Historical nail-making techniques revealed in metal structure

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ABSTRACT: Characteristics diagnostic of manufacturing technique are retained in the microstructure of iron nails even though the original surfaces are lost in corrosion. Distinctive metal structures differentiate hand-forged and machine-made nails. The one-operation machines that automatically cut and headed nails left unique shear bands in the nail-head metal. Presence of these shear bands indicates that nails cut and headed by machine were in use in Rhode Island before 1781. Before about 1815 nail machines in New England operated on pre-heated iron plate, as shown by the recrystallization of the shear band. Nails made thereafter until about 1850 were formed from cold iron and have un-recrystallized shear bands. Cut nails made after about 1850 are in the longitudinal rather then transverse orientation, and have a folded head structure resulting from improved design of the nail machine header grips.

Introduction

From ancient times to the middle of the 18th century the technique used by smiths to make nails remained nearly unchanged. In the hundred years beginning at least as early as 1760 a succession of more sophisticated machine techniques for making nails replaced smiths' hand work in North America. Thereafter manufacture of machine-made nails again changed little to the present day. Architectural historians and historical archaeologists recognize the successive changes in technique visible in the nails themselves as a useful tool for dating late-18th and 19th-century buildings (Adams 2002; Nelson 1968; Wells 1998). Additionally, studies of nails offer historians of technology new information about the development of manufacturing with self-acting machinery in the early American republic, thereby adding nail making to previous research that has focused on clocks, firearms, and sewing machines (Hoke 1990; Hounshell 1984). We report here the results of a study of the metal structures found in nails made by hand and several variants of historic nail machines, in order to identify the nail-making processes used, from the surviving metal structure.

With few exceptions, investigators have relied on the external, visible, and stylistic features of nails to identify the methods used in making them. Nails retrieved from intact buildings may be sufficiently free of corrosion for these features to be preserved, but corrosion usually obscures the diagnostic surface characteristics of nails excavated at historic building sites and other in-ground archaeological contexts. However, the internal metal structure survives in corroded nails, and is a reliable record of the manufacturing technique used. In a pioneering metallographic study, Angus and others (1962) deduced the manufacturing technique used by Roman smiths in making the nails recovered from the huge hoard at Inchtuthill, Scotland. Subsequent studies of metal structure in nails from archaeological contexts were undertaken by Frurip and others (1983), who were concerned with tracing the provenance of nails from Fort Michilimackinac, based on the chemical compositions of slag inclusions, and by Geselowitz, Westcott and Wang (1991).

Methods

Nail specimens were prepared by standard laboratory techniques of sectioning, polishing, and etching for examination with optical or electron microscopes. Nails are often sufficiently abundant at archaeological sites that sectioning may be permissible, to examine the internal metal structure. Most of the nails described here were made of wrought iron. Carbon content was estimated by visual examination of the microstructure. Phosphorus present at high enough concentrations to reduce the ductility of the iron can be recognized in the microstructure, through the characteristic texture which it causes (Stewart *et al* 2000). Consequently, microprobe analysis to determine chemical compositions was needed in only a few cases. Frurip *et al* (1983) recognized the possibility that characteristic elements segregated in the slag inclusions might yield information on nail provenance. However, locating the source of iron from slag composition has not yet proved useful, except in a few special cases where the possible sources are few and well characterized. It has not yet succeeded with nails.

Materials studied

The sources of the nails examined are listed in Table 1. The earliest are from pre-industrial sites in Africa. Specimens were selected from the numerous nails recovered at the Old House, Bog Garden, and Woodhouse sites at the Greene Farm excavations in Warwick, Rhode Island (Ryzewski 2007; Frank *et al* 2006). Mean ceramic and mean clay tobacco pipe bore formulae were used to calculate date ranges for the excavated deposits at these sites (South 1978; Binford 1962; Deetz 1996). The nails were excavated from the undisturbed Old House midden deposit that dates between 1663 and 1711. The earliest known structure on the property was erected *c* 1658 (Deslatte 2007). In the Bog Garden area, the mean date for ceramics excavated along with the nails studied is 1757. The stratigraphy and diagnostic artefacts of the Bog Garden date ironworking activities in the area to a 48-year period between 1733 and 1781.

Table 1: Sources of nail specimens

Source	Date	Specimen
Lower Nubia, Egypt, (Pennsylvania-Yale Expedition)	300 BC–25 BC	16
Askum, Ethiopia	AD 150–350	17
Greene Farm, Old House site, Warwick, Rhode Island	1662–1711 (1687 mean)	39, 40, 41, 45
Greene Farm, Bog Garden site, Warwick, Rhode Island	1733–1782 (1757 mean)	36, 37, 38, 43, 44
Friendship House, Capitol Hill, Washington, DC	*c*1790	3
Greene Farm, Woodhouse site, Warwick, Rhode Island	1762–1820	33, 34, 35
Jefferson's nailery site, Monticello, Virginia	1794–1825	10, 11, 15
Minor-Christopher House, Woodbury, Connecticut (taken from spacers between kitchen rafters and lean-to rafters)	original structure built in 1801	4
Benton-Beecher House, Guilford, Connecticut	1740–1828	20
Minor-Christopher House, Woodbury, Connecticut	second construction period, *c*1820–1840	5, 6, 7
Minor-Christopher House, Woodbury, Connecticut (Second floor, SE room, period III)	*c*1880s	8
Tredegar Ironworks, Richmond, Virginia (puddling works and spike shops)	1880	9
Colonial Williamsburg	1985	1
Wheatley House site, Lebanon, New Hampshire	first house 1776–*c*1800, second house *c*1800–*c*1845	2, 24
Henry Whitfield House, Guilford, Connecticut	1639–1935	12, 13, 14, 18, 19
Glebe House, Woodbury, Connecticut	1750–1866	21, 22, 25, 27, 28
Old Campus, Yale University, New Haven, Connecticut	1750–1950	26
Potowomut, Forge site, Warwick, Rhode Island	1690–1830	42
Factory Island House, Sacco, Maine	1782 house reused through 1930	30, 31, 32
Unknown		23, 29

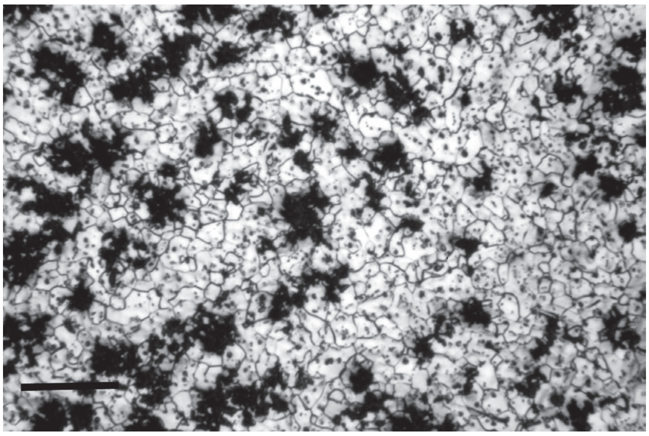

Figure 1: Microstructure of nail 3, from the Friendship House, Capitol Hill, Washington, D C, built c1790. The graphite nodules in a ferrite matrix show that this nail is made of blackheart malleable cast iron. Nital etch; length of scale bar 0.1 mm.

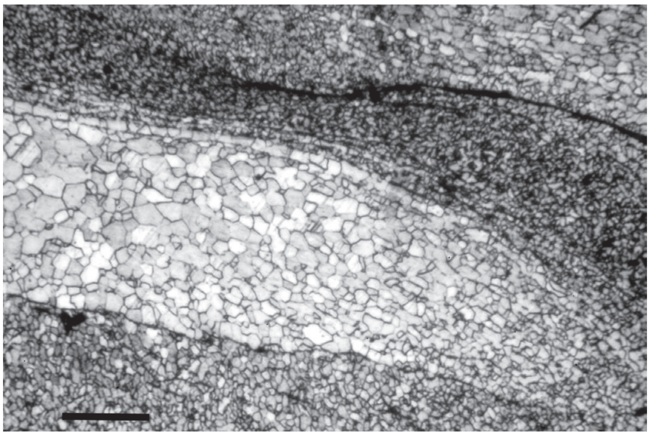

Figure 2: Section of the head of nail 4, from the first period of construction of the Minor-Christopher House in Woodbury, Connecticut, built in 1801. The iron is recrystallized because of forging at red heat. Carbon content controls the ferrite grain size. Nital etch; length of scale bar 0.1 mm.

Other securely-dated nails studied are from the excavations of Thomas Jefferson's nailery at Monticello, Virginia, and from dated structural components of the Minor-Christopher House, Woodbury, Connecticut, and the Benton-Beecher House in Guilford, Connecticut. The remaining specimens are from the sites of historic structures where, because of multiple use, we lack stratigraphic control.

Results - Metal used

One nail among those studied, No. 3, is made of cast iron. It would have been cast in white iron and subsequently annealed to convert it to blackheart malleable iron (Fig 1; Lenik 1977). As the process for making blackheart iron was introduced in the United States by Seth Boyden in 1825, and the nail is securely dated to *c*1790, it must have been imported. All other nails examined are made of wrought iron.

The mechanical properties of wrought iron depend primarily on the size and distribution of the included slag, and its phosphorus and carbon contents. Excess or poorly-distributed slag in wrought iron arose from inadequate or unskilful hammering of the metal once it was removed from the furnace in which it was made. The high slag content of nails indicate that relatively low grades of iron were regularly accepted by nail makers. Iron with large or poorly distributed slag inclusions was liable to split when passing through a nail heading machine, or to break when hammered.

Phosphorus in excess of about 0.2% makes wrought iron 'cold short', lacking in ductility (Gordon and Knopf 2005). Cold-short iron was considered suitable for nails that did not have to be clenched, but could not be used for horse nails, for example. In New England high phosphorus content in iron commonly resulted from bloomeries smelting bog ores, which were often phosphorus-rich. In England, the source of many nails imported into the United States, smelting of phosphoric argillaceous ironstone resulted in the cold-short iron commonly used by nail makers. After about 1830 the puddling process supplanted bloom smelting and fining in the U.S. as the cheapest source of wrought iron for nail making. Puddling mills could supply iron which was free of carbon and whose phosphorus content was controlled by the maker. The abundant supply of soft iron from puddling mills facilitated production by nail machines.

Iron made by bloomery smelting typically had a variable carbon content, which could be high enough to form a considerable amount of pearlite in the metal structure. Even small amounts of carbon had a large effect on the ferrite grain size in nail iron (Fig 2). In this head of a hand-forged nail the iron is fully recrystallized as a result of forging at red heat. Large grains of ferrite formed in the areas free of carbides, while grain growth was restricted where the carbides were present.

Every variety and grade of iron, much of it of poor quality, was found among the nails examined. The metal used in the ancient nails (Nos. 16, 17, and 47) was as good or better than that used by colonial nail makers. All of the nails (Nos. 39, 40, 41, and 45) from the Old House site (17th century) had very high phosphorus contents. Locally available bog ore smelted in a bloomery at or near this site is the probable source of the iron used.

Figure 3: The slag fibres in the shank of nail 8 are oriented parallel with the length of the shank (vertical in the image), thereby showing the longitudinal orientation of a nail. Nital etch; length of scale bar 0.2mm.

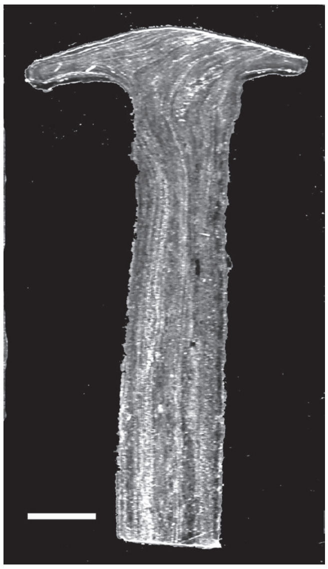

Figure 5: Hand-forged nail 22, from the early-19th-century Glebe House, Woodbury, Connecticut. The folded structure in the head resulted from the initial diagonal blow struck by the smith with the nail in the header. Nital etch; length of scale bar 2mm.

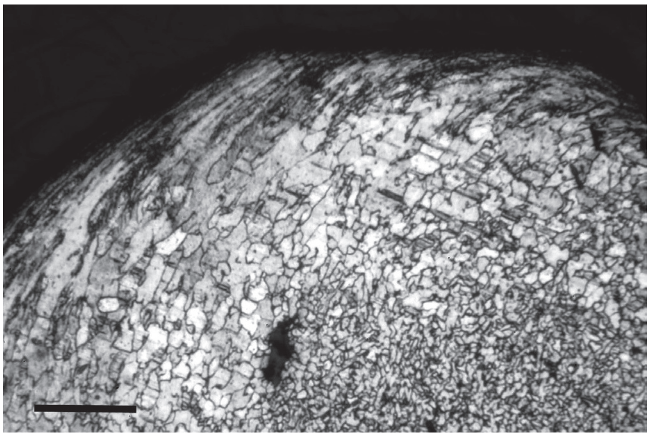

Figure 4: Section at the edge of the head of the nail illustrated in Figure 2 showing deformation of the ferrite grains at the edge of the head, where hammering was continued after the nail had cooled on the smith's anvil. Nital etch; length of scale bar 0.1mm.

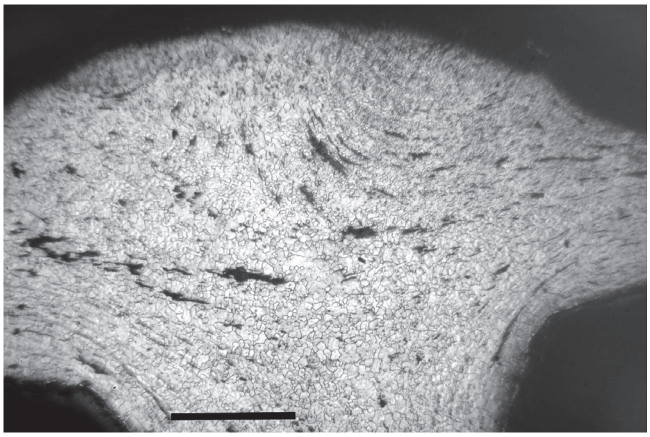

Figure 6: Hand-forged, rose-headed nail 27, recovered from the site of the early-19th-century Glebe House, Woodbury, Connecticut. The nail head was formed with a fuller, thereby creating a nearly symmetrical metal flow. Nital etch; length of scale bar 0.1mm.

Results - Metal structure

The orientation of the included slag shows the direction in which a nail was cut from its parent iron. The density, size, shape, and orientation of the slag fibres is determined by the forging and/or rolling that formed the metal stock used in nail making. Typically these forming processes produce slag fibres parallel with the long axis of the rod or plate that was used by a nail maker. Hence nails made from rod are in the longitudinal orientation. In nails cut from a rolled plate with their long axes transverse to the rolling direction, the included slag fibres are perpendicular to their length (Nelson 1968). The nail orientation relative to its parent stock may be revealed by preferential corrosion on the surface of the iron or, more reliably, by examination of a metallographic specimen. While some of the nails examined had an easily discerned orientation relative to the iron fibre (Fig 3), in others the slag had not been well distributed in the metal stock, probably because it was bloomery iron, made with a minimum of hammer work.

Hand-made nails

The iron is recrystallized in nails forged by hand at red heat (Fig 2). A smith would shape the shank of a nail immediately after the nail rod was taken from the forge fire and, since it recrystallized at a relatively high temperature, a large ferrite grain size resulted. The nail maker might form the head without reheating the work. Additionally, placing the nail in the heading fixture extracts heat rapidly. The head would have recrystallized at a relatively low temperature, making the grain size in the head smaller than in the shank. The small recrystallized grains may then show evidence of further deformation if the maker continued hammering as the metal cooled (Fig 4).

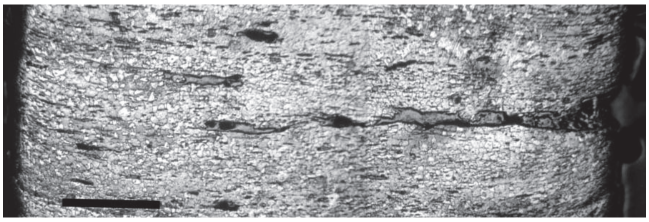

Figure 7: Cross section of the stem of nail 5, which is in the transverse orientation, showing slag fibres elongated in the rolling direction of the parent nail plate. The bend zone at each edge is metal dragged by the knife that cut the nail. Since the bend is in the same direction at each edge, the nail plate was turned over between cuts. Nital etch; length of scale bar 0.5mm.

The grain structure of the nail head can reveal aspects of the smith's technique. One commonly-found structure shows that a lateral hammer blow was followed by diagonal strokes that then folded the head metal (Fig 5). A more symmetrical pattern resulted when the smith struck a vertical blow first, followed by diagonal strokes (Fig 6). The number of strokes used reflects the care taken in the appearance of the finished head. Carlisle and Gunn (1977) have shown how the work of individual nail makers can be recognized on the basis of specific external characteristics of their products. Evidence from the microstructure of the metal could be used for this kind of study in cases where external features have been lost in corrosion.

Cut nails

Characteristic structures are left in a nail when it is cut from a plate by hand-operated or power-driven shears, or in a nail machine. The cut is surrounded by a band of deformed metal that forms the burrs that observers have used to identify nails made with successive rotations or successive rocking of the plate between cuts (Nelson 1968). Even when these burrs are obscured or removed by corrosion the plastic shear zone may be preserved in the microstructure. It is easiest to see in a cross section cut through the nail shank (Fig 7). Grain deformation and tear cracks may sometimes be seen in a longitudinal section along the edges of cut nails, if the amount of metal lost to corrosion is small.

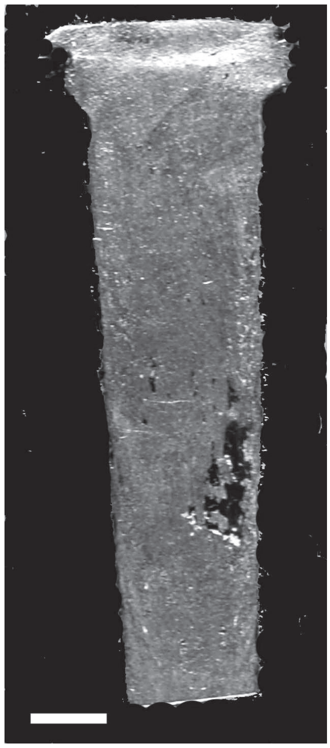

Figure 9: Section of nail 5, from the second period of construction of the Minor-Christopher House in Woodbury, Connecticut, dated to 1820–1840. The structure of the bright band in the nail head is shown in the following figures. Nital etch; length of scale bar 10mm.

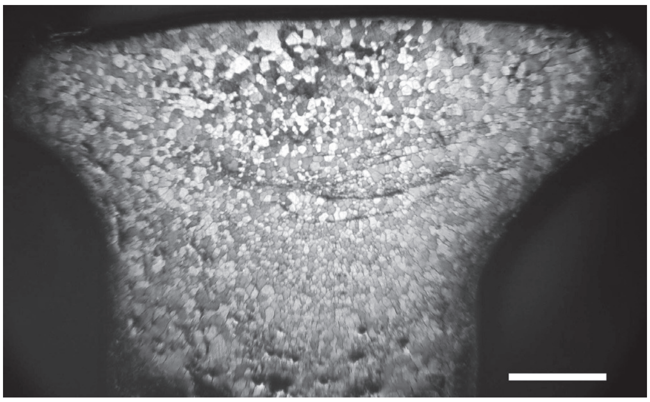

Figure 8: Hand-headed, machine-cut nail 25 recovered from the site of the early 19th century Glebe House, Woodbury, Connecticut. Slag fibres in the nail stem are in the transverse orientation, showing that it was machine cut. The iron in the head is recrystallized with a large grain size showing that it was brought to red heat for heading. Nital etch; length of scale bar 1mm.

Once a nail was cut it might be left unheaded, it might be headed by hand in a separate operation or, if the cutting is done in a 'one-operation' machine, headed in the second machine stage.

Cut nails hand headed

Nail machine inventors found it easier to devise reliable mechanisms for cutting than for heading. Even when a nail factory proprietor had a one-operation machine installed, the difficulty of keeping the heading mechanism in order sometimes led the user to rely on heading by hand after the machine cut the nails. In an 1810 visit to the Salem Iron Factory, William Bentley noticed that while nails were being cut by the power-driven machines in the factory, the heading stations on the machines were not used. The nail makers had found that they could do the heading faster and better by hand than with the heading mechanism (Bradlee 1918). An example of the microstructure found in a hand-headed cut nail is shown in Fig 8.

Cut nails machine headed

All the hand-made nails examined are in the longitudinal orientation. A group of the nails in the transverse

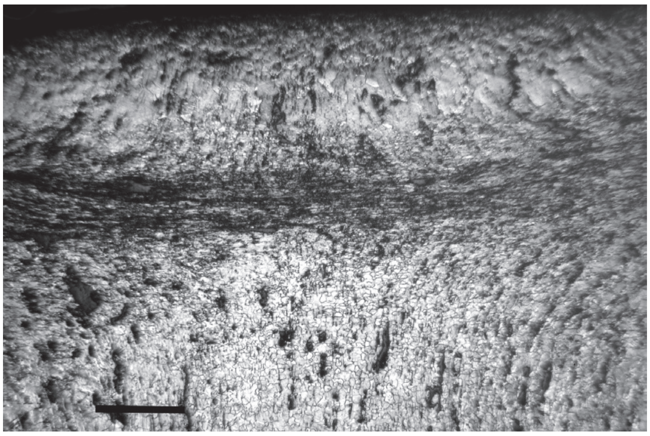

Figure 10: Magnified view of the nail head shown in Figure 9. Iron in the dark band is intensely sheared. Below the shear band iron is bent outward toward the edges of the nail but is not otherwise much deformed. Nital etch; length of scale bar 0.5mm.

Figure 11: At higher magnification the elongation of the ferrite grains in the shear band shown in Fig 10 is revealed. Iron between the shear band and the top of the head is undeformed, as is the iron below, except for the outward bend toward the edges of the nail. Nital etch; length of scale bar 0.2mm.

orientation were found to have a unique metal structure in the nail head, unlike any found in a hand-made nail. A section through one of these nails shows a head with a flat top and a transverse bright band below (Fig 9). An optical micrograph shows the band to be a narrow zone of intense shear, grading to less deformed metal above and below (Fig 10). There is very little deformation in a layer 1mm thick between the nail head and the shear band (Fig 11). Metal is gradually splayed laterally with only slight deformation below the zone of intense shear. We interpret these structural features as formed in a one-operation nail machine that worked on unheated iron plate.

A one-operation machine first sheared a nail from the feedstock, and then mechanically transferred it to a heading station, where it was gripped firmly at its edge by mechanically-actuated clamps. A length of iron, sufficient to make the head, remained exposed

Figure 12: The asymmetrical shear structure found in the head of nail 34, recovered at the Woodhouse site, Greene Farm excavation, Warwick, Rhode Island, is interpreted as resulting from imperfect alignment of the heading die in the one-operation machine that made this nail. Nital etch; length of scale bar 2mm.

outside these clamps. Once gripped, either a hammer stroke or pressure applied by the rapid advance of a die (sometimes called a 'set') formed the head. The metal outside the clamps was forced to flow laterally, and that flow was concentrated in the shear band. However, the metal in contact with the header die could not move laterally because of the friction between the nail iron and the die surface. Hence, a band of undeformed metal was left between the shear zone and the top of the head (Fig 11).

The exact shape of the shear zone and displacement of the metal beneath the zone depended on the details of the design of the clamps that held the nail for heading, and the header die itself in the nail machine, as well as on the temperature of the metal. The earlier well-dated nails in our study that show the shear band structure were held by clamps with little or no chamfer. The pressure they exerted left little evidence of deformation in the underlying metal. They effectively stopped lateral flow below the level of the top surface of the clamp as the heading die advanced. The resulting shear flow was localized, between the metal held in place by friction with the header die and that constrained by the clamps.

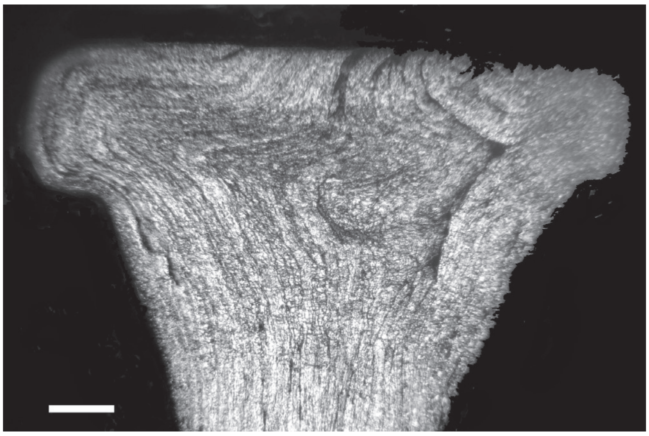

Figure 13: This head section of nail 8, from the 1880 addition to the Minor-Christopher House in Woodbury, Connecticut, shows a folded rather than shear-band structure. This machine-made nail is in the longitudinal orientation. The relatively long tapered section below the head was formed in a chamfer at the end of the heading grip and, by allowing more lateral flow replaced the shear band in the head by a folded structure. Nital etch; length of scale bar 0.5mm.

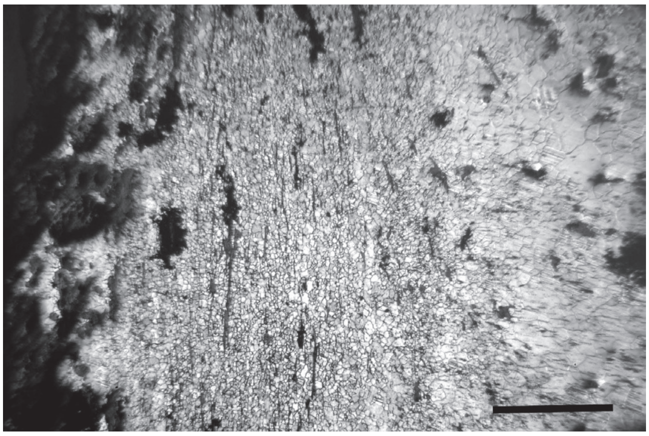

Figure 14: The shear band in machine-headed nail 42, from the Potowomut site in Rhode Island is fully recrystallized with a ferrite grain size smaller that that of the nail plate. It is interpreted as made in a one-operation nail machine from nail plate heated to black heat. Nital etch; length of scale bar 0.5mm.

Variants on the shear zone structure arose from differences in the header die and clamps, as inventors continued to tinker with improvements in their machine designs. Misalignment of the nail stem could result in asymmetric lateral flow and folding in the head (Fig 12). These variants open the possibility of a more detailed nail classification if enough reference samples can be collected and analyzed.

The nail illustrated in Figure 13, dated to about 1880, shows changes which had been made in nail machine design by the time cut nail production reached its peak. This nail is in the longitudinal orientation; this shows that the metal stock used was rolled plate, of sufficient width that a strip could be cut off the end of the plate, with its width equal to the length of the nails to be made. Metal in the nail head was folded over on itself without forming a band of intense shear. The taper beneath the head of this nail is 2.3 mm long, while in the earlier nail (Fig 9) it is only 1.1 mm. The longer chamfer in the header grips allowed some lateral flow in the upper part of the nail shank. The lateral orientation of the 1880 nail facilitated the formation of the folded structure since the metal could split open at the slag fibres. The late date of this nail shows a modernization of the earlier grip design that lacked a deep chamfer; it had the advantage of reducing the force needed to form the head.

Effect of metal temperature

Shaping nails at red heat, as was done in hand forging, was impossible in nail machines, since such a high temperature could not be maintained while the metal stock was in contact with the shear blades and the heading dies. However, the decrease in yield strength of iron is approximately linear with temperature, and the strength is reduced to about half its room temperature value at about 500°C, a temperature described as 'black heat'. The force required to cut and head a nail could be substantially reduced by working warm iron. Difficulties would arise in using warmed metal in a one-operation nail machine since heat would be lost rapidly to the shear blades and the lateral clamps. Nevertheless, evidence of the use of heated stock in these machines was found in some of the nail specimens examined.

The nail shown in Fig 14 has all the characteristics of an early machine-cut and headed nail, but the shear band consists of finer ferrite grains than the nail shank. These finer, undeformed grains are interpreted as originating in recrystallization of the heavily deformed iron in a shear band, which could occur at black heat. The small grain size of the shear band shows that the recrystallization took place at a lower temperature than the red heat at which the metal stock was rolled. The grain size difference also shows that this structure did not originate through reheating of the nail in a fire. In that case, the heavily deformed shear band would be expected to have a coarser grain size than the nail shank, since the entire nail would have been heated to the same temperature, and the more heavily deformed metal in the shear band would have recrystallized first, allowing greater grain growth than in the shank.

Replication experiments

Laboratory trials were undertaken to demonstrate the inferred formation of shear bands in one-operation

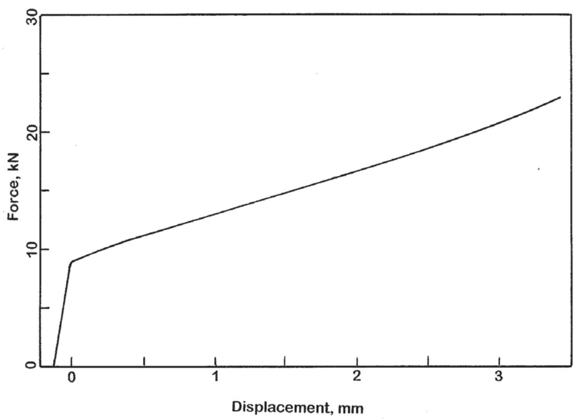

Figure 15: Force displacement curve recorded in the experimental nail heading trial.

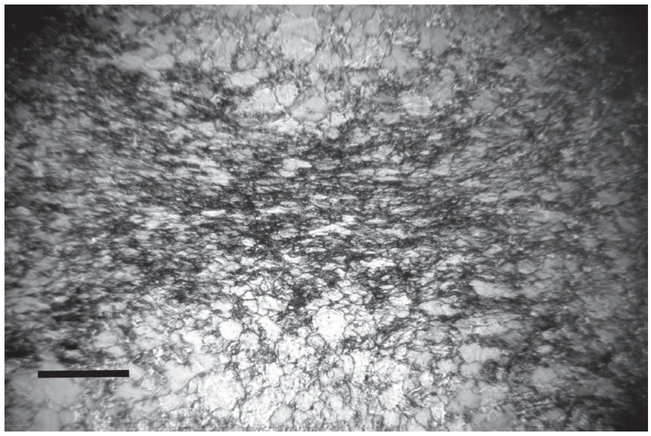

Figure 16: This section of the replica nail head made in the heading trial shows the formation of the shear band between undeformed iron above and below. Nital etch; length of scale bar 0.5mm.

machine-headed nails. Test specimens were cut from a bar of wrought iron free of carbides and phosphorus and with a moderate content of thin slag fibres. A round rather than rectangular specimen shape was used, to simplify specimen preparation. A volume of iron was chosen to match the volume of metal found in the head of the nail illustrated in Fig 9, and was cut to the size of the nail before heading on the end of a large diameter rod having flat and parallel end faces. The large-diameter base prevents lateral flow, thereby simulating the action of the clamping dies in a one-operation nail machine. A hardened steel header die was used to compress the model nail head by an amount equivalent to that needed to form the head on the pattern nail.

Compression was applied at a constant speed of 1 mm/min in an Instron testing machine, and the resulting force-displacement curve was recorded (Fig 15). Plastic yielding began at an applied stress of 345 MPa. This is greater than the 252 MPa tensile yield stress of this iron, because of the short length of iron exposed outside the lateral constraint imposed by the header die and the specimen base. Yield was followed by a linear increase in the force required to continue deformation through the first 2 mm of compression. Thereafter the requisite force increased more rapidly. The test was continued until the model nail head was compressed 3.38 mm, which required an applied force of 22.5 kN. This corresponds with a stress of 982 MPa calculated on the original cross sectional area of the model nail head. The total compression was 47% (compared with 44% compression calculated as required to form the head of the model nail (Fig 9), and the maximum increase in diameter was 41% (compared with 44% for the model nail head).

When the test specimen was sectioned, it was found to have the characteristic shear band, with the iron above (in contact with the header die) undeformed, as found in machine-headed nails (Fig 16). These tests show the substantial heavy construction and the need for a source of mechanical power that would have been required to make a successful heading machine. The stress of 982 MPa applied to the header would be resisted only by a die made of skilfully hardened and tempered steel, such as 0.78% carbon spring-temper steel, whose yield strength is 1,465 MPa, or 0.53% carbon steel in the same temper, which would yield at 1,035 MPa (Brandes 1983: 22–135). Jesse Reed noted in his description of his 1814 nail machine (National Archives 1819) that his design facilitated changing the heading 'set' as 'cavities or indentings are formed upon its surface by use'. We find from the dimensions shown on a drawing of Reed's machine, included with his 1819 deposition, that a force of 3.1 kN (700 lbf) would have to act on the end of the operating lever to apply the force of 22.5 kN to the header die that we found was needed to head a nail made of soft iron. Thus, a substantial mechanical system would have been needed to operate this machine.

The requisite force could be reduced by pre-heating the metal stock. The evidence above shows that this was done in the earliest machine-headed nails. Two difficulties would arise. The metal would cool rapidly once gripped by the lateral clamps. As successive nails were headed the clamps and the header die would become hot enough to soften the steel by drawing its temper. These difficulties led nail makers using one-operation machines to abandon pre-heating their metal stock as soon as they managed to build machines with the requisite rugged construction for cold heading.

A further test of the metal structure formed by a one-operation machine was made by examining the microstructure of copper nails made by the machines preserved at the Strawbery Banke Museum in Portsmouth, New Hampshire. These machines were built *c*1900 to make copper nails for boat builders. They use lever-driven heading dies that operate on the same principle as the improved Reed machine. Nails are cut from half-hard copper plate feedstock that has a yield stress of about 176 MPa, 65% of that of soft wrought iron. A section through a nail made on one of these machines shows the features observed in the heading trial: no deformation of the metal adjacent to the heading die with a sharply defined shear band below extending across the width of the nail head.

Discussion

Interpretation of the fabrication technique used on each of the nails studied, based on the factors discussed above, is summarized in Tables 2 and 3. All the nails known to have been made in the 17th century are hand made. Of the 17 nails with a large phosphorus concentration in the iron, all are from dates earlier than the opening decades of the 19th century, with the majority firmly dated to the 17th and 18th centuries. However, nails 7, 12, and 24 are machine-made, fabricated from high-phosphorus iron. The loss of ductility due to the phosphorus content nevertheless allowed nails 7 and 12 to be machine-cut and headed cold.

The data in Tables 2 and 3 show the variety of methods of working used by smiths making nails by hand. These differences in metal structure illustrate the working preferences of different smiths, as described by Carlisle and Gunn (1977) on the basis of external characteristics. Except that nail rod from slitting mills, when available, could be used in place of hammered-out iron strips, the technique of making nails by hand used in 18th-century North America had changed little from that practised by Roman smiths (Angus *et al* 1962; Franklin 1980), or from even earlier times. A smith hammered a point on the heated end of nail rod held between the fingers so that it could be easily rotated, partially cut it to the required length on the hardie, placed it in the header, and with a few strokes formed the head (Loveday 1983, 7; Gale 1977, 123, 124). Examples of header dies survive in several collections (Kaufman 1966; deValinger 1960). Nail makers in Britain continued with hand methods well into the 20th century (Gale 1977) even though a nail machine of American design was in use Birmingham, England, as early as 1814 (Bathe and Bathe 1943, 38). The large numbers of nails imported from Britain in colonial and early republic years (Adams 2002) would, with few exceptions, have been hand made. Supplies of hand-made nails also flowed into American markets from the work of prisoners, as in Massachusetts (Bentley 1907, I 278) and Connecticut (Raber, Gordon, and Harper 1999).

The simplest kind of machine-made nails are those cut off a strip of hoop iron by shears, and not headed, such as those made at Monticello (Nos. 10, 15). Nails cut this way could also be subsequently hand headed (Nos. 19, 21, 24, 25, 36). The nails from the Greene Farm Bog

Table 2: Nails entirely hand made

	Method description	Specimen & Reference Numbers	Date
Nails entirely hand made	All are in longitudinal orientation, and made from hand-forged nail rod, or rod from a rolling and slitting mill.		
A	Hand-hammered head, forged hot, initial diagonal blow, and then worked symmetrically.	1 (3099)	1985
B	Hand forged, hot, diagonal start blow, and then hammered to an asymmetric head shape; probably with two strokes for clasp nails or four strokes for rose nails.	20 (3601) 22 (3604A) 23 (3605) 28 (3610) 29 (3611)	1740–1828 1750–1866 unknown 1750–1866 unknown
C	Hand forged, hot, lateral initial blow was followed by vertical blows with forming die or swage to shape the head.	4 (3245) 11 (3416) 27 (3609)	1801 1794–1825 1750–1866
D	Forged hot or warm, no evidence of oblique hammer blows.	2 (3158) 16 (3460) 35 (KR10A) 45 (KR19) 39 (KR20) 40 (KR21) 41 (KR22) 44 (KR30)	1776–1840 300–25 BC 1796–1820 1663–1711 (1687 mean) 1663–1711 (1687 mean) 1663–1711 (1687 mean) 1663–1711 (1687 mean) 1739–1772 (1762 mean)
E	Nail rod only	3 (3163)	*c*1790

Garden site, with a date range from 1739 to 1772 and mean of date 1762, show that equipment for shearing nails from rolled plate (No. 36) and for cutting and heading nails from warm iron by machine (Nos. 37, 38) was in use in New England, probably in Rhode Island, in colonial times. Nails made by machines that cut and headed cold iron are widely distributed in late 18th and early 19th century sites, showing the rapid development of this technique in early republic New England.

Nail rod and plate in North America

Adoption of nail-making machines depended on the availability of rolling mills to supply the requisite iron strip. The proprietors of the Saugus ironworks in Massachusetts had their rolling and slitting mill producing nail rod by 1647, but the operations were closed due to bankruptcy as early as 1652 (Hartley 1957). The record of subsequent colonial attempts to build and operate rolling mills is sparse. The Sarum ironworks in Delaware County, Pennsylvania, is reported to have had a rolling and slitting mill operating as early as 1742, and Charming Forge, also in Pennsylvania, sometime before 1775 (Committee 1914). Examination of the account books of the Union & Andover Iron Works in New Jersey shows a rolling and slitting mill there making about 100 tons of nail rod a year until 1776 in

Table 3: Nails cast, cut and machine made

Manufacture method	Method description	Specimen & reference numbers	Date
Nails cut from hoop iron or other rolled plate	These were cut from the end of the plate and therefore are in the transverse orientation. The plate may have been rotated or wiggled between cuts.		
A Machine cut, not headed	Cut from hoop iron but not headed. These were probably cut with hand-operated shears.	10 (3412) 15 (3427)	1796–1825 1796–1825
B Machine cut, hand headed	Cut nail subsequently headed by hand hammering, usually with the iron hot enough to recrystallize. A fuller or die may have been used to help form the head. These could have been cut with hand-operated shears or be the product of the earliest of power-driven nail machines. They were cut from the end of the plate and therefore are in the transverse orientation. The plate may have been rotated or wiggled between cuts. In all our examples it was rotated. Heading continued on cold metal Decorated head	36 (KR12) 19 (3598) 21 (3603) 24 (3606) 25 (3607)	1733–1781 (1757 mean) 1639–1900 1750–1866 1776–1845 1750–1866
C Machine cut and headed cold	Nail cut in the transverse orientation on a two-stage machine. There is a shear band in head with intense to moderate deformation, and little taper below the head. Would have been made before wide nail plates were available. Probably headed cold in an early two-station machine. Headed by pressing rather than hammer blow. Header grip lacked chamfer.	5 (3246A) 6 (3246B) 7 (3247A) 12 (3417) 18 (3597) 33 (KR1) 34 (KR2) 30 (G1) 31 (G2) 32 (G3)	1820–1840 1820–1840 1820–1840 1639–1935 1639–1935 1762–1820 1762–1820 1782–1930 1782–1930 1782–1930
D Machine cut and headed warm	Iron cut nail similar to above but with the shear band recrystallized by warm heading as described by Bentley [1816]. (The possibility of recrystallization due to a structure fire is excluded by the grain size differences between head and shank.)	37 (KR17) 38 (KR18) 42 (KR28)	1739–1772 (1762 mean) 1733–1781 (1757 mean) 1690–1830
E Machine cut, no data on head	Head was removed when specimen mounted	13 (3418)	1639–1935
Machine cut and headed nails made from wide plate	Iron cut nail in the longitudinal orientation, with the plate rotated between cuts. Head formed cold by symmetrical compression that folded metal at both edges. Large taper between head and shank indicates chamfer at the top of the clamping grip in the nail machine. Nails were made in a nail machine after wide nail plate became available so that strips could be cut to allow the longitudinal orientation, with the plate rotated between cuts. Chamfer in the heading grip allowed head to form without a shear band. Example dated to *c*1880 (when the wrought iron cut nail industry was at its peak of output). There is some evidence placing this as early as 1835.	8 (3247B)	*c*1880
Hot-formed head made with header-die	Made in a spike machine. Railroad spike.	9 (3277)	*c*1880
Steel, wire or cut nail	Modern nails, for comparison	14 (3419) 26 (3608) 3595	1639–1935 1750– modern

spite of continuing difficulties with obtaining mill parts, and limited workers' skills (Boyer 1931, Theodore Kury 1995 pers comm). One reason for this sparse record is the Iron Act of 1750, which prohibited colonists from 'erecting mills or engines for slitting or rolling or any plating forge to work with a tilt hammer or any furnace for making steel [to] be erected in America' (Statute 23 Geo. II *c* 23). Colonial governors were required by law to record production figures of existing mills and to report the emergence of any new mills. Thus, in 1768, the governor of the New Jersey colony reported to the British authorities:

> 'There are in this Colony Eight Blast Furnaces for the making of Pig-Iron, and Forty-two Forges for beating out Bar-Iron. There are likewise One Slitting-Mill [probably the one at the Union & Andover works], One Steel-Furnace, and one Plating-Mill, which were erected before the Act of Parliament respecting those Works. I am told that none of the three latter are carried on with Vigor, and that scarce anything has been done at the Steel-Furnace for several Years past.'(New Jersey Archives 1768: 31).

In some colonies, such as New Jersey and Rhode Island, the Act was loosely enforced (New Jersey Archives 1768:31).

With rolling mills scarce or restricted in operation, American iron makers such a Samuel Forbes, in Canaan, Connecticut, supplied large quantities of nail rod made by traditional methods (Howell and Carlson 1980, 36). Once clear of the legal restriction imposed by the crown, Americans quickly set to work building mills for rolling plate and slitting nail rod. Among them were John Adam, Sr., in Taunton, Massachusetts in 1776 (Howell and Carlson 1980, 18), Forbes & Adam in Canaan, Connecticut in 1785 with a second mill in Woodville in 1792 to meet the large demand (Howell and Carlson 1980, 69, 71), and in 1799 J G Pierson in Ramapo Village, New York, where he eventually had 96 nail machines operating in addition to his mill (Bathe and Bathe 1943, 13, Gordon 1996, 69).

Nail machines

Two factors account for the relative absence of archival material documenting earlier experimental mechanized nail-making techniques during the late colonial period: the aforementioned British restrictions on colonial iron manufacture and export, and the decentralized, variable practice of patent regulation in the American colonies. While the Patent Act of 1790 institutionalized the federal patent system, the practice of protecting inventions was not new to Americans, nor were some of the mechanical innovations that later received the first federal patents. In the absence of general patent legislation during the Colonial period, antecedents of federal patents were granted by local colonial legislatures in response to individual petitions. In some cases colonies, such as Massachusetts and Connecticut, enacted simplified versions of the Statute of Monopolies confining the grant of monopoly rights to 'new inventions… for a short time' (Walterscheid 1995).

Given the manufacturing and export restrictions facing the colonists, patents detailing new manufacturing techniques are rare during the late colonial period. However, archival and archaeological evidence exists that suggests colonists were working with material, mechanisms, and techniques that resemble the efficient and improved patented nail-making methods of the late 18th and early 19th centuries. With the late-18th-century enactment of the federally regulated patent system, innovators' rights to market and profit from their inventions were promoted and protected on a significantly larger scale than prior to the Revolution.

Large demand for nails and relative scarcity of artisans coincided with a florescence of mechanical innovation and establishment of a patent system in the first decades of the early American republic (Hoke 1990; Hounshell 1984; Gordon and Malone 1994). Inventors patented nail machines and machine improvements at an increasing rate onward from 1791, when the first patent was issued (Bathe and Bathe 1943, 13). By 1800, 23 patents for improvements in nail machines had been issued (Swank 1892:, 448). Compared with the extensive information we have on the new manufacturing techniques that Yankee inventors in the early republic years developed for clocks and firearms, our knowledge of their numerous mechanical nail making inventions remains sparse. None of the early nail machines survive, and the Patent Office fire in 1836 destroyed the patent drawings for most of these machines. Hence inferences from surviving nails are a promising source of information on this area of American mechanical ingenuity.

The early hand- or foot-operated nail machines, such as those built by Jeremiah Wilkinson (Swank 1892, 448) and Ezekiel Reed (Phillips 1993, 1996) or the one purchased by Thomas Jefferson, simply sheared tapered lengths off the hoop iron that nail makers purchased from operators of rolling and slitting mills (Abdu *et al* 2003). Although by 1797 Jacob Perkins had constructed a one-operation nail machine, and it was reported to be operating in 1800 at his factory in Amesbury, Massachusetts (Bentley 1907, II 338), there were

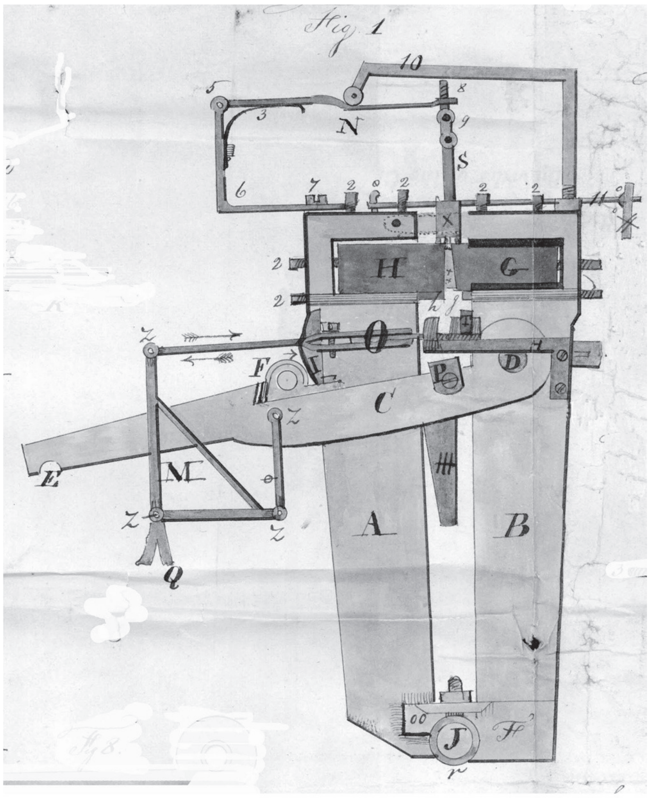

Figure 17: Front view of the Reed one-operation nail machine. Operation of this machine is described in the Appendix (Ordione v. Amesbury, 1814. National Archives, Waltham, MA).

difficulties in keeping the heading mechanism working, and its full operation was delayed until at least 1805 (Phillips 1993, 1996). Nathan Read developed a similar machine to cut and head nails used at the Salem Iron Factory in 1798 (Bradlee 1918, Phillips 1993, 1996). However, it was Jesse Reed's one-operation machine patented in 1807 and incorporating improvements in 1810 and 1814 that, along with Perkin's machine, was the most widely used in the U.S. by the 1820s (Phillips 1993, 1996). Swank (1892), quoting a statement by nail maker Shubal Wilder in 1879, asserts that designs based on the Reed machine had the greatest success, and were the basis for cut nail making equipment through the 19th century. In Reed's machine the nail was successively cut, clamped, and headed by motions driven by a large lever actuated by a mechanical source of power (Fig 17), as described in the appendix. Perkins' machine was similar, but used a toggle joint to develop the force needed for heading. We interpret the nails with transverse shear bands in their heads as having been made by lever-action, one-operation machines based on the Perkins or Reed designs.

Thomas Jefferson reported that the artisans in his shop heated the hoop iron used in his nail machine, which consisted of foot-operated shears, to black heat before cutting (Betts 1953, 428). British practice was to feed nail machines with warmed plates (Britannica 1911). William Bentley on a visit to Haverhill, Massachusetts, watched artisans making nails by cutting heated plates with shears, placing the cut nails in a fixture, and heading them with hammer strokes (Bentley 1907, II 394). While promoting the use of anthracite coal at nail works in Philadelphia in 1810, Jacob Cist found specialized furnaces in use to heat iron plates for nail machines (Powell 1978, 48). In 1816 Bentley (Bradlee 1918) watched a furnace burning mineral coal heating plates for machines that cut large nails at the Iron Factory at Danvers, Massachusetts. As illustrated in Fig 14, we find examples of nails with a shear band in which the metal is recrystallized. These are interpreted as made in one-operation machines from iron preheated to black heat. The difficulties of keeping the metal warm enough to significantly lower it strength coupled with the degrading effect of heat on the strength of the grips and header dies in the one-operation machines led to abandonment of this practice. Machines operating on unheated iron stock produced nails having the features illustrated in Fig 13. In his 1819 deposition in the case of Odiorne vs Amesbury Nail Factory, Jesse Reed pointed out that in his one-operation machine 'cutting and griping is effected within itself thereby producing at one operation of said machine nails from cold iron to the great saving of fuel, labor and loss occasioned by heating the nail plates' (National Archives 1819). Thus it appears that the use of warmed iron in nail machines probably ended shortly after 1815.

Comparison of the patent drawing for Reed's 1814 lever-action one-operation nail machine (Fig 17) with the machines preserved at the Strawbery Banke Museum show that, while the principle of the Reed machine may have been retained, as claimed by Swank, substantial design changes were made. The Reed machine lacked an automatic feed that would rotate the nail plate between cuts. It used a spring-driven slide to transfer the cut nail to the heading station, and a sliding joint to place the header in line with the cut nail and subsequently withdraw it, so that the nail could fall out of the machine. Later machines replaced these devices with positive mechanical movements driven by cams and cranks, that provided accurate timing of the sequence of motions. In the years after 1816 improved grip and header design such as that used in making the nail shown in Fig 13 reduced the force needed to form the nail head and so improved the reliability of the machine.

Once lever-action, one-operation nail machines fed with cold iron were in common use, the next major change in nail making technique was to replace the transverse orientation of the iron stock by longitudinal orientation. We lack good evidence on when and how rapidly this change occurred. One indication is found in the records of New York's Dannemora prison (Inspectors of State Prisons 1868). In 1868 it was recorded that the nail factory built at the prison in 1859 had 48 machines making nails in the transverse orientation. The next year the prison managers changed over to the manufacture of 'Empire' nails, made in the longitudinal orientation, so as to compete better in the nail market. This indicates that nails were commonly made in the transverse orientation in 1859, when the equipment for the Dannemora factory was purchased, and that ten years later they were largely supplanted by nails made in the longitudinal orientation.

Conclusions

Since nails did not have to be made to close dimensional tolerances, the individual nail maker had substantial latitude in choosing technique. The resulting large variations in internal structure in the examples of hand-made nails described above show the wide range of choices made by individual smiths. Use of nail machines constrained individual preferences on methods of working among nail makers, but left open variants in machine design and operation that can be recognized in American machine-made nails. One-operation nail machines leave a distinctive shear band in the microstructure of the nail head. Retention of the deformed structure or the recrystallization of the shear bands distinguishes between the use of warm or cold iron feed-stock for the machine.

The material evidence shows that despite the restrictions the crown placed on manufacturing by the colonists in British North America, colonial inventors and artisans managed to build rolling mills and one-operation nail machines before 1776. Removal of the legal restrictions and the economic recovery in the 1780s led entrepreneurs to expand production of machine-made nails, and to solve the numerous mechanical limitations of the early nail machines. Replacement of hand-made by machine-made nails then followed gradually over several decades of the 19th century.

Acknowledgements

David Harvey, Lindamae Peck, Emory Kemp, Martha Hills, Gregory Galer, Brook Abdu, Emily Casey, Sean Flanagan, and Michael Geselowitz donated nails for this study. Rodney Rowland demonstrated the operation of the nail machines at the Strawbery Banke Museum for us. Robert Knopf and Heather Galli prepared the metallographic specimens. Thomas Tartaron and Marcello Canuto provided information on the excavations at the Henry Whitfield House, and Gordon Pollard on nail making in the New York State prisons.

Appendix

The operation of Jesse Reed's nail machine 1819

Early 19th-century patents generally give limited descriptions of inventions at best. However, Jesse Reed prepared a detailed description of the operation of his nail machine for use in his deposition in the 1819 patent infringement case of Odiorne vs. Amesbury Nail Factory (National Archives 1819). Fig 17 shows a front view of the Reed machine. The arms *A* and *B*, about three feet long, are hinged at the pivot *J*. Cutter blades *G* and *H* are mounted in the arms with gripping dies *g* and *h* beneath them. Arm *B* is fixed in place. Arm *A* is moved toward *B* when force is applied at *E* to lift lever *C*, which turns on pivot *D*. As upward motion of lever *C* forces roller *F* over the cam surface *I* the arms close until the roller reaches the peak of the cam surface. Above this point the cam is made in the arc of a circle so that further upward motion of *C* does not close the arms further.

The lever system *M* is attached to a fixed pivot at *Q* so that as the lever *C* is raised the slide *O* is pulled outward to the left thereby pulling the heading die *T* under the opening in the grips *g* and *h*. As arm *A* moves toward *B* it pushes spring *N* under the roller attached to the frame *10*. This pushes the forcing slide *S* downward.

In the first step in making a nail, the operator inserted a length of nail plate between the cutters *G* and *H* and pushed it into contact with the back of the nail conductor *X*, which was previously adjusted to the required width of the nail. Plate was inserted at an angle fixed by a stand in front of the machine that determines the taper of the sides of the nail. As the power source moved lever *C* upward it caused the following sequence of motions:

- Cutter blade *H* passed behind blade *G* cutting off the nail from the plate.
- Header die *T* was pulled by the fork *O* into position under the nail conductor *X*.
- Clamping dies *g* and *h* advanced toward each other.
- Once the nail was cut it was lodged in the nail conductor *I* and pushed downward by the forcing slide *S* so as to be gripped by the clamping dies *g* and *h* with the metal required for the nail head projecting

toward the heading die *T*.

- Motion of the roller *F* over the curved surface of the cam block *I* kept the clamping dies at a fixed separation while the upward motion of the block *P* on lever *C* forced the die *T* upward to form the nail head.

With the nail now cut and headed, lever *C* moved downward, causing the following events:

- Frame *N* and fork *O* pushed the header die *T* to the right, away from the nail held by the grips *g* and *h*.
- Cutters *G* and *H* along with clamping dies *g*
- and *h* returned to their rest positions.
- The forcing slide *S* pushed the completed nail out of the nail conductor *X*.

The operator then either reversed the nail plate (or perhaps set it to a different angle) and again inserted it so as to begin the sequence of operations again. Since the machine was run by power taken from a constantly revolving water wheel, it would have been in continuous motion. The ability of the machine operator to remove and re-insert the nail plate during the time the cutters were in the open position was probably the limiting factor in the rate of nail production. Improper insertion of the nail plate could damage the more delicate parts of the mechanism.

Successful nail making depended on proper adjustment of all the machine parts to the requisite positions for each size of nail made. Experience with the nail machines at Strawbery Banke shows that this is a difficult task that, once accomplished, would be needed again as parts were worn or damaged in use. Operation of the machine required precise timing of each motion in its proper sequence, which was also dependent on the proper setting of all the parts.

For the heading operation the nail was held in place by friction where the grips *g* and *h* touched the flat sides of the nail. They did not need to penetrate the metal. Once die *T* began to upset the end of the nail the shoulder so formed would have helped hold the nail in place. Hence, the nail could emerge from the machine with no surface or internal evidence of contact with the gripping dies. All of the features of the class-C machine-made nails (Table 3) match the operating characteristics of the Reed machine.

Bibliography

Abdu B, Knopf R and Gordon R 2003, 'Interpretation of artifacts from Thomas Jefferson's nailery at Monticello, Virginia', *Historical Metallurgy* 37(1), 43–50.

Adams W H 2002, 'Machine cut and wire nails: American production and use for dating 19th and early 20th Century sites', *Historical Archaeology* 36(4), 66–68.

Angus N S, Brown G T and Cleere H F 1962, 'The Roman nails from the Roman Legionary Fortress at Inchtuthill, Perthshire', *Journal of the Iron and Steel Institute* 200(11), 956–968.

Bathe G and D 1943, *Jacob Perkins, Philadelphia* (Historical Society of Pennsylvania, Philadelphia).

Bentley W 1907, *The Diary of William Bentley, DD* (The Essex Institute, Salem).

Betts E W (ed) 1953, *Thomas Jefferson's Farm Book* (Princeton).

Binford L 1962, 'A new method of calculating dates from kaolin pipe stem samples', *Southeastern Archaeological Conference Newsletter* 9(1), 19–25.

Boyer C S 1931, *Early forges and furnaces in New Jersey* (Philadelphia).

Bradlee F B C 1918, 'The Salem nail factory', *Historical Collections of the Essex Institute* 54(2), 97–114.

Brandes E A 1983, *Smithells metals reference book* (London).

Britannica 1911, 'Nail' in *The Encyclopaedia Britannica*, 11th ed, Vol 19, 153 (New York).

Carlisle R C and Gunn J 1977, 'Idiosyncratic behavior in the manufacture of handwrought nails', in South S W (ed), *Research Strategies in Historical Archaeology*, 287–305 (New York).

Committee on Historical Research, Pennsylvania Society of the Colonial Dames of America 1914, *Forges and Furnaces in the Province of Pennsylvania* (Philadelphia).

Deetz J 1996, *In small things forgotten* (New York).

Deslatte K 2007, An archaeological examination of a 17th-century midden, Greene Farm, Warwick, Rhode Island. Master's Thesis, Department of Anthropology, University of Massachusetts, Boston.

deValinger L 1960, 'Nail making device at the Delaware State Museum', *Chronicle of the Early American Industries Association*, 13(2), 17.

Frank C, Ryzewski K and Stein Ninian 2006, *Preliminary Field and Historical Report, Greene Farm Archaeology Project, 2005 Field Season.* Report on file with the Rhode Island Historic Preservation and Heritage Commission and the City of Warwick, RI. Also published at http://proteus.brown.edu/greenefarm/1994.

Franklin U M 1980, 'Old iron nails', *CIM Bulletin* 73(821), 120–122.

Frurip D J, Malewicki R and Heldman D P 1983, *Colonial Nails from Michilimackinac* (Mackinac Island State Park Commission).

Gale W K V 1977, *Iron and Steel* (Buxton).

Geselowitz M, Westcott T R and Wang D 1991, 'For want of a nail: archaeometallurgy and dating in historical archaeology', in R M Ehrenreich (ed) *Metals in Society, MASCA Research Papers,* 8(II) 45–55.

Gordon R B 1996, *American Iron 1607–1900* (Baltimore).

Gordon R and Knopf R 2005, 'Evaluation of wrought iron for continued service in historic bridges', *Journal of Materials in Civil Engineering* 17(4), 393–399.

Gordon R and Malone P 1994, *The Texture of Industry* (New York).

Hartley E N 1957, *Ironworks on the Saugus* (University of Oklahoma Press, Norman).

Hoke D 1990, *Ingenious Yankees: The rise of the American System of Manufactures in the private sector* (New York).

Howell K T and Carlson E W 1980, *Men of Iron: Forbes & Adam* (Lakeville, Connecticut).
Hounshell D 1984, *From American System to Mass Production, 1800–1932* (Baltimore).
Inspectors of State Prisons 1868*, 20th Annual Report of the Inspectors of State Prisons of the State on New York.* Transmitted to the Legislature January 29 1868.
Kaufman H J 1966, *Early American Ironware* (Tuttle, Rutland).
Lenik E 1977, 'A study of cast iron nails', *Historical Archaeology* 11, 45–7.
Loveday A J 1983, *The rise and decline of the American cut nail industry* (Westport, Connecticut).
National Archives 1819 Jesse Reed, Ms, Witnesses for Amesbury in Odiorne v. Amesbury Nail Factory, U.S. Circuit Court, May 1819. National Archives, Northeast Region, Waltham, Massachusetts.
Nelson H L 1968, 'Nail chronology as an aid to dating old buildings', *History News* 24(11), (American Association for State and Local History Technical Leaflet 48).
Phillips M 1993, 'Mechanic geniuses and duckies: a revision of New England's cut nail chronology before 1820', *APT Bulletin* 25(3/4), 4–16.
Phillips M 1996, 'Mechanic geniuses and duckies: nail makers and their machines. *APT Bulletin* 27, 47–56.
Powell H B 1978, *Philadelphia's first fuel crisis: Jacob Cist and the developing market for Pennsylvania anthracite* (University Park, Pa).
Raber M S, Gordon R B and Harper M G 1999, 'Archaeological and historical investigations for Old Newgate prison and copper mine.' Connecticut Historical Commission, Hartford.
Ryzewski K (ed) 2007, *Greene Farm Archaeology Project, Field Report 2006–2007.* Report on file with the Rhode Island Historic Preservation and Heritage Commission and the City of Warwick. Contributors: Kaitlin Deslatte, Caroline Frank, and Ninian Stein. Also published at http://proteus.brown.edu/greenefarm/4015.
South S 1978, 'Pattern recognition in historical archaeology', *American Antiquity,* 43(2), 223–230.
Swank J M 1892, *History of the manufacture of iron in all ages*, 2nd ed, American Iron & Steel Institute, Philadelphia.
Stewart J J, Charles J A and Wallach E R 2000, 'Iron-carbon-phosphorus system: Part III, Metallography of low carbon iron-phosphorus alloys', *Materials Science and Technology,* 16(2000b), 291–303.
Walterscheid E C 1995, 'Priority of invention: how the United States came to have a "first-to-invent" patent system'*, American Intellectual Property Association, Quarterly Journal*, 23, 263–265.
Wells T 1998, 'Nail chronology: the use of technologically derived features', *Historical Archaeology,* 32(2), 78–99.

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