
The mechanical properties of wood and the design of Neolithic stone axes

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Abstract:

Despite the importance of wooden tools for early man, and the development of woodworking in the Mesolithic and Neolithic culture, there has been surprisingly little research on how wood can be worked by stone tools or how wooden handles for composite tools were designed. This paper outlines an approach based on an understanding of the structure and mechanical properties of wood. The cell arrangement in wood makes it far less stiff, strong and tough across the grain, especially tangentially. This makes it hard to harvest wood or break it into lengths because it splits down its centre rather than breaking right across. Fortunately, this also makes wood easy to split along the grain, especially radially through its centre into sections and planks.

A model of the splitting process predicted that wood is best split using blunt, broad but smooth wedges, as these would use less energy and would be less likely to get stuck in the wood. The predictions were verified in tests in which hazel coppice poles were split using wedges of contrasting angle, width and surface texture. The results help explain the change from the flaked flint Mesolithic tranchet axes to the broader polished stone Neolithic axe and adze heads. However, further experiments are also needed cutting wood obliquely to test this hypothesis.

The splitting model also helps to understand the design of socketed axe hafts. Failure usually occurs when the handles split at the distal and proximal ends of the socket. To prevent this, handles are best designed with the growth rings parallel to the socket, and with an expanded head, especially with flanges on the distal and proximal ends of the socket. These designs are seen in some of the Neolithic axe handles that have been found in Britain, including the Etton, Ehenside and Shulishader axes. More experimental research is needed to understand the optimal way of hafting axe heads.

Keywords: wood; splitting; axe heads; hafting; woodworking; Neolithic

1. Introduction

The clearance of woodland for agriculture and the development of woodworking were crucial aspects in the progression from the Mesolithic to the Neolithic cultures, especially in Britain (Miles 2016: 220-222); hafted stone axes were increasingly used to cut down trees, split wood, shape wooden structures such as houses and log boats and even make the handles of the tools themselves. These changes coincided with a clear developments in the design of hafted stone axes.



In the Mesolithic and Early Neolithic axe-heads were mostly made from flint and were shaped by transverse blows (Ashton 1988; Bar-Yosef 1995; Barkai 2005: 56-58) to rapidly produce heads with a sharp cutting edge but a rather rough surface. These tranchet axes are usually light and thin; Barkai (2005: 59) found a mean weight of 37 g and thickness of 15 mm for tranchet axe-heads from the Southern Levant.

During the Neolithic, however, a different type of stone axe-head, was developed. Instead of being produced by flaking, these were ground and polished smooth (Barkai & Yerkes 2008; David *et al.* 1995), were made of coarser grain stone such as granite, basalt or limestone (Yerkes *et al.* 2003), and were much heavier and thicker. Barkai (2005: 78-82) found average weights of 191 g and thicknesses of 31.5 mm in his samples from the Southern Levant.

Despite the dramatic nature of these changes, there has been little debate about the potential reasons for them. It has often been suggested that grinding and polishing the axe-heads smooth would strengthen their edges and reduce friction during use (Boydston 1989; Dickson 1981: 45; Hayden 1989; Nami 1984; Olausson 1982) but on the other hand flaked flint axe-heads actually seem to have sharper and more acute edges than the ground ones, features usually associated with greater effectiveness as cutting tools (Atkins 2009: 1). Experimental studies have found that the broad, ground blades of Neolithic axes and adzes cut through tree trunks fairly effectively if they are used to strike the trunk with an oblique blow (Elburg *et al.* 2015; Jorgensen 1985: 20-22; Mathieu & Meyer 1997). Each strike cuts across the trunk a short distance before being deflected so that the wood then splits along the grain, allowing a curved sliver of wood to be removed at each stroke. However, there has been little attempt to compare the effectiveness of tranchet axes and polished-stone ones, and indeed they differ in so many features that it would be difficult for experiments using whole axes to separate the individual effects of the shape, width and smoothness of axe heads on their performance.

More recently, experimental archaeology has demonstrated how Neolithic tool kits including ground stone axes and adzes, and bone or beaver-tooth chisels could have been used to finely carve wood, shape mortice and tenon joints, and even drive holes right through wood, allowing complex wooden structures such as wells (Elburg *et al.* 2015; Tegel *et al.* 2012) and to show how axe handles could be constructed (Harding 2014). However, there has been little discussion about *why* wood has been shaped using these sorts of tools and not by others.

What has been missing is a theoretical basis for understanding how wood behaves mechanically, and in particular how it breaks. Such a theoretical basis would help to predict how best tools should be designed and used to cut wood, and to shape wooden implements. Conversely, it would help to predict the best ways in which wooden implements should be designed to prevent them from breaking. This paper outlines just such an approach, based on the most recent research on wood anatomy and biomechanics. It then goes on to describe how this approach has been used to inform an experimental investigation into splitting wood along the grain, an investigation that has already started to shed light onto the design both of stone axe and adze heads, and the handles of stone axes and adzes.

1.1. The Structure of wood

Wood is an extremely complex material, being composed of tightly packed tubular cells. Its strength and stiffness are given by the cell walls, which are a composite material made up of cellulose fibres held within a softer hemicellulose and lignin matrix (Ennos 2012: 80-82). By far the majority of the tissue, (80-98%) is composed of long narrow tracheids or fibre cells that are orientated longitudinally up and down the trunk and branches (Ennos & van Casteren

2010)(Figure 1). Broadleaved trees also have some wider narrow-walled vessels which help transport water up the trunk more efficiently than narrow tracheids. The only other cells are the ray cells which form spindle-shaped rays that run radially, from the pith to the bark, and which reinforce the trunk in this direction (Figure 1), effectively pinning the growth rings together.

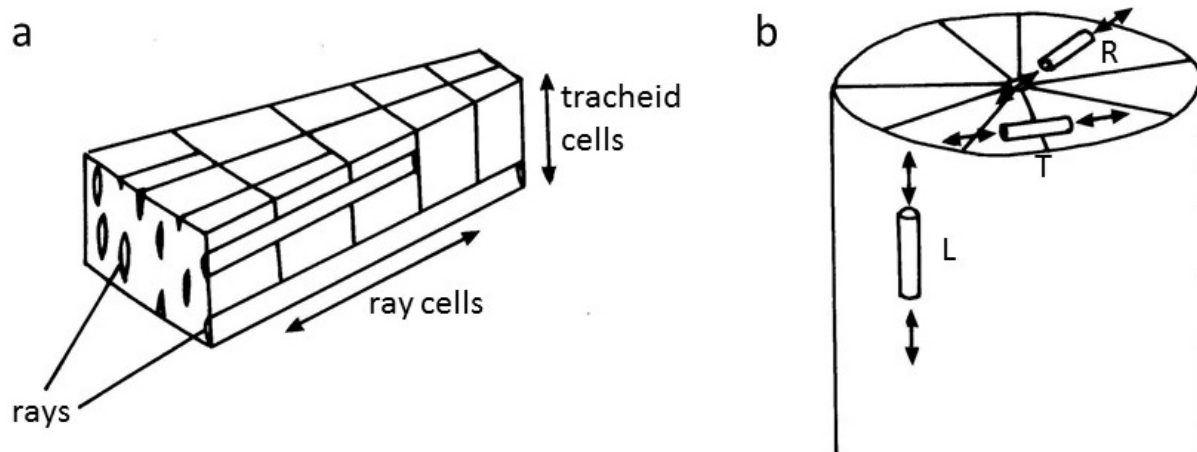


Figure 1. The structure of a branch (Ennos & van Casteren, 2010) (a) most of the wood volume is composed of tightly packed tracheids or fibres, which are oriented longitudinally, while the remainder is made of rays, in which the cells are oriented radially. As a consequence mechanical tests on oriented samples (b) show that tangentially (T) wood is weaker than radially (R) and much weaker than longitudinally (L). Wood is readily split or crushed along the centre-line, along which the rays and tracheids provide no reinforcement

1.2. The mechanical properties of wood

The complex cellular structure of wood makes it highly anisotropic - giving it very different mechanical properties in different directions. Wood is very hard to break across the grain because this involves fracturing the tracheids, whereas it is easily split along the grain, as this just involves separating tracheid cells and breaking the much smaller number of ray cells; splitting a branch radially is even easier as it does not even involve breaking the ray cells. Wood is consequently 8-10 times stronger longitudinally than transversely, and most types of wood are also 20-50% stronger in the radial direction than in the tangential direction because of the reinforcement by the rays (Reiterer *et al.* 2002; van Casteren *et al.* 2012a). The toughness of wood, its ability to absorb energy when broken, shows even greater anisotropy; the work of fracture across the grain (breaking through tracheids) is in the order of 50-100,000 Jm⁻², around 50-100 times greater than the work of fracture along the grain which is in the order of 200-2,000 Jm⁻². The work of fracture in the radial direction is also typically 20-50% higher than in the tangential direction because of the energy required to break through the rays (Ozden & Ennos 2014; Ozden *et al.* 2016; Reiterer *et al.* 2002).

Of course, wood is not all the same. In general the longitudinal strength and work of fracture of wood is proportional to its density; denser woods are stronger and tougher because there is more cell wall material to break (Ennos 2012: 81; Hoadley 2002: 97-98). Transversely, lighter woods are particularly easy to split and crush. In contrast, the difference between the properties in the radial and tangential direction depend largely on the numbers and size of the rays. In general conifer wood has very similar properties in the radial and tangential directions and is easier to split because the rays are small, usually only one cell wide, and constitute only around 2-3% of the wood volume (Ozden *et al.* 2016). The same is true of some hardwoods such as beech and sweet chestnut. In contrast, many hardwoods, such as oak and ash have numerous large rays, constituting up to 25% of the wood volume. In oak the rays are so large they are visible as the characteristic “figure” of the wood and they make

oak particularly anisotropic, having one and a half times the strength and twice the work of fracture radially than tangentially (Ozden & Ennos 2014; Ozden *et al.* 2016; Reiterer *et al.* 2002).

Wood from the branch junctions and forks of trees is also rather different in both structure and properties from normal branch or trunk wood. Branch junctions and forks exhibit interlocking grain (Figure 2) (Slater *et al.* 2014) which greatly strengthens the wood across the grain, making it much harder to split (Slater & Ennos 2015, 2016) and so strengthening the joint.

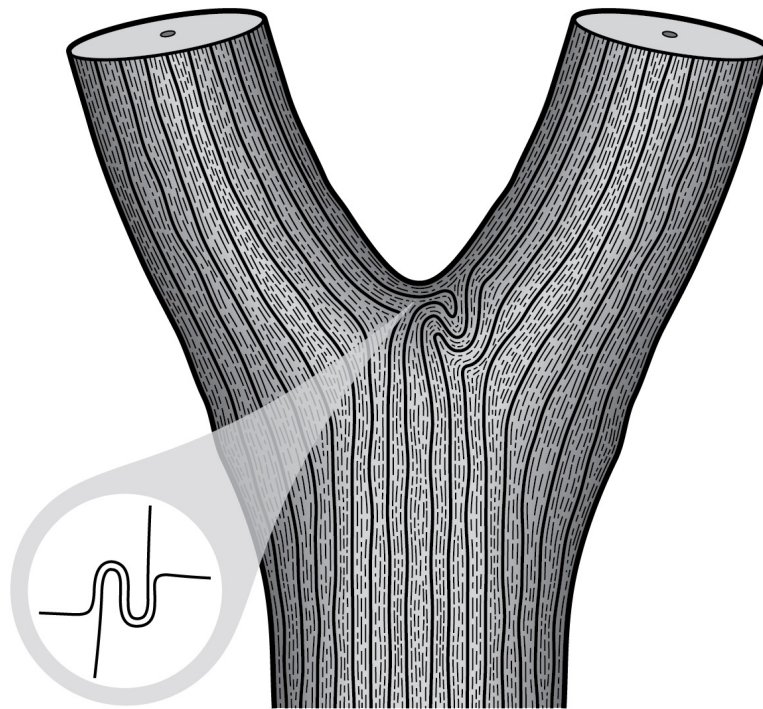


Figure 2. The structure of a fork junction (Slater & Ennos 2016: fig. 1). At the top of the junction the grain is interlocked, strengthening the joint and preventing the branch being pulled off. A similar arrangement is seen in branch junctions with smaller branches emerging from thicker trunks.

Finally, the properties of wood depend strongly on its degree of hydration. In the tree, wood is fully hydrated, but we are fortunate that, unlike most other biological materials, its properties actually improve after it is removed from the main body and dries out; seasoned wood is around twice as stiff as green wood and has similar strength and toughness (Hoadley 2002: 95).

1.3. Implications for the use of wood

All of these aspects of wood - especially its unusually high degree of anisotropy - affect not only its function within the tree, but also how we use and shape it.

1.3.1. Exploiting the strength of wood along the grain

The most obvious way in which the strength of wood is matched to its mechanical function is in the way that both trees and ourselves make use of the strength of wood along the grain. In intact trees, the high strength and stiffness of wood along the trunk and branches enable them to strongly resist the bending forces to which they are subjected by gravity and the wind. The longitudinal fibres are ideally arranged to withstand the longitudinal tension and compression forces that the bending sets up within the branch.

We also use this fact when we use whole tree trunks as beams, or cut the wood up into rods, battens or planks whose long axis runs up and down the tree. Wood cut “along the grain” is much stronger than “across the grain” and much of the skill of carpentry is to make sure wood is never loaded across the grain.

1.3.2. Harvesting wood

Though the strength and toughness of wood are useful properties when wood is in use, they also make it hard to harvest. Large bending forces are needed to break even a slender living branch, and the anisotropy prevents the branch from being readily detached; the branch half breaks, but it then usually splits along its length down the centre and between the rays (Figure 3), a process known as greenstick fracture (Ennos & van Casteren 2010; van Casteren *et al.* 2012a). To detach the branch one then has to twist it off, something nest-building orangutans are particularly adept at doing (van Casteren *et al.* 2012b), but which is hard work and produces a ragged end. This makes it impossible to break branches up into several short lengths by simply bending them till they break.



Figure 3. Greenstick fracture of a living branch of ash *Fraxinus excelsior* showing splitting along the centre-line.

This means that the only practical way to break off branches across the grain is to cut across them using a saw or an axe. Saws made of natural materials such as bone or stone can be effective and can cut directly across a branch (Elburg *et al.* 2015), but due to the limitations of the size of bones, and the tensile strength of stone, they can only really be used on small diameter branches. To cut through thicker branches and tree trunks, adzes and axes can be used to apply a series of blows, but their effectiveness is also limited by the materials available. Stone has limited tensile strength, so stone axes and adze-heads have to be relatively broad, and the axes have to be directed at the tree using a glancing blow, hitting the tree diagonally upwards or downwards (Elburg *et al.* 2015; Jorgensen 1985: 20-22; Mathieu & Meyer 1997). Each blow will only cut through a short distance before the blow is deflected longitudinally and sets up a longitudinal split. This effectively removes a thin sliver of wood, which can be removed before aiming another blow behind the first one, which can then free another sliver. The process has the disadvantages that it is slow, wastes a great deal of wood,

and produces long tapered ends. This means that a trunk cannot be neatly cut into neat logs; Neolithic people, like native Americans, probably used fire to help fell trees and separate the trunk into a series of logs (Tegel *et al.* 2012).

1.3.3. Splitting wood

Fortunately, the anisotropy of wood means that once a branch or trunk has been separated from the tree it can be fairly readily broken up along the grain. Up until the industrial age, wood was mostly broken up into more manageable pieces by splitting it, especially radially which avoids the need to break the rays. Small branches and twigs can be split by hand, scoring a notch through the distal end of a coppice pole before pulling the two ends apart (Bealer 1996: 8-60). To split thicker branches and coppice poles to produce such items as fence posts or the rungs of wooden causeways, a cutting tool such as a froe must be used, pushing it down the centre and progressively separating the two halves. There is good evidence that from the Mesolithic onwards, even whole logs could be split using stone, bone or wooden wedges (Taylor 2011). These were inserted into the ends and sides of the log and hammered in to split it into two halves. The halves could then be further split into quarters and eventually into planks (Bealer 1996: 60-64). The planks themselves could also then be split tangentially to produce battens.

1.3.4. Shaving wood

Wood can also readily be shaped by using cutting tools to make shallow splits in the wood and removing thin shavings. From the Mesolithic onwards, stone axes, and especially stone adzes were used to shape beams and carve out log boats (Elburg *et al.* 2015; Taylor 2011).

1.3.5. The design of stone blades

We have seen that stone blades were extensively used to cut and split wood, but what influenced their design, and what would be the optimal shape of wedges and the blades of axes and adzes? To understand that we need to know what happens when a tool cuts through a material.

2. Methods

We have seen that stone axes and wooden wedges were extensively used to cut and split wood, but what influenced their design, and what would be the optimal shape of wedges and the heads of axes and adzes? To understand that we need to know what happens when a tool cuts through a material.

Because splitting rods and poles was such a major part of early woodworking, and because splitting wood is relatively easy to model, we started by looking at the simplest case, the cleaving of a coppice pole directly down its centre, using a simple wedge-shaped cutting edge. As a wedge is inserted into the end of the pole (Figure 4) it levers open a crack, and drives it in front of the tip of the wedge. Broader wedges will open the crack more quickly (Figure 4a) than thin ones (Figure 4b) and so will initially encounter more resistance. However, since they drive the crack further in front of them, they will be less firmly gripped by the two arms and they will encounter progressively *less* friction (Figure 4c). The model of splitting that we developed (Ennos & Oliveira in prep.) therefore predicts that counterintuitively, blunter and wider wedges should split wood more efficiently than sharp, narrow ones, because they will encounter less friction. For the same reason smoother wedges should also split wood more efficiently than rough ones.

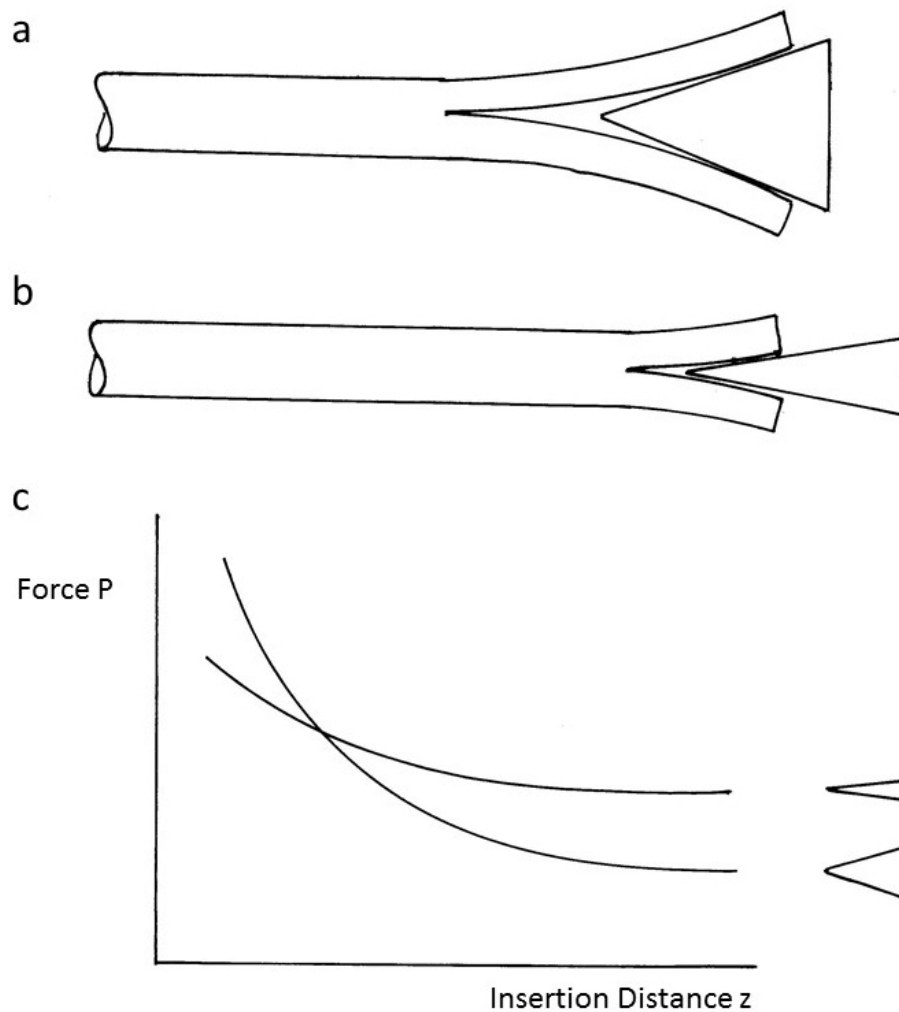


Figure 4. Splitting of a coppice pole by a) a wide angle and b) a low angle wedge. Initially force is higher for the broad wedge because the crack opens further, but it falls to a lower level because the friction drops as the wedge touches the wood further from the crack tip, encountering less friction.

We decided to investigate the process of wedging open coppice poles, and to test our predictions by investigating the force and energy required to split the poles using steel wedges of contrasting designs, the experiments being performed using an Instron 3401 mechanical testing machine. Smooth wedges were made in a variety of angles (Figure 5a) of 7, 10, 15, 20, 25, 30 and 40 degrees. Several 20 degree wedges were also made. Three had contrasting widths of 3.5, 7.1 and 10.6 mm. Finally, two broad 20 degree wedges were compared: one with a smooth surface and the other which had been milled to give a rough surface with grooves around 0.5 mm deep. The wedges were used to split coppice poles of hazel *Corylus avellana* that were 10-15 mm thick. The blades were inserted into 5 mm long grooves cut into the ends of the poles and the mechanical testing machine drove them downwards at a rate of 50 mm min^{-1} splitting the poles open down their centre (Figure 5b). Meanwhile a 1 kN load cell recorded the instantaneous force needed and an interfacing computer calculated the total energy required to split the wood.

3. Data results

The force required to split the coppice poles rose rapidly to a peak before dropping in the way predicted by Figure 5c, providing support for the model, and most of the energy required was used to overcome the friction between the wedge and the wood. The most interesting

findings, however, were the relative efficiencies of the different wedge types. The energy needed to split the coppice poles fell as the wedge angle increased (Figure 6a); it fell as the width of the wedge increased (Figure 6b); and was lower for the smooth wedge. (Figure 6c). Counterintuitively, blunter wedges were almost three times as efficient at cutting than the sharpest, and thick ones almost twice as efficient as thin ones, while more predictably smooth ones were around twice as efficient as rough ones.

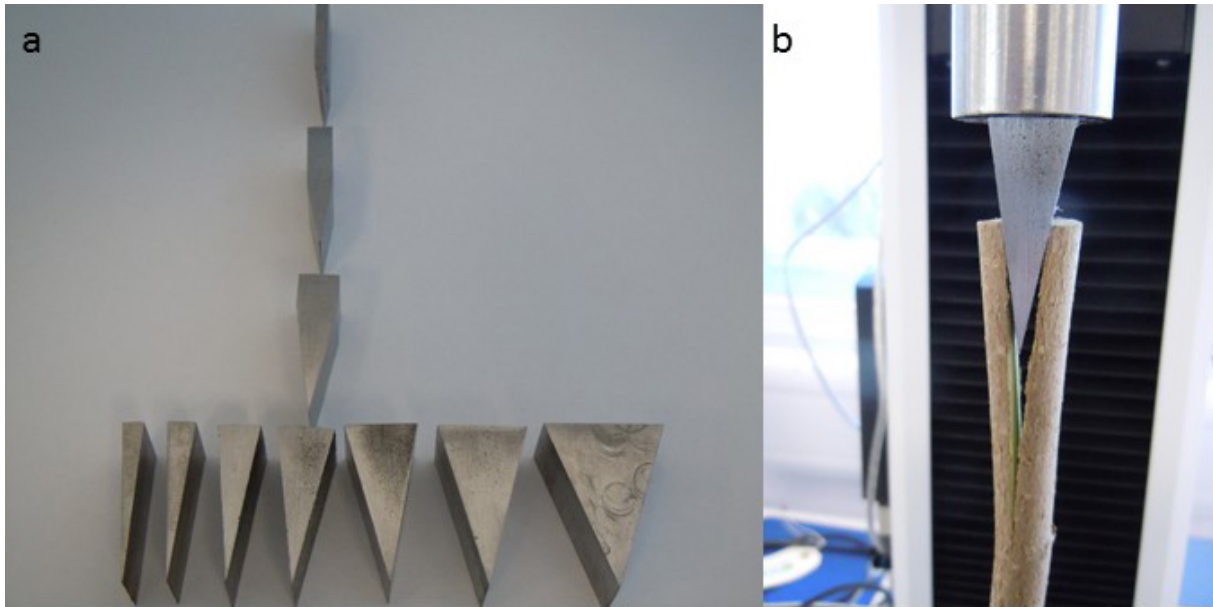


Figure 5. a) The wedges used to split the coppice, with angles of 7, 10, 15, 20, 25, 30 and 40 degrees, while the 20 degree wedge was used with widths of 3.5, 7.1 and 10.6 mm. b) Splitting of a coppice pole by the 20 degree wedge. Note that the crack tip runs well ahead of the blade.

4. Interpretations of the data

Our experimental results have only investigated a single type of wood cutting on one size of branch. Nevertheless, they are striking and could start to illuminate the design of early stone axes and in particular explain the changes that occurred between the Mesolithic and Neolithic in the design of the axe and adze heads themselves (Elburg *et al.* 2015; Yerkes *et al.* 2012). Our results suggest that Neolithic axes, with their broad heads polished smooth, would be more energy efficient at splitting wood than the narrower and rougher, though sharper heads of the typical Mesolithic axe. Given the same amount of energy, a blow with a Neolithic axe head would cut further through wood. Modern splitting mauls are similarly broad-bladed, with angles of 30-35°, a much higher angle than in typical felling axes which are notorious for getting stuck in logs if they are used to split wood (Bealer 1996: 51). The design of the Neolithic axe would have suited settled Neolithic farmers, who needed to clear woodland for their crops and to split and shape wooden beams and branches to build their new settlements. The lack of a sharp cutting edge to their axes would have been no problem since the tip of the axe head would usually never touch the wood.

Of course, splitting wood is only one aspect of woodworking and carpentry. Neolithic people would also have had to use their axes to cut across the grain of wood to enable them to cut down trees. Experimental archaeological investigations suggest that the broad Neolithic axes and adzes were most effective when they were used to cut obliquely up and down the trunk, so that they acted partly to cut across and partly to split the wood (Elburg *et al.* 2015; Jorgensen 1985: 20-23; Mathieu & Meyer, 1997). For this reason we plan future tests in which the effectiveness of axe heads of different design is investigated when they are used to

make just such oblique cuts. We also plan tests in which wood is cut directly across the grain. For this purpose, the sharper flint Mesolithic axe-heads might have been better, like the teeth of beavers, and could perhaps have been more effective when used as chisels to carve and whittle small tools.

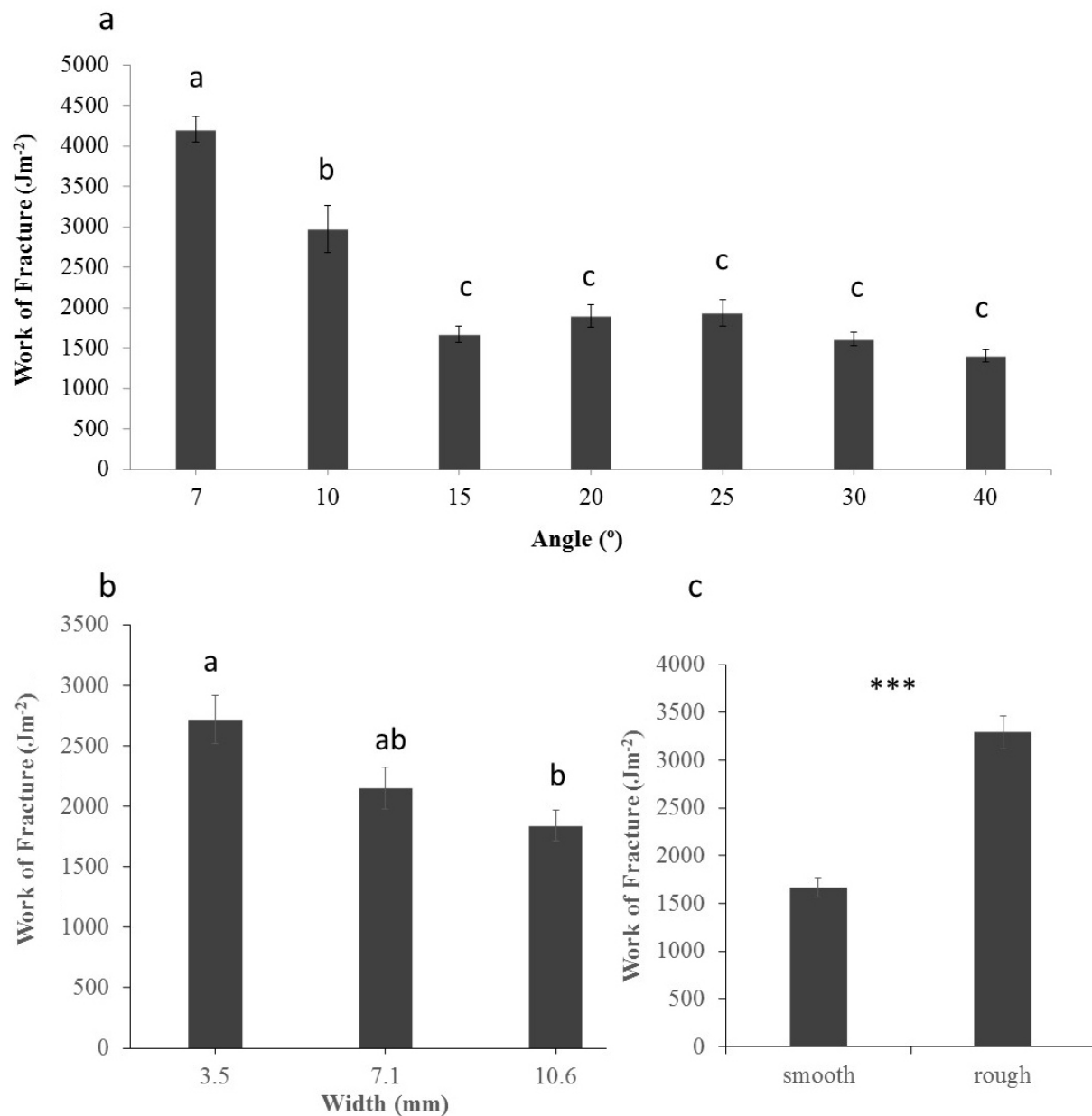


Figure 6. a) The results of the wedge splitting tests. Graphs show the mean work required to create a given fracture surface for wedges with a) different angle b) different width and c) different roughness. For a) and b) bars with a different letter are significantly different from each other. For c), *** denotes a highly significant difference ($P < 0.001$). Note that wedges with higher angle, broader blades and smoother surfaces needed less energy to cut through the coppice wood.

4.1. The design of hafts

Another important aspect of the design of Neolithic axes was the way in which the axe head was hafted onto a wooden handle. Most early handles, particularly in Britain, had male haft type, being arranged with the axe head wedged directly into a socket in the wooden handle (Harding 2014; Taylor 1998). This arrangement is potentially vulnerable to splitting of

the wood around the socket, and indeed several of the British Neolithic axe handles that have been found, including the Etton axe handle, had failed in this way (Taylor 1998); the splits had occurred at the sides of the socket at the distal and proximal ends.

The model analysing the splitting of coppice poles can readily be extended to these axe handles, as the top and bottom of the sockets can be regarded as the tips of cracks. Handles can be designed with key features to maximise the force needed to split the wood at the distal and proximal ends of the socket, and so minimise the chances of such failure.

1) The resistance of the wood to splitting above and below the socket can be increased by maximising the work of fracture of the wood in that plane. This can be performed in three ways.

- a) The handle could be made of wood which has a high transverse work of fracture and which is therefore less prone to split. Typically, hardwoods should therefore be preferred to softwoods, especially wood with more interlocking grain and a greater proportion of rays, such as elm, oak or ash.
- b) The socket could be driven through an area of wood from the base of a branch where there is cross grain and the transverse work of fracture of the wood is greater.
- c) The grain of the wood in the handle could be arranged as in a modern axe handle, with the growth rings parallel to the socket. This means that the rays will be arranged at right angles to the socket, so that they can reinforce its distal and proximal ends against splits and increasing the transverse work of fracture in that direction.

2) The resistance of the wood to splitting could be maximised by increasing the longitudinal stiffness of the wood. This can be achieved by using a denser wood and by allowing the handle to season after it has been carved.

3) The sides of the socket, and therefore the thickness of the distal end of the handle could be made as thick as possible.

4) Extra flanges could be added on the proximal and distal ends of the socket to reinforce its ends and stop cracks from forming, as Harding (2014) suggested.

From the reconstruction of Taylor (1998: 150) the Etton axe handle seems to have used solution 1c, being cut from half a split log with the socket running transversely through the wood, parallel to the growth rings. However, it was made from alder, a light and brittle wood, which might explain why it had broken. The Ehenside axe handle was made from the “hard root” of beech (Evans 1897: 153), so it effectively used solution 1b. The Schulishader axe handle appears to have been made from hawthorn (Harding 2014), which is a dense, strong wood, so it used solution 1a and 2. Solutions 3 and 4 have the disadvantage that they will increase the mass and dimensions of the end of the handle. However, flanges are less clumsy and this solution appears to have been widely used; flanges are seen on all three of the handles shown in Figure 7 (Harding 2014).

Even with these design features, splitting is still likely to be a major problem with simply mounted axe heads, something other designs could have helped overcome. On the continent, many axe heads have been found that were mounted into antler plugs, which were in turn inserted into wooden hafts, an arrangement which it has been suggested would have acted as a shock absorber (Maigrot 2011). Many later Neolithic axes were also designed with a female mount, with the handle running through a hole in the stone head (Rots 2010), which would have overcome the problem of the handle splitting entirely. The design of Neolithic adzes and bronze-age axes also avoided cutting slots into the handle. In both sorts of tools the handles were made from branch junctions, which as we have seen are strengthened by tortuous grain (Slater *et al.* 2014). The heads of adzes were mounted by being strapped onto the shorter arm, while the hollow blades of early bronze-age axes were slotted over it.

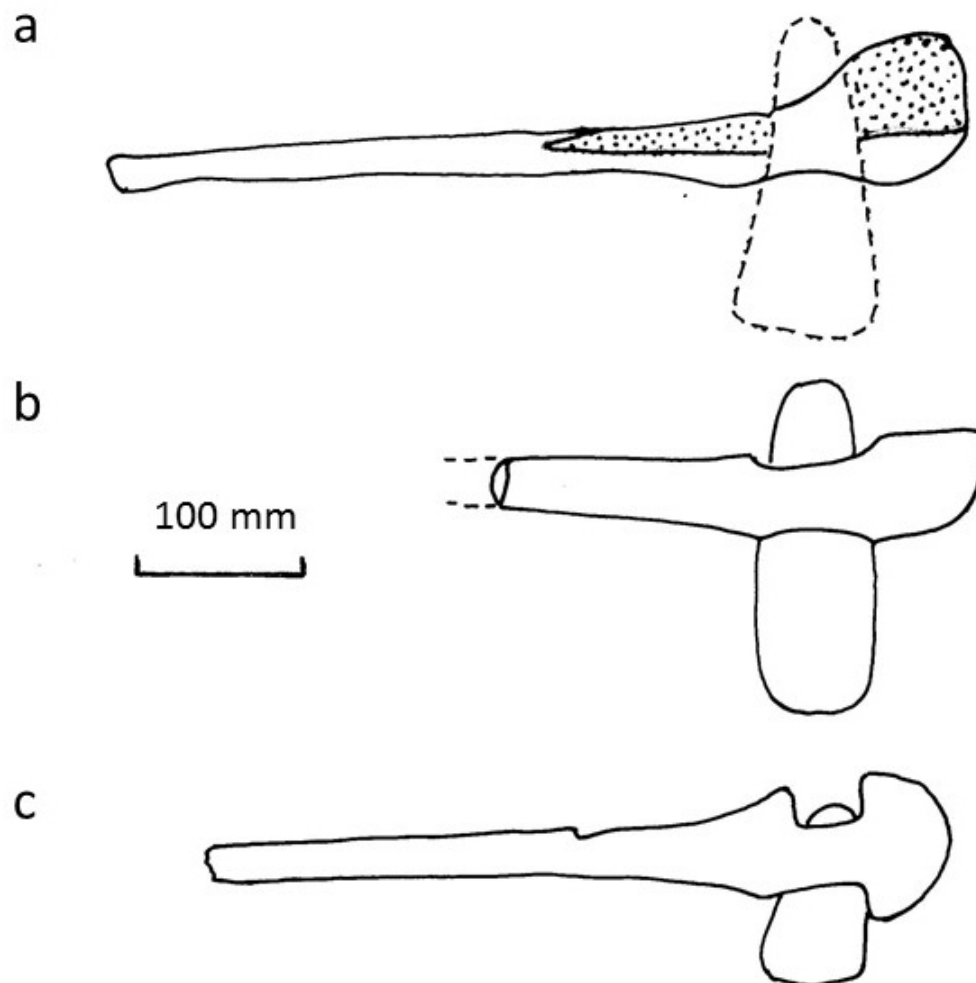


Figure 7. Neolithic axe hafts from Britain (redrawn from Harding 2014, fig. 1). a) The axe from Etton, Cambridgeshire (Taylor 1998: fig. 162). The handle had broken at the edge of the socket, splitting to reveal new surface (dotted area) and releasing the supposed axehead (dashed line). b) the axe from Ehenside tarn Cumbria (Evans 1897: fig. 92). c) The Shulishader axe from Lewis (Sheridan 1992: fig. 78). Note the flanges at the distal and (in b and c) the proximal end of the socket.

Of course, all these arguments only spring from mechanical theory, so experiments are clearly needed to investigate the effects of the different designs on the strength of axe handles and to work out the optimal design.

5. Conclusions

It is clear that understanding the structure and mechanical properties of wood, particularly the ways in which it breaks, can give us a new insight into the design of stone woodworking tools: in the design of the axe heads; in the way they heads are hafted; and in the ways the tools themselves are used. Of course, the work so far has only started to scratch the surface of this topic, and much more work, especially experimental work, is needed to understand the technological developments in woodworking that underpinned the advances of the Neolithic age.

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