Issues in the introduction of tonnage steel in the United States, 1867–1883

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ABSTRACT: Examples of the early US production of puddled, pneumatic, and open hearth steel show variable and uncertain quality due to inadequate control of carbon, phosphorus, and non-metallic inclusions. An inhomogeneous product and difficulties with process control led to the early demise of puddled steel manufacture. Analyses for nitrogen and silicon distinguish between pneumatic and open hearth steel. Makers of open hearth steel had reduced phosphorus to acceptable levels by 1873 but needed longer to gain control of carbon content. Good quality pneumatic steel was made after 1880. John and Washington Roebling, engineers with experience of metallurgy, successfully managed the transition from wrought iron to steel while building the Brooklyn Bridge. The Springfield Armory, operating within a military-government complex, used various kinds of pneumatic and open hearth steels over a decade before reverting back to iron for its rifle barrels.

Introduction

By 1865 several firms in the US had perfected the process for making cast steel in graphite crucibles (Tweedale 1987; Gordon and Tweedale 1990). Although James B Eads incorporated crucible steel alloyed with chromium in his 1869 arch bridge over the Mississippi River at St Louis (Tweedale 1987), the crucible process was not adapted to making the quantities of steel needed in the rapidly expanding US economy. Steel production by the Bessemer pneumatic process began at the Wyandott works in Detroit, Michigan, but it was Winslow, Griswold & Holley in Troy, New York, who in 1865 achieved sustained production (McHugh 1980). At the same time the American Silver Steel Works in Roxbury, Connecticut, began making steel by the puddling process. After a failed attempt to make steel in a Siemens open hearth furnace at Cooper, Hewitt & Co in Trenton, New Jersey, Wellman succeeded at the Bay State Iron Works in South Boston 1870, and a year later at the Nashua Iron Company in New Hampshire (Wellman 1902). By 1873 numerous mills were making pneumatic steel in large quantities, primarily for rails, the puddling process had been abandoned, and expansion of open hearth works outside of New England was just getting underway.

Samples of early tonnage steel were obtained for laboratory analysis from several sources. Professor George Brush at the Sheffield Scientific School in New Haven, Connecticut, collected examples of the early production of rails and puddled steel. Samples of the original 1879 deck of the Brooklyn Bridge, the first suspension bridge to have all its metal parts made of steel, were made available by Robert Vogel of the Smithsonian Institution. A particularly useful set of specimens was received from Professor C Vance Haynes Jr at the University of Arizona. He developed a technique for identifying the dates of manufacture of Springfield rifle barrels from the proof and inspection marks placed on the barrels themselves. His examples span the years from 1868 through the end of production of the model 1873 rifle in 1893, and include several sectioned breech mechanisms that he had prepared for museum display. Table 1 lists the specimens examined in chronological order.

Methods

Sections cut from the artefacts were prepared by standard metallographic polishing followed by etching with nital. Parallel flat surfaces were milled on the larger barrel samples, one of which was then polished and etched. For
the display rifle specimens areas on the sawn sections were polished with hand tools, and etched so that they could be examined with an inverted optical microscope. The Brooklyn Bridge steel specimens were large enough that tensile test specimens could be made. These were broken on a displacement controlled testing machine at a constant extension speed of 2.5mm/min on a gauge length of 42mm.

Microprobe analyses were made with the JEOL JKA-8530F Hyperprobe in the Department of Geology and Geophysics at Yale. Ordinary operating conditions used 15kV accelerating voltage and 10–20nA beam current. Energy dispersive (EDS) analyses were used to identify constituents, and wave length dispersive (WDS) analyses were made for nitrogen, silicon, phosphorus, and manganese. For the nitrogen determinations the WDS technique used 150nA beam current, and 15 minute counting time to achieve a detection limit of 0.010wt% nitrogen with 99wt% (three sigma) confidence.

Results

Ferrite, pearlite, and non-metallic inclusions are the principal constituents in all the specimens. None of the steels had been hardened by heat treating. Carbon content was found from the volume fraction of pearlite. Because the non-metallic inclusions present in most of the specimens vary greatly in size and distribution the average inclusion content is not a useful characterization of the specimens. Instead the largest inclusion found in each specimen was noted. These would have had the most detrimental effect on the strength properties of the steels.

Puddled steel

German innovators by 1850 had found that pig made from spathic ore was particularly suited to steelmaking by the puddling process (Barraclough 1990). The key step needed to make steel rather than iron in a puddling furnace was to reduce the speed of the boil by using a slag rich in manganese (Barraclough 1971a; 1971b). In 1864 a group of US investors acquired a mine of spathic ore in Roxbury, Connecticut, that contained on average 42wt% iron and 2.2wt% manganese. They organized the Shepaug Spopathic Iron and Steel Co, later the American Silver Steel Co, to make puddled steel. They built an integrated steelworks at the mine that had roasting ovens, a blast furnace, puddling furnaces, and a rolling mill. Charcoal fuel for the blast furnace was made in adjacent kilns. Steel production began 1867 (Gordon and Raber 1984).

In 1868 the steel company president gave Professor...
Brush two rolled bars measuring 13 x 45 x 105mm with attached labels reading, ‘Puddled steel, American Silver Steel Works, Roxbury’. Longitudinal sections from each bar were examined (Table 1, Sample P). EDS analysis shows that the steel contains 0.13wt% phosphorus and 0.2wt% manganese. The microstructure of both bars consists of pearlite bands ranging from 2mm to 7mm wide separated by ferrite nearly free of pearlite. Within the bands the carbon content reaches 0.6wt%. The structure is similar to that found in a specimen of English puddled steel examined by Barraclough and Kerr (1973).

Within the pearlite bands the non-metallic inclusions present consist of glass that has a high concentration of silica and manganese (Table 2) which is similar to the composition of an acid steelmaking slag and distinguishes the inclusions from those in wrought iron. Dark silica particles are visible in the largest glassy inclusions. Where the metal is free of pearlite, wustite is present in the inclusions. These originated in parts of the bloom formed in the puddling furnace where the carbon content was insufficient to react with the available wustite in the furnace slag. The presence of K$_2$O indicates use of wood fuel. Rolling mills in New England successfully used wood-fired puddling furnaces until canal and railroad construction gave them access to anthracite from Pennsylvania (Galer et al 1998). Since a railroad reached the Shepaug site only after steel production was abandoned, use of the locally abundant wood fuel would have been the only economic choice.

Uniform distribution of carbon and elimination of non-metallic inclusions was difficult to attain since puddled steel was made as a solid. Inclusions up to 4mm long were found in the specimens examined. These and the coarsely banded structure might be tolerated in applications where strength and machinability were a low priority, but would otherwise severely limit possible uses of the puddled steel. The combination of a poor quality product and a difficult process to execute led Silver Steel Company to abandon steel puddling in 1868.

Another group of US investors, probably unaware of the experience at Roxbury, was willing to try the process again. Charles Burgess received US patent 141,320 in 1873 for making steel by the puddling process. His patent specifies the conditions already established in Europe for the puddled steel process including a high furnace temperature and addition of a flux containing MnO. He had the process operating at an Ironton, Ohio, rolling mill in 1871. He and his partners established the Burgess Iron & Steel Co in Portsmouth, Ohio, where they made puddled steel for agricultural implements until 1876. Burgess, like the Roxbury entrepreneurs, found the puddled steel process poorly adapted to conditions in the US. In 1876 he had the US Siemens’s representative, S T Wellman, build an open hearth furnace for his company similar to the one built in 1870 for the Bay State works in Massachusetts (Rowe 1938, 41, 56).

**Steel rail**

The section of rail examined is 98mm high with a head 54mm wide and an 89mm base, a common size and shape of rail used in the US in 1870 (Table 1, Rail). The records of the Sheffield Scientific School indicate that it came from the Winslow, Griswold & Holley Bessemer steel works in Troy, New York before 1870. The microspecimen was cut from the bottom flange of the rail. WDS analyses show that the steel contains on average 0.32wt% manganese and 0.11wt% phosphorus (Table 3).
Constituents present in the rail microstructure are ferrite and pearlite in proportions that indicate a carbon content of 0.35wt%. The pearlite plate structure is just resolved at high optical magnification. Gray and black non-metallic inclusions are present but not abundant. The longest inclusion found in the microspecimen had a length of 0.4 mm. The gray inclusions are manganese sulphide (Table 4). Black ends on some of these are manganese silicate; others consist entirely of silicate.

Bands containing etch pits, enlarged ferrite grains, and free of pearlite are present in the rail (Fig 1). The band illustrated is over 4mm long. Non-metallic inclusions are concentrated in this band. WDS measurements of phosphorus show an increase from 0.06wt% adjacent to the band to 0.2wt% in the band. Since phosphorus increases the temperature of the austenite-ferrite transformation, ferrite grains are nucleated first in the phosphorus-rich zone during cooling, and are able to grow to larger size than those in the surrounding metal. The concentration of inclusions in the high-phosphorus bands shows that these features formed during ingot solidification. However, they are too large to be inter-dendritic segregation. Other examples of phosphorus-enriched bands were found in a breech block in one of the Springfield rifle specimens and a sample from the mechanism of a Winchester rifle, both made in 1883 (Fig 2).

**Brooklyn Bridge**

When completed in 1883, the New York and Brooklyn Bridge was the world’s longest suspension span, and the first to have both its deck and cables made of steel. John Roebling began plans for the bridge in 1856, and in 1866 redesigned the deck to eliminate all wood and cast iron structural members. When the bridge company received its charter in 1867 it appointed Roebling its chief engineer and accepted his bridge design with its cables made of steel rather than the wrought iron wire used in his earlier bridges. After the cables were up Washington Roebling, who succeeded his father as chief engineer, found he could reduce the weight of the deck by replacing the wrought iron used in his father’s design with steel. The deck steel made by the Cambria Iron Company in Johnstown, Pennsylvania, which had newly-installed Pernot open hearth furnaces, gave satisfactory service for over seventy years (Anon 1882; McHugh 1980, 307; McCullough 1992, 391–6). Samples of the structural members collected when the deck was rebuilt to accommodate modern traffic were examined.
Microspecimens of longitudinal and transverse sections of a tension tie bar designated ‘118L BSS Truss C 1204’ (specimen A) and a bar marked ‘South Face 124’ (specimen B) were examined (Table 1: BB). They are plain carbon steels with the structure of some of the pearlite close to upper bainite. The absence of pearlite-ferrite banding shows that the steel was used in the air cooled condition. Two kinds of non-metallic inclusions with lengths as great as 0.45mm are present. The manganese sulphide inclusions (Table 4) usually have small tails of manganese silicate at their ends (Fig 3). Others that are either rich in silicate or are all silicate are generally longer and thinner than the sulphide inclusions.

The mechanical properties of the deck steel are shown in Table 5, which includes data for modern hot-rolled steel of the same carbon content for comparison. The high concentration of non-metallic inclusions is responsible for the difference in strength properties in the longitudinal and transverse directions. Nevertheless, these steels have strength and ductility similar to modern plain carbon steel with comparable carbon content.

**Springfield Armory**

In 1867 the US Army urgently needed to convert to breech-loading arms made of steel to fight its Indian wars in the West. Initially the Springfield Armory, the army’s only source of small arms at that time, attached a breech mechanism to old wrought-iron barrels whose bore diameter was reduced with an inserted liner. In 1868 it discontinued using old musket barrels, and in 1873 again reduced bore diameter. The M1873 rifle remained the army’s standard weapon until it adopted a bolt-action model in 1892 (Raber and others 1989; Frasca 1997). Table 1 lists the rifle barrels examined in order of date of manufacture as determined from proof and inspection marks on the barrels by Professor Haynes. These marks define the interval of years in which a particular inspector’s stamping system was used. The final three barrels (Table 1, nos 4, 9 and 14) are from the last period of production of the M1873 rifle.

The abundant non-metallic inclusions found in all the barrels show that none were made of crucible steel. Barrel 1 (1867–9) and its inserted liner are made of the same high-quality wrought iron that the armory had used since 1859, when it adopted the technique of welding barrels in a rolling mill (Gordon 1983). Barrel 2 has a circular pattern microstructure in transverse section that shows it was made by bending a flat skelp into a cylinder that was then welded shut. The weld zone is defined by traces of slag inclusions. The weld is sound, and would have the full strength of the adjoining metal. Transverse sections of the remaining barrels show that from 1873 onward the armory abandoned roll welding in favour of drilled out steel rods that were then elongated to the required length by hot rolling.

None of the barrels is made of puddled steel. Barrel 2 is an example of early Bessemer steel. The remaining barrels fall into two groups (Table 1). Those made from 1873 to 1881 are plain carbon steels with carbon contents between 0.16 and 0.5wt%. Barrels 4, 9, and 14, made in the last period of M1873 production, are iron rather than steel.

In 1877 Colonel J G Benton, the Springfield super-

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**Table 5: Brooklyn bridge steel, tensile test data.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Orientation</th>
<th>Yield strength MPa</th>
<th>Tensile strength MPa</th>
<th>% Reduction</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>L</td>
<td>358</td>
<td></td>
<td>47</td>
<td>20</td>
</tr>
<tr>
<td>A</td>
<td>T</td>
<td>331</td>
<td>2.44</td>
<td>41</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>L</td>
<td>303</td>
<td>2.78</td>
<td>53</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>291</td>
<td>2.65</td>
<td>37</td>
<td>20</td>
</tr>
<tr>
<td>HR</td>
<td>L</td>
<td>330</td>
<td>13.71</td>
<td>51</td>
<td>31</td>
</tr>
</tbody>
</table>

Notes: L = longitudinal orientation. T = transverse orientation. HR is modern hot rolled plain carbon steel.
intendent and author of a detailed description of the manufacture of the M1873 rifle, reported that ‘The decarbonized steel now generally used for the principal parts of fire-arms, including the barrel, is made either by the Bessemer or Martins-Siemens process’ (Benton 1878, 22). Later he asserted that ‘Since 1873 all small-arm barrels turned out at the National Armory have been made of decarbonized steel (Bessemer), and about one in six hundred have been found to burst in proof’ (Benton 1878, 165). Microstructural features do not distinguish between pneumatic and open hearth steel in the rifle barrels. However, Bessemer steel made in the 19th century had nitrogen content of 0.015wt% or greater, while in acid open hearth steel it was typically 0.004–0.006wt% (Bodsworth 2000, 121). The WDS microprobe analyses (Table 3) were made to determine the steelmaking process used for the barrel metal.

Barrels 3 and 5 are representative of those with the plain carbon steel microstructure. Their low nitrogen and high silicon content show that they were made by the acid open hearth process. By 1873 this steel could have come from either the Bay State or Nashua works, both near Springfield (Wellman 1902). Barrels 4, 9, and 14 are distinctly different with microstructures characterized by very low carbon content and uniform ferrite grain size. Haynes’s classification places these in the last production run of the M1873 rifle. They have high nitrogen and very low silicon. Since silica brick lining of the 19th-century acid open hearth furnaces had a melting temperature of about 1700°C, steel with the low carbon content of these barrels could not be made in them (Bodsworth 2000, 120). Hence we interpret the last three barrels in the table as made from fully blown Bessemer steel. They show that at this late date the armory substituted iron for the stronger plain carbon steel that it had been using previously.

The rail, made of Bessemer steel, also has a high nitrogen content. Nitrogen is low and silicon high in the bridge deck steel from the Cambria Iron Company, which had the acid open hearth process operating by 1879. For comparison a published analysis of steel recovered from the wreck of the Titanic, and believed to have been made by the acid open hearth process, is included in Table 3 (Leighly et al 2001).

The ferrite-pearlite banding (Fig 4) and the ferrite grain size show that the barrel steels were left in the annealed condition. According to Benton (1878, 23–4) each barrel was heated to red heat in a reverberatory furnace, packed in charcoal with seven others in an iron box, and left to

<table>
<thead>
<tr>
<th>Table 6: EDS analyses of Springfield Barrel 2, wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>a: Non-metallic inclusions, average of 10 analyses, wt%</td>
</tr>
<tr>
<td>Na₂O</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>b: Metal, wt%</td>
</tr>
<tr>
<td>Si</td>
</tr>
<tr>
<td>0.03</td>
</tr>
</tbody>
</table>
cool for three to five days before machining. The banding and ferrite grain size indicate that the red heat used was sufficient to austenitize the steel.

Most of the non-metallic inclusions in Barrel 2, the earliest example of Bessemer steel examined, are glass but some have a crystalline component whose appearance and composition indicate knebelite (Kiessling 1978, 50). The composition of these inclusions (Table 6) is a close match to the slags formed in the Bessemer process as practiced in its early years on into the early 20th century (Barraclough 1990, 99; Camp and Francis 1919, 147). Sparse manganese inclusions are also present in the Barrel 2 steel.

In the barrels identified as open hearth steel and those from the last period of rifle production, most of the non-metallic inclusions are composite with a sulphide core and silicates at their ends, as in Figures 3 and 5. This structure is formed during hot rolling and arises from the difference in the strain rate dependence of the plastic flow stresses of the metal matrix, the sulphide, and silicate components if the inclusions (Abdu et al 2003). Barrels 2, 5, 6, and 15 all have bands or regions with enlarged ferrite grain size (Table 1) that indicate non-uniform distribution of phosphorus in the steel (Fig 6).

**Discussion**

The large and growing market for iron and steel led the firms venturing into tonnage steel production to focus on quantity and cost rather than product quality. They attempted to get monopoly control over processes and products with patents. The US patent office aided and abetted these entrepreneurs as they adopted British and European techniques for making tonnage steel, beginning with the pneumatic steel patent granted to William Kelly (Gordon 1992). Burgess’s puddled steel patent is another example: its thin technical specification recited the technique already well known in Europe and Britain.

The specimens examined here show the limits of control attained over the carbon, phosphorus, and inclusion content of the early US tonnage steel. Chemical analysis and mechanical testing lagged behind the growth of production. By 1875 progressive steelmakers such as Charles Huston at the Lukens Steel Co recognized the need for means of discovering defects in their products that could not be found by visual inspection alone (Johnson 2009, 93). However, little progress was made over the next two decades. Steel companies began to tolerate the presence of a metallographer in their works only at the dawn of the 20th century (Sauveur 1935). In the absence of these essential tools customers could not specify steel with confidence, nor be sure that they got what they paid for.

The arrival of the opportunity to use tonnage steel in the midst of rapid technological advances accompanied by some catastrophic failures of important structures created anxiety for both engineers and their clients. Railroad bridge failures due to poor design, material, or derailments caused by broken rails were a notorious problem. The disastrous collapse of the all-metal bridge in Ashtabula, Ohio, on the main rail line from New York to Chicago alarmed the Brooklyn Bridge commission trustees just at the time Washington Roebling needed them to make a decision on a supplier of steel for his bridge cables. Later, when Roebling wanted to take advantage of the higher strength of plain carbon steel to lighten the bridge deck structure, he found the bridge trustees spooked by the Tay bridge disaster in Scotland, though it is now known that the Tay bridge problem was not defective metal (Lewis and Reynolds 2002). Only after much anxiety among the trustees did Roebling get a decision to use steel in place of wrought iron. The steel furnished by the Cambria works proved an appropriate choice despite its high phosphorus and inclusion content, as was born out by the deck’s seventy years of satisfactory service under ever increasing loads. It was free of the high-phosphorus bands that are present in the early examples of Bessemer steel.

The master armourer at Springfield, an artisan rather than an engineer, made technical decisions in a much more difficult environment than Roebling did in New York. He reported to an army officer commandant who reported to the Ordnance Department in Washington, which in turn often faced scrutiny by hostile Congressional
committees. Roebling was a graduate of the Rensselaer Institute in Troy, New York, where classroom study was coupled with practice in the field. The armory and ordnance department were controlled by graduates of the US Military Academy at West Point. The West Point curriculum was based on the French model that stressed theory and mathematics but left its graduates ill-prepared to deal with problems not amenable to formal, mathematical solutions (Kranakis 1997, 241). West Point officers had a deep commitment to the order and regularity needed to organize large groups of men, characteristics that had served the nation well when the armory managed a massive increase in arms production during the Civil War. Because its acceptance of innovations was strongly tempered by adherence to traditional methods and materials, historians describe the Springfield Armory as a conservative innovator (Raber et al 1989).

Finding suitable metal for gun barrels had been a vexatious problem for US arms makers since they began mechanized production in the late 18th century. Barrels welded up from wrought iron skelps under water-power-ed hammers frequently failed in proof. Remington, Colt, and other private arms makers solved this problem in the 1840s by drilling out bars of crucible steel imported from Sheffield makers such as Thomas Firth & Sons that they then rolled to the required length (Fitch 1880, 624; Rosa 1968; Barnard 1866, 226). However, the Army Ordnance Department remained adamant in its insistence on the use of iron and, emphatically, not steel (Raber et al 1989, 153). As late as 1862 Eli Whitney Jr, then a contractor for Springfield pattern rifle-muskets, wrote to Sanderson Bros in New York:

‘I have received a letter from Gen Ripley today saying that he will not authorize the reception of steel barrels … Under these circumstances it is not prudent to give you an order now. Could you however furnish me a casting of Iron similar to your decarbonized steel, say an ingot 2 ¾ in diameter outside, with a hole and 10 inches long, weighing 11 or 11 1/4 lbs. … This ingot I would roll in the barrel machine as usual, but don’t call it steel. It must be iron. … Please consider this letter confidential – You could invoice and import the ingots as cast iron.’ (Whitney 1862)

The rifle barrel specimens examined indicate that in 1868 the armory bypassed crucible steel, then being made in quantity in the US, and made the leap to the then new and relatively untried Bessemer steel while at the same time retaining its established fabrication technique, roll welding. The armory then switched to plain carbon, open hearth steel bars drilled and then rolled to length as Colt and others had been doing for thirty years. A possible reason for the switch is lack of homogeneity in the Bessemer steel then available. Less than 2% of the Bessemer steel made in 1873 went to products other than railroad rails, which typically had a high carbon content that was not tightly specified. Bessemer steelmakers preferred to avoid making low-carbon steel, which required closer process control (Holley 1875–76).

In the annealed plain carbon steel the armory had a stronger material than either the wrought iron it had used or the Bessemer iron it would use later. These barrel steels were easier to machine than wrought iron, as was shown by the ease with which the specimens used in this study were milled and turned on light-weight machine tools. This was an important factor since the armory was unable to buy new tooling in the decades after 1865.

This decision to revert to iron in place of steel is the more remarkable since the chamber pressures developed in Springfield rifles had increased from about 76MPa in the M1868 to 170MPa in the final version of the M1873 (Haynes pers comm). The maximum tangential stresses in the barrel calculated for these pressures and the barrel dimensions increased from 117 to 265MPa. Typical yield stress for wrought or carbide-free iron is about 225MPa; some deformation of a rifle barrel made of these materials could be expected upon firing. The Brooklyn Bridge deck steel, which has 0.30% carbon, has yield strength of 358MPa. Thus the steel used for barrels in the period 1876 to 1881 would have had yield strengths well above the maximum tangential tensile stress caused by firing the weapon while the iron in barrels 4, 9, and 14 used later would not.

Why then the decision sometime after 1883 to revert to the use of iron? Inadequate materials characterization may have contributed since the armory lacked laboratory or analytical facilities for the materials it used until 1918 (Raber et al 1989, 161). The Ordnance Department had long demanded use of what it called ‘decarbonized steel’. In the conservative atmosphere of the army after the Civil War it is possible that no one wanted, or dared, challenge the accepted doctrine that rifle barrels were to be made of decarbonized steel, and that somehow the Bessemer product became identified as this material.

Conclusions

The specimens examined are a limited sample of the immense range of steel products made in the 1870s and 80s. Additionally, since these were not homogeneous materials the microspecimens may not be fully
representative of the structures and compositions of the artefacts. Within these limitations several generalizations may be drawn from the data presented. The phosphorus levels in the early puddled and Bessemer steels were high, although not so high as in some examples of wrought iron. By 1873 the maker of the open hearth steel supplied to the armory had attained phosphorus levels close to the modern limit for plain carbon steel. Zones of phosphorus concentration in steel were sometimes present at least until 1883. Close control of carbon content took longer to achieve. Although an artisan could judge the amount of carbon in steel by the way it worked while hammering it on an anvil, analyses for carbon took from two to six hours to complete in the 1870s (Pearse 1875–76), and were not yet practical for control within the mill.

Control of non-metallic inclusions proved a particularly difficult problem. Puddled steel could not match the homogeneity attained by repeated piling and welding wrought iron. The early Bessemer steel in the specimens examined had excessively large inclusions. The open hearth steel was better, probably because deoxidation done within the furnace allowed time for slag particles to float to the surface of the melt. The large inclusion content in the steel made for the Brooklyn Bridge deck may reflect the start up of the open hearth process at the Cambria works. The Bessemer steelmaker who supplied the armory in the last production run of the M1873 rifle had achieved low phosphorus, carbon, and inclusions contents.

Gaining acceptance of these steels proved challenging. John Roebling, who through his career as a bridge builder and manufacturer of wire rope had substantial experience with metals, drew on this experience to convince his backers to adopt steel in place of wrought iron for the cables of the Brooklyn Bridge. Similar experience enabled Washington Roebling to gain acceptance of steel in place of wrought iron for the bridge deck. At the Springfield Armory the US Ordnance Department’s longstanding belief in ‘de-carbonized steel’ coupled with lack of both experience and a staff metallurgist complicated the conversion of the army’s rifles from wrought iron to steel. An early example of Bessemer steel contains included slag from the converter. For over a decade the armory used plain carbon, open hearth steel whose carbon content was not well controlled. Eventually it found a source of homogeneous, carbon-free Bessemer iron that matched the decarbonized steel for which it had been searching. Despite its lower strength, and the satisfactory performance of the plain carbon steel it had been using, the armory then reverted to iron rather than steel for its rifles. (In the 20th century the armory would show a similar reluctance to adopt heat-treated alloy steel in place of case hardening for receivers and other highly stress parts of its bolt action rifles.) Inadequate means for characterizing metal properties coupled with a long, complex chain of command appears to be the cause of this dithering. The bridge builders, who were experienced with metal selection and answered to one sponsoring organization dealt with the transition to tonnage steel more successfully.

**Acknowledgements**

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