Rediscovering Makyoh

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TABLE OF CONTENTS

Abstract

Makyoh, also known as “magic mirrors,” are an ancient Chinese art form that date back to the second century B.C.[1] The exact process of their construction has been lost through the centuries. Although this technology is ancient, modern applications for Makyoh include the inspection of semiconductor wafers, forensic recovery of serial numbers on metal objects, and use as a teaching aid[1,2,3,4]. The goal of this project is to recreate these ancient mirrors .

After a failed attempt at casting, explosive forming was the technique chosen to recreate Makyoh. Thin bronze and brass plates were used as blanks in the former. This was a novel approach not discussed in any literature. This method was a relatively simple and fast way to make the mirrors. Explosive forming proved to be viable way to create the mirrors when using simple geometric dies with large features (~0.25”). The need to burnish the mirrors was not eliminated with the explosive forming technique. Reflectivity data indicates bronze rather than brass is better suited to creating Makyoh.

1. Introduction

The ancient Makyoh were cast from bronze with a raised or indented pattern on the side opposite of the mirror face. When collimated light (such as the light from the sun) reflects from the mirror onto a flat surface, the pattern on the back of the mirror is visible on the flat surface[1]. The early (but incorrect) explanation was that light passed through the mirror to create the pattern on the flat surface[1], hence the name "Magic Mirror". The correct explanation for this effect is that the surface of the mirror contains imperfections too small to be visible to the unaided human eye[1,3].

About 1,200 years ago the secrets to creating Makyoh were contained in a book titled *Record of Ancient Mirrors*[5]. Unfortunately, that book was lost in the intervening centuries. The earliest surviving description of the mirrors is in the *Dream Pool Essays*, published in 1086 A.D. by Shen Gua (who owned three of the mirrors as family heirlooms)[5]. The mirrors were considered ancient by Gua's time. Gua correctly believed the mirror's "light penetrating property" was due to tiny variations on the mirror's surface. He incorrectly believed the imperfections were by differing cooling rates on the mirror's surface[5]. The magic mirrors did not come to the attention of Western scientists until 1832[5]. They puzzled scientists for a century until William Henry Bragg developed a suitable theory for the working of Makyoh in 1932[5]. Experiments conducted by European scientists found the mirror was originally cast flat with the pattern on the back of the mirror[5]. Careful scraping on the front of the mirror created the concave shape and caused the plastic deformations that transferred the pattern from the back to the front[5]. A mercury amalgam was applied to the surface of the mirror as a final step which created more preferential buckling[5]. Japanese Christians used the mirrors as a symbol of faith during the Edo Period where Christianity was punishable by death[6].

The objective of this project is to reproduce Makyoh and develop a historically accurate theory for their creation. Despite Bragg's explanation, there are still two theories for Makyoh creation. The first theory argues that careful polishing and scraping on the front of the mirror causes imperceptible imperfections on the mirror's surface[2]. This was the theory investigated in this project. The second theory argues the engraving was made on the front of the mirror and then filled in with a semi-reflective layer (such as a thin layer of gold or silver)[1]. In antiquity this would have been accomplished by applying an amalgam of gold and mercury to the mirror. The mercury would then be volatilized, leaving only the gold behind (in a process known as "fire gilding"). This is not a preferred modern method due to the environmental and health concerns involving mercury vapor.

2. Broader Impact

There are modern applications for Makyoh despite it being an ancient art form. Makyoh are excellent teaching aids. Schools in Hong Kong use Makyoh for this purpose because these ancient mirrors demonstrate interesting optical and material properties[4]. The same technique used to create Makyoh can be used for the forensic recovery of filed off stamped serial numbers on metal objects.[2] Makyoh topography is a surface mapping technique based on these principles used to measures the flatness of mirror-like surfaces[3] (such as those on a silicon wafer). Finally, Makyoh jewelry represents an attractive outlet for commercialization.

3. Procedure

3.1 Materials

- Bronze UNS C22000, H02 Temper, 0.040” thick sheet (McMaster-Carr)
- Brass UNS C26000, H02 Temper, 0.040” thick sheet (McMaster-Carr)
- Remington #4 Yellow .22 blanks (charge for explosive former)
- Forming Die

3.2 Equipment

- Explosive Former
- 240, 320, and 400 Grit Silicon Carbide Polishing Wheels
- Buehler Meta Serv 250 Variable Speed Grinder/Polisher
- 1” Muslin Spiral-Sewn Buffing Wheel on 1/8” Shank (for a hand-held rotary tool)
- Fabulustre Brand Jewelery Buffing Compound (aluminum oxide in stearic acid)
- Fiber-Lite Model 190 Fiber Optic Illuminator (collimated light source)
- Alloy 1045 Steel Forming Dies
- Panasonic Lumix DMC-G2 Digital Camera (for quantitative image analysis)
- Tamron Adaptall 90-210 mm Lens (model 103A, for grid pattern analysis)
- Panasonic Lumix G Vario 14-42 mm Lens (for reflectivity analysis)
- SilkyPix Developer Studio 3.1 SE (software to convert RAW files to uncompressed TIFF for analysis in ImageJ)
- ImageJ (free and open source Windows software for image analysis)

3.3 Experimental Procedure

1.) The engraving die was placed under the metal to be formed (Figures 1 and 2).

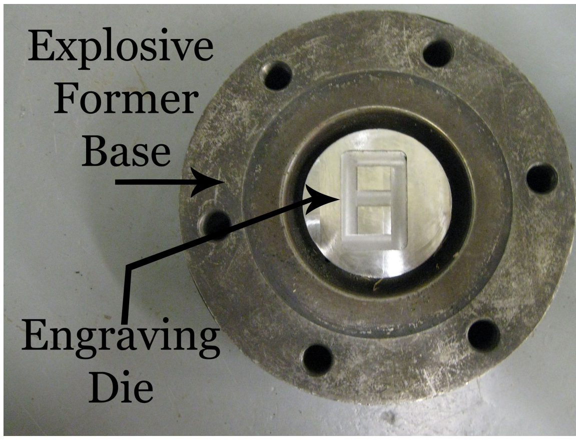

Figure 1: Die in Explosive Former Base

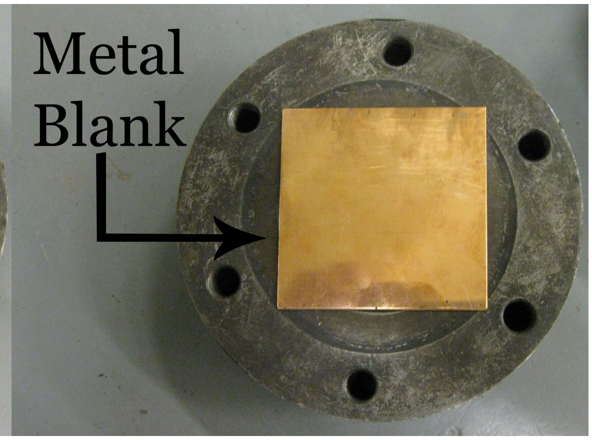

Figure 2: Metal Blank on Explosive Former

2.) Five .22 blanks were fired simultaneously to form the metal (Figure 3). The formed metal was trimmed to size with sheet metal shears. The uncut formed blank is shown in Figure 4. Examples of trimmed, formed blanks are given in Figure 5.

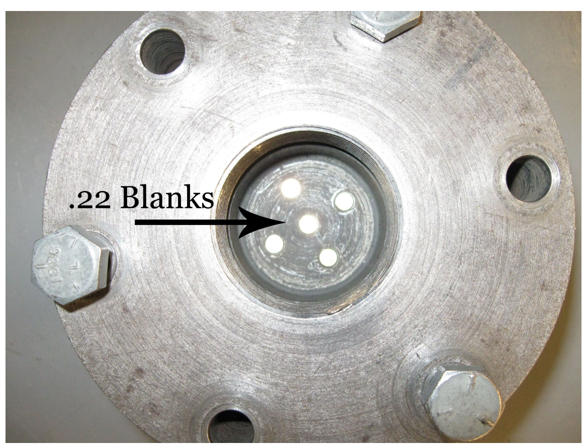

Figure 3: Explosive Former Closed with Blanks Loaded

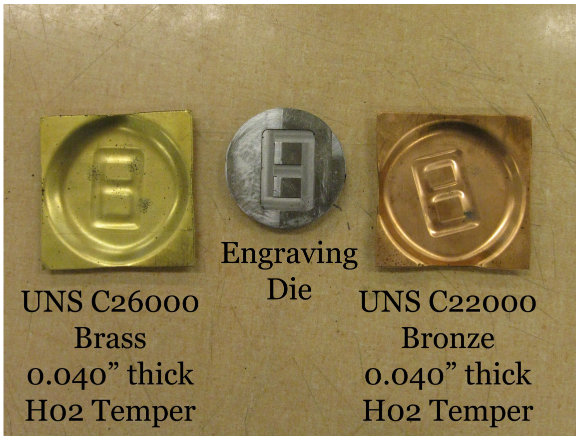

Figure 4: Formed Blanks and Die

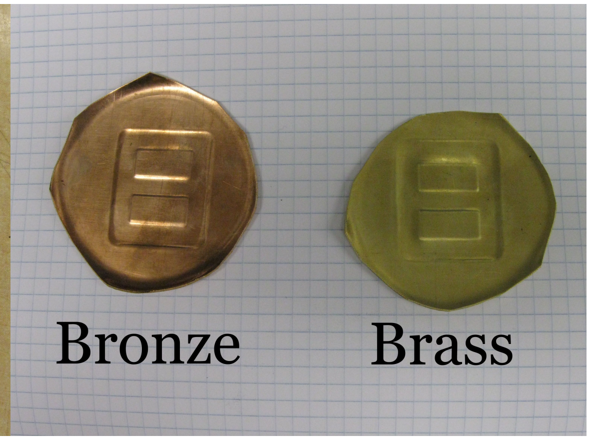

Figure 5: Trimmed Formed Blanks

3.) Each trimmed, formed blank was polished sequentially starting with 240 grit and finishing with 400 grit on the silicon carbide wheels at 300 RPM. The metal was then buffed to a near mirror finish using jewelry polish and a rotary tool. The polish was applied with a muslin wheel turning at 35,000 RPM. Figure 6 shows the mirror after polishing.

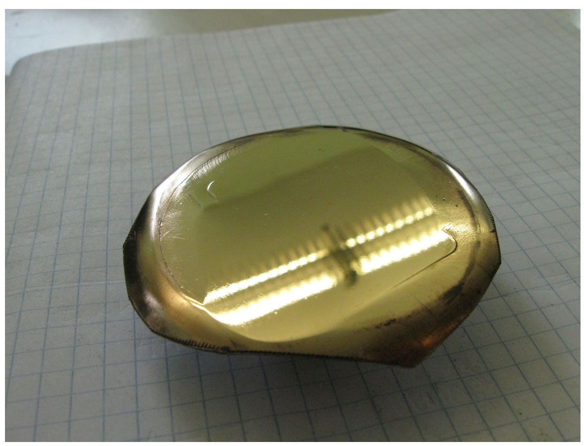

Figure 6: Polished Mirror

4.) After polishing, the mirror was burnished by hand. The detail of the tool is visible in Figure 7 and the mirror after burnishing is shown in Figure 8. Air tool oil was used to lubricate the burnisher. Scratches were present following burnishing but were polished out using jewelry polish and the rotary tool (Shown in Figure 9).


Figure 7: Burnisher Tip

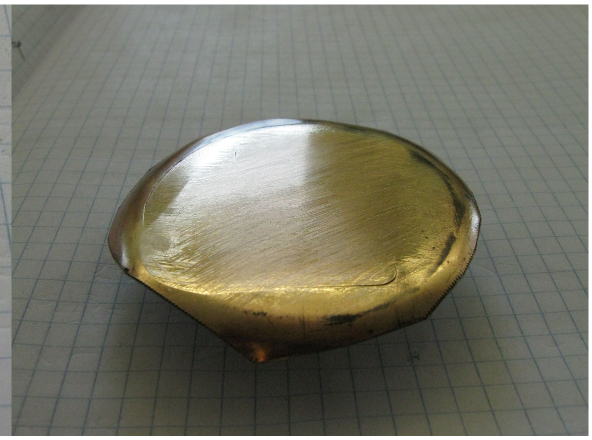
Figure 8: Mirror After Burnishing


Figure 9: Mirror After Final Polish

5.) The polished mirrors were tested on the macro-scale by reflecting light from the fiber optic illuminator onto a flat surface in a dark room (Figure 10).

4. Results

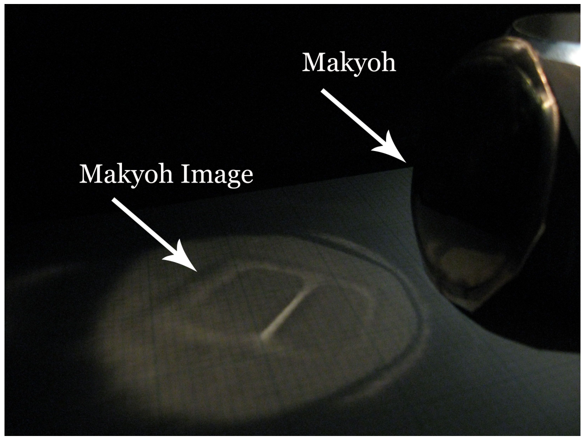

Figure 10: Makyoh and Makyoh Image (from 0.010" die)

Figure 10 shows a working Makyoh created by the described procedure. The procedure was developed by adapting techniques discussed in the literature to work with explosive forming. A simple geometric die was used in the former to create the pattern on the reverse of the mirror. The die was made from alloy 1045 steel milled in the shape of an "8". The "8" was chosen for its definite shape and ease of manufacture. Die depths of 0.030", 0.010", and 0.005" were tested in the explosive former (Figure 11).

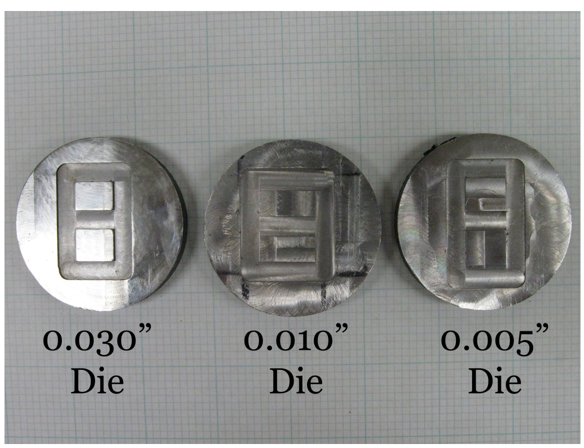

Figure 11: Custom Forming Dies

The die was inserted into the explosive former base while a metal blank was placed on top of the base. The metal blanks were formed using five .22 caliber blanks. The forming caused the “8” to protrude on the front of the formed blank and indent the back. The formed blank was then trimmed and polished as described in section 3.3. The protruding side became the mirror side and was polished flat.

In order to collect quantitative data from the Makyoh, a simple optical bench was constructed. A line grid pattern mounted to flat cardboard was used for the first test. Figure 12 shows the line grid pattern while the optical bench is pictured in Figure 13.

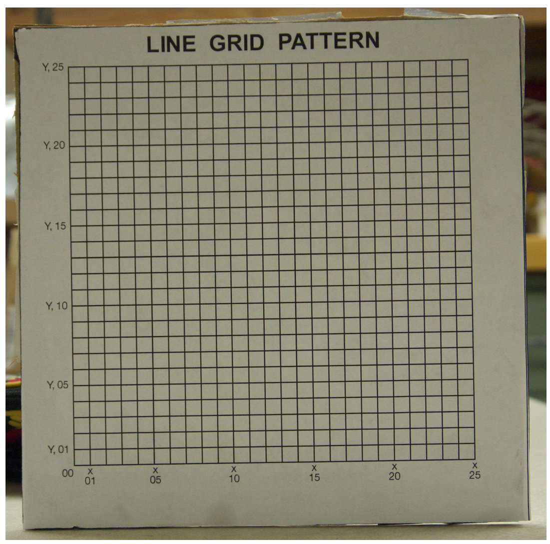

Figure 12: Line Grid Test Pattern

The grid pattern was mounted perpendicular to the table and illuminated with the fiber optic illuminator. The grid pattern was reflected onto the mirror and the reflection from the mirror captured by the camera (shown in Figure 13). The Lumix G2 camera exposure values were adjusted to properly expose each picture. The camera was manually white balanced and the ISO “film” speed was kept at 100 to minimize noise. A Tamron 90-210 mm lens was used and the room lights were turned off to better isolate the reflection from the Makyoh. The raw sensor data was saved and converted to uncompressed TIFF using SilkyPix Developer Studio 3.1 SE. This test evaluated the flatness of the Makyoh. The captured grid pattern images are in Figure 14.

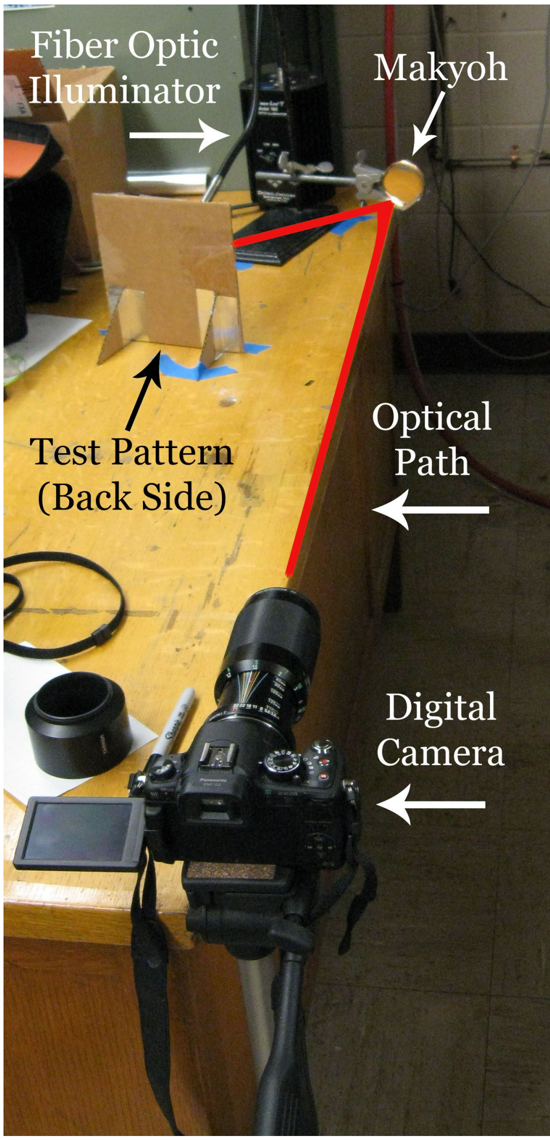

Figure 13: Distortion Optical Bench

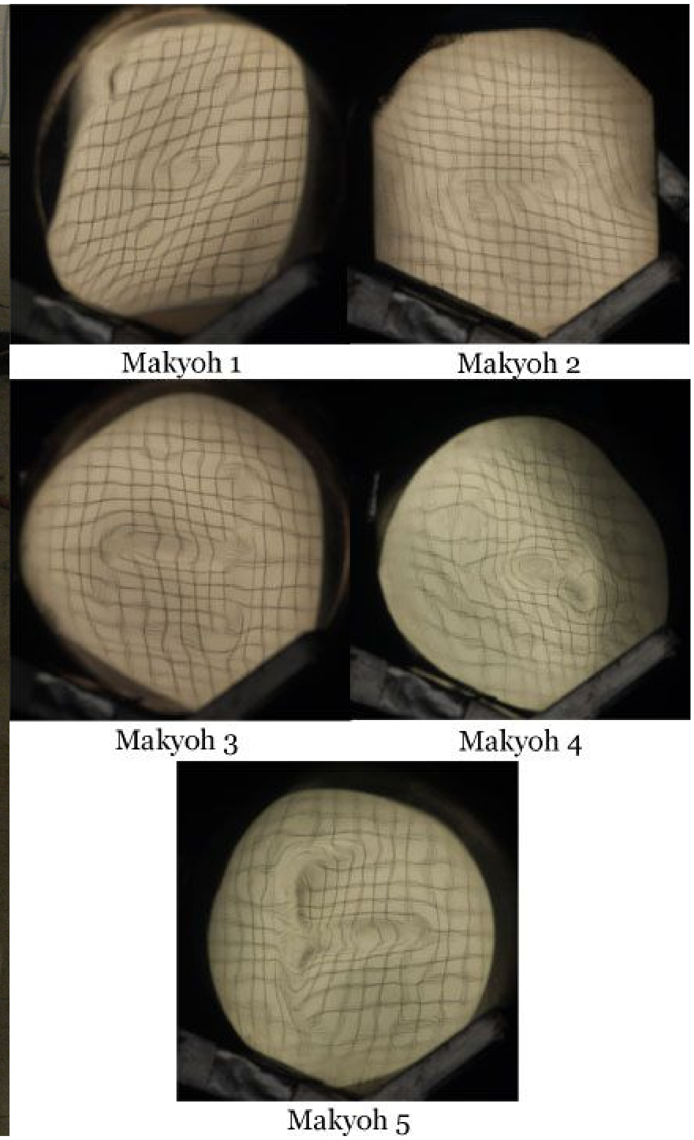

Figure 14: Makyoh with Reflected Grid Pattern

The second test measured the background reflective brightness and pattern reflective brightness. The modified optical bench for this test is shown in Figure 15 below.

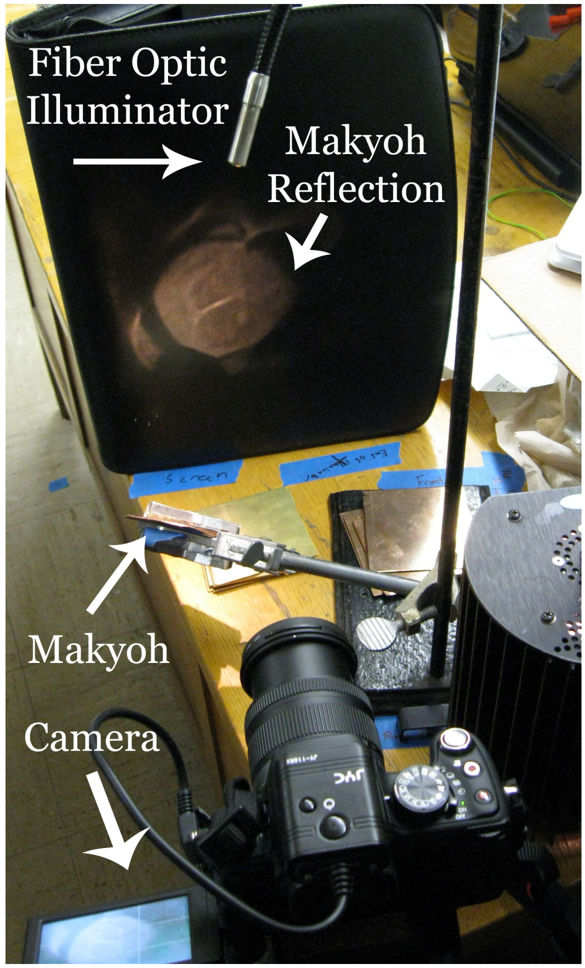

Figure 15: Brightness Optical Bench

The Lumix G2 camera and Makyoh height were kept constant. The Makyoh angle and fiber optic illuminator position were minimally adjusted to ensure the Makyoh reflection was in the center of the camera's field of view. The camera settings were kept constant with $f/5.6$, a 2 second exposure, manual white balance, and ISO “film” speed setting of 100 to minimize noise. This test used a Lumix 14-42 mm lens. The room lights were turned off during the test to isolate the reflection from the Makyoh. The images were saved as raw sensor data which was converted to uncompressed TIFF using SilkyPix Developer Studio 3.1 SE and analyzed in ImageJ. The red box on each reflection image indicates the region of interest on the picture. The brightness of the pixel columns were averaged in the box as a function of distance across the image. The region of interest was maintained for all Makyoh. Due to variations in the size of the Makyoh, the region of interest may intersect slightly different areas on the pattern. However, the region of interest always intersected at least one definite line from the pattern (except in the case of Makyoh 2 which had no definite lines). A contour plot of each Makyoh was taken which recorded the 8-bit gray values. This corresponds to a range from 0-255. These gray values represent the luminance of each pixel. The definition of "luminance" is the same one used in video production where it is equivalent to the brightness of the pixel. All values were greater than 0 and less than 255, so there was no out of range data. Because the brightness values were not calibrated to a source of known intensity, they have arbitrary units. However, these uncalibrated values will work to compare the mirrors against each other. The gray value graphs and images are aligned such that the axes directly correlate. Analyzing the luminance of the Makyoh reflection will provide a quantitative method to determine which Makyoh created the best reflection. Makyoh 2 (Figures 16 and 17) and Makyoh 3 (Figures 18 and 19) are shown below as examples. Makyoh 1, 4, and 5 are in Appendix A. Table 1 summarizes the results of the image analysis.

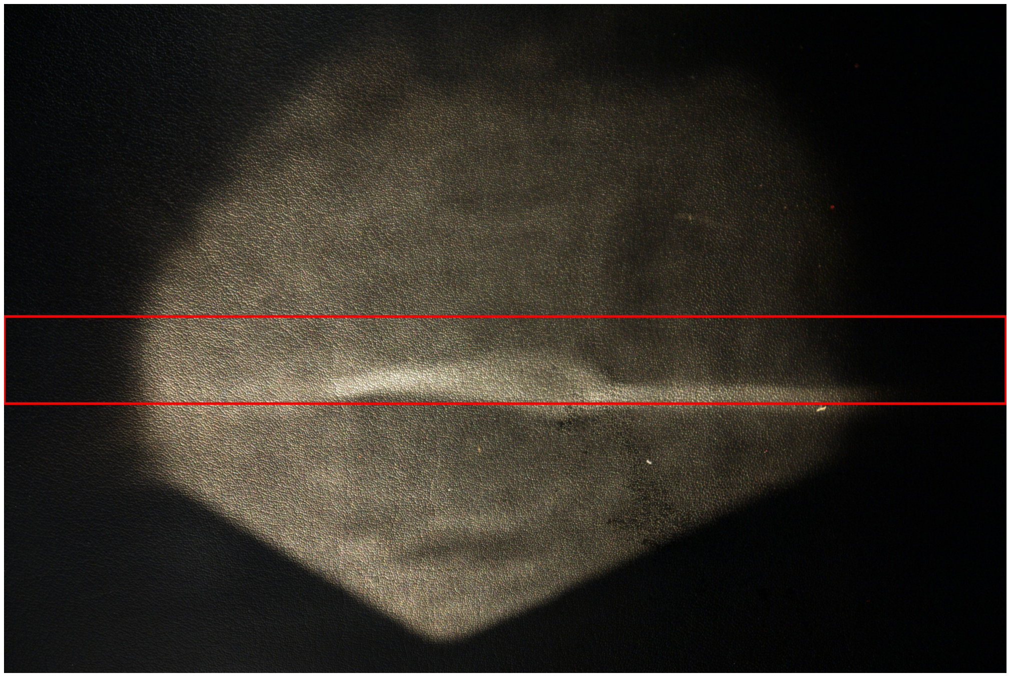

Figure 16: Makyoh 2 with Region of Interest Highlighted

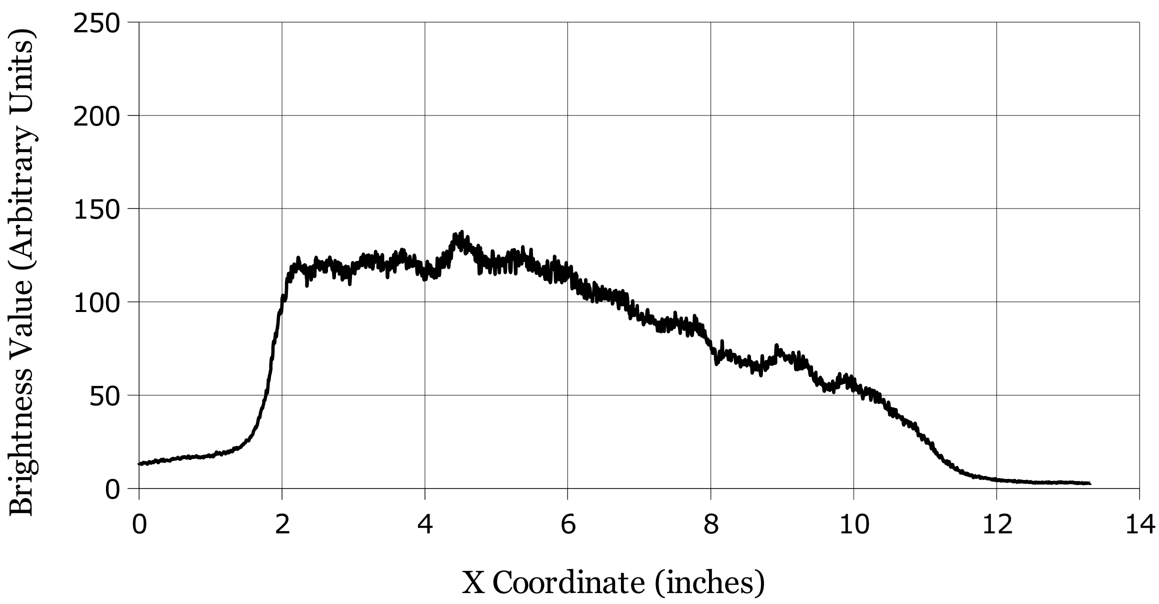

Figure 17: Brightness Contour Plot of Makyoh 2

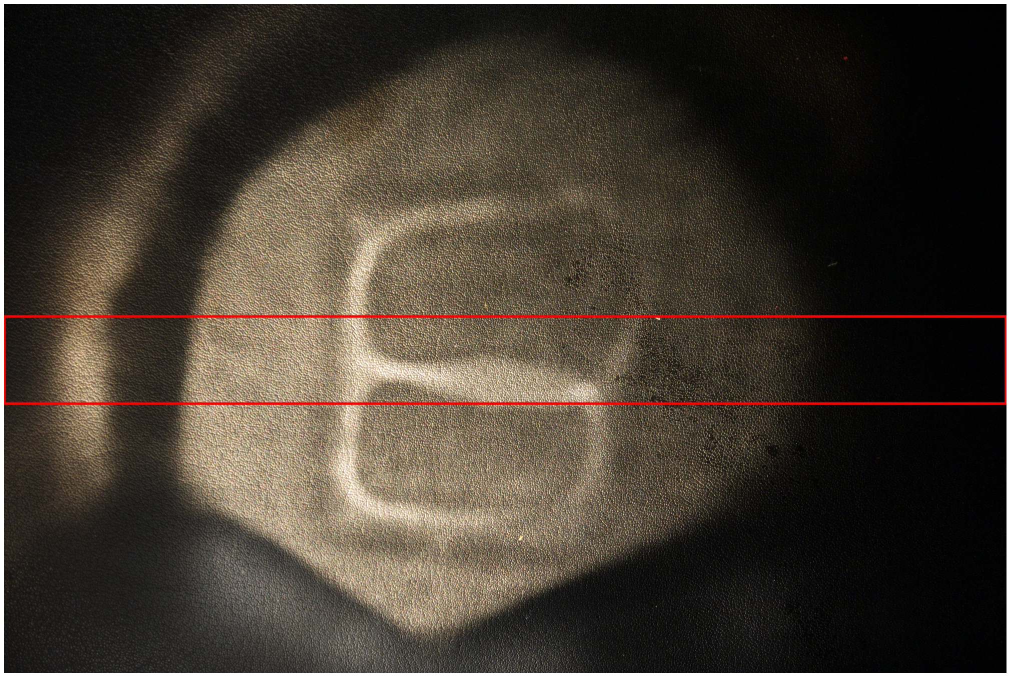

Figure 18: Makyoh 3 with Region of Interest Highlighted

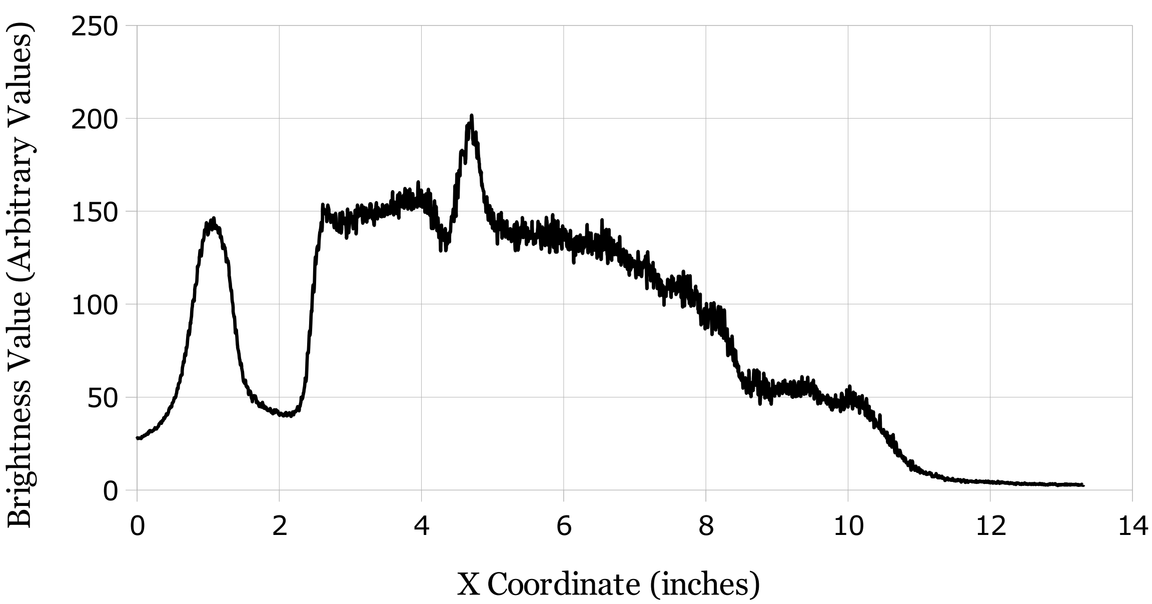

Figure 19: Brightness Contour Plot of Makyoh 3

Table 1: Qualitative Makyoh Results Summary

Makyoh Number	Date Created	Material	Die Depth	Distortion Assessment	Reflection Assessment
1	07/02/12	Bronze	0.005"	Major Distortion	Partial Reflection
2	07/05/12	Bronze	0.005"	Minimal Distortion	Poor Reflection
3	07/09/12	Bronze	0.010"	Moderate Distortion	Strong Reflection
4	07/11/12	Brass	0.005"	Major Distortion	Partial Reflection
5	07/12/12	Brass	0.010"	Minimal Distortion	Partial Reflection

Table II: Makyoh Brightness Analysis (interpreted from graphs)

Makyoh Number	Background Reflectivity (left of peak)	Peak Reflectivity	Peak to Background Difference
1	150	160	10
2	120	135	15
3	150	200	50
4	150	180	30
5	205	200	-5*

*This indicates the image was actually dimmer than the background

5.1 Discussion of Results

Burnishing was the key to creating working Makyoh. This indicates that stress fields are not the primary contributor to the Makyoh effect. The effect is instead due to the plastic deformation on the surface caused by burnishing. The deformation is dictated by the thickness of the pattern on the back. The thinner areas buckle more than the thicker areas. The difference in buckling amounts causes the pattern on the back to transfer to the front.

The results of the distortion test were qualitative. The level of distortion was determined by looking at the amount the grid lines deviated from parallel and perpendicular. All Makyoh showed some distortion. However, the level of distortion did not significantly impact the quality of the Makyoh reflection. Makyoh 2, which had minimal distortion, had the least-defined reflection while Makyoh 3, which had moderate distortion had the most-defined reflection.

The 0.030" dies were not polished because the protrusion of the metal was too great. The thickness of the sheet was only 0.040". If the front side were polished flat, the maximum thickness of that area would be 0.010". This is barely thicker than aluminum foil. If it were burnished, the thin areas would immediately break out. This break out problem was observed with the preliminary pin Makyoh attempts.

Makyoh 3 created the most-defined reflection. The strong peak on Figure 19 supports this. The background luminance was about 150 while the "8" pattern peaked at 200. Makyoh 2 created the least defined reflection. This is supported by the relatively flat line in Figure 19. The brass Makyoh seem to be more reflective than the bronze Makyoh. The background reflection intensity for the bronze Makyoh are 150 or less while the background reflection on the bronze Makyoh are closer to 175-200. This makes sense because brass is lighter in color than bronze (closer to white). The increased hardness of brass may help contribute as well. Although the variations may be due to differences in polishing technique, that seems unlikely given the consistency of the results. Furthermore, the reflections from the brass Makyoh are much more variable than the reflections from the bronze Makyoh and the background reflectivity for brass mirrors are much less defined. In addition, the peak reflections for all mirrors were ~200. If the peak intensity is assumed to primarily be a function of mirror geometry, the peak intensities will be similar for both mirrors. This is supported by the reflection data. Contrast will then be dictated by the background reflectivity of the mirrors rather than the reflectivity of the peaks. Because brass has a higher reflectivity than bronze, the Makyoh images from brass mirrors will have less contrast and be more difficult to see than the images from bronze mirrors. The theory that bronze Makyoh are higher contrast than brass Makyoh is supported by the fact the same depth bronze mirrors created better-defined reflections than their brass counterparts.

Flatness and stiffness of the Makyoh were other major contributing factors to the definition of the image. Makyoh 1, 3 and to a lesser extent 5 show the most recognizable "8" pattern. These Makyoh were cut oversize. Some of the curved flashing from the draw of the die remained on the Makyoh. As a result, these specimens flexed less during burnishing. Makyoh 2, which did not show a recognizable reflection, was cut completely flat and had none of the stiffening flashing. This allowed it to bend during handling. The location where it was bent is visible in Figure 18 as the bright line that crosses the entire mirror.

5.2 Discussion of Preliminary Attempts

Preliminary Makyoh attempts were made with U.S. currency nickels. It was thought these would work well because they are pieces of stamped solid metal. The stamping should have set up the proper stress fields to get the required surface imperfections. Two attempts were made with currency nickels and both attempts failed. However, the nickel was never burnished (as these preliminary attempts occurred before the importance of burnishing was realized). The next attempts used a lapel pin (Figure 20) as a forming die.

Figure 20: Lapel Pin Die and Formed Blank

The back of the pin was ground flat prior to forming. Five .22 caliber blanks were used to form the metal around the pin. The flashing was then trimmed as in Figure 21.

Figure 21: Trimmed Pin Blank

Figure 22: Polished Pin Blank

The face of the blank was ground flat, then polished to a mirror finish (Figure 22). The mirror was polished using a felt pad and 1 micron aluminum oxide suspended in water (this occurred before the jewelry polish was purchased). As a result, it did not appear as reflective as the Makyoh polished with the jewelry polish. The reflection from the polished piece was observed under an overhead projector (this light source is also collimated and the fiber optic illuminator was not yet available). No definite Makyoh reflection was visible.

In order to understand the Makyoh process better, a flat mirror with a visible engraving was prepared. The engraving was created using a pen engraving tool. After engraving, the mirror was polished using the same method as the previous attempts. The goal of this experiment was to determine how large of a feature size was required to create a Makyoh. An overhead projector was used to test the Makyoh reflection. The polished mirror (Figure 23) and resulting reflections (Figure 24) are below.

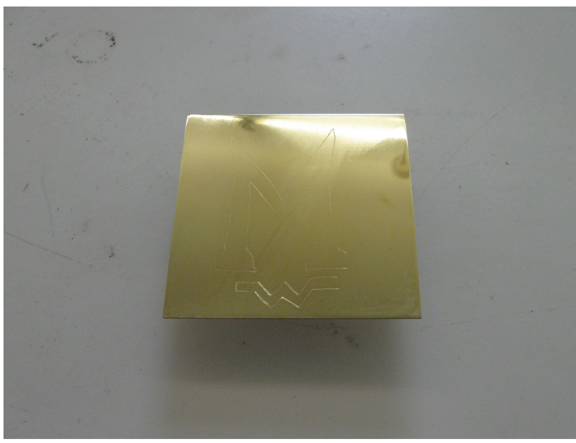

Figure 23: Engraved Brass Mirror

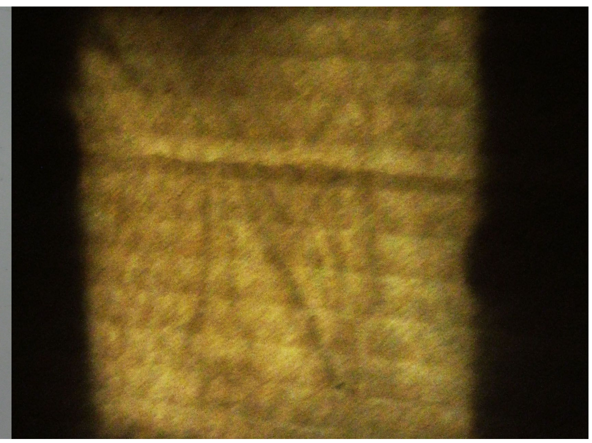

Figure 24: Enhanced Flat Mirror Reflection

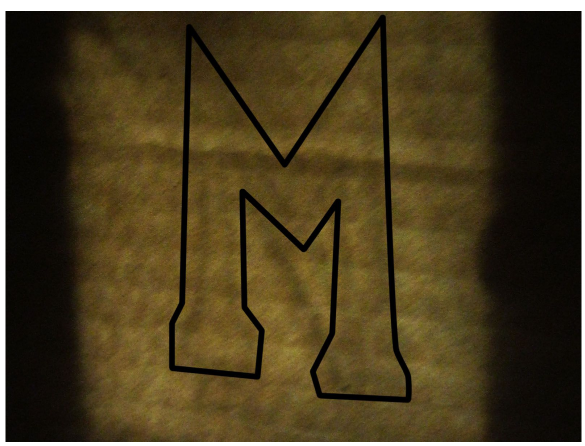

Figure 25: Traced and Enhanced Flat Mirror Reflection

In Figure 24 (digitally enhanced), a dark line outline of the "M" is faint, but visible (Figure 25 shows Figure 24 with the outline traced). The engraved mirror was then observed under a microscope to measure the feature size that gave a visible reflection (Figure 32). For the flat mirror, the marks were about 0.3 mm in width. Although it still may be possible to resolve finer marks, this test provided a good place to start in looking for minimum feature sizes.

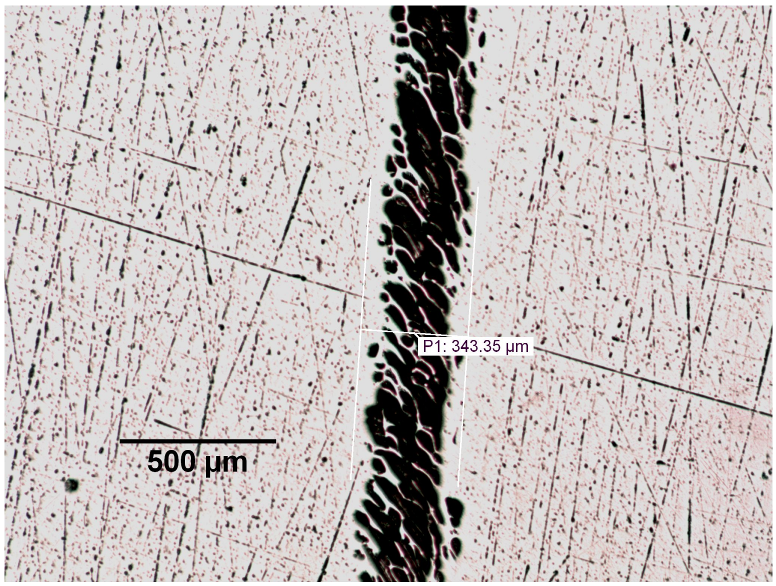

Figure 26: 50x Magnification Engraved Brass Mirror

The brass and bronze pin mirrors were then analyzed under the microscope (Figures 33 and 34). The region of interest was roughly underneath the letters on the edge of the pin.

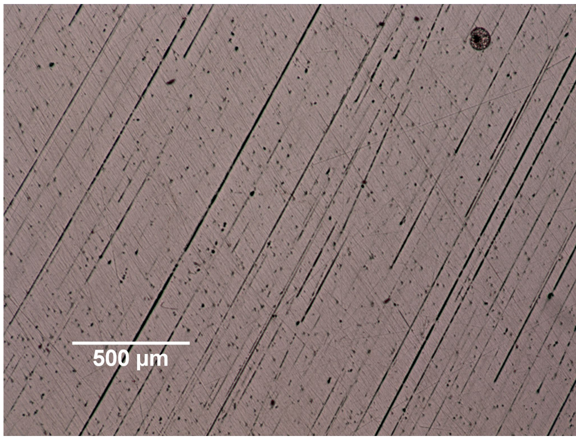

Figure 27: Brass Makyoh

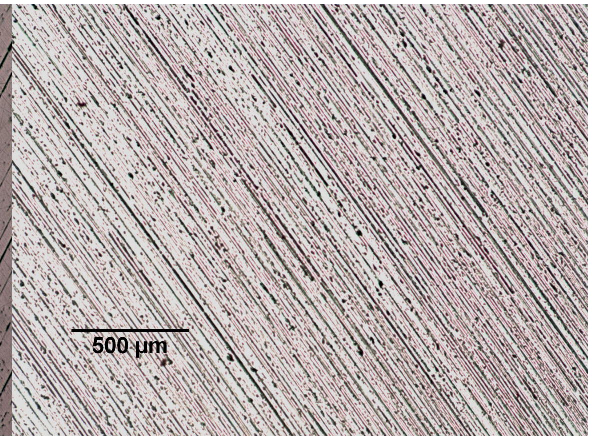

Figure 28: Bronze Makyoh

These two images do not show features discernible against the background scratches. This suggested the feature size of the first engraving die was too small and/or the polishing of the Makyoh was not adequate.

6.1 Conclusions

This project has demonstrated that Makyoh can be produced using explosive forming. This process creates a thin Makyoh that is rapidly polished and burnished. This makes it suitable for commercialization in the jewelry trade. The only difficulty is ensuring the mirror does not flex during burnishing or handling. Burnishing was the key to creating a working Makyoh. This indicates plastic deformation and not internal stresses are responsible for creating the reflected image. It also indicates a Makyoh could be made from any bronze object that is flat on one side and has a pattern of varying height on the back. The reflection data suggests that bronze makes a better Makyoh than brass because the lower reflectivity of bronze creates a greater contrast between the pattern and the background.

Makyoh could be made in antiquity by taking a piece of bronze with a pattern on the back (either cast or tooled) and polishing, burnishing, then polishing on the mirror surface. This could be done without a mercury amalgam. The author suspects the first Makyoh were created by accident. Burnishing leaves a finer finish than a 400 grit silicon carbide buffing wheel. Thus, it could have been used as an intermediate polishing step. The first Makyoh was probably a bronze mirror that had a decorative pattern on the back. Once it was coarsely polished it could have been burnished to achieve a better finish. After being burnished the mirror would be polished to a mirror shine using fine emery or leather pads. When that mirror was used in direct sunlight the Makyoh image would be visible and the first Makyoh created.

6.2 Future Work

Over-penetration was one difficulty observed with explosive forming. This caused the pattern on the back of the mirror to be visible on the surface of the mirror when viewed at a shallow angle after burnishing. Using electro-etching to create a shallower die may help alleviate this problem. Electro-etching has the added benefit of allowing for more detail in the dies and does not require harmful chemicals.

The minimum feature size for explosively formed Makyoh was not investigated in this experiment. The crude tests conducted with the flat mirror suggest features as small as 0.3 mm should be able to be resolved. There is also room for better quantitative analysis. For example, the pixel distances between grid lines for the distortion test could be measured to numerically determine the distortion of the mirror.

Historical Makyoh have concave surfaces. The concave mirror allows the Makyoh image to be in focus over a wider range. This may be achievable in explosive forming through the use of curved dies.

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Appendix A: Brightness Analysis of Makyoh 1, 4 and 5.

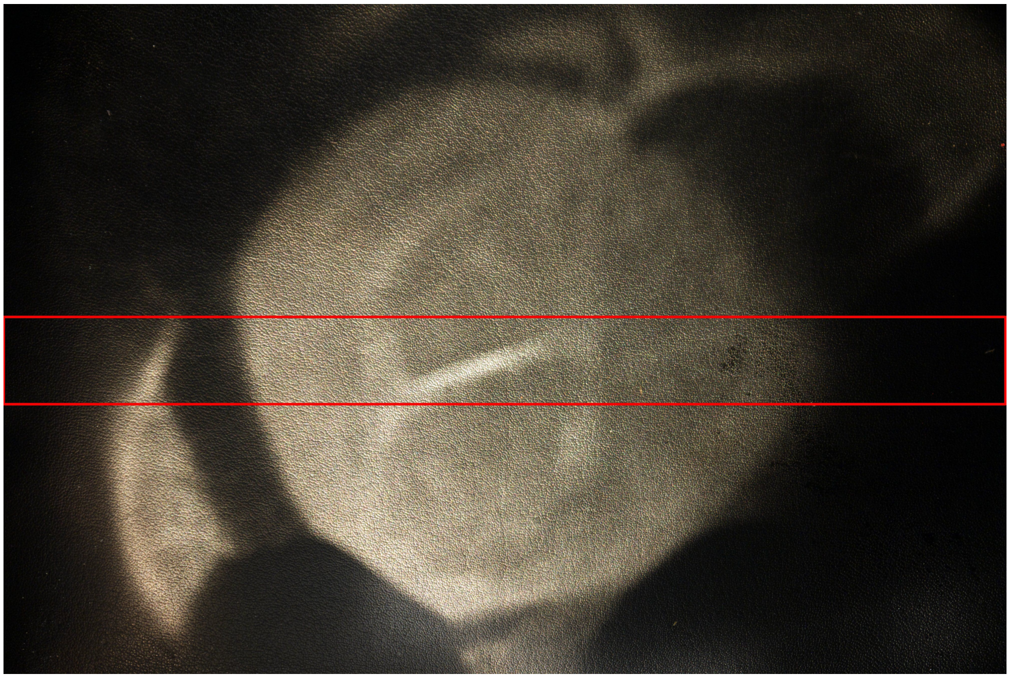

Figure 29: Makyoh 1 with Region of Interest Highlighted

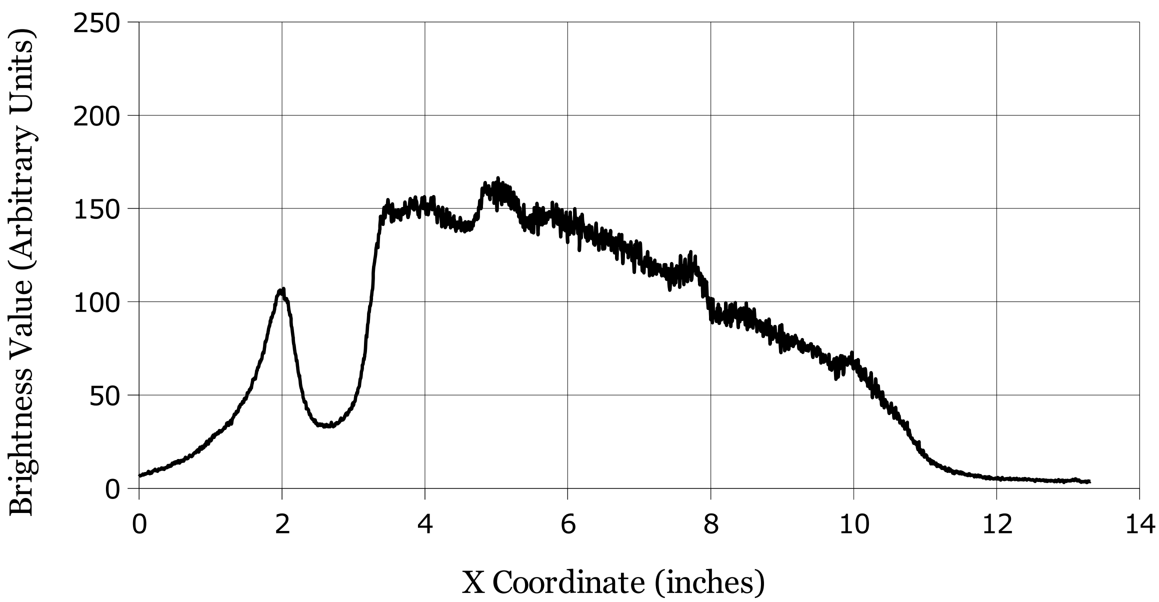

Figure 30: Brightness Contour Plot of Makyoh 1

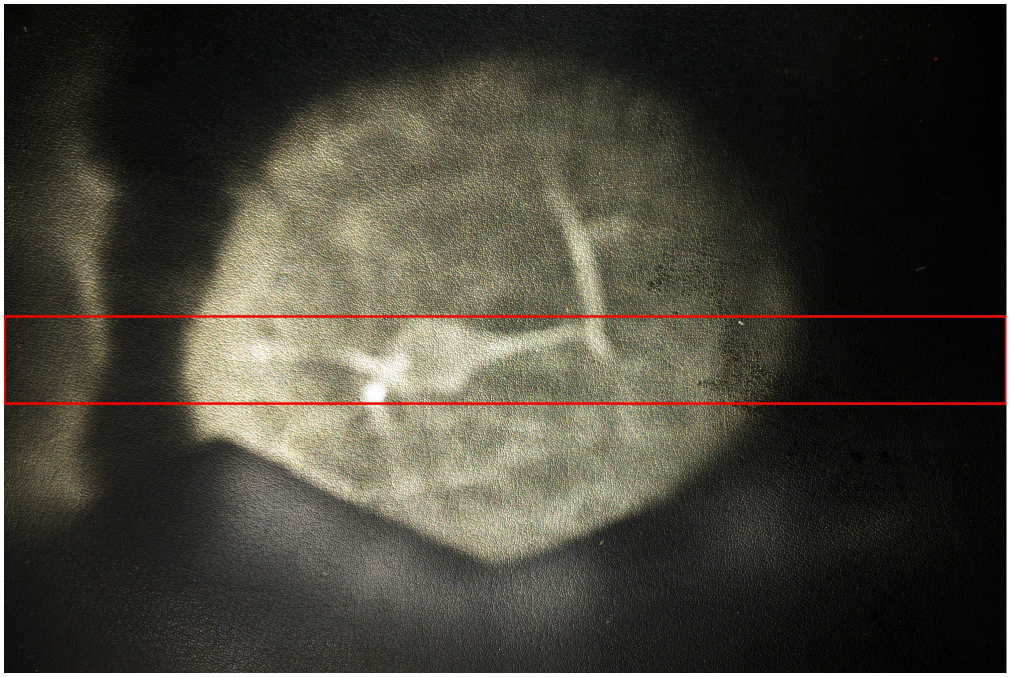

Figure 31: Makyoh 4 with Region of Interest Highlighted

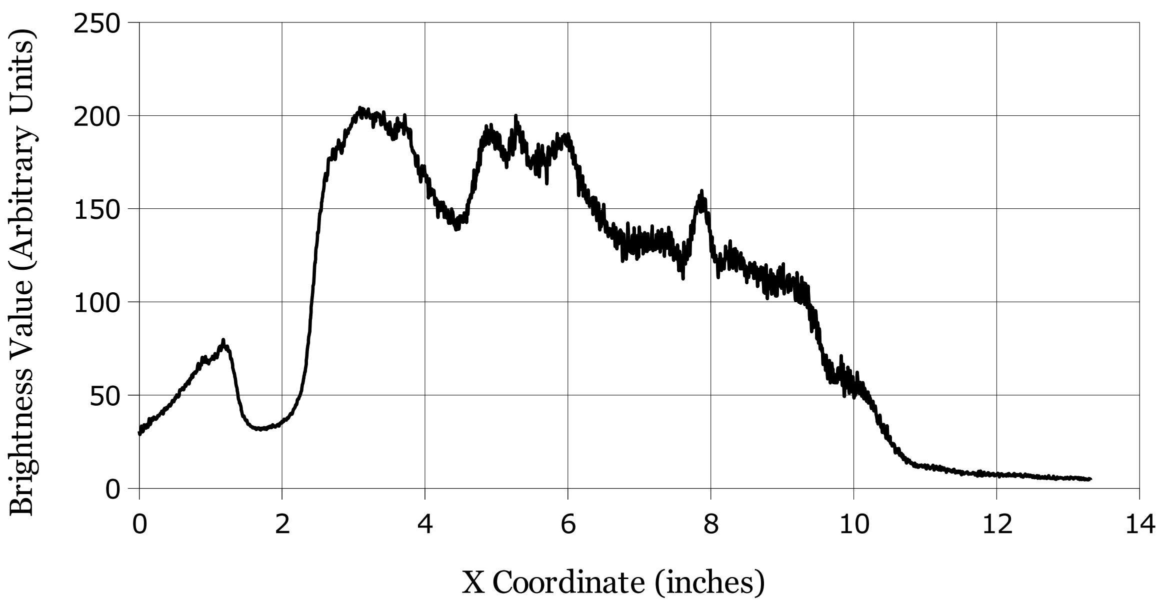

Figure 32: Brightness Contour Plot of Makyoh 4

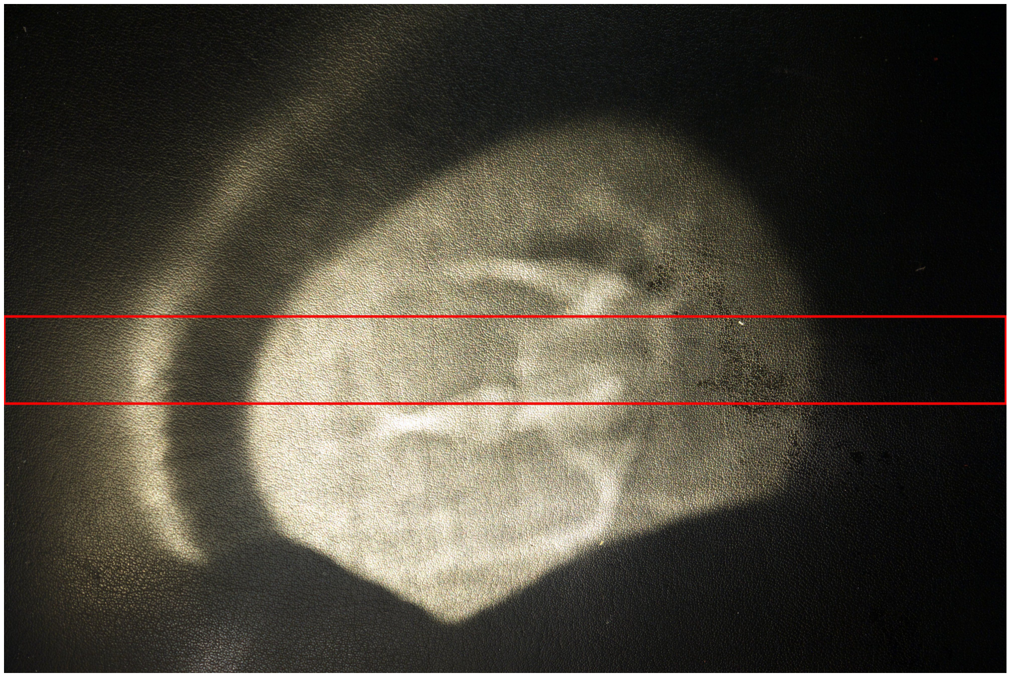

Figure 33: Makyoh 5 with Region of Interest Highlighted

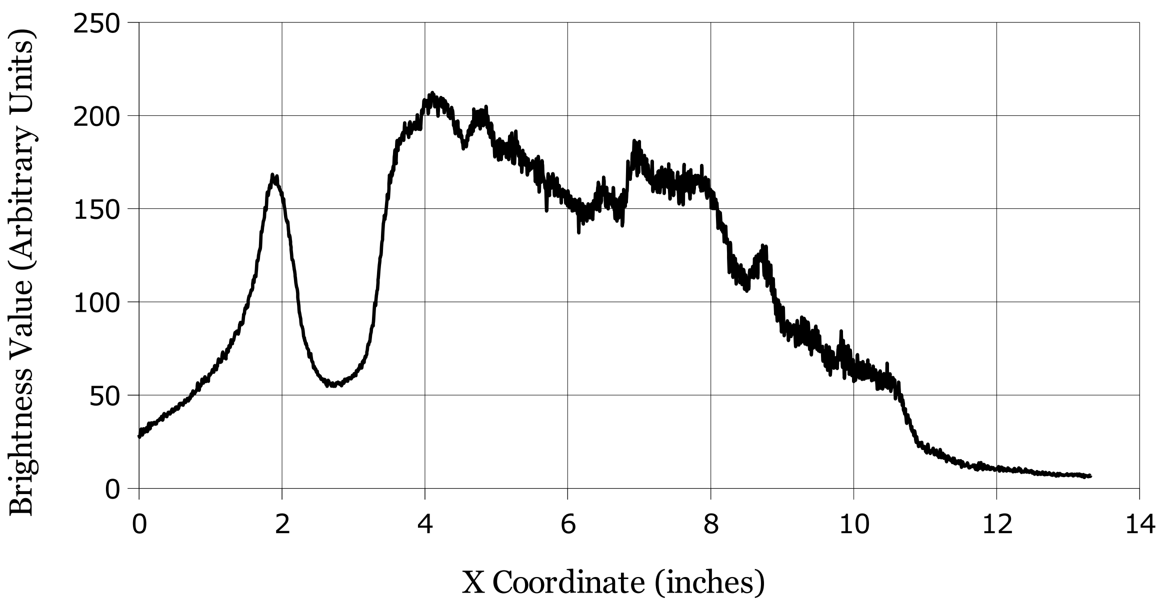

Figure 34:Brightness Contour Plot of Makyoh 5

Appendix B: Computer Tomography Images

Makyoh 3 was additionally scanned in an Xradia MicroXCT 400. The images were not extensively analyzed due to time constraints. Makyoh 3 was placed in the machine mostly perpendicular to the x-ray source. The mirror was then scanned through 360 degrees. Figure 35 shows a side view of the mirror.

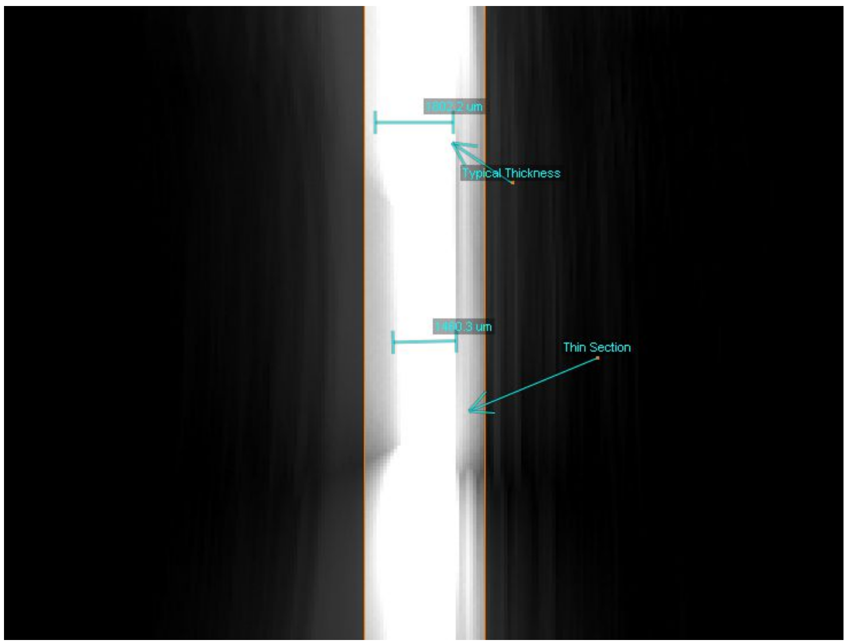

Figure 35: CT Scan Side View of Makyoh 3

The typical thickness of the mirror was was about 1800 (±40) microns, or 0.071 inches. The pattern thickness was about 1460 (±40) microns, or .057 inches. This is curiously thicker than the nominal thickness of the bronze sheet (0.040”, verified with digital calipers). It appears the flashing on the rim of the mirror interfered with the thickness measurements.

Figure 36 is a false-color image that shows the thickness of the Makyoh. Blue is minimal thickness while yellow is maximal thickness.

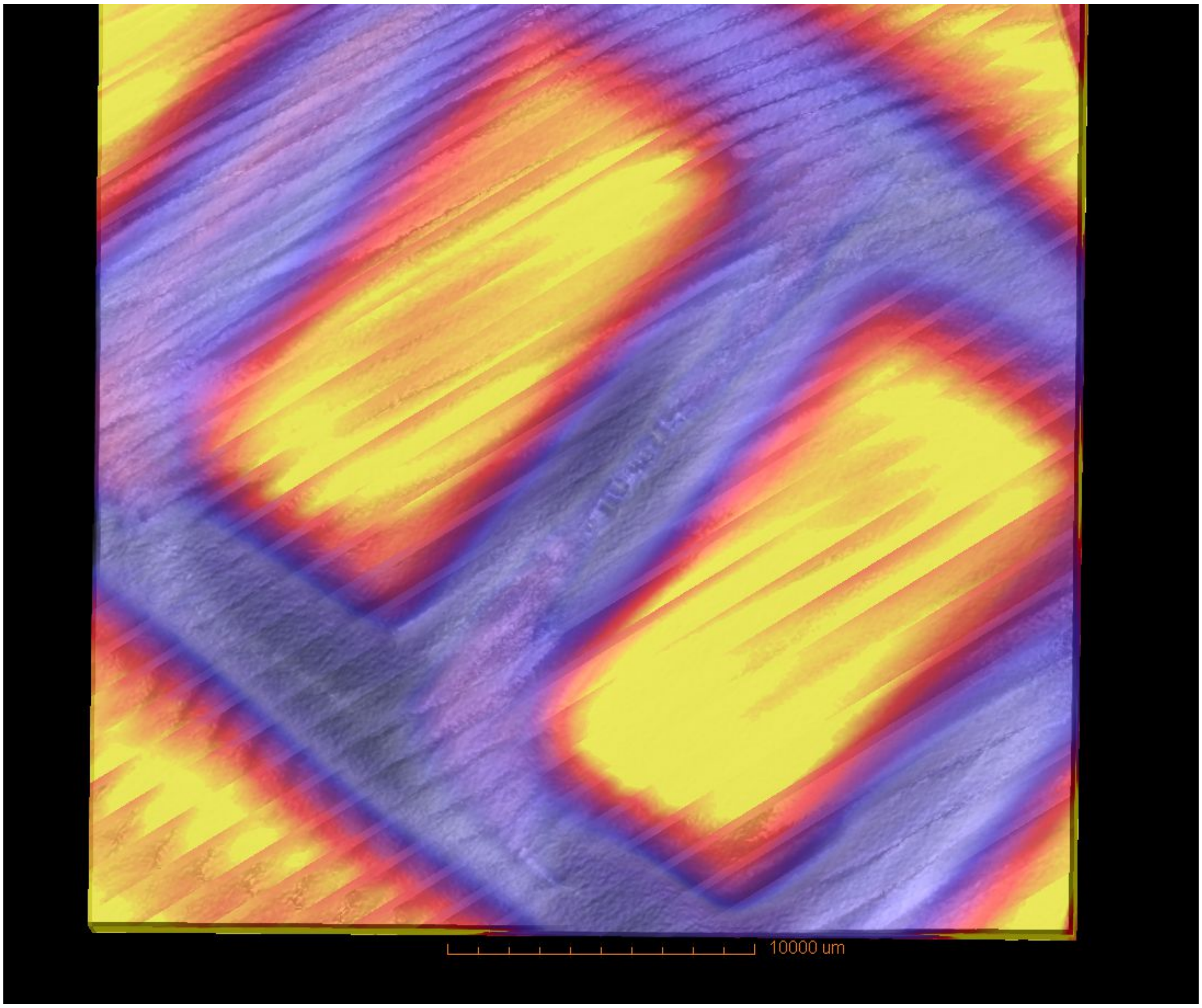

Figure 36: False Color Image of Makyoh