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International Journal of Advanced Research in Management, Architecture, Technology and Engineering (IJARMATE)
Vol. 2, Issue 4, April 2016.

Mechanical Engineering in Ancient Egypt, Part XII: Stone Cutting

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***Abstract*— This paper presents the 12th part of a series of research papers aiming at studying the development of mechanical engineering in ancient Egypt. It presents the techniques and technology used by ancient Egyptians to cut hard stones and produce very complex artifacts. The ancient Egyptians used stone saws, drills and lathe turning and invented instrumentation to generate flat surfaces with accuracy better than 0.005 mm and measure dimensions from 1.3 mm to 10 km.**

***Index Terms*— Mechanical engineering in ancient Egypt, stone cutting, stone sawing. drilling and turning, stone surface flattening, filleting of stone mating surfaces, dimensions measurement.**

I. INTRODUCTION

Ancient Egyptians had the technology and highly qualified man-power to cut hard stones as they cut a piece of cheese. They could do this from thousands of years ago while nowadays people with the facilities of the 21st century are unable to achieve what they achieved with their primitive tools. In this research paper in this series about the mechanical engineering in ancient Egypt, we try to understand how they could hard rocks like granite and produce very heavy products.

Gorelick and Gwinnett (1983) studied the drilling process of stone in ancient Egypt. They started their article saying that neither wall paintings, nor textual information , nor excavated material has provided complete answers as to how drilling was done !!. They presented the words of F. Petrie and A. Locus in this aspect. They concluded that a functional analysis of the drilling of a granite sarcophagus lid from the old kingdom has produced some preliminary insights into the speculative technology used and set the procedure used by ancient Egyptians to drill hard rocks using abrasives or a lubricant such as olive oil [1]. Klemm and Klemm (2001) discussed the petrography, occurrence and main applications of the eleven most popular stone types used in ancient Egypt. They referred to the 42 m length obelisk south of Aswan and how it was cut out of the rock on three sides using stone tools [2]. Nishimoto, Yoshimura and Kondo (2002) stated that large stone blocks appear to have been extracted from quarry at Qurna during the rein of Amenhotep III for his temple in Western Thebes. They feel that the hieratic inscriptions they presented are the first recorded quantifying the successive daily work output of building activity during the rein of Amenhotep III [3]. Lavigne (2006) stated that the ancient Egyptians had very high level of knowledge about working out and geometry. The purpose of her study was to understand the technical methods used throughout the Egyptian history giving more care to collect more information about tools and tool marks [4].

Storemyr et. al. (2007) presented the quarry landscapes project for addressing the importance of ancient quarry landscapes and raising the awareness for the urgent need for protecting such sites. Their work analyzed the condition and legal status of the known ancient quarries in Egypt and the threats facing them [5]. Loggia (2009) analyzed 17 tombs at Saqqara from the first dynasty and 25 tomb from Helwan from the first and second dynasties. She mentioned the robustness of walls construction standing up over a given height and length. She stated also that the design of roofs showed that the ancient Egyptians constructed them with a thorough understanding of stone and temper materials behavior under imposed loads [6]. Saraydar (2012) discussed the Egyptian drilling/boring device dated to the third dynasty. He demonstrated a flint and wood replica of the Egyptian drill capable of rapid unidirectional rotation and effective in drilling two types of stone, limestone and alabaster. He showed that when the drill fitted with crescent-shaped bit, the drill operated with one hand with minimum effort [7].

Ayad (2014) presented a study of the drilling tools and stone vessels fragments of Heit el-Ghurab during the rein of Kings Khafre and Mankaure. He compared the finds with similar parallels of the same time period [8]. Heldal and Storymer (2015) presented features found in five Egyptian quarries and discussed them on a background of rock properties and quarrying techniques. They suggested that the use of fire in stone quarrying reached a highly sophisticated level during the New Kingdom [9].

II. CUTTING QUARRY STONES

The ancient Egyptians cut quarry stones in an optimal way leading to preserving stones and using them in their great projects such as pyramids, temples and tombs. Before talking about tools using in stone cutting, I present some samples of stone cutting from different periods in the ancient Egypt history.

- Fig.1 shows rectangular marks in Aswan granite quarry [10]. The mountain face is almost vertical and the two

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rectangular holes are identical and exact.

Fig.1 Quarry mark at Aswan [10].

- Fig.2 shows a contoured cut granite block from Giza Plateau in the open south of the Great Pyramid [11]. The block has a cylindrical contour at a part of its outside surface which is very accurate without distortion. Mr. Dunn announced that on checking the accuracy of the contoured surface, he found that the surface was extremely precise [11].

Fig.2 Contoured granite block [11].

- Fig.3 shows how old Egyptians applied the filleting design technique to granite blocks [11]. A vertical flat surface is met with a cylindrical part of a granite block. They filleted the mating surface in a very precise way. Mr. Dunn measured the radius of the fillet in many location and found it 11.1 mm [11].

Fig.3 Filleting corners of granite mating surfaces [11].

- Fig.4 shows a saw cut of a basalt block located in the east of the Great Pyramid at Giza [12]. The accuracy of the cut makes one imagine that even though the basalt is a hard rock [13], they are cutting it as if it is a block of wood.

Fig.4 Cutting basalt block [12].

- Fig.5 shows how basalt was cut in the east side of the Great pyramid using a large diameter circular saw [12]. The face is exactly flat

Fig.5 Cutting basalt by circular saw [12].

- Fig.6 shows straight cuts of the hard rock basalt using a rock saw in the basalt paving stones of the Great Pyramid at Giza [14]. The cuts are straight, clean with smooth with parallel sides without traces of walking or wobbling [14].

Fig.6 Straight cuts of basalt using stone saw [14].

- Fig.7 shows the casing granite stones of the Menkaure's Pyramid at Giza [15]. They are cut from Aswan quarry and transferred to the pyramid site at Giza. Looking at the stone blocks we can see and feel how they are accurately cut. They have three distinct geometrical shapes: rectangle, trapezoid and semi-trapezoid. They have almost the same height such that one can imagine that they adjusted them using laser beam !!. The gap between the blocks is uniform and has relatively small value indicating the accuracy of the cutting and finishing of the mating surfaces.

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Fig.7 Casing stones of Menkaure's Pyramid [15].

Those great people could cut hard rocks producing very accurate smooth surfaces with tools designed specially for this purpose from more than 4500 years ago. Just to weigh their outstanding achievements in this aspect we compare we present sample of stone cutting in the 21st century at Egypt also.

- Fig.8 shows a recent highway cut in an Egyptian limestone site. It is clear how the cut with the modern facilities is rough and uneven.

Fig.8 Highway cut in a limestone site [16].

- Fig.9 shown another model of a way cut in a hard rock site [17]. The quality of the cut is very clear from the photo of Fig.9 and depicts the greatness of the old Egyptians.

Fig.9 Road cut in a hard rock site [17].

III. STONE DRILLING

The production of stone vessels requires special drills to remove stone materials efficiently with accurate dimensions. From engineering point of view, this is not an easy task since rocks differ in hardness from type to another. First of all, we will answer the question: Have the ancient Egyptians known stone drills ?. The answer is 'yes' which is proved through the following scenes:

- Fig.10 shows a wall engraved scene from a tomb in Saqqara from the Late Old Kingdom [7]. The drilling operation in this process is performed through two actions. A rotational action of the drilling tool performed by a crank in the hand of the labor, and an axial force performed by tow counterweights located symmetrically around the vertical centerline of the drill. This design in this very early stage (2613 – 2494 BC) is an excellent engineering design and application since it reduces the effort of the labor and allows the application of large forces outside the capability of the human being.

Fig.10 Hole drilling in the 4th Dynasty [7].

- Fig.11 shows two labors working in a stone ware workshop from the Old Kingdom [7]. The two labors are performing the drilling process while they are setting down. The setting style differs from one labor to the others. The common features are having a straight back to avoid any harm effects on their backs. The left labor is boring a large stone bowl holding the drill shaft by his left hand and rotating the drill crank by his right hand.

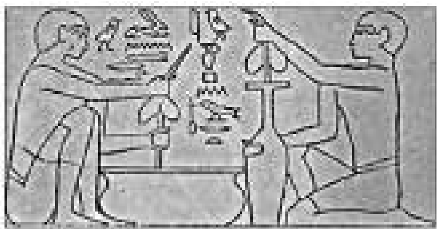

Fig.11 Stone drilling in a stone ware workshop [7].

The right labor is drilling a tall stone vase. He is holding the vase with his right hand and rotating the drill by his left hand. Both are using counterweights to generate the required axial forces.

- Fig.12 shows some details of the boring drill shown in Fig.10 and 11 [18]. It consists of driving shaft a, crankshaft d, forcing weights e secured to the driving shaft by a robe, fork b and cutting bit c [18]. This design is capable of hollowing up vessels of variable inside diameter through changing the cutting bit size.

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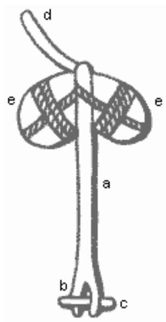
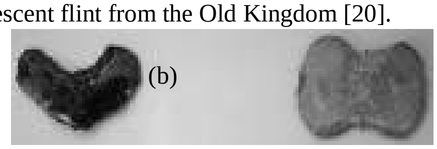


Fig.12 Details of the boring drill [18].

- Fig.13 shows a modified boring drill for the design of Fig.12 applied in the 18th dynasty of the New Kingdom as depicted in the tomb of Rikh-mi-Re at Thebes [19].

Fig.13 Modified boring drill at the 18th dynasty [19].

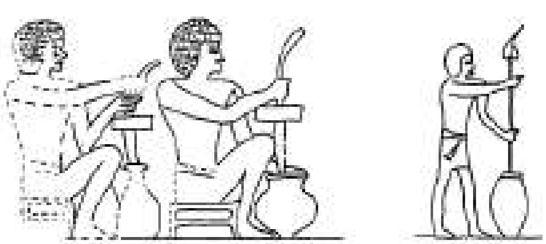
- The cutting tip of the boring drill took different shapes. Fig.14 (a) shows an 8-shape quartzite boring tip from the 1st dynasty fount at Abydos and Fig.14 (b) shows a crescent flint from the Old Kingdom [20].



(a)

Fig.14 Boring bits from 1st dynasty and Old Kingdom [20].

- They designed boring drills for settling labors (short-shaft drill) and boring drills for standing labors (long-shaft drill) as illustrated in Fig.15 [21].



(a) Short-shaft boring drill (18th dynasty)

(b) Long-shaft boring drill (26th dynasty)

Fig.15 Short and long-boring drills [21].

Another type of stone drills used in boring holes is the tube drill. How did archaeologists known his. Artifacts left by ancient Egyptians in tombs and operation sites strengthen this engineering fact. This conclusion is realized from the following findings:

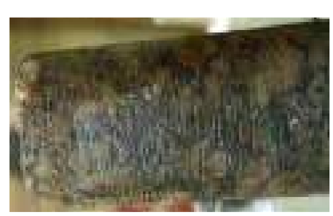
- Fig.16 shows an unfinished 70 mm travertine stone vessel located in Petrie Museum and marked with red paint for coring with drill, possibly from the 6th dynasty [22]. This is a real good mechanical engineering methodology since marking the hole leads to accurate positioning of the vessel interior.

Fig.16 Marking the hole for drilling [22].

- The hole is drilled using a tube drill producing a cylindrical core as shown in the unfinished vase from the 4th dynasty located in Petrie Museum and shown in Fig.17 [22].

Fig.17 Hole drilled by a tube drill [22].

- The ancient Egyptians invented the tube drill to produce stone tubes and generate vessel internal cylindrical holes. Fig.18 (a) shows a granite core cut by a tube drill in the 4th dynasty and located in Petrie Museum [22]. In Fig.18 (b) a basalt tube is cut by a tube drill in the 4th dynasty and located in Petrie Museum [22]. The thickness of the tube is not uniforms meaning that the cut was performed with certain eccentricity.



(a) Granite core cut by a tube drill

(b) Basalt tube cut by a tube drill.

Fig.18 Core and rube cut in the 4th dynasty [22].

- The tube drill of the ancient Egyptians is reconstructed by Denys Stocks in 1993 using a cupper tube cutting bit and a driving bow as shown in Fig.19 [23].

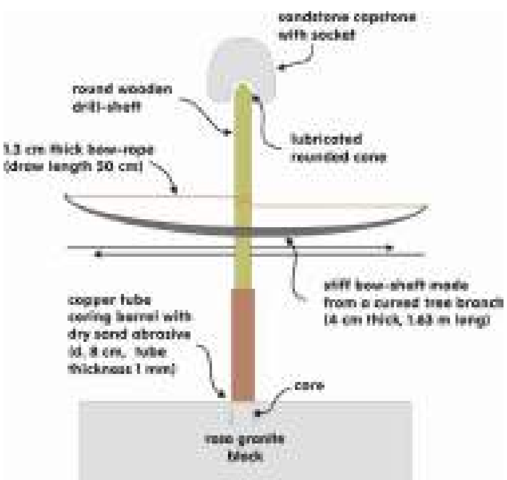


Fig.19 Tube drill constructed by Stocks [23].

- Another model of the stone tube drill was constructed by Stock based on using the copper tube bit and forced by two forcing weights as shown in Fig.20 [24]. It gains its rotational motion using a crank connected to the driving shaft as in the boring drill of Fig.12.

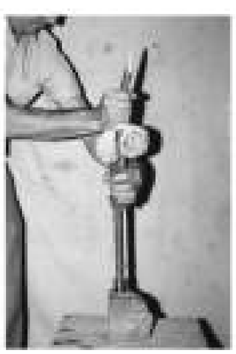


Fig.20 Dead-weights forced tube drill [24].

- The procedure for producing a stone vessel is shown in Fig.21 [22]. The external surface is generated using copper chisels for soft stones or hard stone bounders for hard rocks (stage 1 in Fig.21). The vessel hole location at the neck is marked as shown in Fig.16. Tube drill with increasing copper tube bits is used to generate the internal bore of minimum diameter required by the vessel design (steps 2 and 3). Now a straight bore is cut in the vessel and the cores are removed (step 4). Now, the weight-forced boring drill of Fig 12 of increasing bit length to produce the internal cavity of the vessel (steps 5 to 8).

Fig.21 Procedure for producing a stone vessel [22].

- A model of stone vessels produced by the above technique is shown in Fig.22 from the Middle Kingtom found in one of the pyramids in Mazghuneh and its cross-section is located in the Manchester Museum [22].

Fig.22 Stone vessel produced by drilling [22].

IV. STONE SAWING

Physical evidences indicate that the ancient Egyptians have used the saw in cutting hard stones. Samples of those evidences are as follows:

- Fig.23 shows a basalt stone in the paving layer in the east of the Great pyramid of the 4th dynasty [22]. The cut is clean, straight and perfect.

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Fig.23 Paving basalt stone near the Great Pyramid [22].

- Petrie, the famous archaeological professor of University College London stated that the builders of Giza pyramids had a sophisticated set of tools at their disposal [23]. Fig.24 shows a fine saw cut of basalt stone using a copper saw [23]. The cuts are perfect and surprising. This a hard stone saw cut. How great were those ancient Egyptians !!.

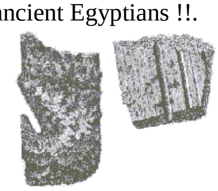

Fig.24 Basalt saw cutting [23].

- Another important application on stone sawing is from the Great Pyramid at Giza. Fig.25 shows the granite sarcophagus in the Great Pyramid at Giza which has 2.278 m length [24]. This lengthy granite box was cut by a stone saw [14]. William Petrie set the stone saw dimensions of the ancient Egyptians as thickness in the range 0.762 mm to 5.08 mm and length up to 2.438 m [25].

Fig.25 Granite coffer in the Great Pyramid [24].

- The last example is a granite box in the rock tunnels at the temple of the Serapeum at Saqqara. It is shown in Fig.26 as drawn by engineer Christopher Dunn [26].

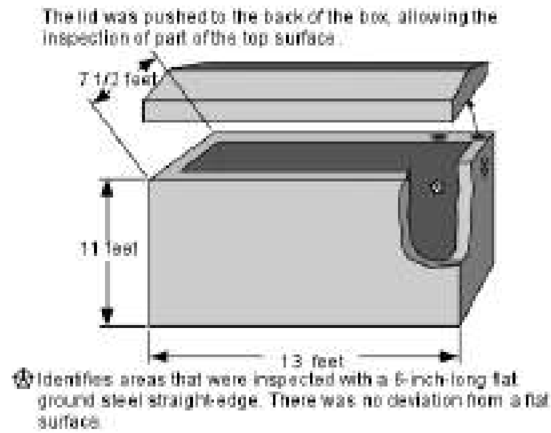

Fig.26 Granite block in the Serapeum temple [26].

This giant box has the dimensions of 3.96 m length x 3.35 m height x 2.286 m width and its mass is 90 ton of granite (body and lid) [26]. Engineer C. Dunn wrote the following comments of the Serapeum granite boxes [27]:

- They are 20 boxes.
- They were quarried at Aswan over 500 miles away and installed in arched crypts recessed into the walls of the labyrinth of underground tunnels.
- Surface was exactly flat as measured by a precision straight edge of accuracy to 0.005 mm.
- All the corners of the base are filleted.
- The inside surfaces are flat vertically and horizontally.
- The surfaces are square and parallel to each other.
- Inside surfaces have high degree of accuracy compared to surfaces of plates in modern manufacturing facilities !.
- Higher levels of technology were used by the ancient Egyptians.

- What is interesting about the level of technology gained by ancient Egyptians is the thinking of Engineer C. Dunn to re-manufacture the Serapeum granite box in one of the modern stone workshops in USA. He discussed with Mr. E. Leither of Tru-Stone Corporation the technical feasibility of creating several artifacts including the granite box in the Serapeum Temple at Saqqara. Mr. Leither final last comments were as follows [28]:

"*My company did not have the equipment and capabilities to produces the boxes in this manner. My company would create the box in 5 pieces, ship them to the customer and bolt them on site*".

V. STONE LATHE TURNING

It is well known that the ancient Egyptians used a woodturning lathe and recorded this in a tomb relief in the 3rd century BD [29]. However, stone (specially hard stones) is completely different than wood (soft material). Now, we will discuss the evidences of using the ancient Egyptians the technology of lathe turning in producing stone artifacts.

- The archaeologist W. Petrie commented that the lathe appears to have been as familiar an instrument in the fourth dynasty, as it is in the modern workshops. The diorite bowls and vases of the Old Kingdom are frequently met with, and show great technical skill. One piece found at Gizeh, shows that the method employed was true turning [30].
- The technologist C. Dunn wrote that while browsing through the Cairo Museum, he found evidence of lathe turning on a large scale. A sarcophagus lid had distinctive marks of lathe turning [31].
- In the Cairo museum and in other museums around the world there are examples of stone ware that were found in and around the step pyramid at Saqqara (built by King Zoser of the 3rd dynasty). Fig.27 shows one of those stone ware produced by lathe turning. It shows the unmistakable tool marks of a lathe manufactured item [32]. It is a multi-cavity stone plate located at the Egyptian Museum. It has a complex design and required relatively high level mechanical technology to produce without breaking the stone flanges bounding the cavities.

Fig.27 Stone plate from the 3rd dynasty [32].

VI. MISCLANEOUS TOOLS

Besides the main tools discussed (drills, saws and lathes), they some other miscellaneous tools in their stoneware manufacturing. Here are some of those tools:

- ***Chisels***: They used chisels to cope with soft stones such as limestone. Fig.28 shows a scene in the tomb of Ankmahor in Saqqara dated to the First Intermediate Period for carvers producing a statue using chisels and mallets [33]. Large number of actual ancient Egypt chisels are available in the world museums. Fig.29 shows two chisels one from the Old Kingdom (a) and one from the Middle Kingdom (b) [34]. Both are located in Petrie Museum. The design in Fig.28 (a) has a sharp tip suitable for producing holes or engravings in the stone block. The design in Fig.28 (b) has a flat tip suitable for flattening surfaces of producing flat surfaces.

Fig.28 Carvers using chisels and mallets [33].

(a) Old Kingdom chisel. (b) Middle Kingdom chisel.
Fig.29 Chisels from Old and Middle Kingdoms [34].

Another chisel designs are shown in Fig.30 from the New Kingdom which are located in Petrie Museum [34]. Both have flat tip. The design in (b) has a tip as wide as about 175 % of the average stem diameter. This increases the efficiency of the chisel during the flattening process of the soft rock.

(a) (b)
Fig.30 Chisels from the New Kingdom [34].

- ***Mallets***: The old Egyptians used mallets in conjunction with chisels to generate soft stone surfaces. A mallet is a hammer-like tool with a head commonly of wood [35]. Fig.31 shows one of the designs of the mallets from the Old Kingdom of Egypt [36]. The hitting surface is irregular to prevent slipping over the chisel during hitting. There are two depressions on the hitting surface plus number of small halls. Its handle takes a conical shape for better security in the labor's hand.

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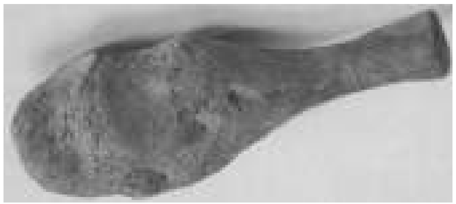

Fig.31 Mallet from the Old Kingdom [36].

Another mallet design from the 18th dynasty of the New Kingdom is shown in Fig.32 [37]. It has one depression all-over the circumference. Its handle is smooth and completely cylindrical. The body is rough to prevent slipping over the chisel head.

Fig.32 Mallet from the New Kingdom [37].

- ***Stone hammers***: They used stone hammers to deal with hard rocks as depicted from the scene shown in Fig.33 for two sculptors dressing a statue [37]. Fig.34 shows an actual complete stone hammer located in the Metropolitan Museum of Art and returns to the age of King Amenemhat I (the 1st King of the 12th dynasty) [36].

Fig.33 Stone hammer in use [37].

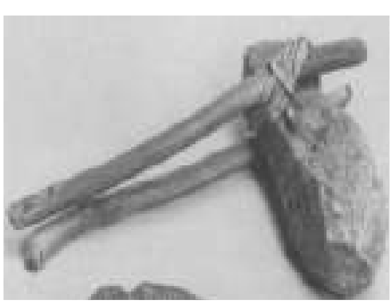

Fig.34 Stone hammer from the rein of Amenemhat I [36].

- ***Stone pounders***: A pounder is a heavy tool of stone or iron that is used to grind and mix material against a slab of stone [38]. They used stone pounders to polish stoneware as depicted from the scene shown in Fig.35 from the tomb of Vizier Rekhmire' at Thebes during the 18th dynasty [22]. There are three sculptors doing the job under the supervision of a foreman. This one of the reasons of their success in performing works looking as miracles.

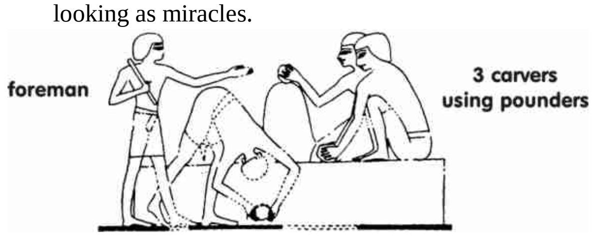

Fig.35 Stone polishing using pounders [22].

Fig.36 shows two stone pounders, one from the first dynasty in (a) located in the Heckscher Museum of Art of NY and manufactured from pink breccias and has a flat base and smooth spherical body[39]. The other pounder in (b) is from the Old Kingdom and exhibited in Michael Carlos Museum [40]. It has a flat base and a hemispherical body to ease holding it by hands without harming the labors.

(a) From the 1st dynasty [39]. (b) From the Old Kingdom [40].

Fig.36 Granite hammers

- ***Geometrical measurements and adjustment***: The ancient Egyptians were able to measure and adjust accurately dimensions through some primitive instruments. They used measurement scales for the river line level from the rein of King Djer (the 3rd King of the first dynasty). They used the royal cubit from the era of the Old Kingdom during the rein of King Zoser (the founder of the 3rd dynasty) [41]. Those generous people designed and used scales for measuring linear dimensions from few mms to as long as 10 km [42]. Fig.37 shows a typical ancient Egyptian cubit located

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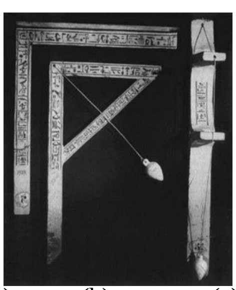
in the Petrie Museum [42]. Another wonderful royal cubit model displaced in the Louvre Museum of Paris is shown in Fig.38 [43]. It has 7 large divisions, each divided into 4 subdivisions, each divided into 14 divisions. With the royal cubit length of 523 mm, the resolution of this cubit is 1.33 mm.

Fig.37 Ancient Egyptian cubit [42].

Fig.37 Royal cubit at Louvre Museum [43].

Furthermore, they have designed set squares and plumps to adjust corners , horizontal and vertical surfaces. Fig.38 shows a set of such instrumentation from the tomb of Sennedjem the high official responsible for the excavation and decoration of the nearby royal tombs in the reins of Seti I and Ramsis II of the 19th dynasty [44], [45]. (a) is a set square graduated from both sides. It adjusts exactly a 90 degrees angle and measures distance in two perpendicular directions. (b) is a set square – plump for adjusting horizontal surfaces. (c) is a plump for adjusting vertical surfaces.



(a) (b) (c)

Fig.38 Adjusting corners and surfaces in the 19th dynasty [44].

Regarding mating surfaces with angles other than the 90 degrees, the architect Kha, who was the overseer of works in Deir El-Medina in the mid- 18th dynasty during the rein of Amenhotep II, Thutmose IV and Amenhotep III [46] invented a protractor found in his tomb. The protractor is shown in Fig.39 as displayed in the Egyptian Museum at Torino of Italy[47] .

Fig.39 Protractor of architect Kha of the 18th dynasty [47].

Another important tool used in adjusting the flatness of stone surfaces is the boning rods. Its use is authorized by a scene from the tomb of Rekhmire, the vizier of Pharaoh Thotmose III of the 18th dynasty shown in Fig.40 [36]. A typical boning rods device located in the Metropolitan Museum of Art of NY found in the Hatshepsut temple at Deir el-Bahari (18th dynasty) is shown in Fig.41 [36]..

Fig.40 Sculptors working with boning rods [36].

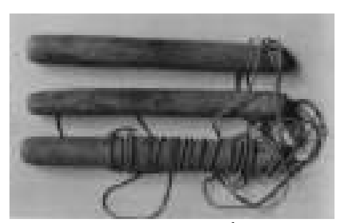


Fig.41 Boning rods from the 18th dynasty [36].

VII. CONCLUSION

- The paper tried to trace some features of stone cutting processes in ancient Egypt.
- It presented samples of ancient Egyptian cutting of granite and basalt hard stones.
- It discussed the ability of ancient Egyptians to produce accurately contoured granite blocks.
- It presented samples of producing corner filleting of stone mating surfaces of hard stones.

- They used sawing, drilling and lathe turning processing to cut hard stones.
- They invented two types of stone drilling equipment, one for hole and the other for tube stone cutting starting from the Old Kingdom.
- They used stone saws of length up to 2.4 m and thickness up to 5.1 mm.
- They could cut granite boxes up to 90 ton mass and 3.96 m length having surface flatness better than 0.005 mm located in the Serapeum of Saqqara.
- An American stone corporation announced that it did not have the equipment and capability to produce the Saqqara granite boxes.
- They used stone turning machines to produce very complex stoneware.
- They used scales for dimensions measurement since the 3rd dynasty. They could design dimension measurement devices to measure dimensions from 1.3 mm to 10 km.
- They invented instruments to measure and adjust right and other angles and adjust flatness of surfaces in both horizontal and vertical directions.

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