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Abstract
Fatimid art is known for the production of luxury artifacts, particularly rock crystal vessels. The appearance in 2008 of the Francis Mills Ewer, which seemed to belong to a famous group of 6–8 rock crystal ewers attributed to Fatimid Egypt, prompted an investigation of the techniques used to carve them. A comparison of the carving technique of the Francis Mills Ewer with that of the other members of the group offers the best criterion for determining whether the new ewer belongs to this group. To this end, the traces of manufacture (mainly polishing and carving) were analysed on a group of fourteen artifacts. The topography of the surfaces has been measured with a confocal rugosimeter using silicon replicas. To identify and characterise the multi-scale wear signature and the traces left by the tools, a Fourier isotropic filtering technique was applied. Using these complementary methods, we were able to confirm that the Francis Mills Ewer belongs to the Fatimid group.

Keywords
Wear traces, Wavelength, Archaeology, Ancient technology, Rock crystal

1. Introduction

1.1. The Fatimid rock crystal ewers

The Fatimid caliphs of Egypt (969–1173 A.D.) are well known for their patronage of luxury and prestige arts and particularly for the production of vessels in one of the harder and most difficult stones to work: rock crystal (7 on the Mohs hardness scale). Amongst these is an especially famous group of pear-shaped vessels — now called the 'Magnificent Seven' — two of which bear Arabic inscriptions indicating that they were produced for the Fatimid court in Egypt in circa 1000 A.D. [1]. These seven masterpieces are plausibly thought to have been manufactured in Cairo in circa 1000 A.D., using similar methods of production. They have certain features in common, including their shape (piriform or globular), their size (H. 15.6–24 cm, D. ranging from 9.5–13.5 cm) and the organisation in three panels of the carved relief decoration (depicting animals and vegetal scrolling and stem work — 'palmette-tree'). Finally all the ewers were carved from a single block of rock crystal, including the integral handle.

1.2. The problem of the authentication of the Francis Mills Ewer

When the ewer (Fig. 1) appeared on the art market in 2008, its authenticity was questioned. Although doubts were initially allayed by the historical and stylistic arguments carefully advanced in the Christie's sale catalogue entry [1], further questions were subsequently raised when it emerged that both the Francis Mills Ewer, and the ewer in the Victoria and Albert Museum which it most closely resembles, were the only two ewers to be first attested in the mid 19th century and had both passed through the hands of the London dealer, John Webb, who is known to have 'improved' and even faked antiquities, including rock crystal objects [2]. Moreover, Webb had occasionally done so with the assistance of the Parisian jeweller Jean-Valentin Morel, who had added the enamelled gold mounts to the Francis Mills Ewer, and is celebrated for having revived the lapidary's art in 19th century France [3]. As already suggested, the ewer presents a number of features in common with the rest of the group (carved from a single block, dimensions, shape, style and organisation of the relief decoration, etc.). While the ewer was attributed to the Fatimid group on stylistic grounds, and was shown not to be a forgery on historical grounds, it remained highly desirable to test the authenticity of the new ewer by comparing the techniques of its manufacture with those of indisputably genuine Fatimid pieces.

Fig. 1. (a) The Francis Mills Ewer and (b) detail of hunting cheetah.

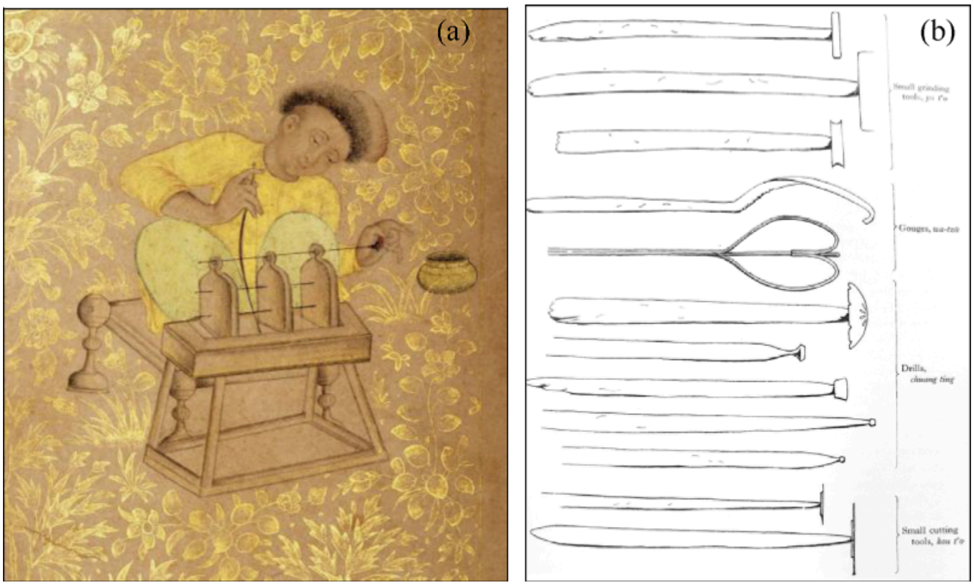

Fig. 2. (a) Lapidary using a bow-lathe to polish a gemstone. From an album of the Mughal emperor Jahāngīr, dated 1610–11 AD. (Prague, Náprstek Museum, MS A.12182, f. 16); and (b) tool kit from a traditional jade-carving workshop in Peking (Hansford [5], Figure 11, p. 81).

2. The ancient techniques: wear traces identification

The manufacturing processes of Fatimid rock crystal vessels remain largely unknown. No tools or workshops of medieval Islamic rock crystal carving industries have so far been reported in Fatimid Egypt or elsewhere. Valuable information on the tools and techniques that might have been used by Fatimid craftsmen is provided by the sparse references in medieval Arabic sources (al-Bīrūnī, al-Tifāshī, etc.), and by the more circumstantial and detailed accounts of early modern and modern European scholars and travellers in Asia (e.g. Bernier, de Thevenot, Fryer [4]). Studies of traditional industries of Chinese jade carving [5] and Indian carnelian manufacture [6] are particularly useful. We have also used data obtained during our previous research on stone vase manufacturing techniques in the East Mediterranean Bronze Age [7,8]. Indeed, despite variations over space and time, the ancient and traditional tools and techniques for hard stone carving have a wide range of common features. This study will focus on carving and polishing techniques.

The first tool to be used was certainly the saw. Probably made of steel, saws were employed with a mixture of water and abrasive for different tasks during the preliminary steps of manufacturing, such as the initial shaping of the raw crystal into the rough form of the finished vessel [9,10]. Smaller bow-saws and files were also used for decoration in China [11]. The lathe was used from the Bronze Age in the Near East for glyptic production [12], and also for gem and soft-stone vase manufacture in the Greek and Roman periods [13]. A series of different tools could be attached to the horizontal axis of a lathe, which was certainly driven by a bow (Fig. 2a) [14].

Among these rotary tools, cutting discs, drill bits of various shapes, and grinding wheels (Fig. 2b), were presumably used as vectors for the abrasive powder that actually did the cutting, which was facilitated by a lubricant. They were employed for the shaping of the object and also, according to their size, for carving the decoration and finishing the surfaces. Cutting was done by discs of different diameters. Different sizes of grinding wheels were employed for grinding down the irregularities and polishing the surface. Decoration was cut using smaller discs of thin sheet steel [15]. In addition, both Chinese and Indian craftsmen used a range of tubular drills and gouges for hollowing the vessel, and a variety of drill bits including diamond points, which seem to have been in use since the 1st Millennium BC in India for beadmaking [16]. The tools employed for the traditional working of hard stone were generally made in soft steel or iron [17] used in conjunction with an abrasive powder made of hard stone such as diamond, garnet (Mohs 7.5) and especially corundum (Mohs 9 — a naturally occurring crystalline form of aluminium oxide) and emery [18]. Such abrasives were used in the shaping and cutting processes; a finer and less effective abrasive must have been employed for final polishing [19]. A powder such as hematite (Mohs 5.5–6.5, the mineral form of ferric oxide) might have been used [20]. Today, to polish quartz, some workshops use an ultra fine powder, such as jeweller's or tin putty, also known as putty powder, which consists chiefly of stannic oxide, mixed with water and applied by a tin wheel. A lubricant was used to contain the abrasive particles during rotation of the tool, and to ensure even distribution of the abrasive on the surface being cut or polished. The lubricant also served to remove loose particles of rock, thereby making the abrasive process more efficient. The viscosity of the lubricant is an important factor in the manufacturing process. In the Fatimid period, vegetable oil (olive or poorer quality 'lamp oils' such as sesame, turnip seed, radish seed etc.), mixed with water in different proportions, might well have been used as a lubricant.

3. Methodology

The Archaeometrical Study of the Early Islamic Rock Crystal Industry is based on an interdisciplinary research project. Archaeological, ethnographic, and historical sources provided us with an initial database of the tools and techniques that might have been used by early Islamic craftsmen. But artifacts such as the Fatimid ewers are fragile, rare, and of great artistic and monetary value, and therefore cannot readily be moved from their present locations, so we have adopted for this study the non-destructive method of taking impressions of details of the surfaces of the artifacts with *Silflos* (*Flexico Developments Limited*), a light bodied silicone rubber impression material with a standardised viscosity, which flows freely into the carved and polished recesses and, when removed, preserves its original shape. The traces of manufacture recorded on these silicone rubber impressions were then described and measured in the laboratory.

Table 1.
Groups of vessels analysed.

Group 1		Fatimid or early Islamic	Group 2		Fatimid or early Islamic
de Unger Collection	Ovoidal flask (R11)	Yes	**Private collection**	Imitation of Fatimid ewer	No
	Jar with 19th century Italian mounts (R9)	Yes			
	Toilet flask (R3)	Yes			
	Cylindrical flask (R7)	Yes			
V & A Museum	The ewer (inv. no. 7904-1862)	Yes	**V & A Museum**	J.-V. Morel's dragon ridden by an *amorino* (inv. no. 1428-1870, Fig. 3)	No
	Ovoidal flask (inv. no. 975-1050)	Yes			
	3 Cylindrical flasks (inv. nos. A.11-1942, A.45-1928, A.46-1928)	Yes			

3.1. Archaeological samples

A sample of eleven artifacts was analysed for which the dates of production are either certain or generally accepted. This first assemblage consists of medieval Islamic vessels (mainly ovoidal and cylindrical flasks and jars) from the Edmund de Unger Collection and the *Museum für Islamische Kunst* (Berlin), and the ewer in the Victoria and Albert Museum (London). The second group includes a vase with cover in the form of a dragon ridden by an *amorino*, attributed to Jean-Valentin Morel (Victoria and Albert Museum, Fig. 3), and an imitation of Fatimid ewer, possibly made in Iran in the late 19th or early 20th century, and now held in a private collection (Table 1).

The traces of manufacture recovered from the Francis Mills Ewer were compared with both those obtained from the medieval objects and those observed on the vase attributed to Morel and the modern imitation. It was hoped that this would permit us both to establish whether or not the tools and techniques used for the Francis Mills Ewer were consistent with those used to produce the other medieval pieces, and to determine whether or not the Francis Mills Ewer bore traces of manufacture found on the vase attributed to Morel and on the modern imitation.

3.2. Different scales of observation, from macroscopic to microscopic analyses of wear traces

The manufacturing processes leave traces on the object's surface that may be observed at different scales. Some traces are visible by the naked eye, but other microscopic traces, measuring no more than a few nanometres, require high magnification. These wear patterns are indicative of the processes of carving and polishing, and of the craftsman's tools and techniques. Attention was focused on the reconstruction of techniques used to create the external relief decoration of the objects, which was done mainly by the creation of raised 'islets' into which the ornament was carved, and by different phases of polishing. In particular, we concentrated upon the techniques used to create a range of motifs common to all or most of the objects examined— including palmettes, leaf-scrolls, multiple circular dots, and the line-and-dot motif. After macroscopic examination of the artifact, a digital microscope was used to examine the surface, and to identify those abrading and cutting traces that were most important or representative of the object under examination. During this initial examination, close attention was paid to the organisation of the traces of production and, in particular, to the overlapping or superimposition of one set of traces over another, so as to reconstruct in part the sequence of the process of manufacture.

To further characterize the traces of manufacture, we measured surface topography with a confocal rugosimeter. The principle of this optical device is based on the chromatic aberration, which focuses different wavelengths of white light at different points. Only the wavelength focused on the surface to be measured passes through a filter located in front of the spectrometer while other wavelengths are removed. The optical system is associated with a confocal microscope, which selects the wavelengths focused on the surface to be measured. The detector consists of a spectrometer that analyses the wavelength with the highest intensity. Knowledge of the relationship between the wavelength and the distance of the focal point permits the measurement of roughness. In order to analyse different motifs with a good lateral resolution, we measured 10 x 10 mm^2 surfaces with a resolution of 4 mm. The surface of the motifs is composed of two families of wavelengths, medium and small. Medium wavelengths give information about the motifs, small wavelengths about their roughness. To identify wear traces of manufacture it is important to analyse small wavelengths. To that end, we applied the Fourier isotrope filtering technique [21–23], which enabled us to obtain three-dimensional images z (x, y) of the wear traces, and to produce a detailed picture of the traces of the tools used by the craftsman. The morphology of the striations and carved relief could also be observed, as well as the profiles of the different traces, at different wavelengths. These precise measurements and detailed 2D and 3D views of the traces of manufacture allowed us to develop a series of working hypotheses on the tools and techniques used by the Fatimid rock crystal craftsmen.

3.3. Hypotheses and experimental reconstitution

In order to pursue further our research on the reconstruction of Fatimid rock crystal production, experiments will be designed to test our working hypotheses concerning ancient tools and techniques. The traces of manufacture observed on the Fatimid objects will be compared with the traces produced by experimental reconstruction. At this early stage, only a few preliminary experiments have been conducted, both for the carving process using a motorised mini-drill fitted with a steel disc and diamond powder, and for the polishing process, using corundum, clay, water and olive oil. We have also started the construction of a bow-lathe.

Fig. 3. Vase attributed to Morel, Victoria and Albert Museum, inv. no. 1428-1870.

4. Results: the attribution of the Francis Mills Ewer to the group of Fatimid ewers

We demonstrated that the traces of manufacture observed on the Francis Mills Ewer were identical to those observed on the other Fatimid objects examined. The same techniques and tools were employed for creation of the relief 'islets', for cutting incised lines, and for drilling ornamental dots. However, markedly different tools and techniques were used to carve both the vase attributed to Morel (Fig. 3) and the modern imitation of a Fatimid ewer (Table 1).

4.1. Preliminary identification of Fatimid tools and techniques

Decoration of the exterior took place after the hollowing of the interior, and after preliminary shaping of the outer surface. As a first step, the craftsman cut the areas of raised relief or 'islets' into which the ornament would subsequently be carved, presumably following a pattern drawn onto the blank exterior of the vessel. Several tools were certainly used in this first stage. One type of trace is characterised by parallel striations of different sizes, which suggest the use of grinding wheels with vertical sides. At the same time, however, the angular shape of the 'islets' indicates that cutting discs, with an acute angled edge, of different sizes and shapes were also used to produce the islets, just as in Chinese traditional jade workshops. The abrasive used, at this stage of our work, is difficult to identify but we suggest the use of a coarse abrasive such as corundum or diamond such as it was used in ancient workshops in Mesopotamia and China [17,18].

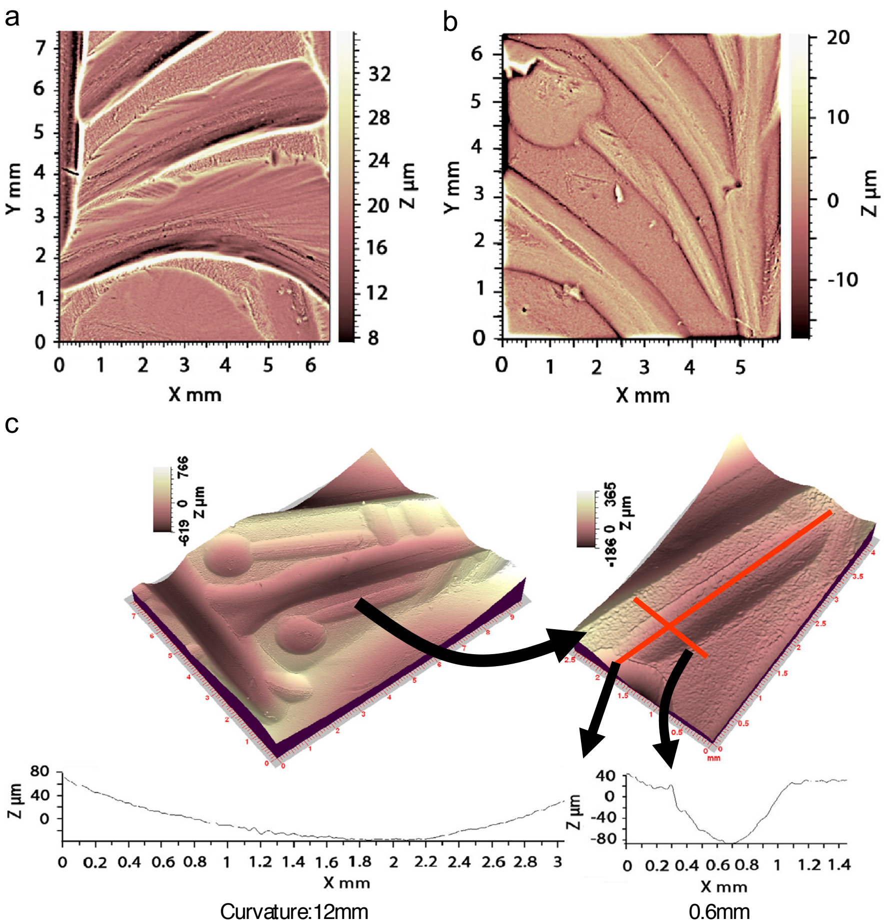

Fig. 4. (a) Cutting disc traces for the creation of curved lines on the jar (R9) in the de Unger Collection; (b) traces showing further cutting by disc to make a curved line on the ovoidal flask (R11), in the de Unger Collection; and (c) 3D view and profile of the cutting disc traces on the Francis Mills Ewer.

As to the carving of the detailed decoration, the cutting disc was used to create both straight and curved lines. Regardless of the desired width and length of the incision, the disc seems always to have been the same. Indeed, we observed cutting marks of similar shape and thickness on different Fatimid artifacts. Thus, to produce a narrow, straight line, the disc was applied to the surface of the object once and for a short time. Whereas, to produce a wide line, the same disc was passed several times along the same groove, enlarging the cutting trace. Similarly, to produce a curved line, the disc was applied repeatedly to cut a succession of lines at different angles, which ultimately formed a composite curved line (Fig. 4a,b).We found that for the entire Fatimid group, including the Francis Mills Ewer, the cutting discs always had a diameter of 2.3 cm–3.2 cm, had blades with a U-sectioned edge, and were always applied vertically to the surface of the object (Fig. 4c).

The diameter of the circular dots (Fig. 5), in the series of dots used to represent the fur of the cheetahs on the Francis Mills Ewer, and in other composite motifs, such as the line-and-dot pattern in the palmette-trees or the dots at the centre of some leaf-spirals, varies in size on the same object from 1–2 mm and larger 4.2 mm. However, the dots on the Fatimid group are always hemispherical, rather than conical, in section and have the same characteristics, suggesting that they were made by the same type of drill bits, albeit with different diameters. In many cases, especially on the ewer and ovoidal flask (R11) in the de Unger Collection, the base of the cavity is a horizontal plateau. Moreover, the dots are not always precisely circular in plan, but can be oval or even completely irregular. These observations suggest that the dots were made by a rotating drill bit fixed to a horizontal lathe, and that the surface of the rock crystal was applied to the drill bit by the craftsman. The drill bit itself was not precisely spherical but rather slightly ovoidal in section. Over prolonged use, the ovoidal point of the bit was flattened by wear, producing the horizontal plateau at the base of some cavities. The Fatimid craftsmen apparently presented the rock crystal at different angles to the drill bit. When applied perpendicular to the surface, the bit produced a dot that was perfectly circular in plan, but when the crystal was presented at an angle to the drill, the dots were oval or irregular in plan, and of shallower depth. It should be noted, however, that we have observed in the laboratory that dots with the irregular outer contours might, in some cases, be caused by lateral scaling, which took place after drilling and final polishing.

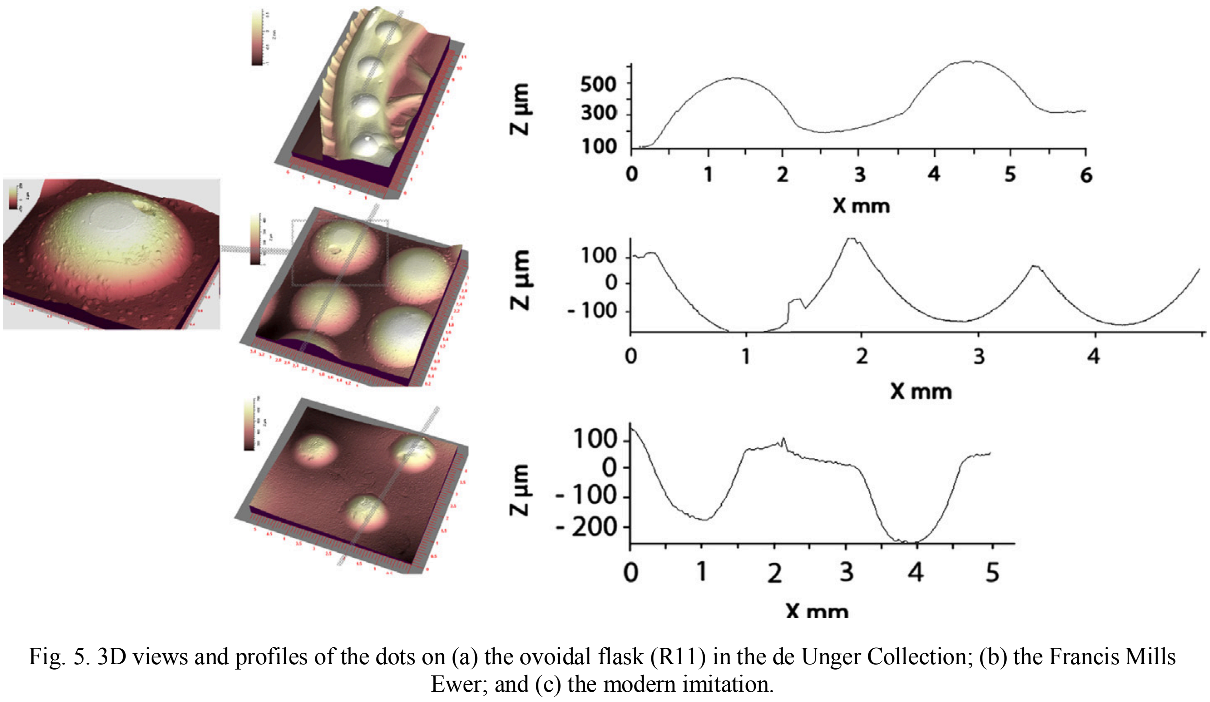

Fig. 5. 3D views and profiles of the dots on (a) the ovoidal flask (R11) in the de Unger Collection; (b) the Francis Mills Ewer; and (c) the modern imitation.

It is suggested that, after the decoration was carved with the cutting disc, the contours of complex curves were occasionally regularised and finished by hand, although traces of this process appear to be scarce and relatively isolated. The deep grooves and straight striations at the base of the incisions appear to be produced by the cutting disc that was used to make a preliminary but very angular and irregular curved line. Subsequently, to harmonise and regularise the contours of the curve, the craftsman used a freehand tool, such as a diamond or corundum point mounted on a rod, which left a series of irregular lines incised or scratches in the bottom of the grooves. These are different from the traces of cutting made by a disc, in that a curved, apparently continuous line can be produced in a single operation.

Preliminary polishing of the outer surface may well have taken place on several occasions during production but, at the end of the process, the crystal was polished for the last time in order to restore its natural transparency. For this final polishing, we suggest the use of a soft abrasive powder such as haematite or stannic oxide mixed with water or, more probably, with oil which added more gloss to the surface. This gives a perfectly transparent, glossy surface. The striations from the passage of the abrasive particles on the surface are almost invisible to the naked eye. Magnified under a digital microscope (x 50), fine crossing lines appear that are the product of the successive polishing sequences. This final work was certainly done by a specialised craftsman, as was the case in the traditional workshops of India and China. Indeed, the relatively homogeneity of the traces of production so far observed on the Fatimid group suggests that only a few highly skilled craftsmen in specialised workshops may have produced these luxury objects.

4.2. The modern imitation and the vase attributed to J.-V. Morel

When compared with the traces of manufacture on vessels from the Fatimid group, the incisions on the modern imitation are much straighter and more regular (Fig. 6a). This suggests that the tool was a steel cutting disc mounted on a modern, possibly motor-driven, rotary system, and that the abrasive was diamond powder. Moreover, the diameter of the cutting disc would seem to have been much smaller (<1 cm) than that used by the Fatimid craftsman (2.3 cm–3.2 cm). Again, the drill bit used to make dots on the modern imitation left very different traces (Fig. 5c) to the bits used on the Fatimid group (Fig. 5a,b). The diameter of the dots is smaller and the section of the cavity more sharply angled, almost conical. Moreover, while the bases of the dots on the Fatimid group are smooth, those on the modern imitation display clear striations, indicating that not only a different type of bit was used, but also a coarser abrasive. Again, it is likely that the drill was powered by a modern, perhaps motorised, device.

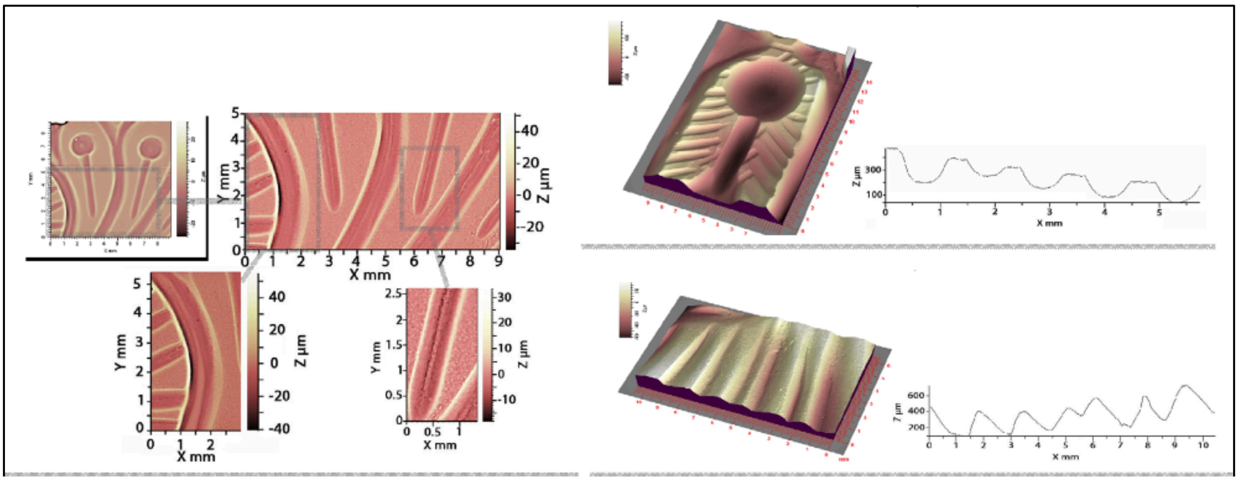

Fig. 6. (a) Views of the carving traces on the modern imitation. A continuous line appears on the base of all the grooves; (b) 3D view and profile of the cutting traces on the Francis Mills Ewer showing the perpendicular angle of the U-shaped disc to the surface; and (c) 3D view and profile of the cutting traces on the vase attributed to Morel showing the oblique angle of the V-shaped disc to the surface.

Finally, the modern craftsman used a particular technique to finish and homogenise all of the lines of the incised ornament. This has left a continuous line in the centre of the base of all of the incised lines, even the curved ones (Fig. 6a). Exactly how such a line could have been made is yet to determine, but its constant and regular appearance is not a feature of the Fatimid group.

As to the vase attributed to J.-V. Morel, the cutting technique that he used for the decoration was identical to that used by the Fatimid craftsman, to the extent that he used cutting discs driven by a rotary lathe. However, the tools were applied in a very different manner, so that the disc was applied at an acute angle to the surface of the crystal (Fig. 6c), instead of perpendicularly (Fig. 6b), leading to very different effect. Moreover, the section of the edge of the disc used by Morel is sharply V-shaped, and very different from the U-shaped section of the blade of the Fatimid cutting disk.

5. Conclusion

Using these complementary methods, we were able to confirm that the traces of manufacture observed on the Francis Mills Ewer are wholly consistent with those present on the Fatimid group of rock crystal objects. Moreover, they are distinctly different from the traces observed on both a modern imitation and the vase attributed to Morel. On this basis, we conclude that the Francis Mills Ewer is exclusively the product of Fatimid craftsmanship, and that Morel's contribution was confined to the addition of the enamelled gold mounts; he did not 'improve' the carved ornament or polish, nor did he himself carve the decoration. As to the modern imitation, the traces of carving present on this vessel are markedly different from those common to the Fatimid group. More importantly for future research, we have established the utility and validity of the methods employed as a first step towards the reconstruction of the tools and techniques used in the medieval Islamic rock crystal industry.

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