NON-DESTRUCTIVE METALLURGICAL ANALYSIS OF ASTROLABES UTILIZING SYNCHROTRON RADIATION

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Astrolabes were widely used for 700 years in Europe and 1000 years in Islamic lands as practical tools to tell time, survey land, and map the heavens to tell one's horoscope. In this study, three astrolabes (two European and one Islamic) of the Adler Planetarium's collection have been analyzed non-destructively utilizing a high-energy collimated X-ray beam produced at the Advanced Photon Source synchrotron at the Argonne National Laboratory. By utilizing high energy (71 keV) X-rays capable of transmitting through the brass astrolabes (up to 1cm thick), metallurgical data can be produced from the bulk of the sample without any harm to the sample. Diffraction, fluorescence, and radiography experiments were performed on the astrolabes. Diffraction experiments allowed composition of the bulk samples as well as mechanical deformation and forming history to be determined. X-ray fluorescence experiments allowed the near surface (~20 μm) composition to be determined, while radiography gave indication of the thickness profiles of the samples. By examining the forming history and compositions, it is possible to learn bulk microstructural characteristics that no other non-destructive technique could furnish. These data were used to learn more about each astrolabe maker as well as if any parts were later (or modern) replacements.

Introduction and Background

The most sophisticated instrument of pre-telescopic astronomy, astrolabes were born out of man's curiosity with the night sky and methodical mapping of the stars movement. However, once developed, the astrolabe was primarily used to aid in the prediction of one's horoscope that was consulted for all major life decisions. This bridging of the modern scientific process with ancient superstitions is representative of the time period during which the astrolabe was in use.

The astrolabe could be used to solve many problems. It was used as a timepiece that could tell time both during the day and night, a surveying tool to measure distances and make more accurate maps, and a practical tool for all sorts of astronomical calculations. However, such a valuable tool was not constructed easily and was often ornately decorated to illustrate an instrument maker's skill. The finest materials available were used (predominantly brass), and the instrument's accuracy was determined by the quality and uniformity of the degree markings with which master engravers finished the astrolabes. Astrolabes represent the state of the art in materials, design, and forming processes during their time of manufacture. As such, astrolabes are also a valuable instrument to study metallurgically and to learn about the technological history of Man.

Due to the intricate engraving and important historical place that astrolabes hold, they are highly desired by private collectors and museums alike. Historically, metallurgical analysis has been a destructive process requiring samples to be cut from the artifact, polished, and etched to reveal their microstructure and forming history. It follows that there has been very little metallurgical analysis [1] performed on astrolabes in the past, because collectors and curators do not want to have the instruments in their collections degraded in any manner.

One technique that is rare in the field of archaeometallurgy is the use of high energy X-rays produced by a synchrotron. Such X-rays are highly intense and collimated, and can be utilized for a number of experiments. It is possible to perform diffraction experiments that give information about microstructure without damaging the object. It is also possible to obtain data on the chemical composition of the sample without requiring a sacrificial sample as in emission spectroscopy experiments. Thus, studying rare and valuable astrolabes via synchrotron experiments allows analysis of the metallurgy of the astrolabes without causing any damage to the astrolabes [2]. The astrolabes studied are listed in Table 1 below.

Table 1 – Astrolabes Studied

Accession #	Place of Origin	Manufacturer	Date
A-70	Lahore Pakistan	Diyā’ al-Dīn Muhammad	1647/8 AD
W-272	Nuremberg Germany	Georg Hartmann	1532 AD
M-22	Nuremberg Germany	Georg Hartmann	1540 AD

Procedure

The synchrotron provides a highly collimated beam of high energy X-rays that can be used for numerous experimental measurements to be discussed below. The techniques are particularly suited for archaeometallurgy due to the very high penetration depth of the X-rays (up to many millimeters depending on the material). This allows for analysis of artifacts without destructive sampling or tarnishing of the sample surface, a key factor when examining artifacts that are often one of a kind and very valuable. Three main types of experiments were performed:

1) X-ray Diffraction Experiments - It is possible to determine the mechanical working history of the sample by the nature of its X-ray diffraction pattern as will be discussed. Four diffraction patterns are shown in Figure 1. These patterns, from Stephenson et.al., illustrate evidence of hammering in parts a and b, rolling in part c, and casting in part d [2]. It is also possible to gain information about the bulk composition of the sample from the radial location of the rings in the X-ray diffraction pattern [3] [4].

2) X-ray Fluorescence Analysis – The near surface composition of the sample can be obtained by measuring the secondary X-rays generated by the impinging X-ray beam [5]. This was performed to determine alloy compositions used for each astrolabe component.

3) X-ray Thickness Profiles - The transmitted intensity of the impinging X-ray beam is related to the thickness of the sample. Thus, by measuring the transmitted intensity it is possible to determine the variation in thickness of the sample. By measuring thickness profiles, information about the sample’s forming history can be found.

Results and Discussion

As an example of this analysis methodology, two examples shall be given: the examination of the A-70 mater and M-22's rule. Figure 2 illustrates a diffraction pattern taken from astrolabe A-70's mater. It is seen that the diffraction rings have a spotty nature indicating that the microstructure of the mater is relatively large grained. It is also seen that the intensity around the rings shows no systematic maxima (as seen in Figure 1c), and thus no preferred texture. This pattern is consistent with the cast component diffraction pattern seen in Figure 1, and was also seen from the maters of Hartmann astrolabes M-22 and W-272.

The chemical composition of the A-70 mater is seen from the fluorescence spectra shown in Figures 3. The presence of Cu and Zn is expected, Sn and Pb were often added to cast alloys of the time to increase their castability. Sb is a tramp element often associated with Sn. From these data we conclude that the A-70 mater was cast with a leaded brass/bronze alloy.

Figure 4 is a diffraction pattern from astrolabe M-22's rule. It is seen that the spottiness present in Figure 2 is gone and very uniform rings are present. This is evidence of a small grain size material that often results from mechanical working. The lack of preferred orientation (as seen in Figure 1c) indicates that the component was formed by a random deformation process such as hammering. The bulk composition of the rule as calculated from the position of the diffraction rings gives a zinc content of 27%. This is at the higher range of cementation brasses manufactured in the Middle Ages.

When the surface composition of the M-22 rule is examined, it is seen that there is only Cu and Zn present as shown in Figure 5. When coupled with the data from the diffraction pattern this result makes sense. For components that must be heavily deformed, a purer brass is much preferred. This pure brass will have increased workability due to its low work hardening. Figure 6 shows a thickness trace along the length of M-22's rule. The thickness is not constant, which is consistent with a hand formed component. These trends are representative of results found in all three astrolabes studied. It can then be seen that in the time period of manufacture of these astrolabes there were separate alloys utilized for casting and mechanical working applications.

Conclusion

From the experiments performed it is possible to determine a wide range of information about the metallurgy of the astrolabes studied. It was found that different brass alloys were used for components that were cast and those that were mechanically deformed. Chemical composition, forming history, and thickness measurements are all determined non-destructively, illustrating that this technique could be useful for many applications with metal artifact analysis where non-intrusive methods are required.

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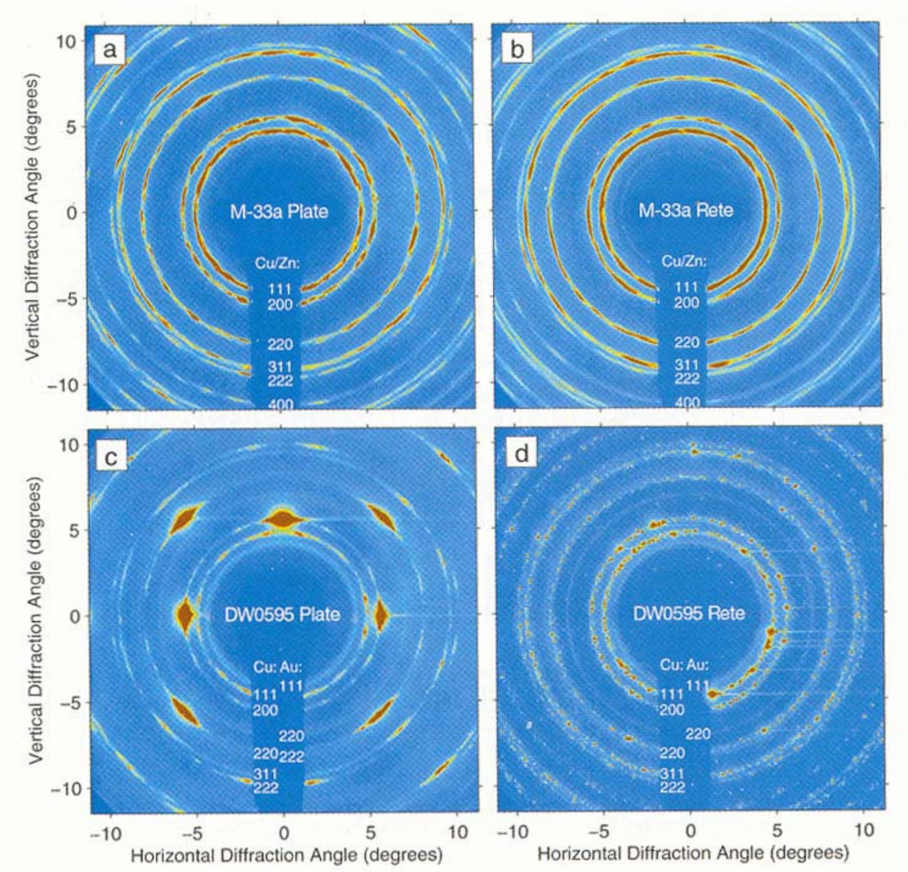

Figure 1 – Illustrations of diffraction pattern for a,b) hammered material, c)rolled material, d)cast material [2].

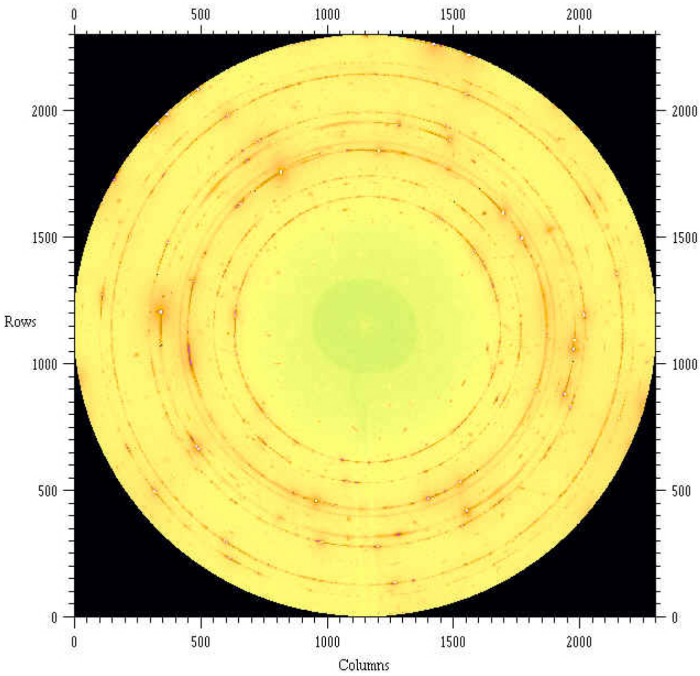

Figure 2 – Diffraction pattern illustrating cast structure of astrolabe A-70 mater.

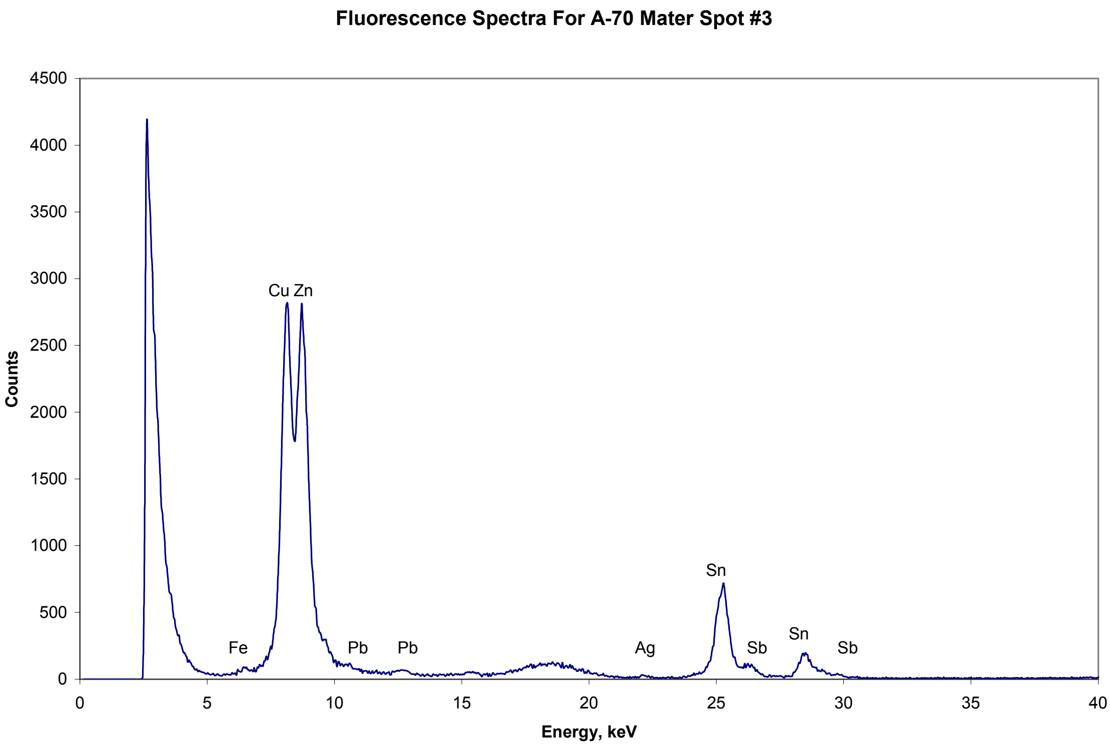

Figure 3 – Fluorescence spectra for astrolabe A-70 mater illustrating presence of Fe, Ag, Sn, Pb, and Sb minority elements.

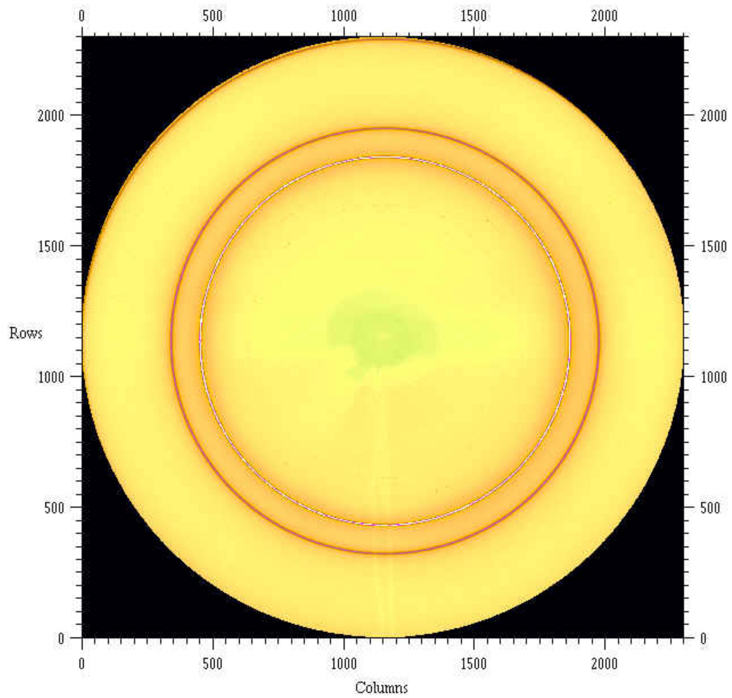

Figure 4 – Diffraction pattern from astrolabe M-22 rule. The diffraction rings are more consistent indicating a small-grained substructure characteristic of mechanical working.

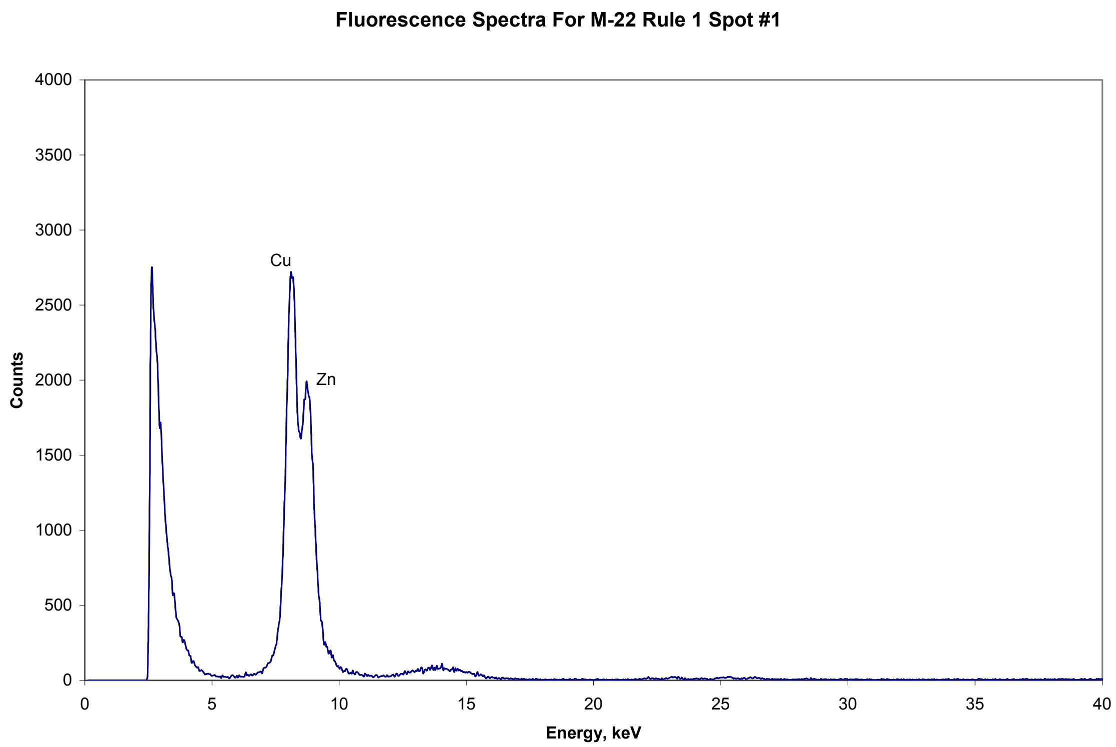

Figure 5 – X-ray fluorescence spectra for astrolabe M-22 rule illustrating pure brass composition.

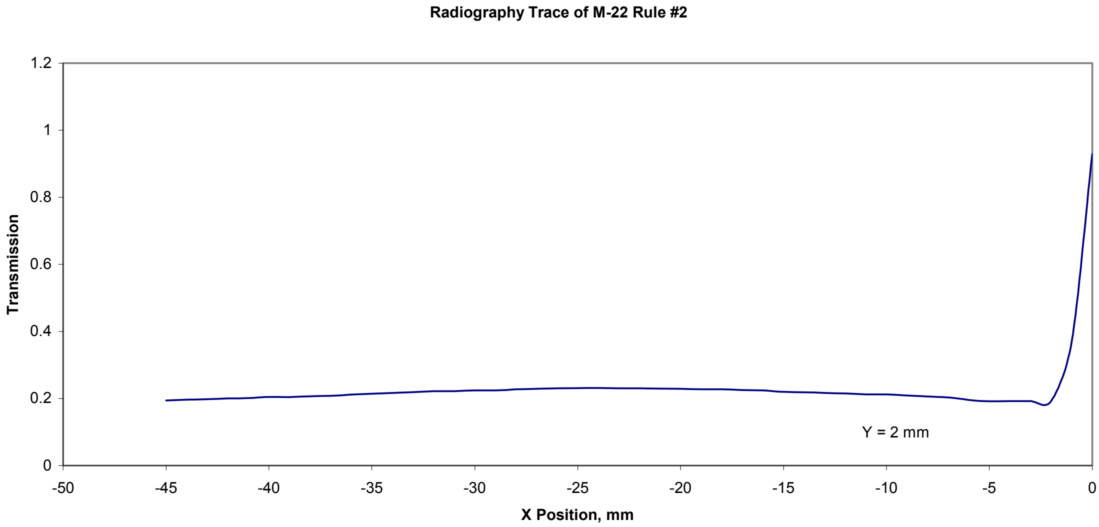

Figure 6 – Radiography trace along length of M-22 rule illustrating non-uniform thickness consistent with hand hammering process.