Interpretation of artefacts from Thomas Jefferson's nailery at Monticello, Virginia

Brook Abdu, Robert Gordon and Robert Knopf

ABSTRACT: Laboratory analyses of nails, nail rod, and hoop iron from Thomas Jefferson's nailery at Monticello, Virginia, yield information about the methods used and the products made at American rolling and slitting mills in the early years of the 19th century. The iron, made by fining pig, is nearly free of phosphorus. It is relatively soft and ductile, having a tensile strength of 290 MN/m² and a reduction of area of 62%. Critical grain growth found in the hoop iron indicates that the metal was at a temperature of about 840°C during its last rolling pass. Rolling conditions produced an unusual pinch-and-swell structure in the slag inclusions. Bending at the edges of the nail rods indicates that the clearance between the slitter discs was about 20% of the nail rod thickness. Ferrite veining in the rod suggests that the iron passed through the slitters at a temperature between 600 and 700°C.

Introduction

Thomas Jefferson's surviving account books, notebooks, and correspondence record many aspects of the nail-making enterprise carried on at his Monticello estate from 1794 to 1825. Archaeological excavations have uncovered evidence of the layout of the nailery buildings along with abundant artefacts that include the nail rod and hoop iron used in making hand-wrought and machine-cut nails. The artefacts, records, and site evidence make the Monticello nailery a valuable source of information on iron and nail making techniques in early republic times.

Jefferson's wide-ranging interests coupled with his frequent and prolonged absences from home led to indebtedness arising from poor management by the overseers he employed at his Virginia estates. In December 1793 Jefferson returned to what he intended to be permanent residence in Virginia as a farmer and manager. Faced with a precarious financial position, he searched for ways to increase his income through better use of his assets, which included a large number of slaves that he had inherited. Monticello, then on the fringe of frontier settlement in Virginia, was well placed

Figure 1: Virginia and the eastern United States.

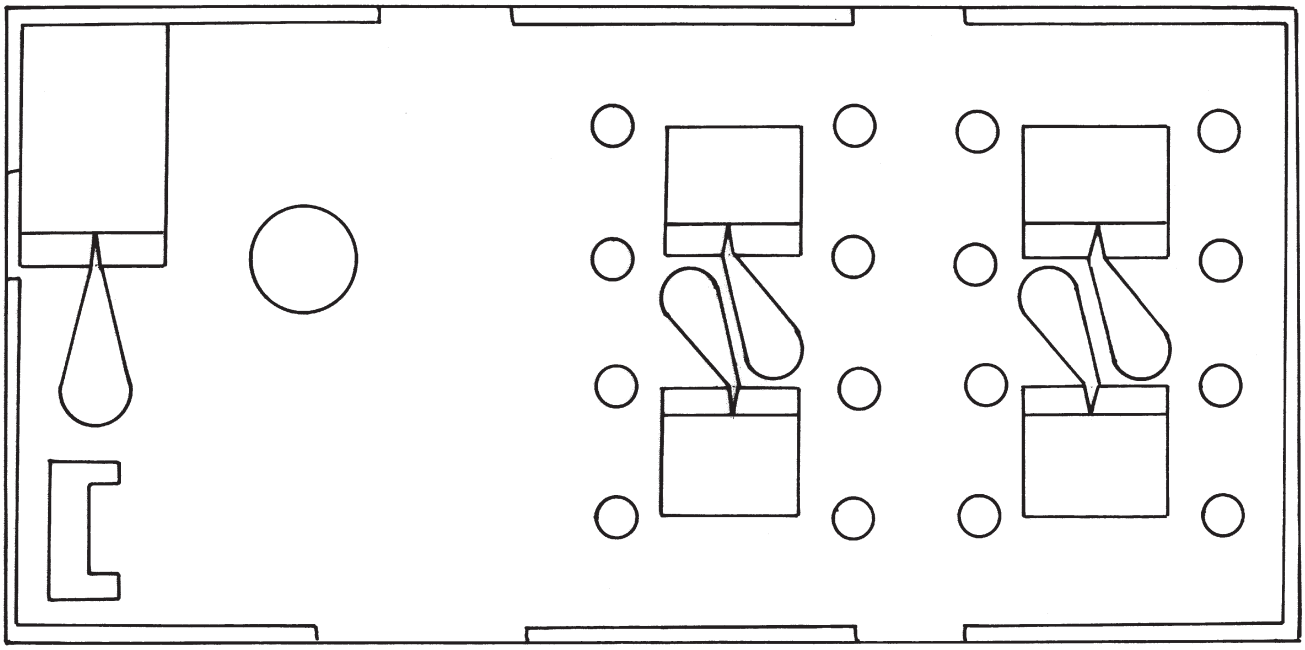

Figure 2: Jefferson proposed this layout for a combined nailery and smithy. Circles represent anvil bases. Nailers' hearths were to be placed back-to-back, with overhead bellows. Based on an undated plan found among Jefferson's papers (Betts 1953, 56).

to supply the nails that were in high demand for new construction in the surrounding counties. Since nail making was labour intensive, Jefferson could use his abundant slave labour to produce a commodity that would sell for cash, if he could obtain a supply of iron. He found that he could buy nail rod from ironmongers in Philadelphia, have it shipped by sea to Richmond, boated upriver to Milton on the Rivanna, and thence hauled on wagons to Monticello (Bear 1967, 16). Jefferson ordered a ton of nail rod from Caleb Lownes, ironmonger of Philadelphia. With the arrival of forty bundles of nail rod in April 1794, his young slaves commenced making wrought nails (Bear and Stanton 1997, 914). Jefferson had studied nail making techniques — his description in his *Farm Book* closely follows that by Diderot — and his nailers used these established methods. The plan that he drew for a nailery (Fig 2) shows a compact arrangement with the four fires each blown by a bellows and placed back to back in pairs (Betts 1953, 56). His favourite slave, Isaac Jefferson, later described how five young men and boys, each supplied with a nailer's hammer and anvil, worked in a cluster around each of two forge fires (Bear 1967, 53).

Jefferson's nailers primarily made wrought nails in size from 4d to 30d, with 8d and 10d the most common. (Nail sizes were designated by price in pence per hundred: 4d, 1 1/2 inches; 8d, 2 1/2 inches; 10d, 3 inches; and 30d, 6 inches long, designations that remain in use today.) In February 1796 he acquired a machine for cutting hoop iron into nails. Isaac Jefferson believed that the machine came from England, and was the first to be used in Virginia (Bear 1967, 16; Betts 1953, 433). However, we have no record of the design or the maker of the machine. Jefferson's cut nails, brads 25 to 32mm long for use in attaching shingles and laths, made up a small part of the nailery output. Production of wrought and cut nails at Monticello went on almost continuously until the Royal Navy blocked coastal trade during the War of 1812 and, hence, stopped shipment of nail rod from Philadelphia to Virginia. From 1815 to 1823 Jefferson, faced with increased difficulty in collecting payments from buyers,

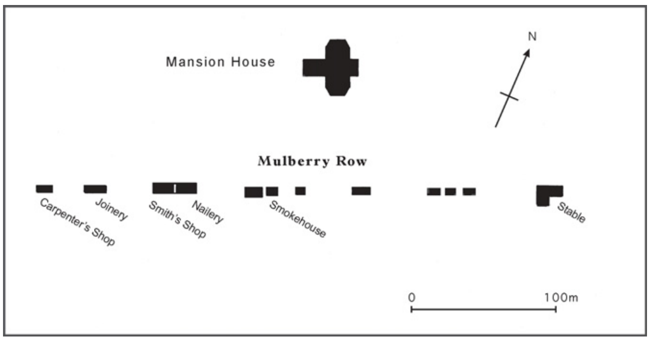

Figure 3: Jefferson showed the location of the nailery with its adjacent smithy along with other industrial buildings on Mulberry Row, a short distance from his mansion house, in a plan he prepared for fire insurance in 1796 (Betts 1953, 6, 426).

Figure 4: Examples of the hoop iron found during of the excavation at Building 'J' in 1982–3. Photograph courtesy of the Thomas Jefferson Foundation.

operated the nailery only intermittently.

Excavations in 1982–83 at the site of a structure designated 'Building J' (Fig 3) uncovered evidence of nail making, and showed that the building either collapsed or was dismantled, leaving the in-ground remains undisturbed. The excavators recovered hoop iron strips about 37mm wide (Fig 4), nail rod in bundles and individual pieces (Fig 5), numerous wrought and cut nails, hardy wasters (pieces prematurely severed from the nail rod), and anvil wasters (nail blanks with excessive metal left for the heads) (Sanford 1983). Examples were sent to Yale for examination through the courtesy of the Thomas Jefferson Memorial Foundation. The artefacts studied are listed in Table 1Archaeologists at Monticello have recently found evidence of a second nailery, designated 'Site 18', at a location near the overseer's house. Documents show that Jefferson moved his nail making to this new site about 1803 (F Neiman pers comm 2002). Hence the unused metal stock found at the site of Building J is probably a remnant of material on hand in 1803.

Figure 5: Among the artefacts found at the site of Building 'J' were a bundle of nail rod, a welded and pointed nail rod, and (left to right) two hardys, a hammer head, and a nail header. Photograph courtesy of the Thomas Jefferson Foundation.

Table 1: Artifacts examined

Item	Site number	Dimensions (mm)
Hoop iron	ER 162A	280 x 38 x 3
		152 x 36 x 3
Nail rod	ER 162A	483 x 5 x 3
		228 x 8 x 3
Machine-cut nails	ER 162	32 x 10 x 3
12d rose nail	166C	89

Metal Used

The slag inclusions in the Monticello iron are free of the particles of iron sulphide characteristic of metal made by the puddling process with mineral coal (Killick and Gordon 1987; Gordon 1997). Hence it is unlikely that the metal supplied to Jefferson was imported from England, where puddling with mineral coal fuel was in common use by 1803. American ironmasters did not begin puddling iron with mineral coal until after Jefferson abandoned nail making (Gordon 1996, 136).

Hunter's ironworks on the Rappahannock River about two miles above Fredericksburg, Virginia, is reported to have had a rolling and slitting mill under construction in 1774, and was able to supply some rod to Virginia nailers. This enterprise appears not to have survived competition arising from the resumption of trade with Great Britain after the termination of hostilities in 1783 (Keene 1972). Hence, Jefferson had to turn to northern suppliers for nail-making materials.

Individuals and family partnerships began building slitting mills near Philadelphia at least as early as 1740 (Committee 1914). Among them Isaac Pennock had a highly profitable business making hoop iron and nail rod at his Federal Slitting Mill on Buck Run near Coatesville, Pennsylvania, in 1794. By 1810 Pennock had added the Brandywine Iron and Nail Works (parent of the well-known Lukens Steel Company, that remained in business well into the 20th century) to his enterprises (Graystone 1994). In nearby New Jersey,

Table 2: Ferrite composition and hardness

Item	Al (wt%)	Si (wt%)	P (wt%)	S (wt%)	Hardness (Hv)
Hoop iron	0.08	0.19	0.10	0.05	135-150
Nail rod	0.12	0.17	0.07	0.06	94-189
Cut nail	0.08	0.15	0.06	0.02	141-159
Wrought nail	0.11	0.20	0.09	0.05	118-128

William Allen and Joseph Turner of Philadelphia established the Union Iron Works in 1742. Allen and Turner made pig iron in their blast furnace from magnetite ore and converted it to wrought iron in a finery forge. They reported that they had a slitting mill erected before 24 June 1750, the date of a proclamation issued by Governor Belcher of New Jersey in response to demands from the British government for the suspension of manufactures in the North American colonies. Although faced with many difficulties, including lack of managers and artisans with suitable technical skills, Allen and Turner made about 100 tons of nail rods a year. Their advertisement in December 1780 offered 'nail rods of good quality and different sizes' that could easily be shipped to Philadelphia (Boyer 1931). Thus, the Philadelphia iron merchants who supplied Jefferson could draw on many nearby suppliers. Howell & James of Philadelphia filled Jefferson's last order for nail rod and hoop iron in 1823 (Betts 1953).

All the iron samples examined have elongated bands containing grain-boundary carbide precipitates or pearlite and ferrite alternating with bands virtually free of carbides. All of the metal has a slag content near the low end of the range commonly found in wrought iron. Both these features are found in iron made by fining pig from charcoal-fired blast furnaces in early republic times. The phosphorus content of the ferrite in the hoop iron, nail rod, and finished nails is low, as shown in Table 2, which reports an average of three or more analyses for each type of metal. A tensile test of a length of nail rod showed that the metal is free of the discontinuous yielding often found in wrought iron. It had a yield strength of 240MN/m^2 and a tensile strength of 290MN/m^2. The reduction of area was 62% and the elongation 15%. This places the metal at the low strength/high ductility end of the range of properties usually found in wrought iron (Gordon 1988). Jefferson's nails could be clinched without breaking. The low strength, low phosphorus content, and high ductility are characteristic of iron fined from pig smelted from 'mountain ore' (magnetite, hematite, or goethite mined in upland areas) as distinct from the bog ore used at furnaces located in the coastal plain near Philadelphia.

Microhardness data obtained with a diamond pyramid indenter and a 0.1kgf load are shown in Table 2. The range of hardness numbers for each item reflects the inhomogeneity of the metal. Pearlite has a relatively small effect, increasing hardness relative to pearlite-free ferrite by about 10 points. Carbon and nitrogen retained in supersaturated solution in the ferrite raises its hardness to 190 from the value of 90 found in metal in which precipitation has been complete.

Table 3 shows an analysis of a representative slag inclusion in each of the different kinds of iron. The compositions of the slag inclusions in the hoop and nail rod samples studied are sufficiently similar to indicate that both came from the same source. The higher calcium content of the slag in the wrought and cut nails suggests that these artefacts were made of metal that originated at a different forge from the source of the hoop iron and rods. We believe that the Philadelphia ironmongers who supplied Jefferson dealt with many

Table 3: Elemental composition of slag inclusions (%)

Item	Al	Si	P	S	Mg	Na	K	Ca	Ti	Mn	Fe
Hoop iron	1.6	18.3	0.56	0.06	0.67	0.23	1.41	8.3	0.33	1.51	37.8
Wrought iron	1.4	18.8	0.22	0.03	0.74	-	1.90	6.2	0.05	0.66	41.3
Cut nail	4.0	31.7	0.10	0.07	1.26	0.40	4.30	19.3	0.73	0.21	38.0
Wrought nail	3.5	17.1	0.95	0.21	0.92	0.10	2.22	19.7	0.30	0.44	28.8

Note: balance in each analysis is oxygen.

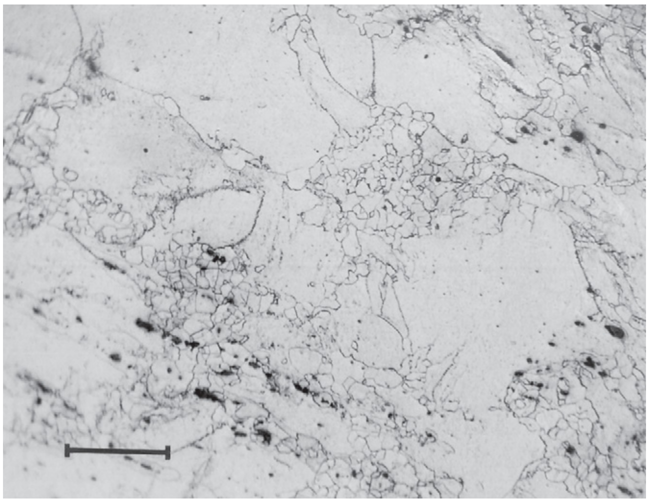

Figure 6: Microstructure of the hoop iron in a plane parallel with the rolled surface, showing the large ferrite grains surrounded by small grains that are characteristic of critical grain growth. Length of the scale bar is 0.1mm.

of the numerous nearby forges, so that mixed origins and compositions are possible.

Hoop Iron

The hoop iron artefacts were heavily corroded. However, traces of the microstructure of the lost metal are retained in the corrosion product, and can be used to determine the original thickness of the rolled strip. After correction for the expansion of the corrosion product, we find that the original thickness was a little over 3mm, and was probably intended to be 1/8th inch.

The microstructure of the hoop iron contains three features that indicate how the metal was rolled: ferrite grain size, shape of the slag particles, and form of the carbides. Interpretation of these structures can draw on the extensive experience that metallurgists have had with plain carbon steel (for the carbon-rich regions) and with rolled low-carbon strip steel (for the carbon-free regions).

The form of the carbide constituent present in the iron has a controlling influence on the ferrite grain size. Pearlite, where present, keeps the ferrite grains small. Elsewhere, carbide particles precipitated in the grain boundaries have mostly inhibited ferrite grain growth. However, examples of critical grain growth, a form of secondary recrystallization, are found in the microstructure of the hoop iron seen in the rolling plane (Fig 6). Examination of a transverse section shows that these large grains are thin with a plate-like shape. Critical grain growth arises from the recrystallization of ferrite in iron that is nearly free of carbon after deformation equivalent to 2 to 10% elongation at high-temperature (Samuels 1980). Data obtained in studies of the rolling of low-carbon steel strip (Cartwright and Dowding 1958) indicate that the critical grain growth observed in the hoop iron resulted from the metal entering its last pass through the rolls at a temperature of about 840˚C. At this temperature both ferrite and austenite grains were present. The newly formed ferrite cooled rapidly by contact with the roll surfaces while simultaneously being deformed sufficiently to induce critical grain growth. The very fine plate spacing of the pearlite present in the carbon-containing bands within the iron indicates subsequent rapid cooling through the eutectoid transformation temperature (723˚C).

To make wrought iron, a bloom (made by direct reduction of ore), a loup (made by fining), or a puddle ball (from a puddling furnace) is drawn into a bar by hammering or by rolling at a temperature high enough for the included slag to flow as a fluid into long fibres. The iron stock from which the hoop iron was made contained long slag fibres. Rolling the hoop iron caused the slag fibres alternately to pinch and swell (Fig 7), forming a structure not usually seen in longitudinal sections of wrought iron. Rolling forces metal to extrude forward through the rolls as it is simultaneously compressed between the rolls. In the hoop iron the resultant elongating flow of the slag became unstable, causing growth of alternating zones of thickening and thinning. The growth of the resulting clumps of slag perpendicular to the rolling direction is shown by the vertical displacement of adjoining material visible in Figure 7. As seen in a section parallel to the rolled surface, the slag now appears as separate, short,

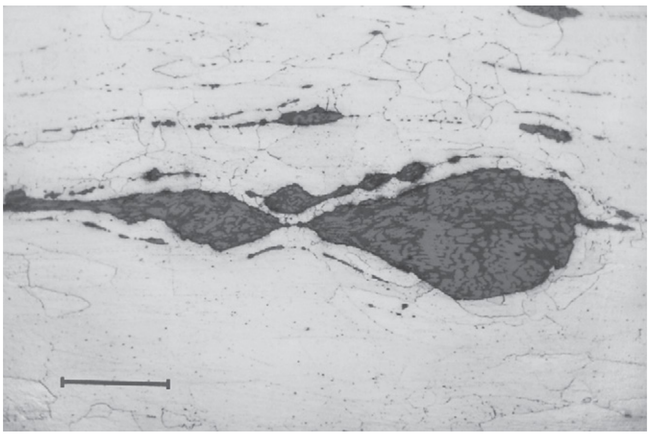

Figure 7: Microstructure of the hoop iron in a longitudinal section showing the pinch and swell of the slag fibres formed during rolling. Length of the scale bar is 0.1mm.

transverse segments arranged in lines parallel with the length of the plate. The pinch-and-swell structure of the slag in the hoop iron structure is analogous to the boudinage structure described by geologists (Ramberg 1955). The necessary conditions for its formation are described in the Appendix. The pinch-and-swell structure is uncommon in wrought iron. Additional examples might show it to be characteristic of wrought iron made by the rolling and slitting process.

Nail Rod

The microstructure of the nail rod has the same features found in the hoop iron: low slag content, bands containing iron carbides, critical grain growth in carbon-free zones, and slag boudins. In the slitting process meshing discs shear alternate sections of a rolled plate in opposite directions. The discs must have sharp edges, be closely spaced, rigid, and held in accurate alignment to produce good rod. When iron is sheared a surface of smooth, burnished metal is formed, followed by the rough texture of a ductile fracture. Shearing begins with penetration of the shear blade into the metal, forming the smooth surface finish. Penetration is followed by ductile rupture, which forms the rough surface (Lyman 1969). Any gap between the shear blades adds bending to the shearing process. Ductile fractures or tears may be formed in the bent metal. These are found at the edges of the nail rods we examined, and are evidence of bending during slitting. The tears are in a zone of heavily deformed metal that extends in to a depth of 1mm on each side of the 8mm wide rod. This depth of bending indicates that the spacing of the slitter disks was more than 20% of the disc thickness.

Slitting the nail rod from a rolled strip would be easier if the iron were heated so as to reduce the shear strength of the metal. The iron in the bend zone of the nail rods we examined is not recrystallized. This shows that the slitting was done with the metal at a temperature lower than about 730˚C. Further evidence of the temperature at which the iron passed through the slitter discs is found in a defect in one of the nail rod samples examined. Part of the rod separated along its mid section and was sharply bent while passing through the slitters. The ferrite grains in this bent section have the veining structure (Fig 8) characteristic of carbon-free iron air-cooled after deformation near the A_1 temperature. Comparison with the ferrite veining structures studied by Hultgren and others (1958) indicates that the rod was at a temperature between 600 and 700˚C as it passed through the slitter discs.

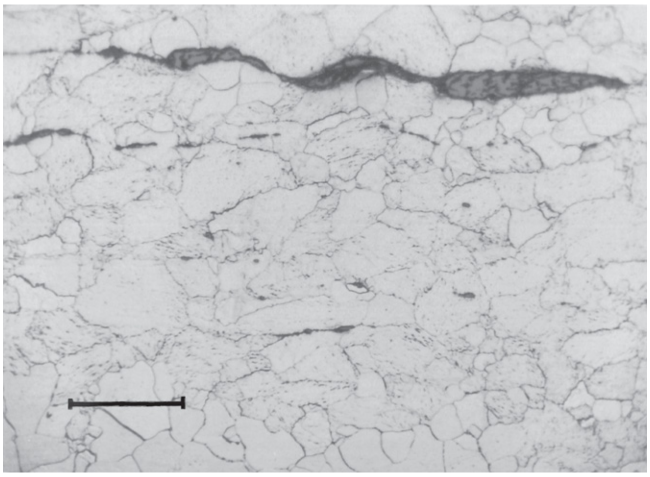

Figure 8: Microstructure in a longitudinal section of nail rod showing veining in the ferrite grains. Length of the scale bar is 0.1mm.

Some of the nail rods examined consist of two pieces welded together. The explanation of this is found in Jefferson's description of the nail-making process: Once a rod became so short that the nailer could no longer remove it from the forge fire by grasping its end with his bare hands, he welded it to another rod, which then served as a handle (Betts, 56). The nailers did not protect their hands with gloves nor did they use tongs. Instead, Jefferson provided small spring pincers for picking up bits of hot iron.

Cut Nails

The metal in the cut nails we examined has the same evidence of critical grain growth and slag boudinage found in the hoop iron. In a letter to Thomas Perkins in 1801 Jefferson stated that he cut his nails warm (Jefferson to Perkins, 1801). The presence of a bending zone at the edges of the cut nails would indicate the alignment and sharpness of the shear blades in Jefferson's nail cutting machine. To search for evidence on these points, several nails were cut from one of the samples of hoop iron with a gear-driven, hand-operated shearing machine in the laboratory. One of these nails was then cold-headed. Deformed metal is found to a depth of about 0.2mm at the edges of these newly-cut nails. The most intense deformation is in a layer 0.05mm deep that also contains ductile fractures formed by the bending that accompanies shearing. The deformation caused by cold heading with hammer blows extends to a depth of about 0.15mm.

Observation of features on the original edges of the nailery artefacts is limited by loss of metal through corrosion. However, examination of places where penetration of corrosion was small, as shown by the retained metal structure in the corrosion product, indicates that the deformation produced by shearing in Jefferson's nail making machine ranged up to a depth of 0.2mm at most. Small fragments of metal that were not detached from the nail during shearing retain their heavily-deformed microstructure. All these observations are consistent with cold shearing. However, they do not eliminate the possibility that the hoop iron was cut warm, but at a temperature well below that needed to recrystallize the iron.

Wrought Nails

A cross-section of a 10d rose-head wrought nail showed the ferrite fully recrystallized and free of traces of deformation. This indicates that the shaping and heading of the nail was done while it was at a temperature above about 700°C. A band of particularly large ferrite grains running along the length of the nail serves as a marker of the pattern of metal flow under the nailer's hammer. This band is bent first about 30° to one side and is then doubled over. This deformation pattern corresponds with the steps in forming the nail head described by Jefferson: the head end of the nail was first partially bent before being placed in the heading die, and then shaped into the head by several diagonal and, finally, end-on hammer blows.

Discussion

Robert Plot's 1686 description of the rolling and slitting process tells us that artisans cut hammered bars to convenient lengths and then placed them in a furnace until they reached a bright red heat. They passed the hot bars through the rolls to attain a uniform thickness and then, without reheating, passed them through the slitter discs to be cut into rods (Plot 1686). The metallurgical evidence above shows that the American makers of the nail rod used by Jefferson followed this same procedure.

Builders of rolling and slitting mills through the colonial and early years of the republic probably used designs similar to those in use in Sweden (Smith 1966). Direct evidence is sparse, however. We have few artefacts, because these mills, which required substantial power, were often placed on rapidly-flowing streams at locations that afforded a good head of water. The floods that frequent such sites have carried away traces of most of these mills. Additionally, other ironmaking enterprises often re-used slitting mills' water power privileges, as at the site of the Forbes & Adam mill in Canaan, Connecticut, later used for a blast furnace (Gordon and Raber 2000, 125). We have some information from the Saugus works in Massachusetts (now the Saugus Iron Works National Historic Site), where Americans' experience with the rolling and slitting process began with a mill built about 1647 (Hartley 1957, 179). Roland Robbins found a spacer plate and a few pieces of rolled and cut iron from the slitting mill in his excavations at Saugus. In an excavation at the site of the Dover Union Mill in Dover, Massachusetts in 1954, Robbins found the remains of the massive wheel that powered the mill and some additional spacer and slitter discs (R H Vara pers comm 2002). From examination of a piece of plate that had jammed the Saugus mill, C S Smith deduced that the slitters cut strips of hoop iron 100mm wide by 7 to 8mm thick into nine rods that averaged about 6 to 7mm wide. He inferred that the mill had slitter discs 300mm in diameter and 6mm thick that cut at a rake angle of 30 to 40° as determined by the 290mm spacing of the shaft centres (Smith 1966).

A spacer disc for the slitters found at Saugus has a diameter of only 168mm. Hence, a 65mm radius of each slitter blade would have been unsupported against lateral motion. This would make it impossible to maintain the small clearance between the blades needed for shearing without bending. The 1mm-wide bending zone with tears found in the Monticello nail rods indicates that constructing slitting mills with the necessary precision and rigidity to hold the cutter discs in alignment with close clearance remained a difficult challenge for American ironmasters into the 19th century (Gordon 2001, 40). Jefferson's complaints to his suppliers about 'flawy' nail rods, sometimes making up as much as half the content of a bundle, indicates the poor performance of the American mills in the early republic (Jefferson to Jones and Howell 1805, see Betts 1953, 445).

Jefferson's nailery remained a rural enterprise at a time when entrepreneurs in the northern states were shifting to large-scale industrial production of nails. Inmates of Newgate, the former copper mine that Connecticut turned into its state prison in 1790, stood chained to their anvils for ten hours a day making nails until the prison closed in 1827. Nearby ironmasters sought the lucrative state contracts to supply nail rod to the Newgate prison (Howell and Carlson 1980, 77). In Virginia, inmates at the state's penitentiary in Richmond were set to work making nails by about 1800 (Keene 1972). However, machines soon gained the advantage over both forced and slave labour. Thus, as early as 1798 Josiah Pierson had 96 nail cutting and heading machines operating at his slitting mill and nailery in Ramapo Village, New York (Gordon 1996, 69). Jefferson found it increasingly difficult to sell his nails, despite the relatively low cost of his slave labour, in any area that could be supplied by trade with the northern states or with England, where industrial production flourished.

Acknowledgments

The specimens from Monticello were sent to Yale for study through the kindness of David Harvey of Colonial Williamsburg and M Drake Patton of the Thomas Jefferson Memorial Foundation. Curtis White of the Saugus Iron Works National Historic Site, R H Vara of Dover, Massachusetts, and Fraser Neiman, Director of Archaeology at the Thomas Jefferson Foundation, provided helpful information. We thank Dr James Eckert for carrying out the microprobe analyses and Derek Wheeler for the photographs of the artefacts.

Appendix

Pinch and swell phenomenon (boudinage) can arise in the deformation of a material that contains layers or columns of an included substance that has different physical properties from the matrix material surrounding it. The material has to be simultaneously compressed perpendicular, and elongated parallel, to the layers. Passing a material through a rolling mill generates this kind of plastic flow.

The theory of boudinage development is derived for flow in non-Newtonian viscous materials characterized by a strain rate proportional to σ^n, where σ is the applied stress and n is a measure of the sensitivity to the strain rate (Smith 1977). A necessary condition is that the effective viscosity of the enclosed material be greater than that of the matrix. Although not usually described as viscous, plastic flow of a metal is approximated by viscous deformation with a large n while the flow of slag, a silicate with a glassy matrix, can be characterized by a smaller n. Under these conditions the ratio of the spacing of the boudins to the original thickness of the slag will fall in a range of about 5 to 50. We lack the physical property data for the metal and slag needed to make a quantitative test of the theory. However, the observed spacing-to-thickness ratio of the boudins in the hoop iron and nail rod — about ten — falls in the range of parameters expected for these materials.

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The Authors

Brook Abdu (brook.abdu@yale.edu) is a Senior in Yale College, Robert Gordon (robert.gordon@yale.edu) is professor, and Robert Knopf (n22@snet.net), research affiliate, Kline Geology Laboratory, Yale University, PO Box 208109, New Haven, Connecticut 06520-8109 USA.