Archaeol Anthropol Sci (2012) 4:199–208
DOI 10.1007/s12520-012-0091-6

ORIGINAL PAPER

Mycenaean shipwright tool kit: its reconstruction and evaluation

Elena Maragoudaki · Panayiotis K. Kavvouras

Received: 10 October 2011 / Accepted: 23 February 2012 / Published online: 11 April 2012

Abstract The present study aims to answer questions of utility and efficiency, on the basis of archaeological evidence, of the nominated Mycenaean shipwright tool kit through experimental methods. The target set was established through the recording of archaeological data, examination of the available findings, classification of the finds, gathering of the relevant sources (literature, iconography, archeological parallels and preserved traces), reconstruction of the findings (casting, elaboration of the metallic parts and reconstruction of the hafts), usage of the reconstructed tools and the evaluation of them qualitatively, quantitatively and ergonomically via the reconstruction of a segment of the Uluburun shipwreck hull. Knowledge of tool production of the Late Bronze Age has been furthered. Questions on the casting of the metal parts of tools and the elaboration of their different parts have been answered. The reconstructed tools appear suitable for use in pegged mortise-and-tenon joinery in shipbuilding by skilled woodworkers. Moreover, the reconstructed tools proved to be user friendly. Experimental methods proved useful in the allocation of efficient criteria for the use-based classification of tools. Functional differences between the tools were shown, and questions on utility were answered. The Late Bronze Age shipwright, as master of his craft and tool use, could make new tools or adjust them to the demands of a particular job, as well as to his own body build. The range of tools used for shipbuilding in the Late Bronze period is comparable to those used today.

Keywords Late Bronze Age · Shipwright toolkit · Mortise and tenon shipbuilding technique

E. Maragoudaki
LZ Ephorate of Prehistoric and Classical Antiquities,
Ministry of Culture and Tourism,
Loutraki, Greece
e-mail: emaragoudaki@yahoo.com

P. K. Kavvouras (✉)
Wood Science and Technology Laboratory, Forest Research Institute, National Agricultural Research Foundation,
Terma Alkmanos,
115 28 Athens, Greece
e-mail: pkavv@fria.gr

Introduction

The Late Bronze Age (LBA) shipwright appears to have had a good array of tools and an in-depth knowledge of woodworking techniques. The need to produce stiffer hulls, to allow sailing in rougher seas with increased loads, led to the transition from the laced ship construction to mortise-and-tenon construction, which required the ability to solve more complex structural problems (Dürring 1995; Mark 2005). The shipwrights had to invest considerable time in applying different types of joinery and new types of tools required for the work. The application of pegged mortise-and-tenon joinery, the use of thicker planking wales and more internal stringers (McGrail 2004) resulted in the enlargement of the shipwright's tool kit.

Odysseus could have built a simple boat with the tool kit provided by Calypso (Odyssey 5.234-57), i.e. an axe (tree felling, log splitting or trimming), an adze (shaping, smoothing and edge fitting hull planks) and drills (boring the holes for the fasteners) (Mark 2005; Casson 1964). In the case of a pegged mortise-and-tenon craft, this tool kit would not be adequate. The Mycenaean shipbuilder would additionally require chisels (mortise, paring and parting) for mortise cutting, thicker and longer drill bits for opening the holes for the location of the wooden pegs to lock the joints and more efficient saws for cutting along and across the grain.

Based on archaeological evidence (Fig. 1), the Mycenaean shipwright tool kit appears to consist of cutting (axe, adze, chisel and saw), perforation (drill and awl) and percussion tools (hammer and mallet) (Maragoudaki 2010). Naturally, questions arose of the utility and efficiency of the nominated shipwright tool kit and, thus, had to be answered through experimental methods. Tool reconstructions based on available archaeological evidence could offer an insight into the realities of the LBA shipwright, which otherwise would be unattainable.

The target of the present work is the reconstruction and evaluation of the LBA shipwright tool kit by combining various sources of information and applying methods of experimental archeology. The target set was developed through the recording, examination and classification of the available archaeological data, gathering the sources, reconstructing the chosen tools and by evaluating their efficiency through the reconstruction of a fraction of the Uluburun shipwreck hull (Pulak 1999, 2002, 2003; Yalçin et al. 2005).

Materials and methods

Tool reconstruction It was decided to reconstruct certain types of tool from each of the tool categories in the shipwright tool kit. The tools chosen to be reconstructed were determined by a combination of certain criteria and restraints (Maragoudaki 2010). In particular, the available archaeological evidence, the particular tool characteristics necessary for construction of the hull section and the available means and materials needed for the elaboration and the finishing of the tool blades were taken into consideration.

Eight types of cutting, perforation and percussion woodworking tools were reconstructed and their characteristics are shown in Table 1. The change to the initial chisel dimensions is due to the constructional need for opening a mortise of 150 mm in depth (Pulak 2003). So therefore, a length of 250 mm was necessary for the shaft. Chisels labelled as double (DBL) bevelled had one dominant bevelled side while the opposite side had only a slight inclination created during edge hammering. Saw tooth shaping and sharpening was carried out using files of different sizes and forms because the technique used during the LBA is not known. The bell-shaped mallet was reconstructed according to an Egyptian parallel (Killen 1980) due to the fact that no such wooden tool from the Mycenaean period has been preserved in archaeological records.

The alloy used for the reconstruction of tool blades was in accordance with the results of chemical analysis of LBA tools from continental Greece (Mangou and Ioannou 1999). It was decided to follow the classical metallurgical “recipe” for a medium tin bronze alloy (Papadimitriou 2001). Chemically pure copper in the form of lump and tin in the form of bar, in percentages of 90–91 % and 9–10 %, respectively, were used for the alloy (Maragoudaki 2010). The casting was made in a silicon carbide crucible due to its fire resistance (up to 1,830 °C). First, the copper was melted, and then tin was added at the end of the procedure so as not to be vaporised due to its low melting point (232 °C) in comparison to copper’s (1,083 °C) (Lowe Fri 2007).

During the heating of the alloy, the moulds were prepared. After experimenting with moulds of different materials, it was decided to use two-piece moulds made of stone with a sand covering, or made only of sand or only of clay. The use of stone as a raw material for moulds was already known since the beginning of the Bronze Age and was regarded as a rather popular practice during the LBA period throughout Greece (Andreou and Kotsakis 1996; Evely 2000; Hakulin 2004; Adrymi-Sismani 2004). Schist and serpentinised peridotite were used for the stone moulds. Although the use of sand in mould construction has not been attested to the period due to the material’s nature, it can indirectly be detected through the comparative study of metallographic analysis of the findings and through the application of previously reconstructed moulds (Ottaway

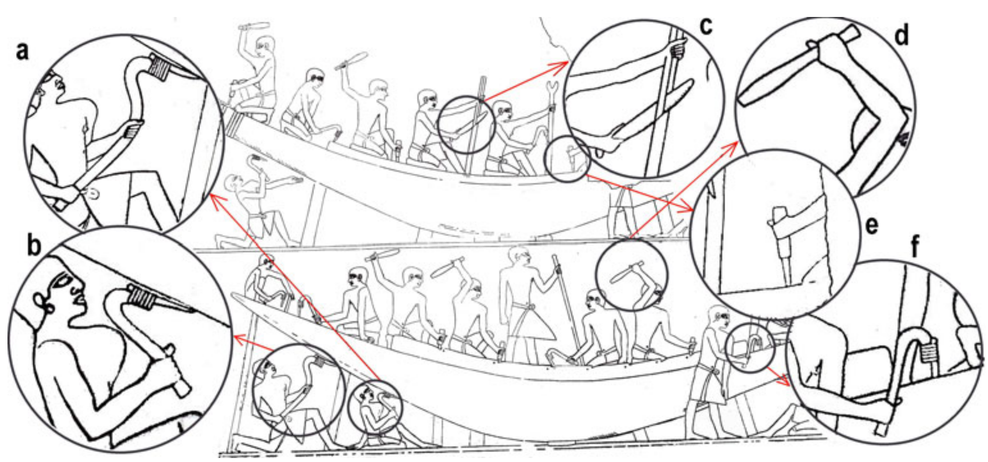

Fig. 1 Building an Egyptian ship (Wild 1953, pls CXXVIII, CXXIX). Shipwright tools: **a**, **b** chipping adze, **c** saw, **d** bat-shaped mallet, **e** mortising chisel and **f** chopping adze

Table 1 Types and technical characteristics of reconstructed tools

Tool category	Tool type	Prototype origin	Prototype dimensions (L × W × Th; mm)	Reconstructed tool dimensions (L × W × Th; mm)	Tool characteristics				
					Blade/bit geometry	Cutting edge width (mm)	Sharpening angle (°)	Hafting angle (°)	Tooth set (mm)
Cutting	Chisel	Perati (Iakovidis 1969, 236, 338, Fig. 114 left, Table 77a: M36)	192×16–21×9	180×17–23×7	Parting chisel DBL bevelled	23	30	–	–
		Perati (Iakovidis 1969, 444, 338, Fig. 133 right, M 164)	81×7×7	26×7×7	Parting chisel DBL bevelled	7	30	–	
		Acropolis Hoard, Athens (Spyropoulos 1972, 69, Fig. 129, Table 120d)	125×31×4.5	125×31×4.5	Paring chisel SGL bevelled	31	20	–	–
		Acropolis Hoard, Athens (Spyropoulos 1972, 69, Fig. 128, Table 20c).	181×31–42×6	181×31–42×6	Paring chisel SGL bevelled	42	15	–	
		Tsountas Hoard, Mycenes, (Spyropoulos 1972, 45, Fig. 79, Table 15b)	180×7–13×7	180×7–13×7	Mortising chisel SGL bevelled	13	17, 25	–	–
		Tsountas Hoard, Mycenes, (Spyropoulos 1972, 45, Fig. 80, Table 15b)	142×8–10×8	240×8–10×8	Mortising chisel SGL bevelled	10	20	–	
		Palace of Nestor, (Blegen and Rawson M 1966, 244, Fig. 300:11)	135×10–18×8	225×10–18×8 225×17–30×8	Mortising chisel SGL bevelled	18 30	25	–	–
		Lefkandi, Euboea, (Evely 2006, 282, Fig. 5.9.6., pl. 88.1)	159×12–15×9	240×12–15×9	Mortising chisel SGL bevelled	15	25	–	
	Adze	Acropolis Hoard, Athens, (Spyropoulos 1972, 69, Fig. 128, Table 20c).	181×31–42×6	181×31–42×6		42	12	55	–
		Tsountas Hoard, Mycenes, (Spyropoulos 1972, 22–23, Fig. 22, Table 9d)	163×10–41×8	163×10–41×8		41	12	50	–
	Saw	Androniani region, Euboea, (Paschalidis 2007, 434-435, pl. CVII a g)	557×77–90×1.8	557×77–90×1.8	Crosscut saw Rip saw	–	–	–	0.31
		Prosymna, Argolis, (Blegen 1937, 346, Fig. 244:1)	217×39×1	217×39×1	Flush cutting saw	–	–	–	0.00
	Axe	House of Tripods, Mycenes, (Onasoglou 1995, 49, Fig. 57, Table 13).	222×37–60×2.8	222×37–60×28	Double axe		15 25		
		Anthedon Hoard Boeotia, (Spyropoulos 1972, 61, pl. 17: XI)	201×42	201×42×8	Trunnion axe,SGL bevelled		25		
		Teichos Dymaion, Achaia, (Papadopoulos 1979, 226: 139, Fig. 306c)	138×41×8	138×41×8	Trunnion axe,DBL bevelled		25		
		Lindos (Blinkerberg 1931, 67:27, pl. 3:27)	150×42	150×42×8	Trunnion axe,SGL bevelled		20		
Perforation	Drill	Anthedon Hoard, Boeotia, (Spyropoulos 1972, 61, Table 17: IX)	Unpublished	190×19×3.5	Diamond shape bit SGL bevelled		25		
		Kalami Tholos, Chania, (Evely 1993, 78, pl. 19)	Cretan paral.	190×19×3.5	Diamond shape bit DBL bevelled		33		
	Awl	Tsountas Hoard (Mycenes), (Spyropoulos 1972, 37, Fig. 64, Table 13i)	152×7×7	152×7×7	Pyramidical Shape bit				
Percussion	Hammer	Acropolis Hoard, Athens, (Spyropoulos 1972,73, Fig. 136–137, Table 23a)	147×44×40	147×44×40					
	Mallet	Egyptian parallel, bell-shape, (Killen 1980,18, pl. 16)	230×30–112	230×30–112					

2003). The shape of the tool was chiselled into the surface of the stone, while, in the case of sand moulds, the imprint was created by impressing the required shape into the damp sand using wooden patterns. This technique is archaeologically attested (Kienlin and Ottaway 1996).

After 3.5 hours, the alloy was ready to be poured into the moulds with a silicon carbide crucible. It is worth noting that the stone moulds were heated so as to avoid rupture from thermal shock while the hot metal was being poured. The shaped tools were immersed into cold water while hot, a method which has been experimentally proved (Ottaway 2003).

Next, came the elaboration of the of the tool blades, which comprised the following steps: annealing at 600–700 °C for about an hour, immersing in cold water and, finally, cold hammering. At first, the cutting tools were formatted. As for the axes, the double axe (Table 1) had its cutting edges cold hammered and then sharpened. Annealing wasn't necessary because its as-cast condition was very close to the final product. The trunnion axe was made in three replicas (Table 1), including single (SGL) and DBL bevel. The sharpening angles were formed at 20–25° after cold-hammering, annealing, immersing in water, cold hammering and, finally, sharpening. As far as the chisels and the adzes are concerned, it is worth noting that, due to their simple forms, they were cast into rectangular bars or wedge-shaped forms, enabling their edges to be crafted following the aforementioned elaboration cycle. The two paring chisels had a single bevelled cutting edge with sharpening angles of 15° and 20°, respectively (Fig. 2a). The two mortising chisels (Fig. 2b) also had single bevelled cutting edges with sharpening angles of 20–25°. A file was for the primary shaping of the tool edge, which was followed by honing the edge with an oil slip stone.

The cutting edges of the two adze replicas were single bevelled (Fig. 2c), and the sharpening angles were formatted at 12° in one phase of elaboration for both the Acropolis and Tsountas Hoard replicas, while the hafting angles were formatted at 50° and 55°, respectively. The saw blades were of rectangular shape and 4 mm thick. After repeating the cycle of annealing at 1,600 °C, immersing in cold water and hammering, the thickness of the blades was reduced to the desirable level (50 and 25 % of their initial thickness for the Androniani and the Prosymna saw, respectively). Saw filing followed, i.e. tooth shaping, setting and sharpening. The use of a file was preferred for the formation of serration so as to achieve uniformity and exact inclinations of the teeth. As far as the flush cutting saw is concerned, the teeth, 6-7 per cm, with an average height of 1.2 mm, were filed with inclinations of 45° towards the haft and 45° towards the rounded end. The Androniani saws had 3–4 teeth/cm with an average height of 2.3 mm, inclined 35° towards the haft and 45° towards the rounded end (pull stroke saw). The tooth setting on the Androniani saws was carried out by using bearing strokes with a 15-mm cold chisel on the base of every set of three teeth alternatively between the left and right levels till the desired set, i.e. 0.31 mm, was achieved (Maragoudaki and Kavvouras 2007). During tooth setting, the saw blade was laid on a softwood board.

The reconstructed drill bit measuring 200×8–18×10–12 mm had a lozenge/diamond-shaped cutting end (point angle, 100° and width, 18 mm) (Fig. 2d). The selection of the most suitable constructional geometry for the drill bit was based on a number of experiments. The best shape was that of the diamond-shaped drill bit, sharpened alternatively on each side so as to cut while pulling. Moreover, an awl was also constructed from a square section, slightly tapered bar of 157×7×4–7 mm (Fig. 2e). The awl's tip was shaped on a coarse-grained whetstone.

Two different types of hammers were constructed: a bronze hammer (Fig. 2f) (Spyropoulos 1972, 73, Figs. 136–137, Table 23a) and two mallets, a bell-shaped and a

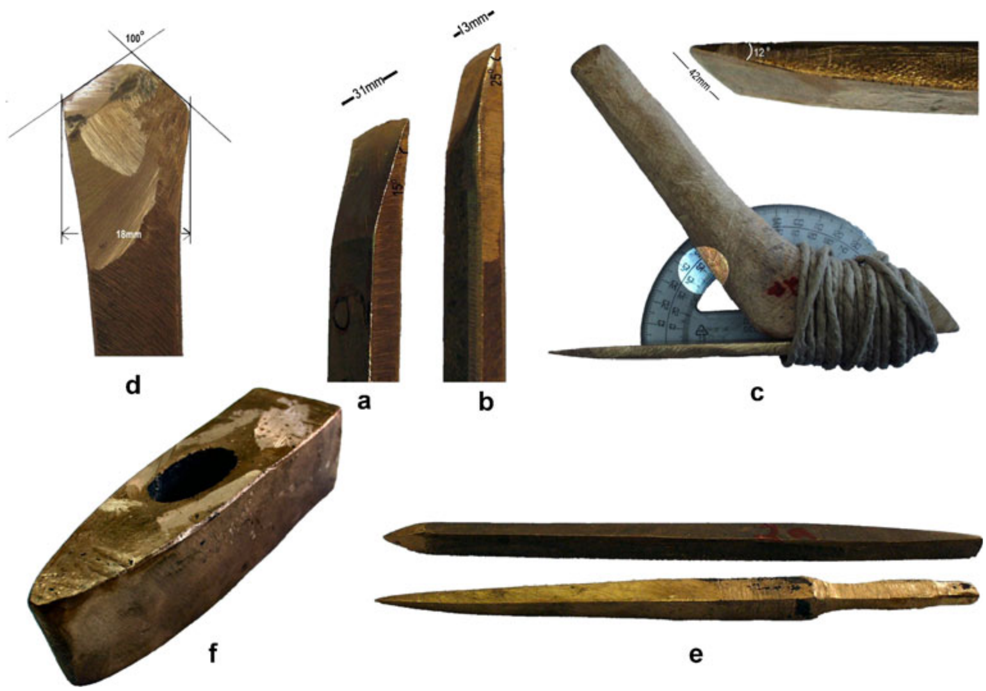

Fig. 2 Blades of reconstructed cutting, perforation and percussion tools

bat-shaped one, both based on Egyptian parallels (Killen 1980, 18, pl. 16; Stocks 2003, 30, Fig. 2.8). The bronze hammer was trapezoidal in shape with an elliptical hole for shafting. The reconstruction of the bell-shaped mallet, weighing 1450 g and measuring 230 mm in length (i.e. head length, 136 mm and handle length, 94 mm) and 112 mm in diameter, was completely based on an Egyptian parallel (Killen 1980, 18, pl. 16) due to the fact that no relevant evidence has been preserved from this period.

After shaping and elaborating the tool blades, it was time to reconstruct and adjust the handles, all made of oak or olive wood. The choice of wood species was based on their mechanical properties (i.e. bending and impact strength), as well as to satisfy evidence from the available literature and archaeological evidence (Maragoudaki 2010). The haft shapes were inspired by Egyptian parallels (Killen 1980; Petrie 1917) while ergonomic needs were also taken into consideration. The double axe handle was straight, 435 mm in length and 39 mm in diameter. As for the single trunnion axe, its haft was 410 mm in length and 34 mm in diameter with a rectangular hole of 25–30×8×30 mm positioned 25 mm from the tip to allow for the insertion of the blade. The axe blade passed through the handle up to the point of the horns (Evely 1993) in order to prevent it from driving back into the shaft under the impact of the blows. The chisels had handles of cylindrical shape, 30–35 mm in diameter and 150 mm in length, tapered slightly at the butt. Shafting of the adzes was based on Egyptian parallels, the shape of which was adapted to the reconstructed tools. Two types of handles, a Λ shaped (with one side more elongated than the other) as well as an S-shape, were used. Both shapes were based on Egyptian parallels of the 5th Dynasty (Steindorff 1913, Taf. 119). The handles varied from 250–350 mm in length and 27–40 mm in diameter. Both types of handles were adjusted to the reconstructed blades which were tied to them with the bevels facing the hafts.

For the reconstruction of the saw handles, the depictions of hieroglyphic ideograms, Linear A and Linear B scripts and the traces left from the wooden handle on the metallic blade of a saw from Akrotiri (Doumas 1994) were taken into consideration. Specifically, two grip-shapes were constructed, i.e. the knife grip for the Prosymna saw and the pistol grip for the Androniani saw (Table 1). Their dimensions were 195×29–38×22 and 290×36–58×21 mm, respectively. Next the points for the rivets, three for the bigger saw and two for the smaller, were marked and holes of 5 mm and 3 mm in diameter were opened respectively with the help of an electric drill. The awl haft of 130×26–30×30 mm was of the same type as that of the chisels.

The reconstruction of the bow-drill parts, i.e. the bow, the cap and the haft of the drill bit, was based exclusively on Egyptian parallels (Killen 1980). The haft of the drill bit was almost the same as that of the chisel intitially, but with a more conical butt so as to turn easily inside the cap. During the experimental work, in order to prevent the cord slipping while turning, the cylindrical shape of the handle was adjusted to a bobbin shape measuring 215 mm in length. The handle diameter was 37–43 mm at each end and 31 mm in its middle. The opening of the bow was measured at 590 mm and its diameter at 33 mm. The bow had an angled shape with natural inclination containing one hole at its end for the passing and securing of the cord. The semi-spherical shaped cap was wooden, though it could also be of stone, and its external diameter was 100 mm. In the centre of its base, a cavity of 40 mm in diameter was chiseled to enable the unobstructed turning of the drill shaft.

Finally, the construction of the cord was based on the preserved findings of such perishable material from Akrotiri of Thera (Spantidaki and Moulhérat 2006, 285–287). It was made of linen fibres and measured 4 mm in diameter. It is of the type z3S, which means that it was constructed of three strands in an S-twist (once twisted to the left and three times to the right). Once the twisting was finished, the surface of the cord was then covered with a layer of beeswax so as to prevent it from unraveling whilst being used. The angle bow's cord needed to be frequently stretched during use to secure a continuous, smooth turning of the drill shaft. For this task, the presence of two persons was necessary in order to achieve better results.

In concluding this section on tool construction, it is worth mentioning that the reconstructed axes (double and trunnion) and the hammer were not used in the following phase of tool evaluation work as the wood used was already sawn into boards.

Evaluation of the reconstructed tools As tools are made for use, their replicas can only serve their main purpose if they work, too, and their performance can be assessed by proper measurements. Performance evaluation of the reconstructed tools was attempted through the rebuilding of a segment of the Uluburun shipwreck hull, achieved by following a preset work plan. The Uluburun wreck is the only well-known Late Bronze Age wreck dated to the LH IIIB1 (Pulak 1987) to be found in the Mediterranean Sea. Built with the shell-first construction technique, this ship provides the earliest example of pegged mortise-and-tenon joinery in shipbuilding. The largest and best preserved part of the ship’s hull, measuring approximately 1.75 m along the line of the keel-plank and 1.00 m in width, likely corresponds to the ship’s midsection, including portions of the ship’s keel, port garboard, the second port strake at full width, and fragments of the third port strake (Pulak 2002). For the tool evaluation work plan to materialise, it was decided to reconstruct a portion of the survived Uluburun ship wreck. Two planks with the dimensions of the Uluburun shipwreck’s second strake (1,170×260×63 mm) were edge joined with tenons

(300×61×16 mm) placed at 210-mm intervals. The mortise-and-tenon joints were locked with pegs 20 mm in diameter. To ensure the proper curvature of the hull segment, the adjoining edge surfaces of the two planks were bevelled 95° inwards, set to the bevel measurements of the adjoining edge of the port garboard and first strake of the Uluburun shipwreck hull (Pulak 2002).

The tool evaluation work plan consisted of six successive steps, i.e. plank cutting to size with rip and cross-cut saws, adjusting the bevel angle of the plank edge with adze, mortising with chisels, tenon manufacturing with saws and chisels, tenon-locking peg manufacturing, opening of the holes for the location of the wooden pegs with a bow drill and hull smoothing with an adze.

During each of the aforementioned steps, the efficiency of the tools used was evaluated quantitatively, qualitatively and ergonomically. The efficiency evaluation criteria used were respectively the time required for the completion of the work, excluding sharpening time, the accuracy of cutting together with the quality of the surface created and labour intensity gauged through testimony of fatigue from the craftsman.

In an effort to objectively evaluate the efficiency of the tools, it was decided to reconstruct two replicas of the aforementioned segment of the Uluburun shipwreck hull. The first replica was elaborated in the Wood Technology Laboratory of the Forest Research Institute by the authors of this article, and the second was executed by the professional shipwright, Mr. N. Daroukakis, at his own shipyard on the island of Aegina. The unskilled, female worker employed in the construction of the laboratory replica painstakingly followed the work plan, allowing for the tool evaluation measurements to be taken appropriately. It is obvious that the results of the tool evaluation measurements have comparative and not absolute value. The skilled craftsman, specialised in traditional boat building, employed in the construction of the second replica, despite not following the pre-set work plan, offered relatively more down-to-earth conclusions on the tool evaluation to be drawn.

Air dried (15 % moisture content) Austrian pine wood (*Pinus nigra*) was used for the hull planks and Broadleaved oak wood (*Quercus conferta*) for the tenons and pegs. The keel and hull planking of the Uluburun ship hull was made of cedar (*Cedrus* sp.) (Pulak 2002) while the tenons and the pegs were made of Turkey oak (*Quercus cerris*) (Pulak 2002). The final dimensions of the oversized planks were engraved on the surfaces with an awl. Then, the cross-cut and rip pull saw (Maragoudaki and Kavvouras 2007) were used for cutting the planks to the desired size. After cutting along 150 mm of the plank's length, the rip saw started to get wedged. At first, a bigger set was applied, but it had an unsatisfactory result because saw pulling then became more power demanding. The insertion of a wooden wedge at the beginning of the section helped to provide the unobstructed movement of the tool.

It seems that the Uluburun shipwreck shell was formed strake by strake, as has been attested by the Egyptian pictorial evidence (Steindorff 1913, Taf. 119). The shipwright built the hull from the keel up with planks joined to each other edge to edge. To generate the desired final shape of the hull, the shipwright had to adjust the bevel angle of the plank edge. During the construction of the Uluburun hull replicas, the 50° hafting angle adze was used for the adjustment of the bevel angle (5°), and also plank edge smoothing was used for a tight joint between the planks to ensure water tightness of the hull (Table 1). The technique used for mortise opening should ensure the proper inclination of the planks when joined together. As the inboard sides of the port garboard and first strake meet at an angle of 95°, the mortise should be cut at an angle, and thus, securing the proper plank inclination at tenon insertion (Fig. 3). To achieve this inclination, the plank was edge rested on wooden wedges of 5° during mortising. By holding the chisel vertically, the mortise was cut so that its axis was perpendicular to the edge surface of the plank. Along the total length of the planks, five mortises 150 mm deep, 60 mm long and 17 mm wide were designed to be cut. In the classic tradition of mortising, a chisel was hammered into the wood with the bell-shaped

Fig. 3 Mortise cut at an angle for securing the proper plank inclination after tenon insertion

mallet, and then levered out to remove waste. Mortising chisels must have the thickness to withstand the levering out, the stout blade angle to resist abuse and the length to add leverage to the levering out. The reconstructed chisels were of three types, i.e. the mortising chisel to cut the wood, the parting chisel to remove the waste and the paring chisel to finish the sides of the mortise. The need for the use of a parting chisel came up after discovering that the mortising chisel was strong enough to withstand mallet blows, but not robust enough to withstand the bending stresses which develop during the levering out (waste removal). An SGL bevelled mortising chisel with a cutting edge of 30 mm and another with a cutting edge of 15 mm were used for the cutting of the long and the narrow sides of the mortises, respectively (Table 1) (Maragoudaki 2010).

Two Broadleaved oak boards measuring 1,500×60×20 mm were used for tenon manufacturing. The five tenons were cut from the board with the use of the cross-cutting saw. For the formation of the tapered ends of each tenon, the adze with a 65° hafting angle (Table 1) was used, while the SGL bevelled paring chisel of 31 mm cutting-edge was used to finish the surface of the tenon in order to achieve the best fit.

The drilling points for opening the holes for the location of the wooden pegs were set with an awl at 52 mm from the plank's edge, while the space between the pegs securing the two tenons was measured at 210 mm to the same surface of the plank, as has been attested for the Uluburun hull (Pulak 2002). Then, holes of 18 mm in diameter were opened with a depth of 50 mm by using the bow drill.

From the same boards used in the construction of the tenons, several square section bars of 20 mm were cut. The bars, then secured in a vice, were transformed into tenon-locking pegs with the use of the SGL bevelled paring chisel of 31-mm cutting edge and the mallet. After reaching the desired diameter, the peg was located in the hole from the inboard side with the help of the bell-shaped mallet, and then was sawed evenly to the surface of the plank with the flush cutting saw to securing the tenon inside the mortise just as was attested on the Uluburun ship hull (Pulak 1999).

As for the smoothing of the plank surfaces with the adze, it is interesting to note the existence of a variety of adzes for different tasks. This has been attested not only in Egyptian iconography (Wild 1953), but also in traditional shipbuilding (Damianidis 1998). After "locking" the tenons, the outboard surface of the hull segment was smoothed by using both "types" of reconstructed adzes. At first, the angled surfaces of the plank seams were trimmed with the thicker adze of 55° hafting angle to provide the curvature needed and then were planed with the slender 50° hafting angle adze so as to be smooth and flat.

During the construction of the second replica, the shipwright was free to choose the tools most suitable for the task. After the examination of all the reconstructed tools and their trial use, the shipwright chose the ones he considered most appropriate. The differences in the construction of the second replica in relation to the first were confined mainly to the tools used and the working method followed. Furthermore, the skill of the traditional shipbuilder, as well as his physical strength, should be taken into account. Throughout the mortising process the craftsman exclusively used the single bevelled mortising chisel for the opening of the mortises to a depth of 150 mm. Then, he "cleared" the sides of the mortises with the single bevelled paring and mortising chisels so as to secure the unobstructed insertion of the tenons. The shipwright opened two mortises at a time in order to use the same tools and keep a constant work rhythm. Also, it was decided to open one of the mortises with modern single bevelled mortising chisels made of steel. Due to the fact that the modern chisels could reach a depth of 120 mm, the use of the bronze SGL bevelled mortising chisel of 15 mm cutting edge was necessary to finish the work. It took the shipwright about 30 min to open a mortise using either the steel or bronze chisels, excluding any time needed for whetting the bronze ones (3–4 min). During the tenon manufacturing, the traditional shipwright used both of the reconstructed adzes. For the initial formation of the tenon surfaces and the tapered ends, he used the adze of 55° hafting and 12° sharpening angle, while for the smoothing of the surfaces he used the adze of 50° hafting and 12° sharpening angle. For the best fit of the tenons, he repeatedly inserted them into the mortises and gradually reduced their width and thickness with the adzes. The lower half of the tenons was a little bit thicker than the upper half so as to stay stable while placing the overhead plank. Finally, the construction of the tenon-locking pegs was completed using the SGL bevelled paring chisel of 31-mm cutting edge which functioned like a plane, leaving many facets along their length. The mallet was not used during this task because the craftsman held the wooden bar with his left hand and worked the surface of the pegs with his right hand.

Results

Elaboration of tool blades Simple tool blades which are flat on one side, e.g. adzes, chisels and axes, can be cast by pouring the molten metal into a hollowed-out shape in sand. The sand moulds were relatively easy to make and proved better than stone or clay moulds in casting. Specific advantages of sand moulds are the smoother and "closer" surfaces of the shaped bronze blades as well as their virtually limitless working life. The widespread use of moulds made of 'perishable' materials seems plausible. The annealing process applied to work and harden the woodworking tool blades has been proved quite efficient (Papadimitriou 2001). In the case of mortise chisels and adzes, where sharp

Fig. 4 The reconstructed Mycenaean shipwright tool kit

edges are important, it is preferable to refrain from annealing them after the final hammering, since the hardness (and hence the ability to maintain a sharp edge) may be more important than the potential brittleness (and hence the tendency to break).

Finishing of tool blades Simple tool blades, e.g. adzes, chisels, and axes, need whetting with oil as a lubricant. Not only the two-bevelled, but also the single bevelled blades require honing at both sides. The frequency of whetting depends on the particular use of the tools and the nature of the elaborated material. For instance, during the opening of a 150-mm mortise, the mortising chisels were honed at least once every half hour. Also, during the opening of a 50-mm hole through the pine plank and in the oak tenon for the insertion of a wooden peg, the lozenge bit of the bow drill needed to be re-sharpened once. The 0.31-mm set of the Androniani type saw proved insufficient for ripping. Although the saw set was then increased, the result was still not what was expected. The use of a wooden wedge facilitated the cutting parallel to the grain.

Hafting It has been proved that the shape of the handle is significant in woodworking tool specialisation. Adzes with Λ shaped handles have been found to be suitable for chopping (cutting across the grain) while adzes with S-shaped handles have been proved to be appropriate for surface smoothing or chipping (cutting along the grain). More delicate use of the S-shaped handle allowed the control necessary to perform work in fine detail. Evaluation of the saw handle proved that this particular grip shape was totally ergonomic, because its curvature allowed it to be grasped in the user's palm to serve equally well in both pulling and pushing movements, while the "swollen" end prevented the tool from the slipping from the hand. It was also clear that the LBA tool manufacturer was well aware of the ergonomic importance of tool handle shapes.

Plank cutting to size While cutting along the grain (ripping), the increased set, i.e. more than the initial 0.31 mm of the saw teeth, was not adequate to allow the blade to pass freely through the wood. A wooden wedge inserted in the kerf provided the necessary clearance. Generally, the saws used offered precision of cutting and a satisfactory wood surface quality since the examined fibres appeared to be cut rather than torn. As far as tool productivity is concerned, the cross-cutting of the planks measuring 260 mm in width took about 10 min, i.e. 26 mm/min while ripping of the same planks measuring 1,200 mm in length took about 2 hours, i.e. 10 mm/min. The execution of both tasks could be characterised as satisfactory as far as sawing accuracy and surface quality are concerned.

Mortising During the opening of the mortises the unskilled, female worker used all the reconstructed chisel types, i.e. mortising, paring and parting chisel. In particular, the DBL bevelled ones were used at the beginning of the process for outlining the cutting lines. Then the single bevelled paring chisel was used to smooth the surfaces of the mortise so as to facilitate the insertion of the tenon while the single bevelled mortising chisel was used to cut and extract the inner part of the mortise. The SGL bevelled chisel was preferred due to the fact that it helped keep mortise dimensions constant to the bottom of the mortise while also creating smooth surfaces, characteristics of great importance to the quality of mortise-and-tenon joints. The opening of the mortise took almost 2 hours with three intermediary re-sharpenings.

On the contrary, the skilled craftsman used mainly one tool, the SGL bevelled mortising chisel of 18-mm cutting edge, to open the mortise. Comparing the mortises of the two replicas, the superiority of the shipwright's work was obvious as far as the uniformity of mortise dimensions and inner surface quality are concerned. The skilled craftsman opened a mortise in 30 min, not including a 5-min interval and three intermediate re-sharpenings. He needed 30 min to open another mortise with modern, steel chisels which did not need re-sharpening.

Tenon manufacturing The traditional shipwright used both of the reconstructed adzes exclusively for this task while the unskilled worker used mainly the SGL bevelled paring chisel of 31-mm cutting edge to form the tenon surfaces and the adze of 65° hafting angle to taper their edges. The adze with the bigger sharpening and hafting angle proved to be suitable for chopping while the slender adze with the thinner blade was appropriate for chipping, functioning as a plane.

Opening of the holes for the location of the wooden pegs The drill with the diamond shaped drill bit proved to be suitable for opening holes into the wood. The existence of its pointed end helped the users to hold it steady while it was rotated to create circular holes. The angled bow proved user friendly, although the presence of two operators proved necessary for better results. Regarding drill productivity, each hole of 20 mm in diameter and of 50 mm in depth was opened by the unskilled worker in approximately 20 min while the shipwright executed the task in a quarter of an hour, not taking into account the time needed for re-sharpening the drill bit in both cases.

Smoothing with the adze The whole process of the flattening and smoothing of the outboard surface of the planks by the shipwright lasted almost 30 min in comparison to the 45 min required by the unskilled, female worker.

Conclusions

The Late Bronze Age shipwright, as master of his craft and tool use, could make new tools or adjust them to the demands of a particular job, as well as to his own body build. The range of tools used for shipbuilding in the Late Bronze Age is comparable to those used today.

The efficiency of the nominated shipwright tool kit (Fig. 4) has been proved through experimental methods. The reconstructed tools appear suitable for use in pegged mortise-and-tenon joinery by skilled woodworkers in shipbuilding. Moreover, the reconstructed tools proved to be user friendly. Experimental methods proved useful in the allocation of efficient criteria for the use-based classification of tools. The efficiency of the reconstructed tools could only be evaluated qualitatively, quantitatively and ergonomically through their use in the construction of a structure.

It seems that the most basic and essential tool for a shipwright is the adze. In the hands of a well-trained craftsman, and sharpened to a razor's edge, it was very good at finishing heavy timbers in hull construction, leaving a fine, almost planed, finish. The adze handles were of a different configuration because the shipwright used the adze throughout the construction of a hull. If the handles were the same, this would be very difficult, if not impossible. The handle with a double curvature seems the most appropriate for finishing work.

Accepting the principle that the perfection of a saw is to cut as fast and as smoothly as possible, with as little energy expenditure, as possible (Holly 1864) and also bearing in mind the outcome of the qualitative, quantitative and ergonomic evaluation of the reconstructed saws, it could be claimed that the Mycenaean shipwrights had the almost perfect bronze saws at their disposal. The application of tooth setting improved the efficiency of the Mycenaean saw in comparison to the Egyptian saw. The perfection of saws resulted in the downgrading of axes to being woodworking tools for rough splitting or trimming of logs.

Chisels were essential components of the tool kit. In order to open mortises of the proper shape and size with vertical and smooth sides, the Mycenaean shipwright should have had at least two types of chisels in his tool kit, i.e. one for chopping and the other for paring the mortise sides. Wooden mallets were used in conjunction with chisels to open mortises, to fit planks tightly together and to hammer in tenons and wooden pegs.

Further research work should be done on woodworking tool construction techniques, as well as on tool specialization, to reveal further unknown aspects of Late Bronze Age shipbuilding technology.

References

Adrymi-Sismani V (2004) Le palais de Iolkos et sa destruction. BCH 128–129 (2004–2005) Études 1–54

Andreou St, Kotsakis K (1996) Η προϊστορική τούμπα της Θεσσαλονίκης. Παλιά και νέα ερωτήματα ΑΕΜΘ 10:369–387

Blegen CW (1937) Prosymna: the Helladic Settlement preceding the Argive Hereum. Cambridge University Press, Cambridge

Blegen CW, Rawson M (1966) The Palace of Nestor at Pylos in Western Messenia. Princeton University Press, Princeton

Blinkenberg Chr (1931) Lindos: fouilles de l'acropole 1902–1914: les petits objets. Walter de Gruyter et Cie, Berlin

Casson L, 1 (1964) Odysseus' Boat (Od., V, 244-257). AJPh 85:61
Damianidis KA (1998) Greek vernacular boat building. ETVA, Athens
Doumas C (1994) Ανασκαφή Ακρωτηρίου Θήρας. Praktika (ΠΑΕ): 155–166
Dürring N (1995) Materialien zum Schiffbau im alten Ägypten, Abhandlungen des Deutschen Archaeologischen Instituts Kairo, Ägyptologische Reihe, Band 11, Berlin
Evely RDG (1993) Minoan crafts: tools and techniques. an introduction, vol. I (SIMA 92: 1). Paul Åströms Förlag, Gothenburg
Evely RDG (2000) Minoan crafts: tools and techniques. An introduction, vol. II (SIMA 92:2). Paul Aström Förlag, Jonsered
Evely RDG (2006) The small finds. In: Evely RDG, Crouwel J, French E, Popham M, Reese D, Sackett H, Schofield E, Sherratt S (eds) Lefkandi IV. The Bronze Age. The Late Helladic IIIC settlement at Xeropolis, supp, vol. 39., pp 265–292
Hakulin L (2004) Bronzeworking on Late Minoan Crete, A diachronic study. BAR International Series 1245. Archaeopress, Oxford
Holly HW (1864) The art of saw filing scientifically treated and explained on philosophical principles. Wiley, New York
Iakovidis S (1969) Περατή. Το νεκροταφείον. Βιβλιοθήκη της εν Αθήναις Αρχαιολογικής Εταιρείας 67. Αθήνα
Kienlin TL, Ottaway BS (1996) Flanged axes of the North-Alpine region: an assessment of the possibilities of use wear analysis on metal artefacts. In: Mordant C, Pernot M, Rychner V (eds) L' atelier du bronzier en Europe du XXe au VIIIe siècle avant notre ère, Actes du Colloque International "Bronze '96, Neuchatel—Dijon. CTHS, Paris, p 271
Killen G (1980) Ancient Egyptian furniture l: 4000–1300 BC. Aris & Phillips, Warminster
Lowe Fri M (2007) The double axe in Minoan Crete: a functional analysis of production and use. Dissertation, University of Stockholm
Mangou H, Ioannou PV (1999) On the chemical composition of prehistoric Greek copper-based artefacts from mainland Greece. BSA 94:81–100
Maragoudaki E (2010) Mycenaean woodworking tools used in shipbuilding. Dissertation, University of Athens
Maragoudaki E, Kavvouras P (2007) Μυκηναϊκά εργαλεία ξυλουργικής: η περίπτωση του πρίονος. (English summary,"Mycenaean carpentry tools: the case of saw"). In: Acts of the seventh International Congress of Peloponnesian Studies, Gastouni-Amaliada, 11–17 September 2005, Athens, pp 319–336
Mark S (2005) Homeric seafaring. Texas A&M University Press, College Station
McGrail S (2004) Boats of the World: from the Stone Age to Medieval Times. Oxford University Press, Oxford
Onasoglou AA (1995) Η Οικία του Τάφου των Τριπόδων στις Μυκήνες. Βιβλιοθήκη της εν Αθήναις Αρχαιολογικής Εταιρείας 147, Αθήνα
Ottaway BS (2003) Experimental archaeometallurgy. In: Stollner T, Korlin G, Steffens G, Cierny J (eds) Man and mining. Studies in honor of Gerd Weisgerber on occasion of his 65th birthday. Dt. Bergbaumuseum, Bochum, pp 341–348
Papadimitriou G (2001) Simulation study of ancient bronzes: their mechanical and metalworking properties. In: Bassiakos Y, Aloupi E, Facorellis G (eds) Archeometry issues in Greek prehistory and antiquity. Hellenic Society for Archaeometry and Society for Archaeological Messenian Studies, Athens, pp 713–733
Papadopoulos TJ (1979) Mycenaean Achaea. Paul Åströms Förlag, Gothenburg
Paschalidis K (2007) Euboea at the crossroads of the metal trade: the Aegean and the Black Sea in the Late bronze Age: In Galanaki I, Tomas H, Galanakis Y, Laffineur R(eds), Between the Aegean and the Baltic seas. Prehistory across borders. Proceedings of the International Conference, Bronze and Early Iron Age Interconnections and Contemporary Developments between Aegean and the Regions of the Balkan Peninsula, Central and Northern Europe, University of Zagreb, 11–14 April 2005. Aegeum 27, pp 433–442
Petrie WHF (1917) Tools and weapons: illustrated by the Egyptian Collection in University College, London and 2000 outlines from other sources. British School of Egyptian Archaeology, London
Pulak C (1987) The Uluburun shipwreck: In: Swiny S, Hohlfelder RL, Swiny HW (eds), Res Maritimae. Cypus and the eastern Mediterranean from prehistory to late antiquity. Proceedings of the 2nd International Symposium "Cities on the sea", Nicosia, Cyprus, October 18-22, 1994, Cyprus American Archaeological Research Institute, Monograph Series, vol. 1. Atlanta, Georgia, pp 233–262
Pulak C (1999) The late Bronze Age Shipwreck at Uluburun: aspects of Hull Construction. In: Phelps W, Lolos Y, Vichos Y (eds) The Point Iria wreck: interconnections in the Mediterranean ca. 1200 BC. Proceedings of the International Conference, Island of Spetses, 19 September 1998. Athens, pp 209–239
Pulak C (2002) The Uluburun hull remains. In: Tzalas H (ed) Tropis VII. Proceedings of the 7th International Symposium on Ship Construction in Antiquity, Pylos 26–29 August 1999, vol. I. Athens, pp 615–636
Pulak C (2003) Mortice and Tenon Joints of Bronze Age Seagoing Ships. In: Beltrame C (ed) Boats, ships and shipyards. Proceedings of the 9th International Symposium on Boat and Ship archaeology. Oxford, pp 28–4
Spantidaki G, Moulhérat C (2006) Κλωστές, σπάγκοι, σχοινιά στην Σαντορίνη, Αρχαία Ελληνική Τεχνολογία, 2ο Διεθνές Συνέδριο, Αθήνα, pp 284–289
Spyropoulos TG (1972) Υστερομυκηναϊκοί ελλαδικοί θησαυροί. Αρχαιολογική Εταιρεία, Αθήνα
Steindorff G (1913) Das Grab des Tí. Hinrichs, Leipzig
Stocks DA (2003) Experiments in Egyptian archaeology. Stone working technology in ancient Egypt, London
Wild H (1953) Le tombeau de Ti, II, La chapelle (première partie). IFAO, Cairo
Yalcin Ü, Pulak C, Slott R (Hrsg.) (2005) Das Schiff von Uluburun, Welthandel vor 3000 Jahren, Katalog der Ausstellung des Deutschen Bergbau-Museum, Bochum von 15. Juli 2005 bis 16. Juli 2006. Bochum