“Fire-Hardening” spear wood does slightly harden it, but makes it much weaker and more brittle.

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Abstract

It is usually assumed that “fire hardening” the tips of spears, as practised by hunter gatherers and early *Homo spp.*, makes them harder and better suited for hunting. This suggestion was tested by subjecting coppiced poles of hazel to a fire hardening process and comparing their mechanical properties to those of naturally seasoned poles. A Shore D hardness test sho wed that fire treatment slightly increased the hardness of the wood, but flexural and impact tests showed that it reduced the strength and work of fracture by 30% and 36% respectively. These results suggest that though potentially slightly sharper and more durable, fire hardened tips would actually be more likely to break off when used, as may have been the case with the earliest known wooden tool, the Clacton spear. Fire might first have been used to help sharpen the tips of spears, and fire-hardening would have been a mostly negative side-effect, not its primary purpose.

Keywords

Wood, spears, fire hardening, hardness, mechanical properties

Introduction

Since our closest living relatives, the chimpanzees, make and use spears (1) it is likely that stabbing and throwing spears must have been invented early in human history. However because wood preserves so poorly, the earliest wooden spears date from only 400-450 thousand years ago, having been preserved in the anaerobic acid soils of Northern Europe. The earliest complete spears are spruce throwing spears from Schöningen, Germany (2), which date from around 400,000 years ago. An even earlier survivor is the "Clacton spear", dating from 450,000 years ago, a pointed yew fragment, broken off at the thick end, which has been interpreted as being either the tip of a digging stick or a spear (3,4).

Despite the advantages of fitting spears with a stone tip, an advance that was made as long ago as the upper Palaeolithic (5), simple wooden spears continue to be made and used by groups of hunter gatherers around the world (6,7). Such groups are said to "fire harden" the points of their spears by inserting them into or above fires, either after manufacture, or during sharpening of the point. The process could have originated as long ago as the deliberate human use of fire, which could date as far back as the early Palaeolithic, between 700-300 thousand years ago (8,9). It is usually assumed that this process "hardens" the wood, improving its ability to penetrate animal hides.

Unfortunately little is known about the actual mechanical effects of fire hardening, which could affect many of the properties of wood (8), not only hardness (its resistance to being indented); but also stiffness (its resistance to being deformed); strength (its resistance to being broken by applied forces); and toughness (its ability to absorb energy). This study aimed to determine whether fire hardening does confer any mechanical benefits to wood, by measuring the mechanical properties of wooden rods which have either been fire treated or left to season naturally.

Methods

Heat Treatment

Since most hunter gathers (and indeed early humans) live or lived in tropical or subtropical regions where angiosperm trees are by far the most common species (9) we decided to examine the effect of fire hardening on a hardwood. We chose coppice poles of hazel *Corylus avellana,* because these are composed of homogenous straight-grained wood, and this was sourced from trees growing at the University of Hull's botanical grounds, Cottingham, UK.

Twenty 60 cm long poles of around 1 cm diameter (aged 2-3 years) were harvested, cut into 30 cm long rods, stripped of bark and split into two groups. One half of each pole was allowed to dry naturally in the laboratory at a temperature of 19°C and humidity of 40% for two weeks to give 20 untreated rods. The other half was subjected to simulated fire hardening. Rods were laid out on top of a disposable barbecue holding glowing charcoal. They were continually turned as the internal water was expelled, and subsequently heated further. The rods were removed once they had browned but before they had started to blacken, though two samples had started to char and were discarded. The process took approximately 30 minutes.

These rods were also transferred to the laboratory, where they were allowed to stabilise alongside the control rods.

Mechanical tests

a) Hardness Tests

The hardness of each rod was measured using Shore D durometer, a low angle penetrometer that produces millimetre-sized indentations. On this scale readings for wood typically vary from 10 for the light spring wood of redwood to 90 for dense woods such as kiln dried ebony (Marty Jacobson, Jacobson Mandolins, pers. comm). Each rod was indented four times over its outer surface, avoiding any carbonised regions in the heat treated rod, and an average hardness was calculated.

b) Flexural Tests

The stiffness and strength of the wood was determined by carrying out 3 point bending tests on the rods (8) in an Instron 3344 universal testing machine with a 1 kN load cell. Each rod rested on supports 22 cm apart and a semicircular probe of diameter 20 mm was lowered at a rate of 30 mm min^{-1}, bending the rod until it either broke or the wood failed and the force started to fall, while an interfacing computer measured the displacement and load, and produced a graph of force against displacement. The stiffness, or Young's modulus, and strength or breaking stress of the rods were calculated by the computer using well known engineering equations (8).

The mechanism of failure of each rod was also noted. Rods can fail in one of three ways (10): they can break fully across; they can break halfway across but then split down the middle, so-called "greenstick fracture"; or they can yield without breaking.

c) Impact Tests

The work of fracture, a measure of the toughness of the wood across the grain was then measured using a Houndsfield impact tester which measures the energy absorbed per unit cross sectional area when a rod of wood is broken in bending as the two arms of the machine swing past each other.

d) Water Content

The water content of the rods was finally measured on 2 cm long sections of the rod, which were weighed before and after being put into a drying oven at 90°C for two weeks.

e) Statistical Analysis

The mechanical properties and water content of the treated and untreated rods were compared using paired t tests to remove the effect of differences between coppice poles, tests being conducted on SPSS version 20.

Results

a) Hardness Tests

Heat treated rods were harder, at 58.7 SD = 2.1 on the Shore D scale than untreated rods, at 56.6 SD = 2.9 (Fig.1a), a difference which a paired t test showed was highly significant ($t_{18} = 3.24$, $p = 0.005$). In both treatments the point indented the wood by buckling and compacting the cell walls around it.

b) Flexural Tests

The flexural tests showed that though the stiffness of the wood in heat treated rods was 9% lower (Figure 1b) and much more variable, it was not significantly different from that in untreated rods ($t_{17} = 1.91$, $p = 0.073$). In contrast the strength of the treated wood (Figure 1c) was 30% lower than untreated ($t_{17} = 3.84$, $p = 0.001$). The treated and untreated rods also tended to fail in different ways; nine out of eighteen treated rods showed complete breaks while nine showed incomplete fracture (the rod either underwent greenstick fracture or buckled); in contrast only one of the untreated rods showed a complete break, a difference which a χ^2 test for association showed was statistically significant ($\chi^2_1 = 8.86$, $p < 0.01$)

c) Impact Tests

The impact tests showed that the heat treated rods had a work of fracture that was 36% lower (Figure 1e) than untreated rods a difference that a paired t test showed was highly significant ($t_{17} = 6.79$, $p < 0.0005$). The treated and untreated rods also tended to fail in different ways; thirteen out of eighteen treated rods showed complete breaks while five showed incomplete fracture (the rod either underwent greenstick fracture or buckled); in contrast only three of the untreated rods showed a complete break, a difference that a χ^2 test for association was statistically significant ($\chi^2_1 = 11.25$, $p < 0.001$).

d) Water Content

The water content of treated rods (Fig.1f) was 16% less than that of untreated rods a difference that a paired t test showed was highly significant ($t_{18} = 4.99$, $p < = 0.0005$).

Discussion

The results of the mechanical tests shows that heat treatment *did* increase the hardness of the hazel rods, but the difference in hardness was small, only 2 units of the Shore D scale, a much smaller change than the difference between dense and light wood. Moreover this came at the expense of other important mechanical properties, such as strength and work of fracture, which were reduced by 30% and 36% respectively. These changes coincided with a reduction in water content of the wood from 8.2% to 7.2% which would on its own have caused only small increases in hardness and stiffness, and have no effect on strength or work of fracture. Since both treated and untreated wood had been allowed to equilibrate at the same humidity, the changes in water content were probably due to chemical changes in the cell walls during the fire hardening which were responsible for the difference in mechanical properties.

Timber engineers have shown that heat treating wood to temperatures between 150-250°C produces similar changes to those we found in our fire-hardened wood (11); it becomes more durable, but with marked falls in both strength and work of fracture. Above 180°C the amorphous hemicelluloses in the cell wall apparently crystallise, removing bound water and hardening the cell wall. Since the amorphous hemicellulose in wood acts as the matrix for the crystalline cellulose fibres in the composite material of the cell wall, its crystallisation also prevents the cell wall deformations that toughen the wood (12). This reduces its strength and work of fracture. Because the cellulose fibres that reinforce the wood are unaffected, however, its stiffness is unaltered. It is possible that different types of wood, especially the dense softwoods such as the yew and spruce that were used to manufacture the Schöningen and Clacton spears might be affected to different extents by fire hardening, but the consistent results obtained by wood engineers (11) makes this unlikely.

This work has implications for the design of spears by hunter gatherers and the potential use of fire-hardening by our ancestors. First, it casts doubt on the supposed mechanical benefits of fire-hardening. It does indeed slightly harden the wood and it might improve the durability of a spear point, but it would weaken the tip and make it more brittle, making it much more likely to be broken off when used. It is also unlikely that hardening the tip of a wooden spear would improve its ability to kill animals. Wood is far harder than animal skin, so it would not be blunted by penetrating a hide, and fire hardening would not harden it sufficiently to allow it to penetrate bone. Indeed Waguespack et al (5) showed that even stone-tipped arrows achieved barely 10% improved penetration of ballistic gel than sharpened wooden ones. Of course our fire hardening process was extremely simple, so a more lengthy and careful process of manufacture, in which the wood is impregnated by oils, fats and silica might have hardened the wood to a greater extent and help make sharper, longer lasting blades.

It is possible that fire was initially used by our ancestors to facilitate the sharpening of the spear tip. It has been shown for instance, that the Clacton spear point could have been produced shaving the end with a sharp “Clactonian notch” flint blade (13), but that this process can be speeded up from 2 hours to 45 minutes by alternately charring the tip and removing the carbonised layer with the notch (14). Fire-hardening of spears may therefore have originated as a bye-product of their manufacture; the benefits of the process are equivocal and it may be that the world’s oldest surviving spear tip, the Clacton spear actually broke off *because* it had been fire hardened.

Data Accessibility

Date can be accessed in the Dryad repository http://dx.doi.org/10.5061/dryad.06vm1

Ethics

No ethical approval was required for this research.

Competing Interests

We have no competing interests.

Authors' Contributions

ARE conceived the study and designed the practical procedures. TLC and ARE together carried out and analysed the experimental work, and ARE wrote the manuscript with help from TLC. Both authors approve of the final version and agree to be held responsible for the work performed.

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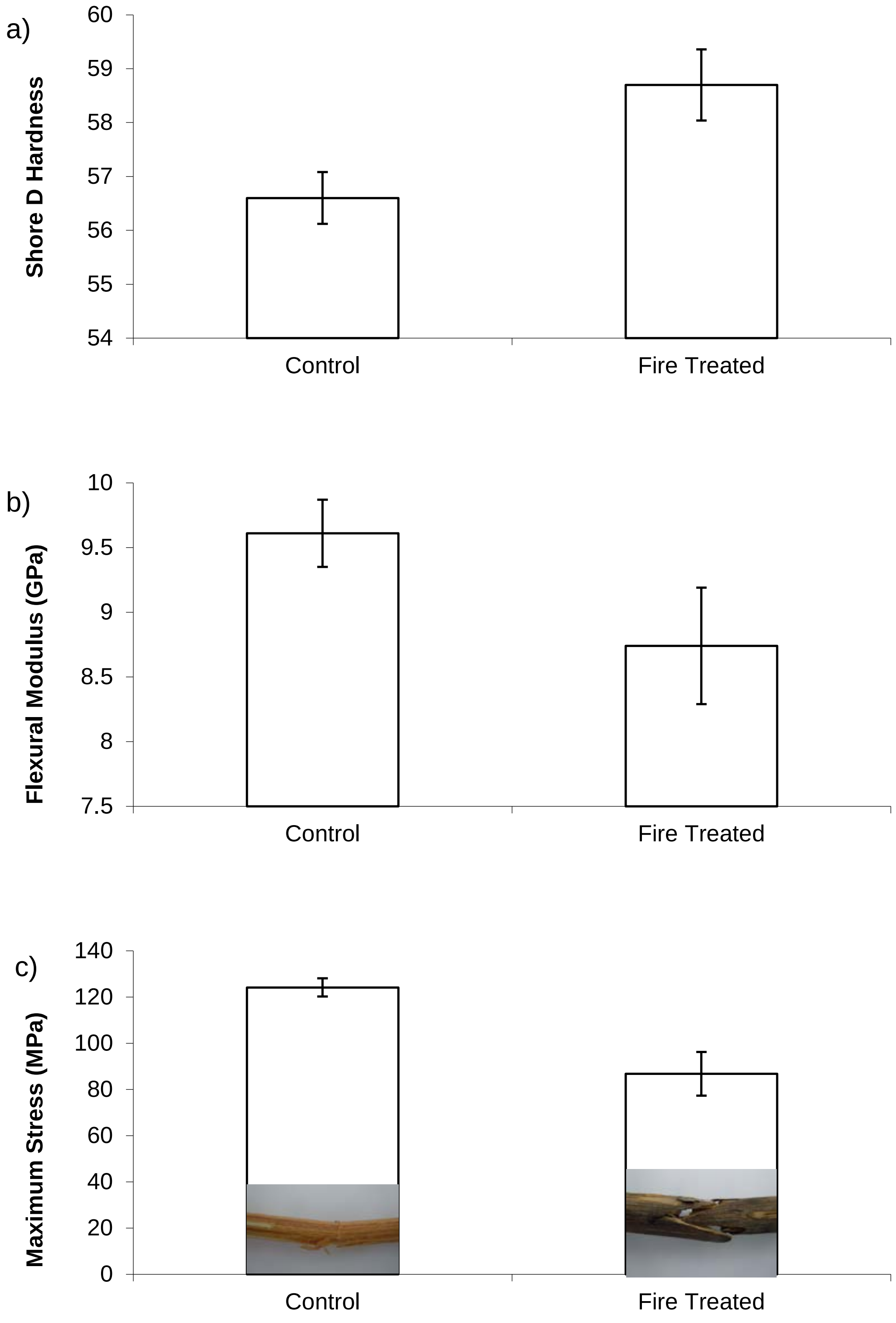
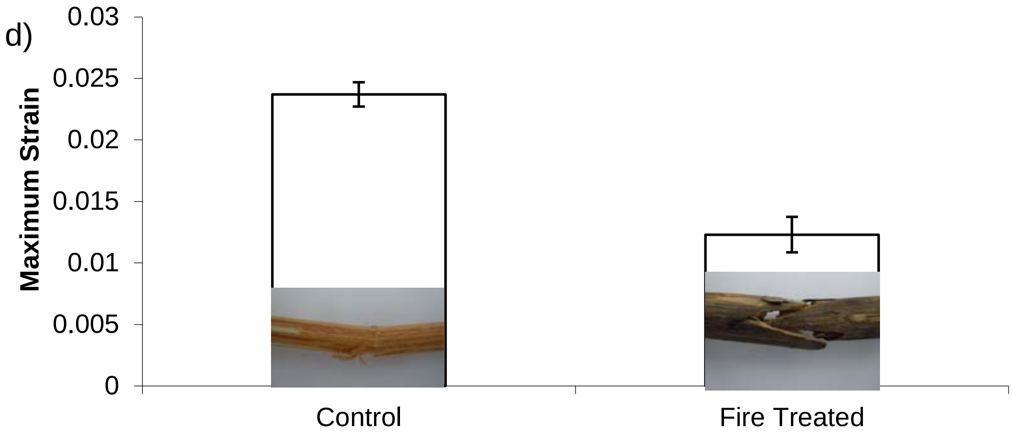
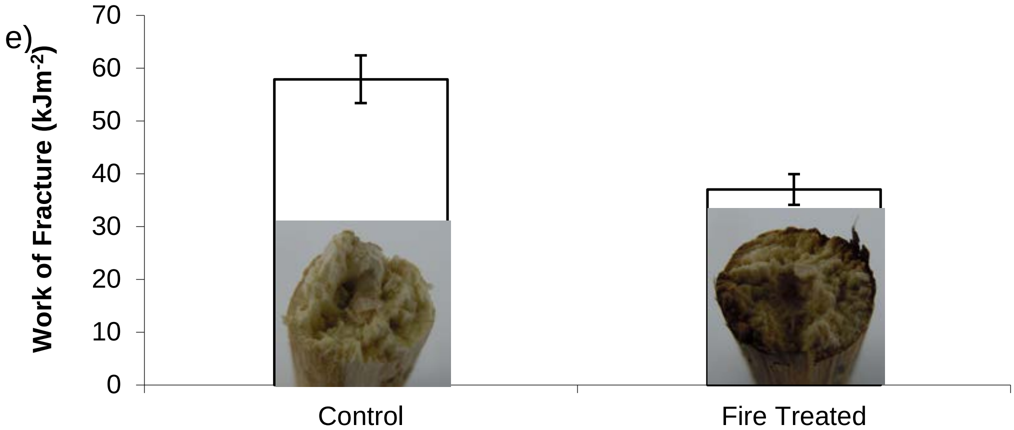
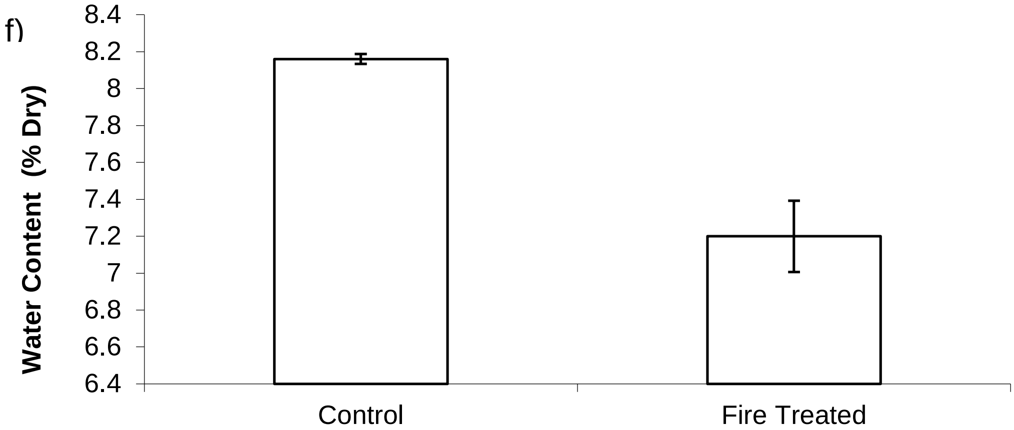
Legends to Figures

Fig.1. Comparison of the mechanical properties of control and fire-treated wooden rods. a) hardness; b) stiffness, c) maximum stress (strength), d) strain at maximum load e) work of fracture and f) water content. Pictures show typical patterns of failure. Bars show means and standard errors.


a)
Shore D Hardness
60
59
58
57
56
55
54
Control
Fire Treated
b)
Flexural Modulus (GPa)
10
9.5
9
8.5
8
7.5
Control
Fire Treated
c)
Maximum Stress (MPa)
140
120
100
80
60
40
20
0
Control
Fire Treated


d)
Maximum Strain
0.03
0.025
0.02
0.015
0.01
0.005
0
Control
Fire Treated


e)
Work of Fracture (kJm-2)
70
60
50
40
30
20
10
0
Control
Fire Treated


f)
Water Content (% Dry)
8.4
8.2
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
Control
Fire Treated