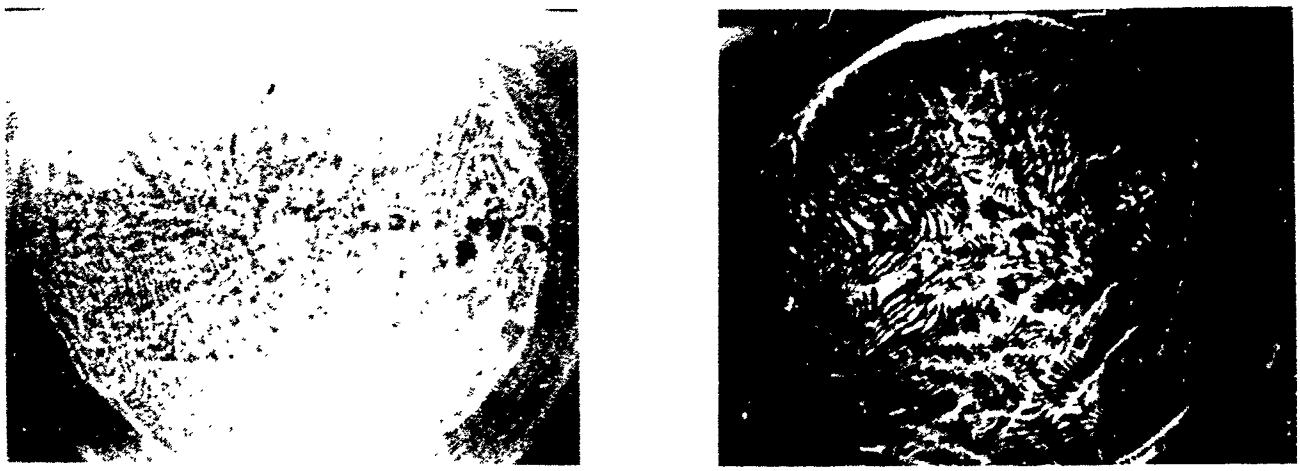
Two additional single crystal orientations (<110> and <111>) were evaluated to help modify the residual strains obtained with the <100> oriented crystals used in the research process. Cylindrical crystals of each were hot isostatically forged (4000 psi) at the normal 250°C first-stage forging condition and at 300°C. The results obtained are given in Figures 27 and 28. The strain patterns were altered with the <110> and <111> orientations but very complex optical figures were still obtained. The 300°C forging did appear to reduce residual strain, particularly with the <100> forging (F/N 031) and some regularity of the optical figure for the concave surface appeared for all three orientations. However, other changes (lower pressure and forging rate) produced better results which will be discussed below.



The reverse of this page is blank.



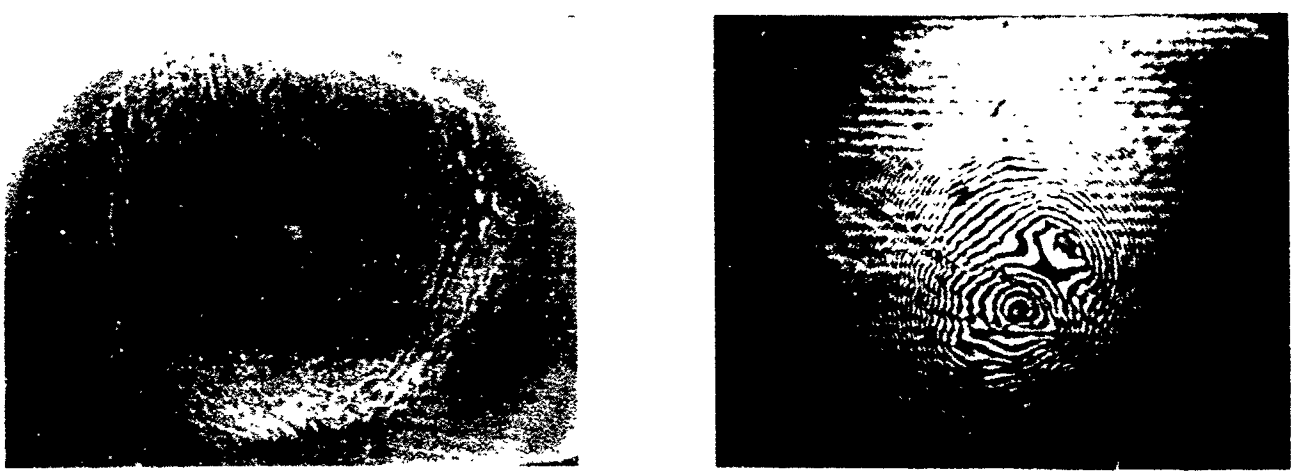
a. RESIDUAL STRAIN IN LENSES (POLARISCOPE)



RADIUS = 16.96 IN. THICKNESS = 0.264 IN.

RADIUS = 16.95 IN. THICKNESS = 0.257 IN.

b. CONCAVE SURFACE OPTICAL FIGURE



c. PLANO SURFACE OPTICAL FIGURE

F/N 027 <100>

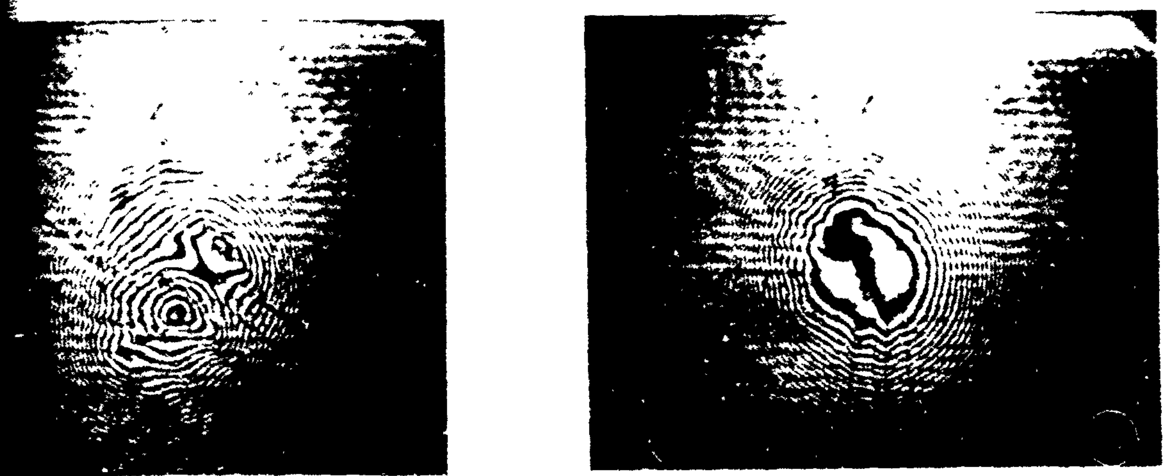
F/N 029 <110>

*Figure 27. Influence of crystallographic axis on optical properties lenses forged at 250°C and 1000 psi.*

L STRAIN IN LENSES (POLARISCOPE)

= 16.95 IN. THICKNESS = 0.257 IN. RADIUS = 17.00 IN. THICKNESS = 0.257 IN.

CAVE SURFACE OPTICAL FIGURE



NO SURFACE OPTICAL FIGURE

F/N 029 <110> F/N 030 <111>

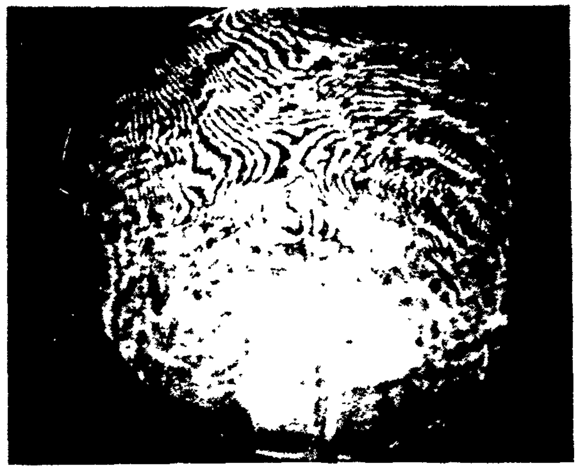
*stallographic axis on optical properties of KBr*
*250°C and 1000 psi.*



The reverse of this page is blank

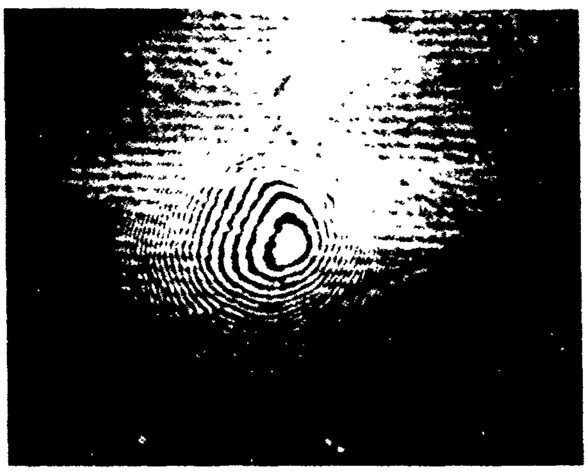
a. RESIDUAL STRAIN IN LENSES (POLARISCOPE)

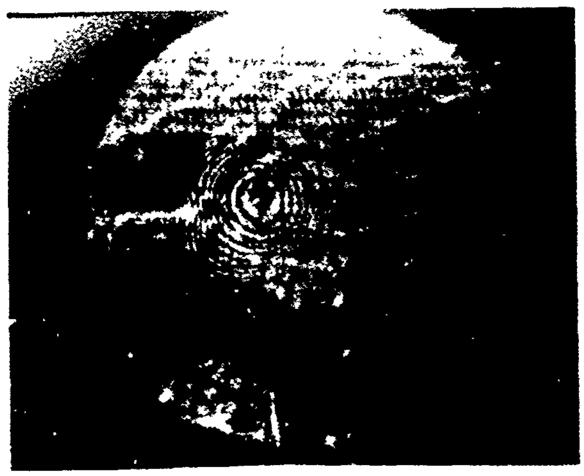
RADIUS = 16.91 IN. THICKNESS = 0.259 IN.



RADIUS - 16.79 IN. THICKNESS = 0.262 IN.

b. CONCAVE SURFACE OPTICAL FIGURE





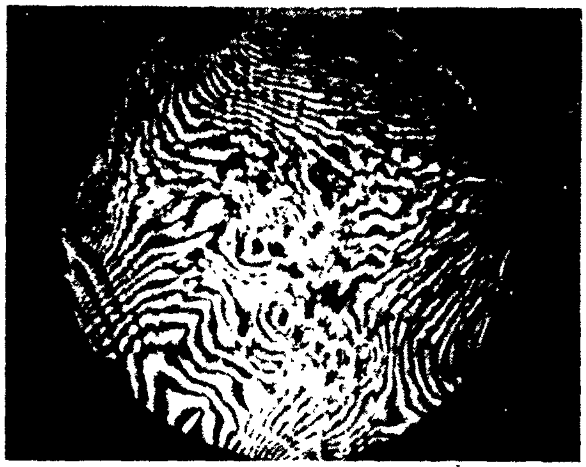
c. PLANO SURFACE OPTICAL FIGURE

F/N 031 <100>

F/N 032 <110>

*Figure 28. Influence of crystallographic area on optical prop lenses forged at 300°C and 4000 psi.*

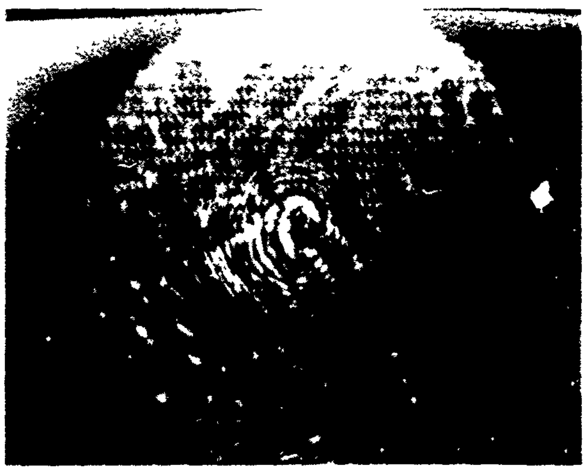
. STRAIN IN LENSES (POLARISCOPE)



= 16.79 IN. THICKNESS = 0.262 IN.

RADIUS = 16.78 IN. THICKNESS = 0.262 IN.

CAVE SURFACE OPTICAL FIGURE



ANO SURFACE OPTICAL FIGURE

F/N 032 <110>

F/N 033 <111>

*·tie... of crystallographic area on optical properties of KBr*
*...ged at 300°C and 4000 psi.*



The reverse of this page is blank

### 3.1.5 Forging Rate

In the research process, the first-stage forgings were produced at 250°C where the ram rate was held constant. As the thickness was reduced the KBr was worked extremely fast. Therefore, six forgings, Figure 29, were produced at six constant strain rates, 1.6 to 52.32%/min. Figure 29 shows the residual strain in these first-stage forgings. Note that the residual strain does increase slightly for the very high strain rates but that the presence of the optical cross strain pattern is very low in all forgings. Figure 30 gives the results for three of these after the second-stage lens forming operation. Note the improved regularity in the optical figures and the less sharp changes in strain obtained for the lower constant strain rate first-stage forgings.

#### One-Step Forging

Two attempts were made at forging preshaped single crystals directly to final lens shape. The first (F/N 081) was done by the normal one-at-a-time process. This lens was not completely formed but did show sufficient promise to warrant a second attempt. In the second attempt, series forgings (F/N 082 and 083) were attempted. Three of the four glass dies fractured; therefore, this approach was not pursued further.

## 3.2 MULTIPLE FORGINGS

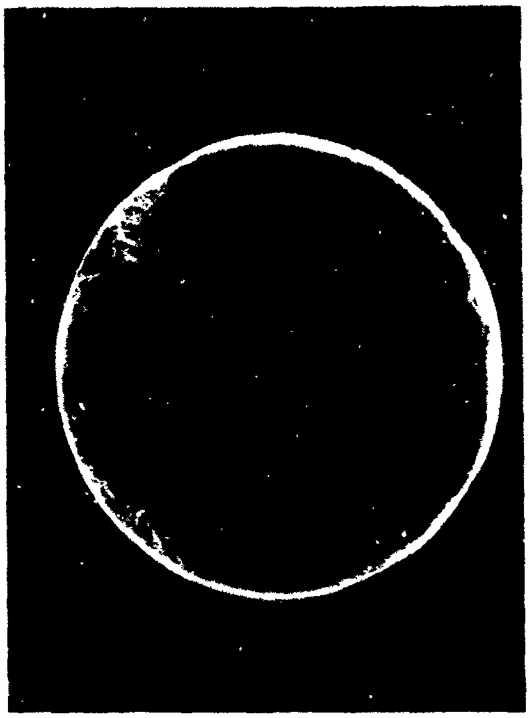
After the one-at-a-time process was optimized, the approach of hot forging two lenses in series was evaluated. In this phase 26 forgings were attempted and 22 lenses were obtained free of cracks or other defects. Three of the failures were due to breakage of the glass dies, while the fourth had internal flaws, Table 5.

The first pair of lenses (F/N 068 and 069) were attempted with double-conical first-stage forgings on Pyrex dies. Two satisfactory forgings were obtained; therefore, two sets of series forgings were attempted simultaneously, by this approach with F/N 60, 61, 74 and 75. In this attempt the glass die set with F/N 75 cracked. The lens replicated the cracked die but was otherwise undamaged and was used for research coating experiments. It was concluded that it was difficult to maintain alignment of the two, double conical first-stage forgings in the series forging approach. Therefore, the plano-conical first-stage forging shape shown in Figure 4 was used in the series die set shown in Figure 10.

Next, a one-step forging approach with two die sets in series was attempted for F/N 082 and 083. As discussed above, three of the four glass dies cracked and F/N 082 was destroyed. F/N 083 was still sound and was salvaged by reforging to a first-stage forging shape. This suggests that sound lenses which do not meet optical figures can be salvaged by reforging.



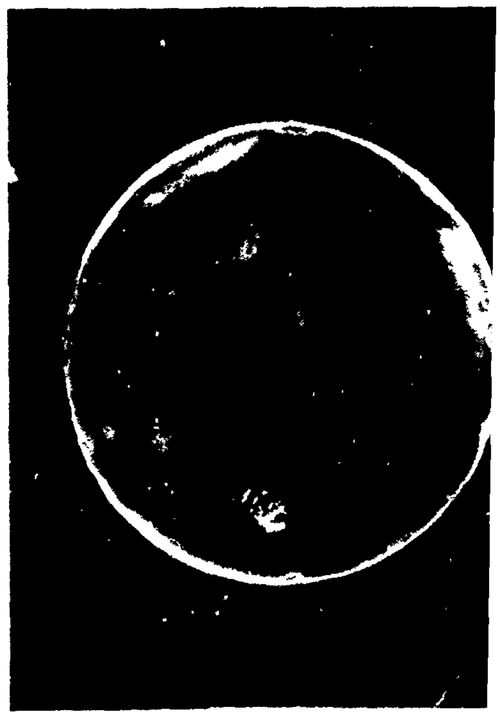
The reverse of this page is blank.



F/N 035 0.016 IN/IN/MIN

F/N 028 0.033 IN/IN/MIN

F/N 036 0.128 IN/IN/MIN



F/N 037 0.258 IN/IN/MIN

*Figure 29. Resident strain in first-stage forgings a rates.*

F/N 028 0.033 IN/IN/MIN

F/N 034 0.066 IN/IN/MIN

F/N 037 0.258 IN/IN/MIN

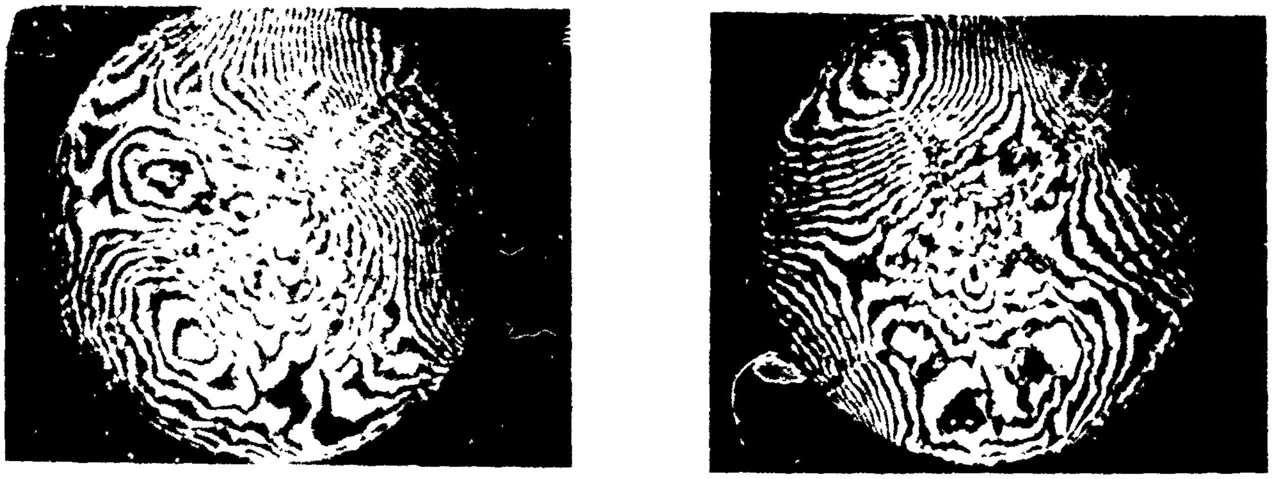
F/N 038 0.523 IN/IN/MIN

*rain in first-stage forgir ıs at various constant strain*



The reverse of this page is blank

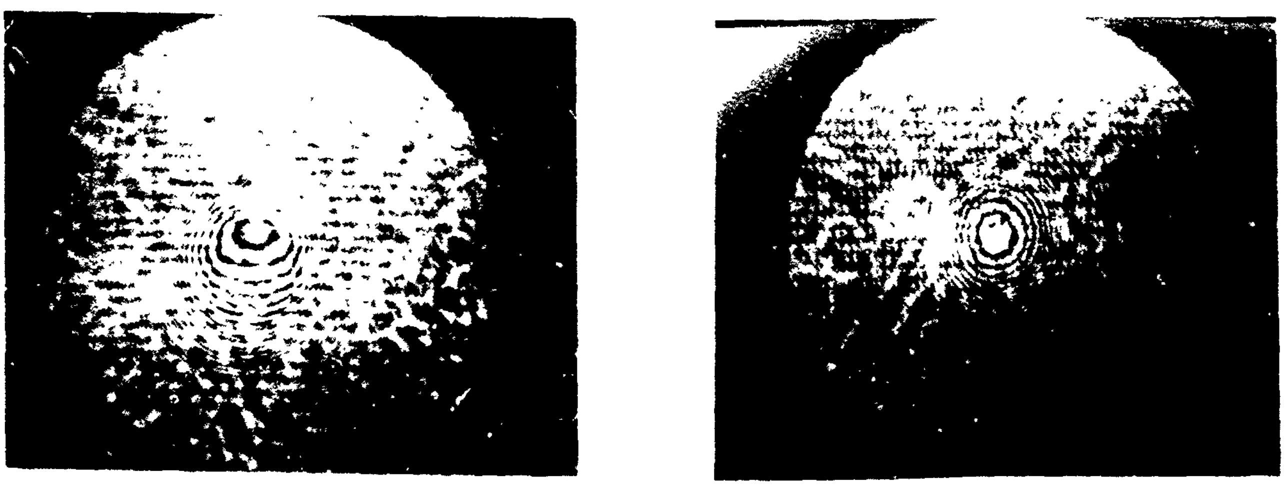
a. RESIDUAL STRAIN IN LENSES (POLARISCOPE)



RADIUS = 16.96 IN. THICKNESS = 0.262 IN.

RADIUS = 16.82 IN. THICKNESS = 0.264 IN.

b. CONCAVE SURFACE OPTICAL FIGURE

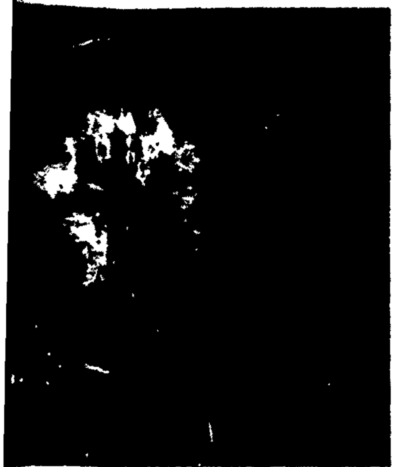


c. PLANO SURFACE OPTICAL FIGURE

F/N 035 0.016 IN/IN/MIN (4000 psi)

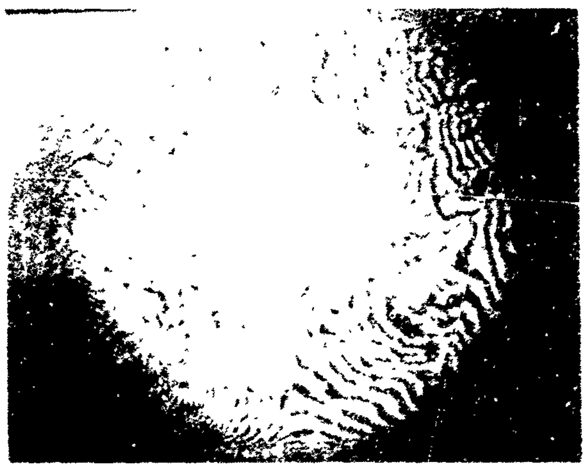
F/N 034 0.066 IN/IN/MIN (4000 psi)

*Figure 30. Influence of various first-stage forging constant optical properties of KBr lenses.*



TRAIN IN LENSES (POLARISCOPE)

.82 IN. THICKNESS = 0.264 IN.



RADIUS = 17.40 IN. THICKNESS = 0.267 IN.

E SURFACE OPTICAL FIGURE

d. TOTAL WAVEFRONT DISTORTION (SHEARING)

4 0.066 IN/IN/MIN (4000 psi)

F/N 038 0.523 IN/IN/MIN (2000 psi)

*rious first-stage forging constant strain rates on*
*ties of KBr lenses.*



The reverse of this page is blank

## TABLE 5. TEST RESULTS FOR KBr MULTIPLE-FORGED LENSES

| F/N | Single Crystal | | First-Stage Forging | | Second-Stage Forgings | | | |
|---|---|---|---|---|---|---|---|---|
| | Strain | Configuration | Special Conditions | Strain | Special Conditions | Strain | Condition | Remarks |
| 068-069 (1×2) | High/med | (100) cyl | Double cones | Med-high | 1×2 on Pyrex, 250°C manually controlled 0 012"/min | Med | O.K | First series forging |
| 060 061 (2×2) | High/med | (110) cubes | Double cones | Very high/ high | 2×2 on Pyrex, 225°C manually controlled 0 012"/min | High | O K | Forged with #074 and 075 |
| 074-075 | High | (110) cyl | Double cones | High | 2×2 on Pyrex, 225°C manually controlled 0 012"/min | High | 074-O K. 075-surface defect | Die broke on #075, lens surface replicated crack Used coatings experiments Forged with F/N 060,06 |
| 082-083 (1×2) | High | (100)cyl | One-step forged on Pyrex, 250°C | | | Failed | | Both dies on 082 and one die on 083 broke Lens #082 no good Lens #083 suffered damage, reforged on steel to double-cone blank |
| 084 089 (2×3 #1) | 87-high 89-med Others low | (100) cyl. | Plano-conical | Low | 2×3 at 225°C, manually controlled 0 012"/min 084,085,087,088 on Pyrex 086 on Cervit 089 on high expansion glass | Med | All intact | Curved die on f/n 088 broke Lens O K and used for coatings experiments |
| 090,092 095,099 (2×3 #2) | Low med | (100) cyl | Plano-conical 092,093 fast forged, rate ≈ 15%/min | 092,093 high others low | 2×3, 225°C, automatic controls at 0 012"/min 090,094,095,099 on Pyrex 092 on Cervit 093 on high expansion glass | Low | F/N 090 has internal flaws,N G rest O K | F/N 092 also has slight internal flaws which machined out—lens was satisfactory |
| 096 098,100 102 (2×3 #3) | Low-med | (100) cyl | Plano-conical | 097 med others low | 2×3 on Pyrex, automatic controls, 0 012"/min, 225°C Teflon shims | Low | O K | Lens #098 broken during machining |
| 103 114 (2×3 #4&5, (final run) | Low-med | (100) cyl | Plano conical | Low | 2×3 on Pyrex, automatic controls 0 012"/min, 225° Teflon shims | Low | F/N 107, 114 Incomplete failure Fill from die Rest O K | Die on F/N 107 broke, incomplete Fill on lens Complementary lens #114 also did not replicate properly |

Next, three sets of dies containing two lenses (2 × 3 or six-lenses-at-a-time) were forged simultaneously with manual controls to formed F/N 084 to 089. One glass die broke with F/N 088 but again this lens was saved. Apparently, this die set saw excessive pressure. Figure 31 shows the low residual strain obtained for this set of lenses and no significant evidence that the cracked die with F/N 088 influenced the residual strain in this lens.

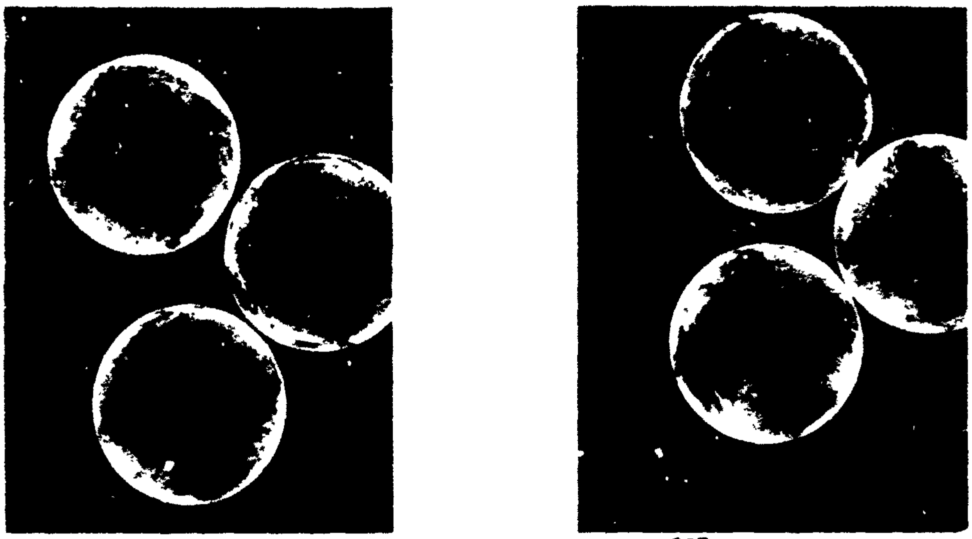
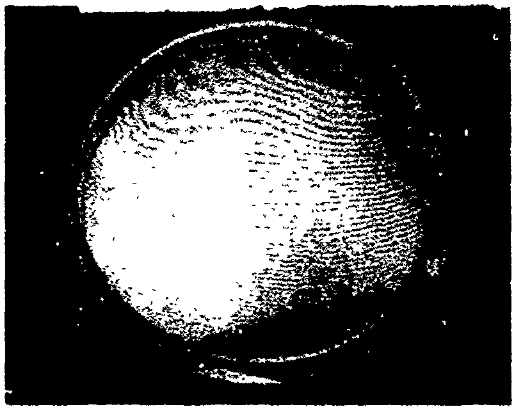



*Figure 31. Residual strain in KBr lenses—manual control.*

Note the excellent optical figures and low total wavefront distortion obtained with F/N 085 and 087, Figure 32. The next two runs for the 2 × 3 approach were made with the computer automated control system. F/N 90 and 92 to 102 were produced in these runs. To minimize the problems of one sleeve receiving excessive pressure, 0.005-inch thick teflon shims were placed on the top and bottom of each two-high assembly, Figure 11. Under excessive pressure the teflon deforms and helps distribute the pressure more uniformly on the three dies. The automated controls maintained a 0.012-inch/min forging speed or 0.006-inch/min per lens. Note the low residual strain shown in Figure 33 for six of these lenses as compared to those of the manual 2 × 3 forging shown in Figure 31. Two of the forgings (F/N 92 and 93) were fast-forged during first-stage forging, thus producing high-strain blanks. Figure 34 shows this higher strain for the lens from F/N 93. The resultant final forging, Figure 33, showed no higher strain than the other forgings produced in these runs; however, the optical behavior of the final lens surfaces was very irregular.



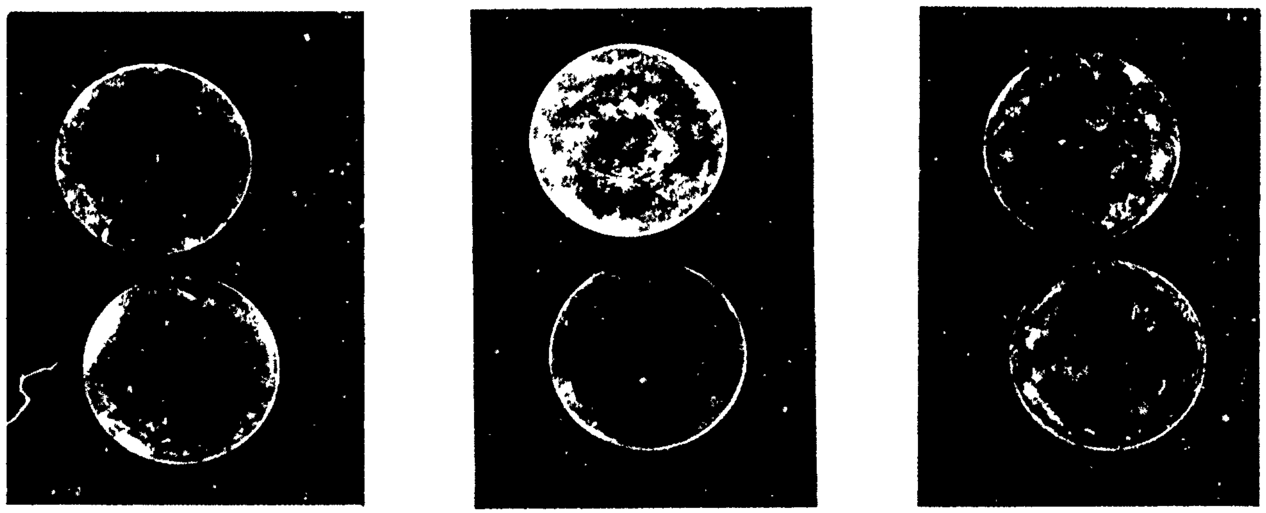
a. CONCAVE SURFACE OPTICAL FIGURE

b. PLANO SURFACE OPTICAL FIGURE

c. TOTAL WAVEFRONT DISTORTION

F/N 085 F/N 087

*Figure 32. Optical data for first 23 forging test.*



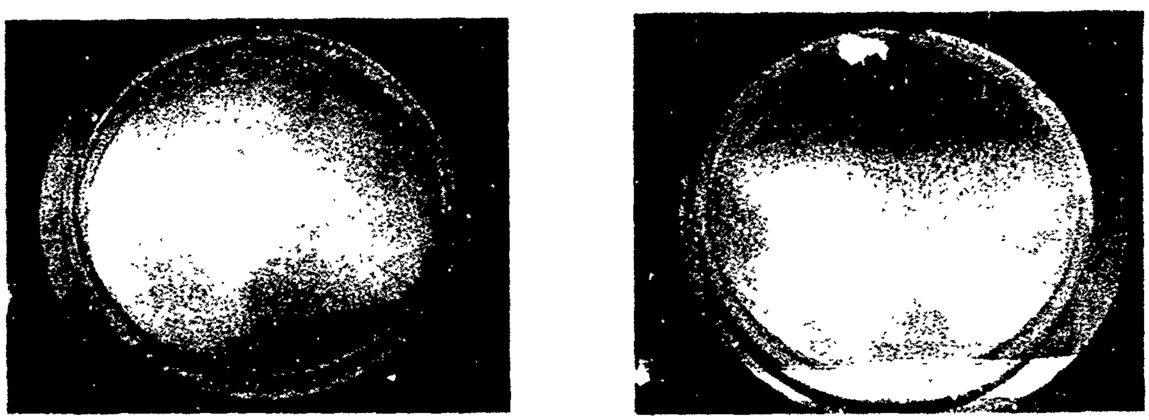
092
093

090
094

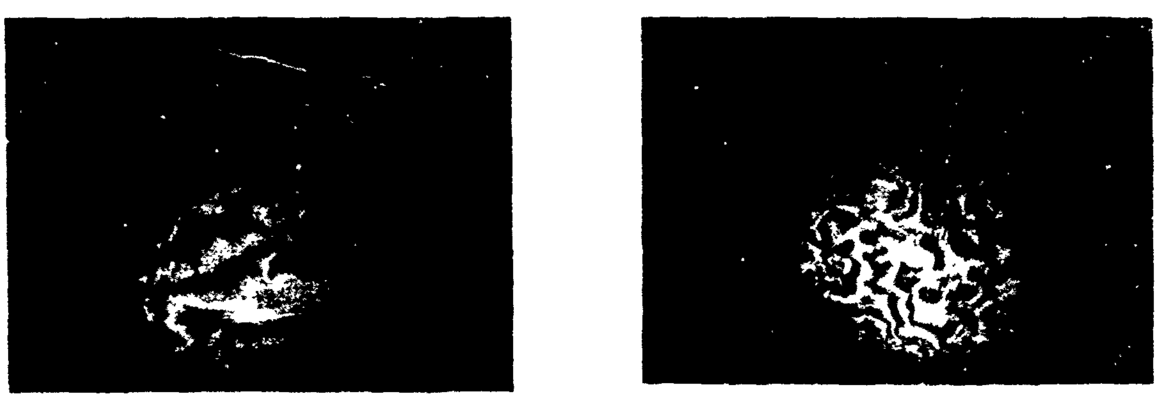
095
099

*Figure 33. Residual strain in KBr lenses—second 2x3 forging with automatic controls.*

a. RESIDUAL STRAIN (POLARISCOPE) AFTER FIRST-STAGE FORGING



b. CONCAVE SURFACE OPTICAL FIGURE



c. TOTAL WAVEFRONT DISTORTION

F/N 089 FIRST 2 x 3 F/N 093 SECOND 2 x 3

*Figure 34. Optical data for KBr lenses forged on high thermal expansion glass dies.*

During the first and second 2 × 3 runs two lenses were forged on high thermal expansion soda-lime glass (F/N 089 and 093) and two lenses were forged on low expansion Cervit dies (F/N 086 and 092). No noticable difference could be seen between the Pyrex and Cervit dies, but definite degradation of lens quality could be seen in the lenses forged on the high-expansion glass. Figure 34 shows the wavefront distortion of these two lenses, which is much worse than the lenses forged on Pyrex as shown in Figure 32. The much higher distortion obtained for F/N 093 is attributed to the high strain produced in the first-stage forging even through the residual strain after second-stage forging (Figure 33) was about the same.

As may be seen in Figure 33 two lenses, F/N 090 and 092, possessed internal flaws after forging. Internal flaws in the center of F/N 090 caused this lens to be rejected. The flaws in F/N 092 were close enough to the edge to be machined out during final machining.

Significant improvements were made in the fabrication process which not only improved lens quality, but also greatly reduced fabrication costs, increased yield and made production feasible (compare Figure 32 to the initial lenses in Figure 22).

## 3.3 OPTICAL QUALIFICATION

The ability of the hot forged-to-shape process to produce KBr lenses suitable for the FLIR imager was monitored at various stages of this program. Table 6 gives the optical performance of 10 lenses produced in this MM&T program in a SU-103/UA (large) IR imager. Data on two research lenses and a standard ZnSe lens are also included in this table.

Only 2 (F/N 093 and 095) of the 10 MM&T lenses evaluated failed to pass the MTF tests. Figure 35 for F/N 094 and 095 clearly shows the high distortion in F/N 095. This lens did not meet the MTF requirement because it did not completely fill the die. The weight of the KBr was low and die replication was not achieved. This is verified by the high focal length of this part. F/N 093 shown in Figure 34 was clearly the worst lens evaluated in these tests. The reasons for this were discussed in the previous section.

The effective and flange focal lengths were held quite close to their nominal values of 67.3 and 17.9mm, respectively. Slight die modifications would bring the effective focal length closer to the specified value of 67.8mm.

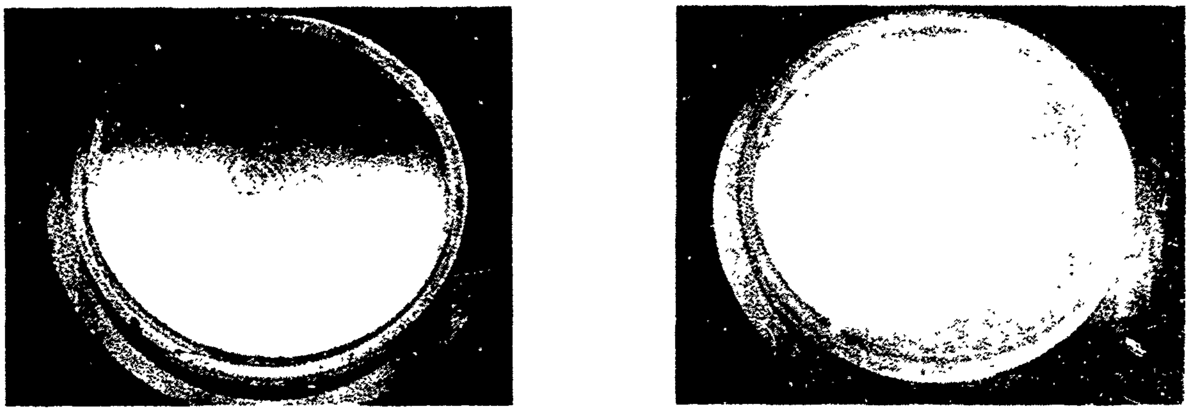
The hot forged-to-shaped process as defined in Section 2 would have rejected all of the defective lenses described above. However, a broad selection of lenses were evaluated for MTF to make sure that we have selected the right acceptance criteria.

It is concluded that the manufacturing and inspection procedures established in this MM&T program will produce acceptable plano-concave KBr lenses for the Army's common modular IR imagers (SU-103/UA).

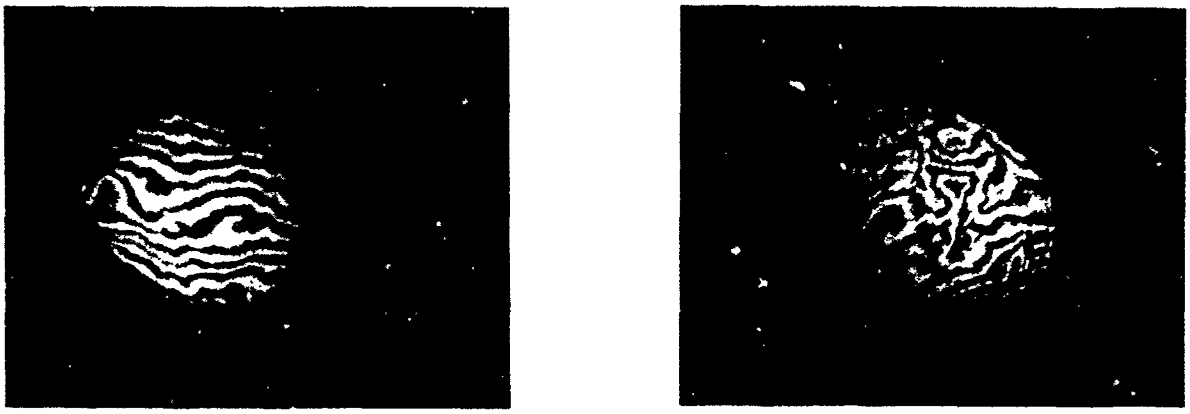
**TABLE 6. OPTICAL DATA FOR LENS PERFORMANCE IN A FLIR IR IMAGER**

| Sample No. | % MTF | | Effective Focal Length (mm) | Flange Focal Length (mm) | Peak-to-Valley* Error (λ) |
|---|---|---|---|---|---|
| | On Axis | Off Axis | | | |
| Specification | >74% | >66% | 67.8 ± 0.7 | 17.86 ± 0.25 | |
| ZnSe | 77.5 | 74 | 68.13 | (17.29) | |
| #597 | 75.48 | | (69.29) | 17.62 | |
| #719 | (69.00) | | | | (>4) |
| 014 | 74.69 | 71.04 | 67.08 | 17.69 | 3.5 |
| 018 | 77.29 | 72.84 | 67.23 | 17.76 | 2 |
| 038 | 74.98 | 68.69 | 67.16 | 17.71 | 3 |
| 049 | 76 | | (66.86) | 18.05 | 1.5 |
| 085 | 76 | | (66.86) | 18.05 | 1.5 |
| 087 | 77.5 | 71.5 | 67.32 | 17.96 | 2 |
| 089 | 75.0 | 70.0 | 67.17 | 17.98 | 3 |
| 093 | (68.0) | (63.0) | 67.35 | 17.87 | (>>4) |
| 094 | 77.0 | 68.0 | 67.29 | 18.00 | 1.5 |
| 095 | (72.0) | (60.5) | (68.83) | (17.28) | (>4) |

* Linear shearing interferometer
(    ) Below or above tolerance parameters



a. CONCAVE SURFACE OPTICAL FIGURE



b. TOTAL WAVEFRONT DISTORTION

F/N 094 F/N 095

*Figure 35. Optical data for KBr lenses—second 2x3 forging with automatic controls.*

## 3.4 FINAL PILOT RUN

Two additional 2 × 3 forging runs were performed by the processes defined in Section 2 to produce 12 KBr lenses (F/N 103-114). All of these were sound forgings; however, one of the glass dies associated with F/N 107 cracked. As a result only half of this lens replicated the die and the accompanying lens (F/N 114) also did not properly replicate its glass dies.

Table 7 gives the optical surface distortion, maximum point-to-point deviation and the maximum wavefront distortion for the full 2.25-inch clear aperture for each of the 12 lenses. All of the other 10 lenses met the specifications established for the white light interferometer test. Figure 36 shows the typical format of the data obtained for the plano and concave surfaces of the F/N 112 lens. Note how well centered the two surfaces are (location of "0" value) and that the maximum distortion points are at the outside edge of the lens. If we reject the outer edge data, the values of maximum surface distortion would be 680 and 830 instead of 765 and 990 for the plano and concave surfaces, respectively.

Lens F/N 113 did exceed the 300 value for maximum point to point deviation and maximum wavefront distortion; however, we expect this value is specified too low. Even if this lens were also considered a rejected lens, we would have achieved a 75% yield. It is expected that at least two of the three rejected lenses could be reforged to produce a satisfactory lens which would raise the yield to over 90%.

*TABLE 7. OPTICAL TEST DATA USING WHITE LIGHT INTERFEROMETER FOR PILOT RUN KBr LENSES*

| F/N | Surface | Maximum Surface Distortion* (0.01$\mu$m units) | Maximum Point-to-Point Deviation* (0.01$\mu$m units) | Maximum Wavefront Distortion* |
|---|---|---|---|---|
| 103 | flat | 694 | 298 | 292 |
| | curved | 402 | 259 | |
| 104 | flat | 897 | 290 | 190 |
| | curved | 1087 | 292 | |
| 105 | flat | 1572 | 270 | 185 |
| | curved | 1387 | 252 | |
| 106 | flat | 909 | 224 | 286 |
| | curved | 623 | 297 | |
| 107 | flat | No good due to die failure | | |
| | curved | | | |
| 108 | flat | 846 | 200 | 248 |
| | curved | 598 | 127 | |
| 109 | flat | 846 | 180 | 63 |
| | curved | 783 | 103 | |
| 110 | flat | 1013 | 114 | 268 |
| | curved | 745 | 163 | |
| 111 | flat | 1453 | 299 | 294 |
| | curved | 1159 | 260 | |
| 112 | flat | 765 | 226 | 225 |
| | curved | 990 | 141 | |
| 113 | flat | 1095 | 300 | 364 |
| | curved | 731 | 117 | |
| 114 | flat | Incomplete filling due to die failure in F/N 107 | | |
| | curved | | | |
| Specification | | 2000 | 300 | 300 |

* For full 2.28 inch clear aperture

```
999999999999999  47   39   21   38   87  13899999999 9999999
999999999999999

9999999999 158 101   76   57   77  112  169 2749999 99999999
999999999999999

9999999 168 139 110   92   78   93  127  165  242  291 99999999
999999999999999

999 250 182 129 101   81   77   94  132  177  229  289  3039999
999999999999999

399 299 213 147 100   71   61   77  112  161  204  268  293 285
399999999999999

536 395 266 166  92   43   25   41   66  121  170  244  300 331
999999999999999

629 482 339 206 104   33    49999   26   73  140  243  325 387
999999999999999

706 555 414 276 155   64   19    0    6   67  154  279  375 445
999999999999999

718 611 483 355 233 130   71   40   50  123  224  349  463 517
999999999999999

999 638 546 442 341 243 174 145 159 220 303 435  5599999
999999999999999

999 688 650 560 476 399 331 299 314 351 421 565  6679999
999999999999999

9999999 774 733 664 592 528 501 505 524 583 67[illegible] 99999999
999999999999999

9999999999 860 832 769 764 726 702 676 7063999 99999999
999999999999999

9999999999999999999999 990 942 3729999999999999 99999999
```

a. CONCAVE SURFACE DISTORTIONS x $10^{-2} \mu m$
(IGNORE 9999s)

*Figure 36. White light interferometer data for F/N 112.*

```
9999999999999999999999999999999 385 3639999999999999999999999999999999999
9999999999999999999
                                                                  9999999999999999999
9999999999999999999 330 313 311 333 347 361 394 448 9999999999999999999
9999999999999999999
                                                                  9999999999999999999
9999999999 404 355 315 289 280 283 296 317 330 361 372 4209999999999999
9999999999999999999
                                                                  9999999999999999999
9999999 484 416 353 303 260 237 236 250 264 269 275 294 335 3359999999
9999999999999999999
                                                                  9999999999999999999
9999999 481 416 351 284 226 191 186 200 216 222 227 235 266 309 3299999
9999999999999999999
                                                                  9999999999999999999
999 559 488 411 331 254 187 145 134 151 178 184 190 195 219 272 3139999
9999999999999999999
                                                                  9999999999999999999
999 561 490 400 305 217 142  98  82  94 125 139 151 167 190 236 293 343
9999999999999999999
                                                                  9999999999999999999
656 584 504 409 299 194 112  64  40  38  59  80 107 136 167 203 239 274
9999999999999999999
                                                                  9999999999999999999
629 582 522 429 309 194 102  47  13   3  17  37  78 115 149 179 202 219
9999999999999999999
                                                                  9999999999999999999
628 585 539 455 335 215 117  56  14   0   4  20  67 103 134 157 168 [illegible]
9999999999999999999
                                                                  9999999999999999999
665 594 553 486 373 252 157 100  49  23  18  25  68 100 126 142 141 151
9999999999999999999
                                                                  9999999999999999999
728 652 578 510 405 302 221 162 106  68  51  45  77 107 129 137 147 178
9999999999999999999
                                                                  9999999999999999999
999 691 608 547 458 391 323 253 181 134 103  86 101 123 134 136 1419999
9999999999999999999
                                                                  9999999999999999999
999 765 681 607 528 467 394 322 253 202 162 136 139 152 148 141 1539999
9999999999999999999
                                                                  9999999999999999999
9999999 742 683 594 519 444 380 314 262 218 180 175 179 162 13899999999
9999999999999999999
                                                                  9999999999999999999
9999999999 711 651 558 474 413 354 311 279 237 228 236 2009999999999999
9999999999999999999
                                                                  9999999999999999999
9999999999999999 654 574 492 433 377 341 324 304 285 3129999999999999999
9999999999999999999
9999999999999999999999 503 459 405 369 360 3699999999999999999999999999
```

b. PLANO SURFACE DISTORTION × $10^{-2}\mu m$
(IGNORE 9999s)

***Figure 36. White light interferometer data for F/N 112. (Concluded)***

# SECTION 4
# CONCLUSIONS

This MM&T program to establish a manufacturing method for production of hot forged KBr lenses directly to optical figure and surface finish has met all of its objectives. Low cost, readily available KBr single crystals were hot forged-to-shape with tooling and equipment which can modestly produce 100 lenses in one, eight-hour production shift. This rate is at least six times the original goal of 300 per month. A semiautomatic, computer process controlled system built by Honeywell was used for this purpose. No optical finishing operations were required to meet the optical specifications established for this lens design.

The fabrication process inherited at the start of the program produced reasonable quality lenses on a one-at-a-time basis, but involved expensive tooling. This expensive, high-pressure tooling was eliminated and the process scaled up to produce six lenses in one forging operation with low cost tooling. The quality of these lenses has shown great improvement over the initial lenses. To prove out the finalized process, a capability demonstration was performed and video-taped. (Copies are available through the Honeywell Ceramics Center or the Army Night Vision and Electro Optics Laboratory.) Twelve lenses were fabricated and evaluated as part of this demonstration. Eighty percent of these lenses passed the acceptance requirements and were suitable for use in the SU-103/UA IR Imager.

A new optical testing method was established using an interferometer which used a novel data analysis technique to determine the lens surface and its wave front distortions. The equipment is very suitable for the required analysis, and by correlating results to actual %MTF data, a set of acceptance parameters were developed.

The optical test equipment, which was procured as a deliverable contract requirement for evaluating the KBr lens, is unique and a breakthrough technique. It is a computer automated test procedure which was not only suitable for evaluating the forged optical surfaces of the KBr lens but one which will have wide usage for quickly evaluating optical flats, spherical and most asperical surfaces.

It is estimated that the lower cost of this lens would save the government about $300,000 per year over that where a ZnSe lens is presently used. The techniques established can be adapted for many other optical materials and configurations.

It is indeed unfortunate that development of a suitable MIL-STD coatings for the humidity sensitivity of KBr (beyond the scope of this M&T program) has not proceeded to the point where KBr lenses can be deployed for the IR-image systems. We do believe that the capabilities established and the currently available protective coatings will find D.O.D. applications for low cost internal IR optical components which have short duration exposure to humid atmospheres-such as in IR-guided missiles, munitions and bomblets.

## SECTION 5
## PRESENTATIONS, PUBLICATIONS AND REPORTS

- A talk relating to hot forging of KBr lenses was given at the Optical Society of America workshop held at West Falmouth, Massachusetts, on September 21-22, 1980. The paper presented was entitled: "Hot Forging and Infrared Lens: Potassium Bromide, F.M. Schmit, R.H. Anderson, K.M. Leung and R.J. Betsen. This paper was published by the Optical Society of America as page 83-86 in "Workshop on Optical Fabrication and Testing."

- Paper was presented at the 14th Annual Symposium on Optical materials for High Power Lasers, November 19 & 20, 1982 "Hot Forging of KBr Lenses Direct to Optical Figure" J.B. Weigner and W.B. Harrison.

**Abstract**

A video tape which describes the process for manufacturing and optical testing of KBr plano-concave lens by the hot forge-to-optical figure technique was presented.

- Paper was presented at the 31st National Infrared Information Symposium (IRIS) May 4, 1983 "Hot forging of KBr Lenses Directly to Optical Figure" J.D. Weigner and W.B. Harrison.

**Abstract**

Techniques have been developed for hot forging KBr lenses directly to optical figure. This process eliminates the necessity for extensive optical fabrication and polishing. The production procedures for such lenses are described as are the testing techniques that are used to evaluate the lenses.

# REFERENCES


1. R.H. Anderson, E. Bernal, G.K.M. Leung, T.J. Moravec, and D. Wertman, Honeywell Semiannual Technical Report No. 1 on NV&EOL Contract DAAK70-77-C-0218, April 12, 1978.

2. R.H. Anderson, E. Bernal, G.K.M. Leung, T.J. Moravec, F.N. Schmit and D. Wertman, Honeywell Semiannual Technical Report No. 2 on NV&EOL Contract DAAK70-77-C-0218, October 13, 1978.

3. R.H. Anderson, et. al., "Alkali Halide FLIR Lens Development," Honeywell Final Technical Report on DARPA Coantract MDA 903-80-C-0098, October 1980.

4. W.B. Harrison, G.O. Hendrickson and J.E. Starling, "Exploratory Development on Antireflective Coatings for Alkali Halide Internal Laser Windows," Honeywell Final Report on AFWAL Contract F33615-77-C-5038, April 1981; AFWAL-TR-80-4190.




The reverse of this page is blank.

# APPENDIX A
# DEFINITIONS, DRAWINGS AND SPECIFICATIONS

This section contains the definitions, drawings and tooling specifications required for the manufacturing and testing of KBr plano-concave lens by the hot forged-to-optical figure process. The drawings given in this section are:

| Drawing Number | Title |
|---|---|
| 27062 | Material Specification for KBr Single Crystals |
| 28100607 | KBr Color Correction Lens |
| 28100608 | First-Stage Forging Assembly/Tooling |
| 28100609 | Second-Stage Forging Assembly/Tooling |
| 28100610 | Tooling for Lens Final Machining |
| 28100611 | KBr Lens Machining Alignment System |
| 28100612 | Plano-Conical KBr First-Stage Forging |
| 28100613 | Vacuum Chuck—First-Stage Forging |
| 28100614 | Crystal Cleaving Approach |
| 28100615 | Schematic of White Light Interferometer |
| 28100616 | Cubic Beam Splitter for White Light Interferometer |
| 28100617 | Aluminum Cooling Plate |
| 28100618 | Strain Standards—First-Stage Forgings |
| 28100619 | Strain Standards—Single Crystals |
| 28100620 | Strain Standards—Final KBr Lens |
| 28100621 | Definitions for Hot Forged-to-Optical Figure Process |

## 1.0 SCOPE

1.1 This specification covers the single crystal blanks for use in the manufacture of infrared transmitting windows.

## 2.0 APPLICABLE DOCUMENTS

None

## 3.0 REQUIREMENTS

3.1 Number of lots in shipment - Unless otherwise specified, each shipment shall consist of not more than one lot of any given raw material used in the crystal growth process (homogeneous throughout and manufactured at one time under controlled conditions).

3.2 Form and color - The material shall be supplied as optically transparent crystal blanks with an absorption at 10.6 $\mu$m to be less than 0.00125 $cm^{-1}$.

3.3 Chemical analysis -

| | | | |
|---|---|---|---|
| Ba | 5 | Mg | 5 |
| Br | Major | N | 5 |
| Ca | 5 | Na | 100 |
| C | 50 | OH | 0.1 |
| Cl | 50 | O | 1 |
| Cs | 5 | Pb | 1 |
| Fe | 1 | Rb | 10 |
| I | 50 | S | 1 |
| K | Major | Si | 2 |
| Li | 1 | Sr | 5 |

3.4 Crystal Orientation - End faces of cylindrical single crystals shall be parallel to the <100> crystal orientation.

3.5 Workmanship - The workmanship shall be such that the material is uniform in quality and condition, clean and dry and free from foreign particles, cracks or other defects which would interfere with the optical transmission of this blank.

3.6 Identification - Each crystal blank suplied must be identified in such a manner that traceability will be maintained to the following:

1. raw material lot used in growth process
2. ingot number, date of growth, furnace number, etc.

MATERIAL SPECIFICATION
FOR KBr SINGLE CRYSTALS

| REV | | | |
|---|---|---|---|
| SIZE A | DWG NO 27062 | | |
| SCALE | DAAK70-79-C-0138 | SHEET | 1 OF 2 |

## 4.0 QUALITY ASSURANCE PROVISIONS

4.1 Qualification - Qualification of a new supplier shall be based upon assurance that his material is capable of meeting all the requirements of Section 3 plus satisfactory performance when device tests are deemed necessary. The supplier shall also agree to comply with Section 5.

4.2 Acceptance - Unless otherwise specified, each shipment shall be accepted or rejected as a result of the testing of a representative sample of the lot against 3.0.

4.3 Inspection - the number of lots of each shipment shall be verified by the vendor plus further testing as deemed necessary.

4.3.1 Surface Finish - An optical method shall be used for this method.

4.3.2 Form, color and workmanship - The form, color and workmanship of each blank shall be checked 100% by visual examination under 4X magnification. Optical absorption measurements at 10,6 $\mu$m shall be made on a representative sample from each ingot.

4.3.3 Composition - The composition shall be quantitatively checked by means of emission spectrography, atomic absorption, flame photometry and wet chemical.

## 5.0 PREPARATION FOR DELIVERY

5.1 Packing - Each optical blank shall be individually sealed to be adequately protected against normal mechanical damage during shipment and against moisture and foreign material contamination.

5.2 Marking - The marking on each container shall be durable and legible and shall include the following:

a. Manufacturer's name and address
b. This specification number
c. Quantity per outside container
d. Manufacturer's lot number
e. Honeywell purchase order number

| REV | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| SIZE A | DWG NO 27062 | |
|---|---|---|
| SCALE | DAAK70-79-C-0138 | SHEET 2 OF 3 |

## 6.0 NOTES

6.1 Ordering data - Procurement documents should include the following:

a. Title and specification number

b. A minimum of 50 grams of the parent ingot material from the area adjacent to the blanks will be identified and submitted for chemical evaluation. Such a sample will be included with each shipment and for each ingot used in this shipment.

c. Destination of production material

d. Request for verification that shipments represent only one lot as per 3.1.

e. Request for and description of vendor's data per 3.0.

f. Quantity per container

g. Note: Honeywell Purchasing should send a copy of the purchase order to the pertinent Product Quality Engineer.

6.2 Handling and storage - Normal handling procedures should be adequate. Storage should be in a dry location.

6.3 Shelf life - This material exhibits indefinite long shelf life.

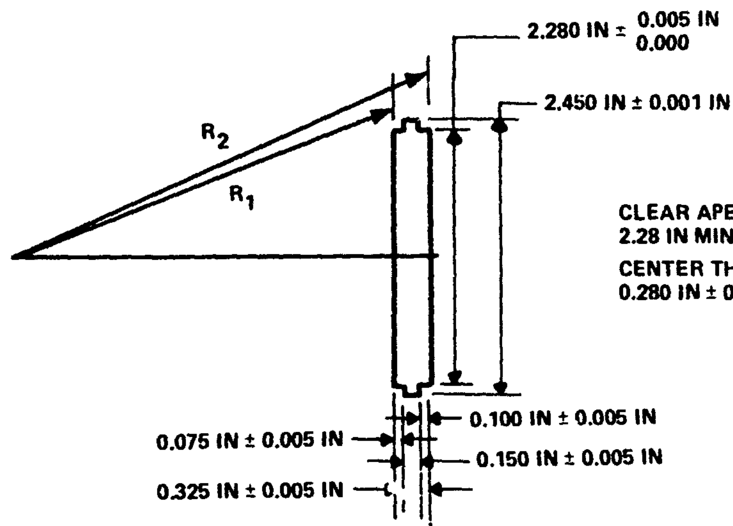
6.4 Approved product - Only material made by an approved supplier listed below shall be considered for acceptance when ordered to meet this specification. Representative samples of material from other suppliers of material from other suppliers shall be tested against and shall meet the qualification requirements in order that the material may be used and listed on the approved product lists following:

Approved Vendors: Harshaw
Optovac

| REV | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| SIZE | DWG NO |
|---|---|
| A | 27062 |

| SCALE | DAAK70-79-C-0138 | SHEET 3 OF 3 |
|---|---|---|




CLEAR APERTURE
2.28 IN MINIMUM

CENTER THICKNESS
0.280 IN ± 0.010 IN

| RADII | | SURFACE QUALITY |
|---|---|---|
| $R_1$ | 17.25 IN ± 0.25 IN | 80/50 |
| $R_2$ | ∞ | 80/50 |

KBr COLOR CORRECTION LENS

| REV | | | |
|---|---|---|---|
| SIZE A | | DWG NO 28100607 | |
| SCALE 1" = 1.5" | | DAAK70-79-C-0138 | SHEET 1 OF 2 |

HD-378

Interferometer Evaluation:

Using Digital Optics Model 2300 testing device: (Drawing No. 28100615)

Maximum surface departure from reference, spherical or flat surfaces:

2000 units maximum (0.01$\mu$m/unit) with tilt removed.
Maximum deviation, point-to-point = 300 units (0.01$\mu$m/unit)

Subtracted distortion (simulated wavefront distortion):

Maximum departure (tilt removed) = 300 units (0.01$\mu$m/unit)
Maximum Deviation, point to point = 50 units (0.01$\mu$m/unit)

Beam splitter specifications for the white light interferometer used in the Model 2300 Aspheric Tester: (See Drawing No. 28100616)

Using standard interferometric techniques, specifications required are:

Maximum surface figure departure, spherical or flat surfaces:

10 $\lambda$ for $\lambda$ = 632.8nm

Maximum wavefront distortion, single pass (sheering) interferometer:

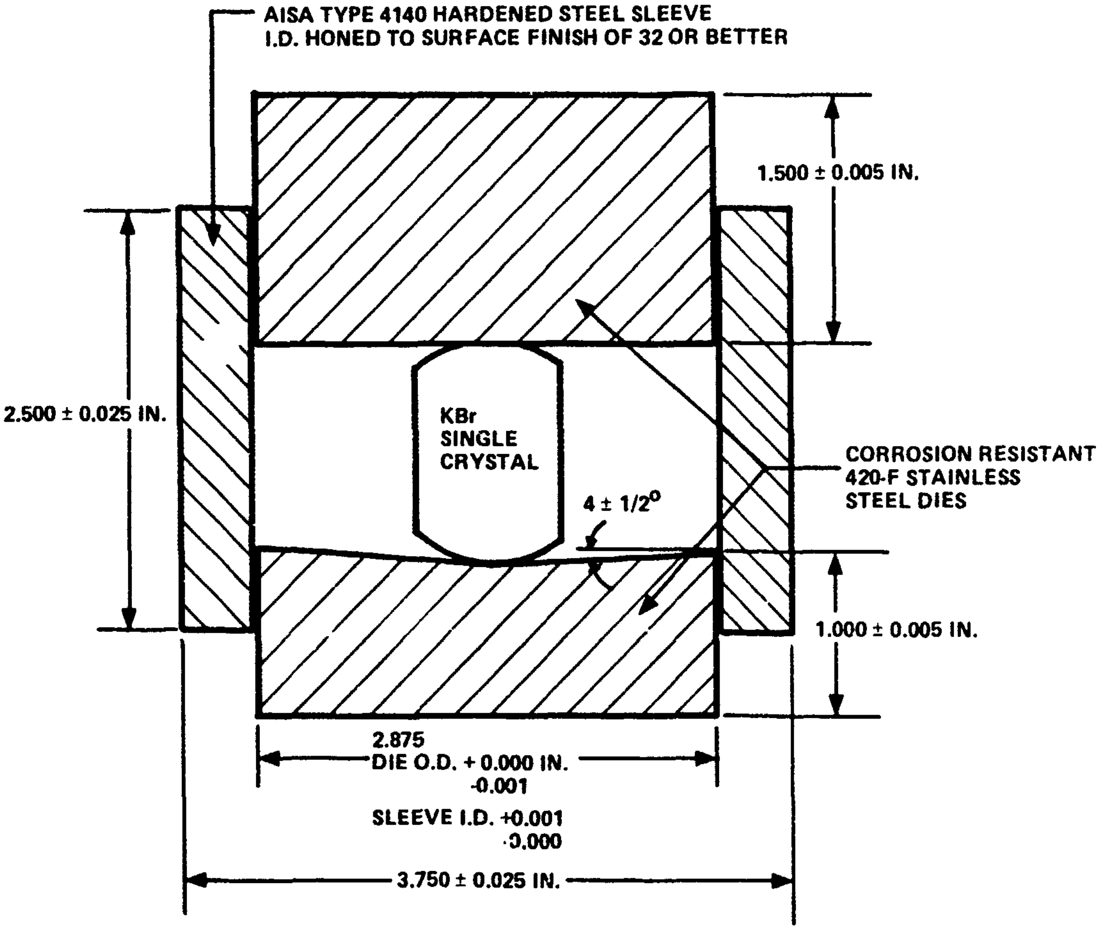
4 $\lambda$ for $\lambda$ = 632.8nm

The lens specifications in the MTF Imager are as follows:

MTF on-axis: >74%
MTF off-axis: >66%
Effective focal length: 67.8 ± .7mm
Flange focal length: 17.86 ± .25mm

| REV | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

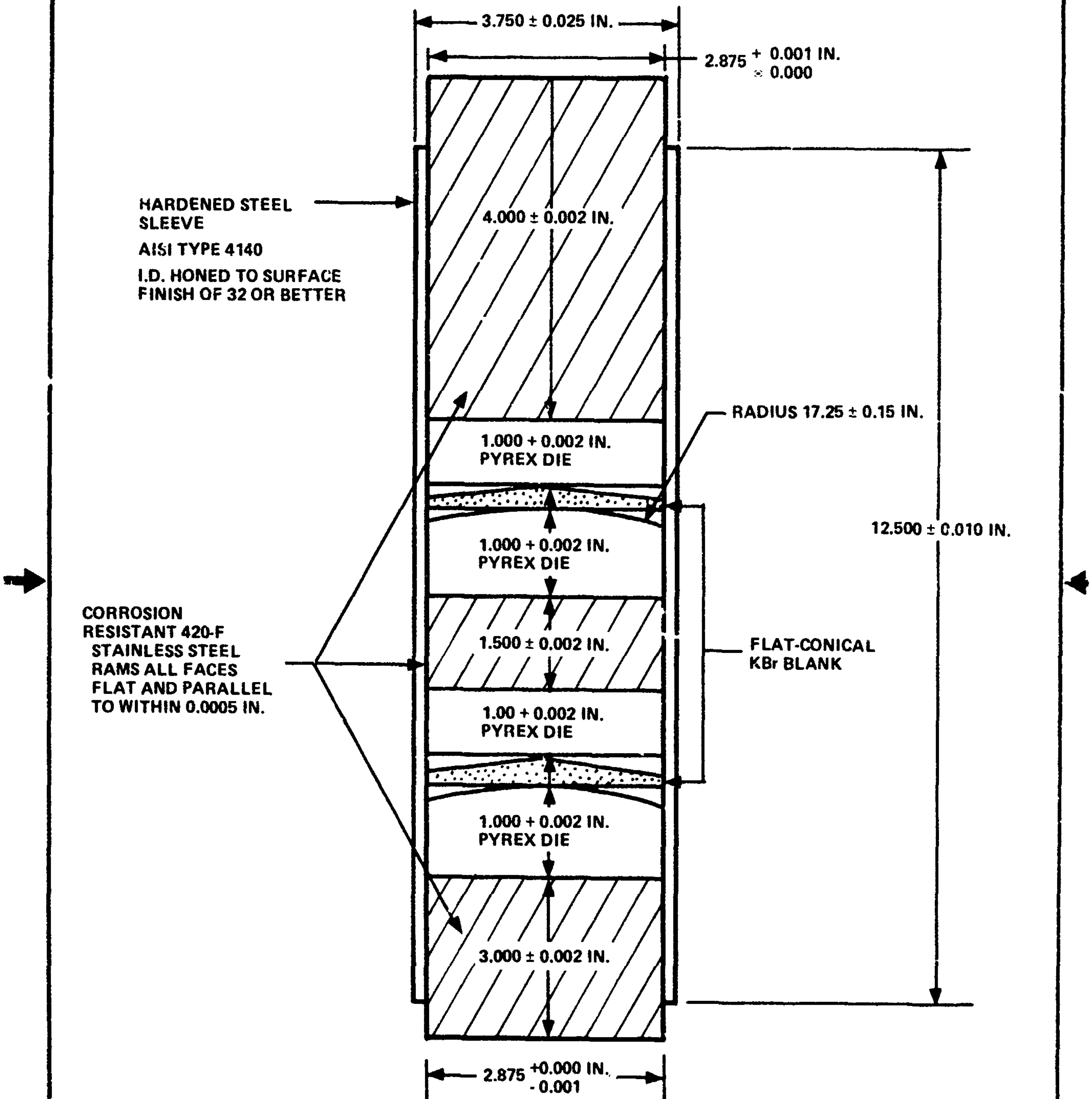
| SIZE A | | DWG NO 28100607 |
|---|---|---|
| SCALE NONE | DAAK70-79-C-0138 | SHEET 2 OF 2 |




FIRST-STATE FORGING ASSEMBLY/TOOLING

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100608 | |
| SCALE 1" = 1" | DAAK70-79-C-0138 | SHEET 1 OF 1 | |

HD-378




SECOND-STAGE FORGING ASSEMBLY/TOOLING

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100609 | |
| SCALE NONE | DAAK 0-79-C-0138 | SHEET 1 OF 2 | |

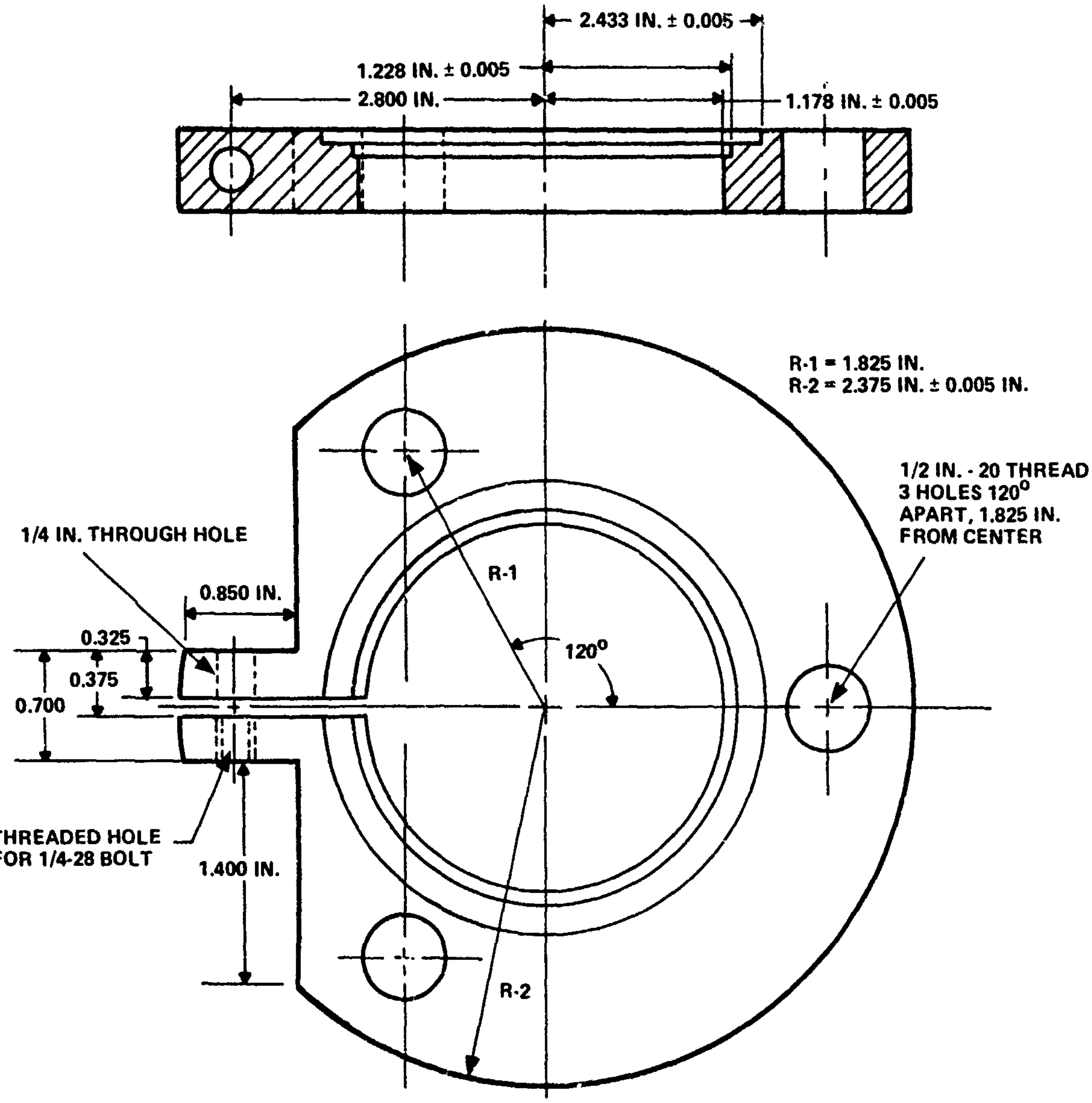


HD-378

Second Stage Flat Forging Die—Pyrex glass, 1.000″ ± .002″ thick, both faces optically polished flat to 1/4λ, scratch/dig 60/40. Glass must be visibly clear and free of visible inclusions, pits or other defects. Die diameter to be 2.875 +0.000″ -0.001.

Second Stage Convex Forging Die—Pyrex glass, 1.000″ + .002″ center thickness, flat side polished flat to 1/4λ, convex side polished spherical to 1/4λ to within 1/16″ of edge, with a radius of curvature of 17.25 ± 0.15″. Diameter to be 2.875 +0.000″ -0.001.

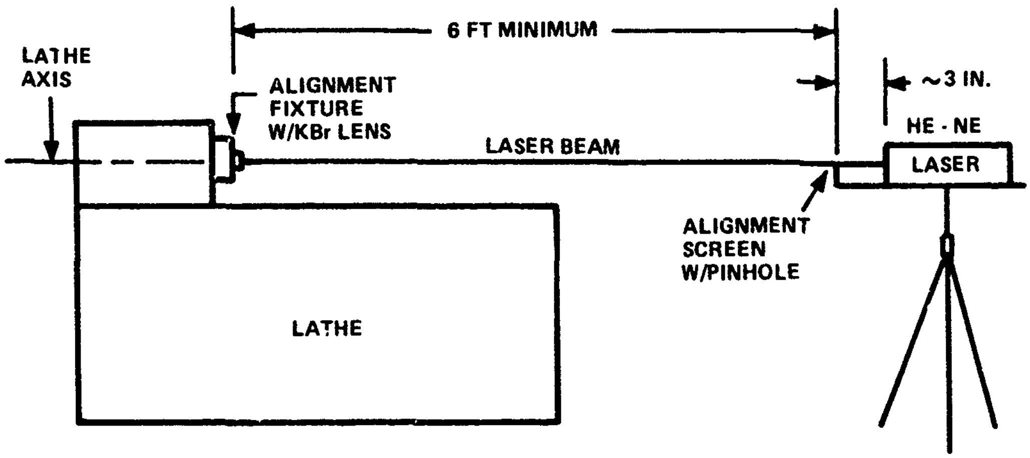
| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100609 | |
| SCALE | DAAK70-79-C-0138 | SHEET | 2 OF 2 |




**TOOLING FOR LENS FINAL MACHINING**

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100610 | |
| SCALE 1" = 1" | DAAK70-79-C-0138 | SHEET 1 OF 1 | |

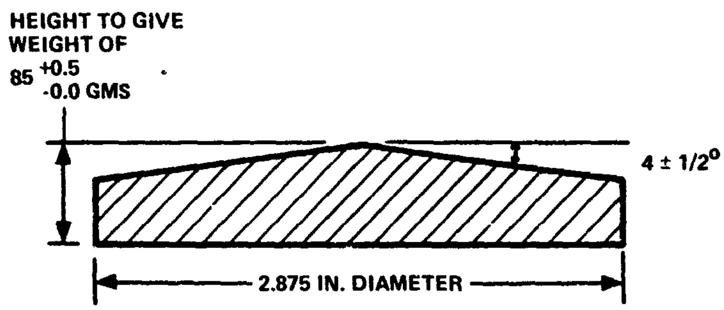
HD-378




**KBr LENS MACHINING ALIGNMENT SYSTEM**

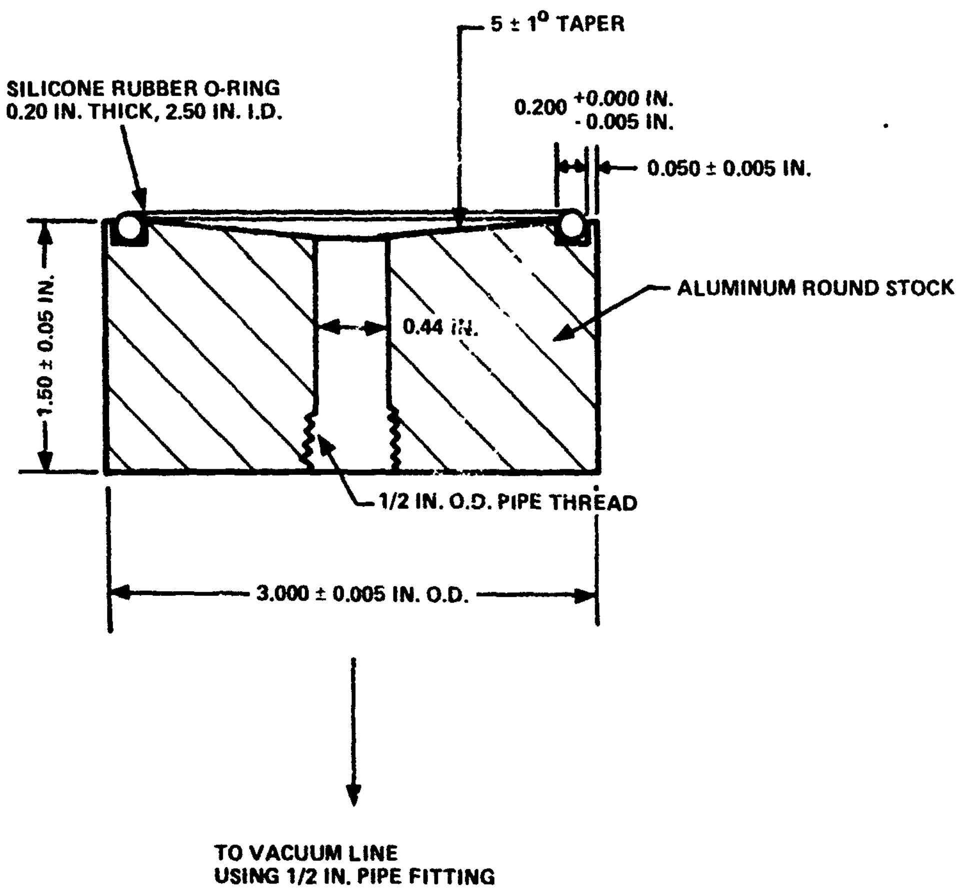
| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100611 | |
| SCALE NONE | DAAK70-79-C-0138 | SHEET 1 OF 1 | |

HD-378




PLANO-CONICAL KBr FIRST-STAGE FORGING

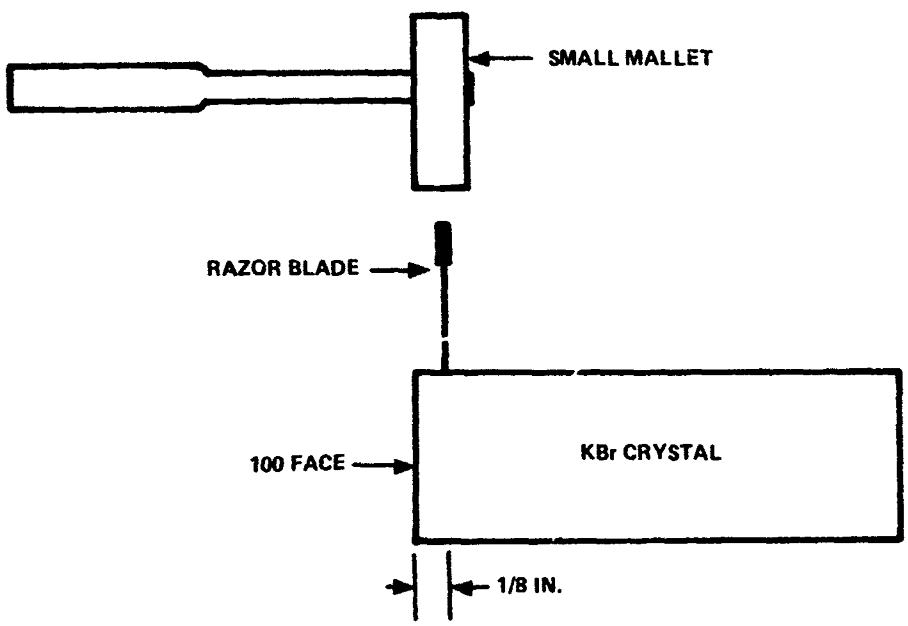
| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO. 28100612 | |
| SCALE NONE | | DAAK70-79-C-0138 | SHEET 1 OF 1 |




VACUUM CHUCK-FIRST-STAGE FORGING

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO. 28100613 | |
| SCALE 1" = 1" | DAAK70-79-C-0138 | SHEET 1 OF 1 | |

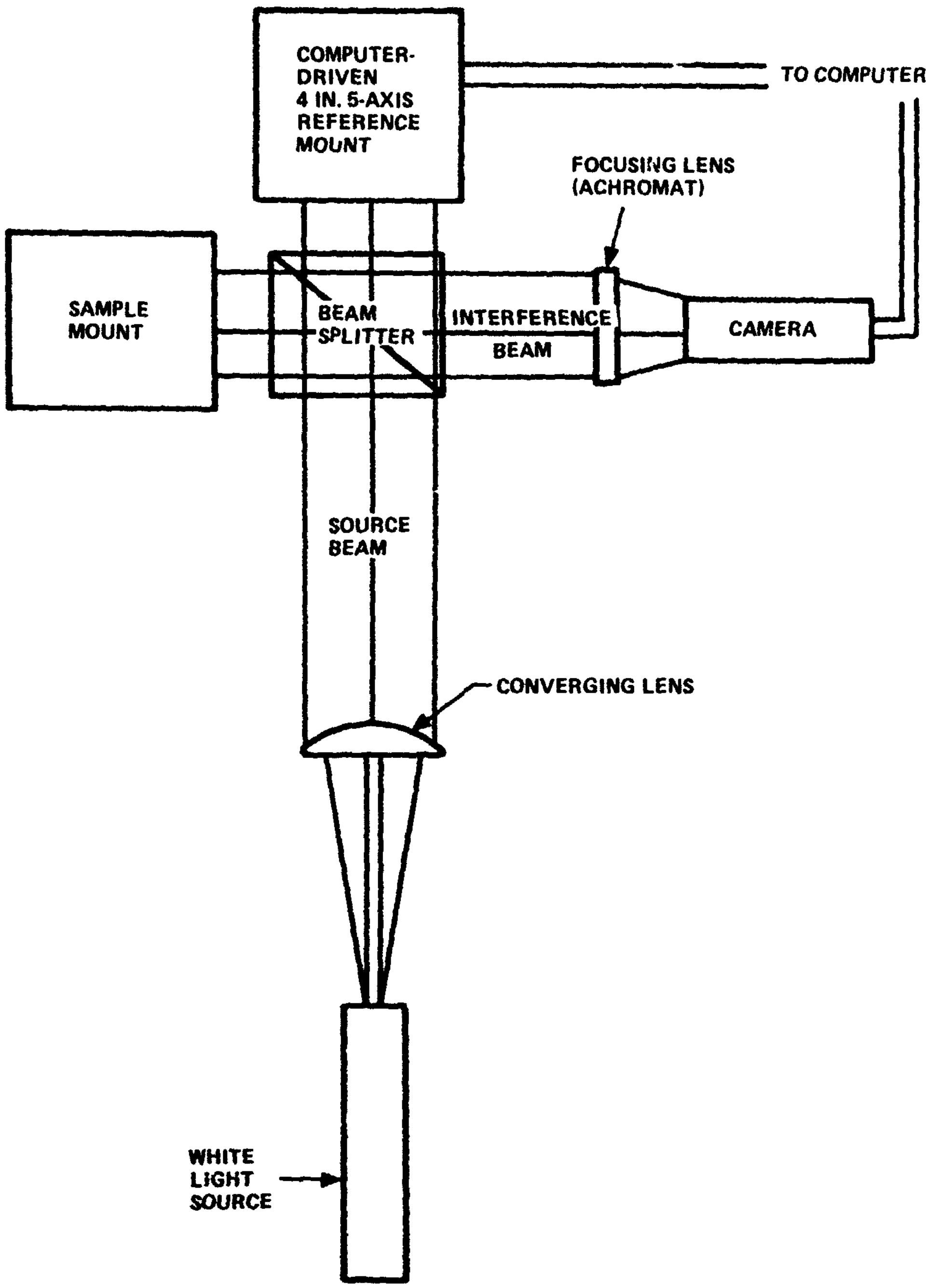
HD-378




CRYSTAL CLEAVING APPROACH

| | | |
|---|---|---|
| REV | | |
| SIZE A | DWG NO. 28100614 | |
| SCALE NONE | DAAK70-79-C-0138 | SHEET 1 OF 1 |

HD-378

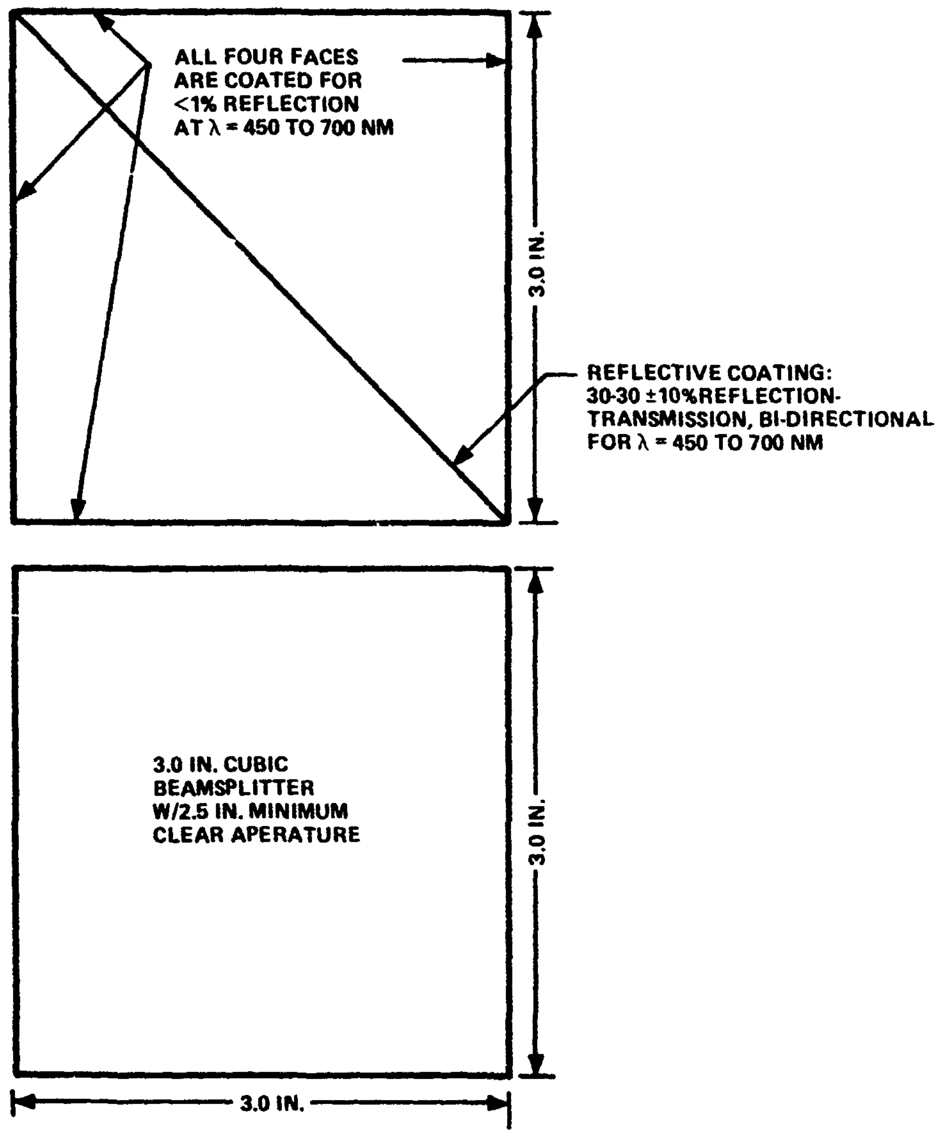



SCHEMATIC OF WHITE LIGHT INTERFEROMETER

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100615 | |
| SCALE NONE | DAAK70-79-C-0138 | SHEET 1 OF 1 | |

HD-378

Material: KB-7, interferometer quality (PH-3 or better)
Wavefront Distortion: λ/4 wave or better in reflection and transmission
Wavefront Irregularity: λ/8/cm or better in reflection and transmission
Angles: 30′ or better
Size/O.P.D. Matching: ±0.025mm

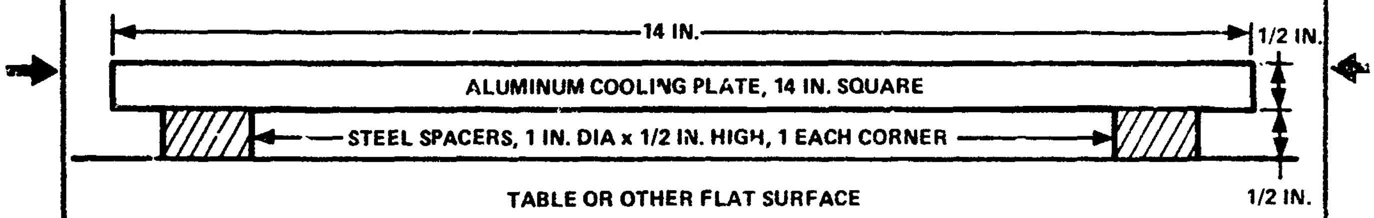



**CUBIC BEAM SPLITTER SPECIFICATION FOR WHITE-LIGHT INTERFEROMETER**

| REV | | |
|---|---|---|
| SIZE A | DWG NO 28100616 | |
| SCALE NONE | DAAK79-C-0138 | SHEET 1 OF 1 |



HD-378




ALUMINUM COOLING PLATE

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100617 | |
| SCALE | DAAK70-79-C-0138 | SHEET | 1 OF 1 |

HD-378

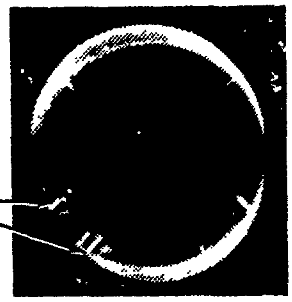
MAXIMUM ALLOWABLE
STRAIN PATTERN

FIRST-STAGE FORGING NO GO STRAIN STANDARD

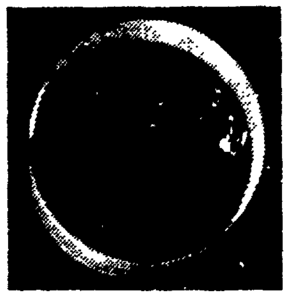
| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100618 | |
| SCALE NONE | | DAAK70-79-C 0138 | SHEET 1 of 1 |

HD 378

CORNER CRACKS
(MUST BE WATER POLISHED
OUT PRIOR TO FORGING)



OPTIMUM STRAIN-FREE CRYSTAL



HIGH STRAIN LIMIT

INCOMING SINGLE CRYSTAL NO GO STRAIN STANDARD

| | | | |
|---|---|---|---|
| REV | | | |
| SIZE A | | DWG NO 28100619 | |
| SCALE NONE | | DAAK70-79-C-0138 | SHEET 1 OF 1 |

HD-378

NON-ACCEPTABLE STRAIN
THIS LEVEL OR HIGHER

FINAL LENS NO GO STRAIN STANDARD

| REV | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| SIZE A | | DWG NO 28100620 | |
|---|---|---|---|
| SCALE NONE | | DAAK70-79-C-0138 | SHEET 1 OF 1 |

HD-378

Forging Die is all of the assembled Pyrex or steel parts of tooling, which are required for shaping the Potassium Bromide lens element to its final optical figure. (See Dwg. No. 28100609)

Forging Rams are the steel components used for spacing the dies and providing the proper height for forging. (See Dwg. No. 28100609)

Forging Sleeve is the steel cylinder which contains the forging dies, rams and KBr elements for the purpose of forging Potassium Bromide blanks or lenses. (See Dwg. No. 28100609)

First-Stage Forging refers to the operation which shapes a KBr single crystal into a plano-conical first stage forging blank (See Dwg. No. 28100612). It also refers to the KBr element which has undergone first stage forging (usually referred to as first stage forging blank).

Second-Stage Forging refers to the operation which shapes the first stage forging blank into a plano-concave optically finished lens blank (See Dwg. No. 28100607).

Lens Machining is that operation which optically aligns the lens and machines the diameter and flanges to the final finished lens dimensions.

| REV | | |
|---|---|---|
| SIZE A | | DWG NO. 28100621 |
| SCALE | DAAK70-79-C-0138 | SHEET 1 OF 1 |

# APPENDIX B
# EQUIPMENT SPECIFICATIONS

This section specifies the equipment that was used for the manufacturing process described in Section 2.3 and the testing requirements in Section 2.4. A complete list of the manufacturing and test equipment follows:

1. Rotary Lap
2. Polariscope
3. Filtered Flow Bench
4. Humidity Controlled Room
5. Heating Oven
6. Forging Press
7. Computer Controls
8. Vacuum Pump
9. Nitrogen Blow-Off Station
10. Triple Beam Balance
11. Caliper
12. Machining Lathe
13. Helium-Neon Laser
14. Heat Sealer
15. Camera
16. Interferometer
17. Namarski Microscope

MANUFACTURING AND TEST EQUIPMENT DESCRIPTIONS

| | |
|---|---|
| B1 Rotary Lap: | Buehler type RA H56 with 115 v. 0.25 A motor, or equivalent<br>Maximum Motor RPM = 1725<br>Maximum lap RPM = 246<br>Lap diameter = 8″ |
| B2 Polariscope: | Consists of white tungsten filament light source with an opal glass diffusion plate, two linear polarizers (polaroid type HN-38) and a full wave retarder of 560 nm, to produce a red-violet isochromic strain pattern. |
| B3 Filtered Flow Bench: | Dexon Primaire model HF76E-675 with 2′ × 6′ working surface, or equivalent. |
| B4 Humidity Controlled Room: | Clean area is conditioned to 70-75°F, 10-35% RH using a Liskey Air Model UW-10 Air Conditioner or equivalent 152,000 BTU total capacity. Conditioned air is filtered through two one-inch thick pre-filters and two four-inch thick final filters having a filter rating of 60% NBS down to 10μm particles. A 3 HP blower provides 5000 CFM nominal air flow creating a positive room pressure. |

**B5 Heating Oven:** Blue M, Model EM-106 FX, or equivalent
Temperature Range: 5°C above ambient to: +316°C (+600°F)
Interior Dimensions: 19" W × 20" D × 39" H (10 cu. ft.)
Voltage: 240 Volts/Three Phase/60 Hz AC 8.8 Total KVA

**B6 Forging Press:** Model 40A Rodgers 350 ton press or equivalent with heated platens top and bottom, capable of maintaining 300°C. Ram is 8" dia. × 20" travel. Low-pressure fast rate has flow of 11 gal/min. High-pressure slow travel has flow of 2.6 gal/min. Must be controllable at forging rates as low as 0.006"/min.

**B7 Computer Controls:** The major accomplishment in the area of special equipment has been the design of the automatic equipment required for the forging process. The actual automation was done with Honeywell funding because the equipment was not bid into the contract. This includes the alterations to the press hydraulics and the electronic equipment necessary to control the press. Figure B-1 shows the forging press layout and Figure B-2 is a schematic of the automated controls and interfaces between equipment.

The calculator receives the temperature, pressure, and distance parameters, and uses this information to control the forging operation. During second stage forging upon starting the cycle, the press will close to the proximity of the forging rams. The calculator then controls the rate by reading the Acurite Distance Meter over a fixed time base and making current adjustments to the servo metering valve. During this time the pressure and limit switches are being monitored, and when the pressure reaches the desired value, forging stops. After a preset soak time at pressure, the press returns to an open position ready for the next series of forgings. The rate for 2 × 3 forging is controlled to 0.012"/min, which corresponds to 0.006"/min for each lens. During any one minute period, the rate may vary by ±0.002"/min, but averaged over the entire forging cycle the rate variation is typically less than ±0.001"/min. This type of control is phenominal for a press of this size.

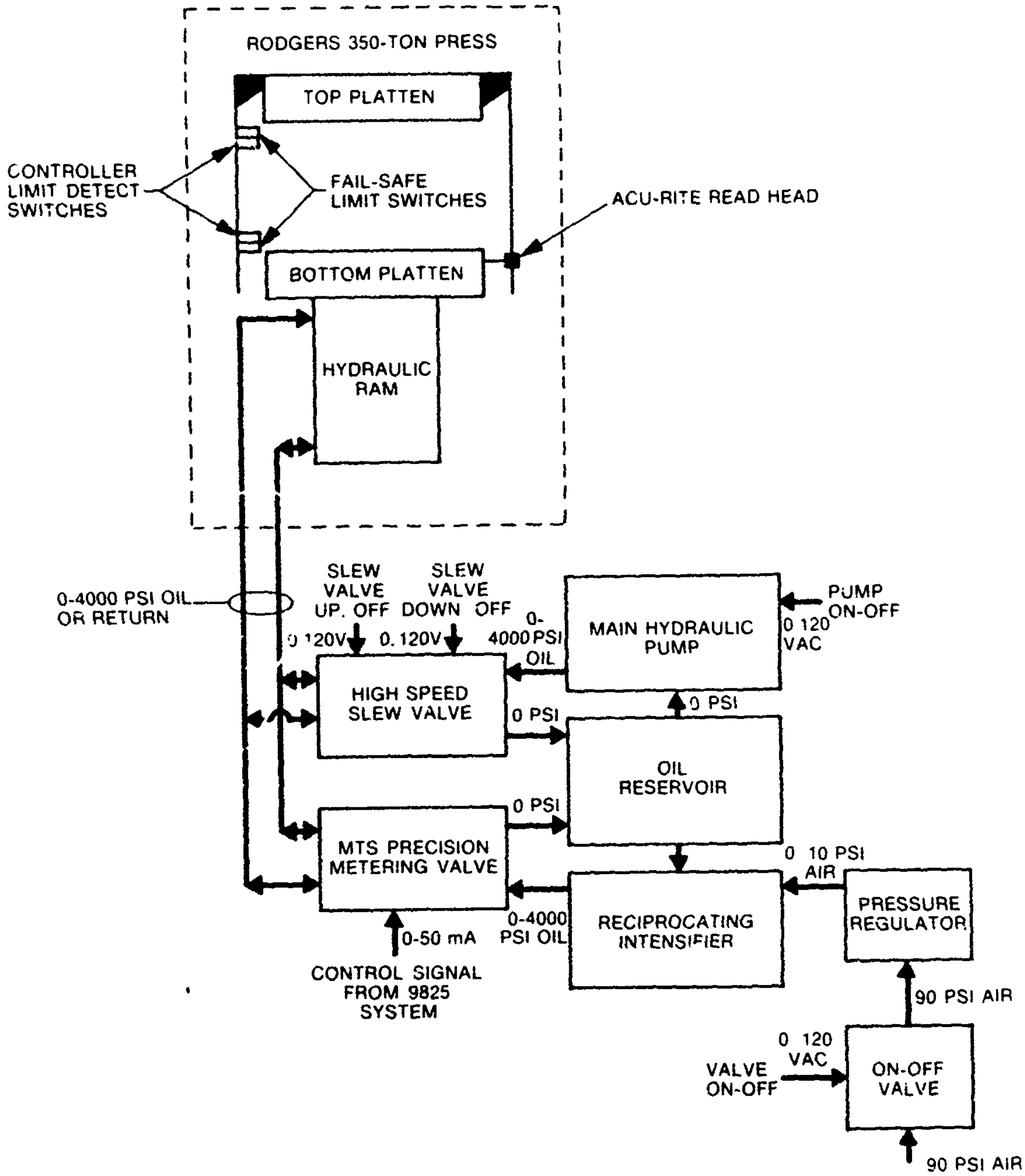



*Figure B-1. Schematic of forging press.*

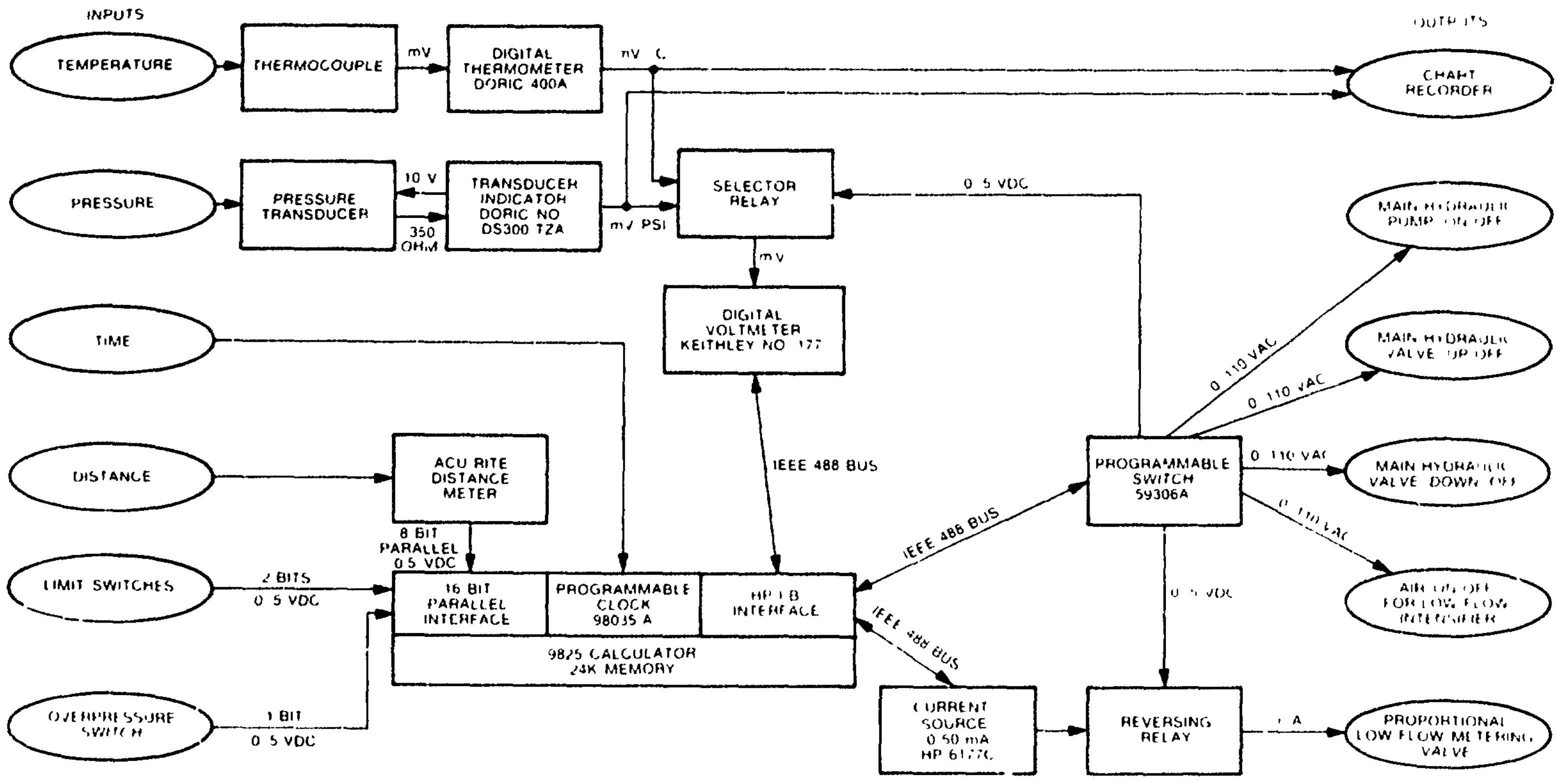



Figure B-2. Schematic of automated controls.

The automated equipment is of particular benefit for controlling the forging rate in first-stage forging. When given the initial conditions, the computer can control forging at a constant speed for a given time interval (i.e., 30 seconds), recompute the speed required for the next interval to ensure a constant strain rate, and re-adjust the ram speed accordingly. While this will result in a step function rather than a smooth decrease in ram speed, the resulting approximation is much more accurate than manually monitoring and controlling the ram speed.

Figure B-3 is a photograph of the major press modifications which include the metering valve for controlling the slow forging, the pressure transducer, high pressure filter, and overpressure switch. Figure B-4 shows the console containing the calculator, Acurite display, temperature and pressure indicators, current source for the servo valve, programmable switch, and relay indicators.

| | |
|---|---|
| B8 Vacuum Pump: | Welch Scientific Model R1403 Capable of producing a minimum vacuum of 28" of Mercury, or equivalent. |
| B9 Nitrogen Blow-Off Station: | Extra Dry Nitrogen tank, 2500 psi, with Matheson Model 3075 high pressure regulator or equivalent. Foot switch (Treadlite #T51S or equivalent) controls solenoid and valve (ASCO Valve #8262A 215 and solenoid #80173, or equivalent) to release gas stream. |
| B10 Triple Beam Ballance: | OHAUS Dec-O-Gram 2610 gram capacity, or equivalent. |
| B11 Calipers: | 0-6" dial calipers with 0.001" increments, or equivalent. |
| B12 Machining Lathe: | Southbend 10" quick change gear lathe Model 186Y or equivalent. |
| B13 Helium-Neon Laser: | Hughs Model 3222H-PC 5 milliwatt output, or equivalent. |
| B14 Heat Sealer: | Doughboy Model B2952G Plastic bag sealer, or equivalent. |
| B15 Camera: | C. Koch System using Sinar lens (f.5.6-45) and swivel mounts with Polaroid film mount, or equivalent. |

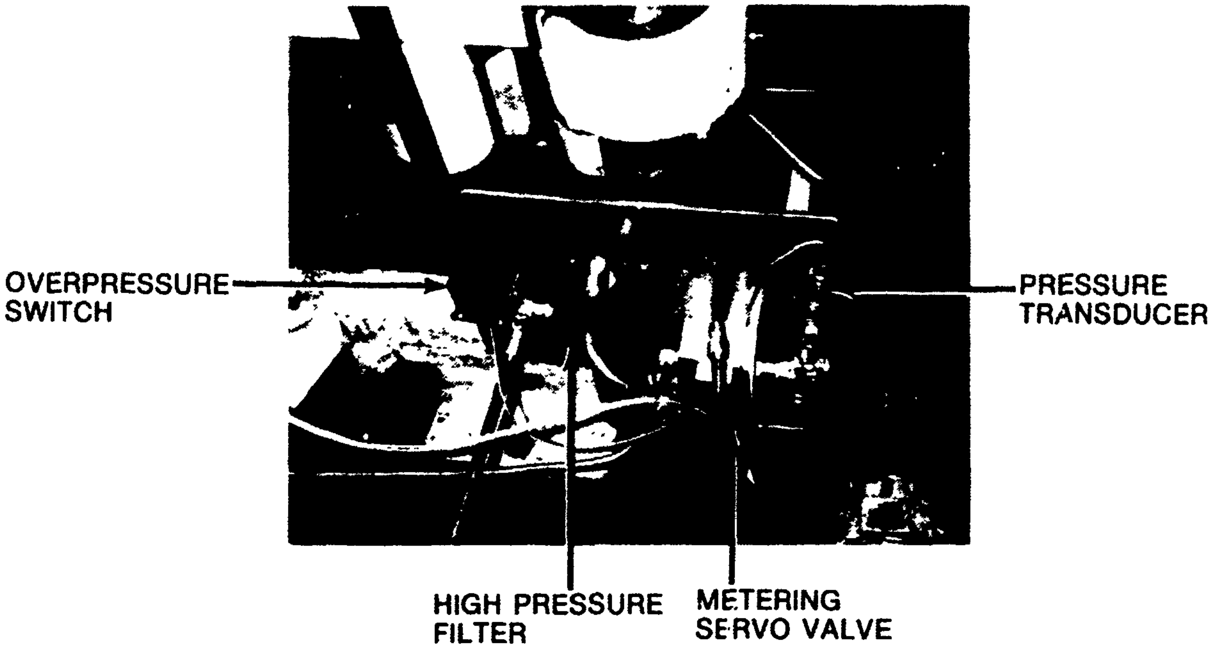



*Figure B-3. Press modification for automatic control.*

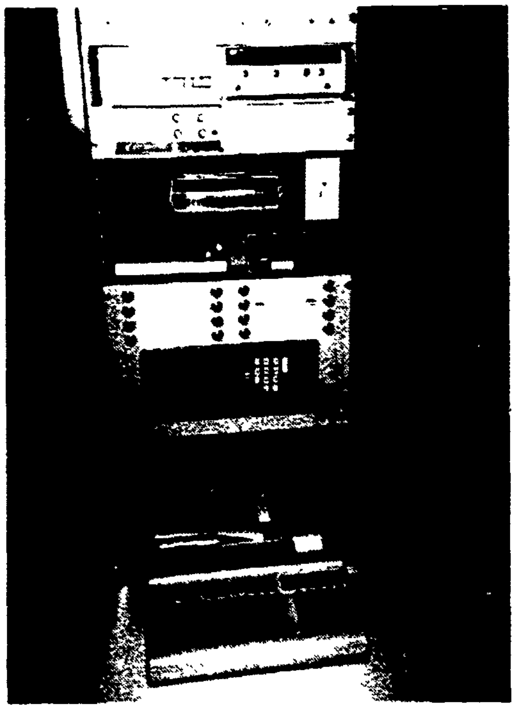


*Figure B-4. Console containing electronic controls for press automation.*

B16 Interferometer: Digital Optics Model 2300 with:

| | |
|---|---|
| Measurement Aperture | Nominal 50mm<br>Can be increased or reduced by proper selection of null optics. |
| F-Number of Test Optics | Depends entirely on the null optics used. |
| Resolution of Surface deviation measurement | .01 microns |
| Repeatability of measurement | .05 microns |
| Accuracy of measurement | .1 microns |
| Measurement data point array | 64 × 64 |
| Individual sampling aperture diameter | 1/1000th of the measurement aperture. |
| Surface deviation measurement dynamic range | 2000:1 |
| Test surface reflectability | Minimum 4% |
| Data Output | Line contours on CRT display and output through RS-232 port |
| Overall measurement time | Less than 200 secs. |

B17 Namarski Microscope: Unitron Model ME-1416 Polycontrast with 50-400x magnification, or equivalent.

## Appendix C
## Distribution List

Commander
Defense Documentation Center
ATTN: DDC-TCA (Quantity 12)
Cameron Station, Building 5
Alexandria, VA 22314 — 12

HQDA (DAMA-WSA)
ATTN: LTC Waddel
Washington, DC 20310 — 1

HQDA
ATTN: DAMA-CSC-ST
Room 3D43
Pentagon
Washington, DC 20310 — 1

Commander
Air Research and Development Command
ATTN: RDTCT
Andrews AFB
Washington, DC — 1

Development and Readiness Command
ATTN: DRCMT (Mr. Fred Michel)
5001 Eisenhower Avenue
Alexandria, VA 22333 — 1

Commander
US Army Materiel Development
and Readiness Command
ATTN: DRCQA
4001 Eisenhower Avenue
Alexandria, VA 22333 — 1

Commandant
US Army Aviation School
ATTN: ATZQ-D-MA (O. Heath)
Fort Rucker, AL 36360 — 1

Director
US Army Production Equipment Agency
ATTN: Mr. C. McBurney
Rock Island Arsenal
Rock Island, IL 61299 — 1

Commander
US Army Missile Command
ATTN: DRSMI-RR (Dr. J.P. Hallowes)
Redstone Arsenal, AL 35809 1

Commander
US Army Tank-Automative Command
ATTN: DRSTA-RW-L
Warren, MI 48090 1

Commander
US Army Missile Command
ATTN: DRSMI-RE (Mr. Pittman)
Redstone Arsenal, AL 35809 1

Commander
US Army Tank-Automative Command
ATTN: DRSTA-RHP (Dr. J. Parks)
Warren, MI 48090 1

Commander
US Army Missile Command
Redstone Scientific Information Center
ATTN: Chief, Document Section
Redstone Arsenal, AL 35809 1

US Army Missile Command
ATTN: DRSMI-RGP (Mr. Victor Ruwe)
Redstone Arsenal, AL 35809 1

Commander
US Army Materials and Mechanics
Research Center
ATTN: DRXMR-M (N.H. Fahey)
Watertown, MA 02172 1

Director
US Army Industrial Base Engineering Activity
ATTN: DRXIB-MT
Rock Island, IL 61299 1

Commander
Picatinny Arsenal
ATTN: SARPA-TS-S No. 59
Dover, NJ 07801 1

Northrop Corporation
Electro-Mechanical Division
ATTN: Mr. Paul Holderman
500 East Orangethorpe Avenue
Anaheim, CA 92801 1

| | |
|---|---|
| Optic-Electronic Corporation<br>ATTN: Mr. Bryan Coon<br>11477 Page Mill Road<br>Dallas, TX 75243 | 1 |
| Optical Coating Laboratory, Inc.<br>2789 Giffen Avenue<br>P.O. Box 1599<br>Santa Rosa, CA 95402 | 1 |
| Optical Systems and Technology Inc.<br>ATTN: Mr. Harry W.A. Vandermeer<br>4 Alfred Circle<br>Bedford, MA 01730 | 1 |
| Rockwell International<br>Corporation Science Center<br>Thousand Oaks, CA | 1 |
| Space Optics Research Labs<br>ATTN: Mr. C.A. Pipan<br>7 Stuart Road<br>Chelmsford, MA 01824 | 1 |
| Tinsley Laboratories, Inc.<br>2448 Sixth Street<br>Berkeley, CA 94710 | 1 |
| Director<br>US Army Night Vision and Electro-optics<br>Laboratory (Quantity 5)<br>ATTN: DELNV-SI (R. Spande)<br>Fort Belvoir, VA 22060 | 5 |
| Harshaw Chemical Co.<br>Crystal and Electronic Products Dept.<br>6801 Cochran Road<br>Solon, OH 44139 | 1 |
| II - VI, Inc.<br>Saxonburg Blvd.<br>Saxonburg, PA 16056 | 1 |
| Commander<br>US Naval Air Systems Command<br>ATTN: AIR 335 (Mr. E. Cosgrove)<br>Washington, DC 20361 | 1 |
| Commander<br>Department of the Navy, ELEX 05143A<br>ATTN: A.H. Young<br>Electronics System Command<br>Washington, DC 20360 | 1 |

Chief 1
Naval Ship Systems Command
Department of the Navy
ATTN: Code 681A2b (Mr. L. Gumina)
Room 3329
Washington, DC

Commander 1
US Navy Weapons Center
Michelson Lab
ATTN: Code 6018 (H.E. Barnett)
China Lake, CA 93555

Director 1
Naval Research Laboratory
ATTN: Code 2627
Washington, DC 20375

Commander 1
US Naval Air Development Center
ATTN: Code 202 (Mr. T.J. Shopple)
Johnsville, Warminister, PA 18974

Commander 1
Naval Ocean Systems Center
Code 9254 (ATTN: Mr. Richard Gamble)
San Diego, CA 92152

Commander 1
US Air Force Materials Laboratory
ATTN: AFML/CPO (Mr. D. Fisher)
Wright-Patterson AFB
Dayton, OH 45433

Optovac, Inc. 1
East Brookfield Road
North Brookfield, MA 01535

NASA Scientific and Tech Information Facility 1
P.O. Box 8757
Baltimore/Washington, Int'l Airport

Bell and Howell Corporation 1
ATTN: Mr. George R. McGee
7100 McCormick Road
Chicago, IL 60645

Director 1
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Dr. Arthur Cox 1
1116 South Aldine Avenue
Park Ridge, IL 60068

Farrand Optical Co., Inc. 1
ATTN: Mr. Martin Shenker
117 Wall Street
Valhalla, NY 10595

Grumman Aerospace Corporation 1
Research Department and Advanced
Development Department
Bethpage, NY 11714

Hughes Aircraft Corporation 1
ATTN: Mr. Phil Henning
P.O. Box 90515
Los Angeles, CA 90009

Martin Marietta Corporation 1
ATTN: Mr. James Ohmart (MP276)
P.O. Box 5837
Orlando, FL 32805

Melles Griot 1
1770 Kettering Street
Irvine, CA 92714



The reverse of this page is blank.