Successful Transition From Wrought Iron To Steel In Hot Work Processing With Mechanism Differences

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Abstract. The metallurgical revolution of increased supply and decreased cost followed three stages: 1) coke use in the blast furnace, 2) puddling process for wrought iron (WI) and 3) Bessemer or Siemens processes for steel. The second gave rise to the conversion from wooden (iron-reinforced) machines to iron machines such as railroad engines, ships and long-span bridges, all hot-riveted. The self-made mechanical engineers raised the precision, scale and speed of mechanical shaping technology; this was transferred from WI to ingot steel with little difficulty for the same products with increased strength. Accurately measured mechanical properties of WI and steel were related for the first time to microstructure and processing by David Kirkaldy to improve Clyde-built ships and to propel metallurgy from artisanal to science-based.

Introduction; Blast Furnaces, Blacksmiths, 'Finery' Forges

When steel furnaces were introduced into small iron works, hot working procedures developed 1780- 1860 for wrought iron (WI, highly malleable ferrite), were transferred to steel ingots that could be best processed in the austenite condition [1-7]. With little knowledge of the fundamental mechanisms, such fortuitous flexibility had precedents in blacksmithing. The equipment and techniques, vastly improved through developments in steam engines, machining accuracy and novel designs, were available to manufacture the same expanded variety of products with steel substituted for WI [6,7]. From the revolution in mechanical and microstructural testing techniques occasioned by competition between steel and WI, David Kirkaldy [8] clarified in about 1860 the optimum thermo-mechanical processing (TMP) for WI by showing that a uniformly fibrous structure (Fig. 1) had the best longitudinal strength and resistance to transverse cracking [5,6,9,10]. The defining hot work mechanism for WI was elongation of viscous siliceous slag near 1100ºC for malleability and fluxing of forge welding [5,6]. Such temperature was ideal for working ingot steel to homogenize the cast structure [5,7]. The processing alterations to overcome transition problems lead to advances in understanding of steel metallurgy over the period 1860-1920.

From ancient times, ductile deformable iron was produced as un-melted sponge mixed with slag in low-stack, low T furnaces (Catalan forge) with a mild air blow and reducing charcoal [1,2]. Much of the slag (almost liquefied) could be eliminated through hot forging to long strips that could be welded together by hot hammering. During the Middle Ages in Europe, liquid pig iron (3-5%C) from improved high-stack blast furnaces was easily cast into inherently brittle products. Such cast iron bars were decarburized by long heating in 'finery' forges (excess air) accelerated by hammering into thin strips [1,2,10]. As introduced by Rèaumur (1722), high-graphitic grey iron could be distinguished by its fracture appearance from low-C white iron (specular Fe_3C facets) that was much more easily decarburized [9,10]; such fractography was a first step in understanding iron structures. In the decade before 1750, the European iron industry was in crisis as charcoal became increasingly scarce and costly. Iron production in Britain dropped to about 17,000 t/y (tons per year), requiring imports of about 4kt/y from American colonies that later used the 10kt/y capacity to arm the revolution [10]. British industry with conversion to coke (1750) and the puddling process below (1780) exported in 1840 some 100kt of bar iron to America, 30% of its production [2,3,10].

Before 1780, the costly difficult production of WI limited it, on one hand, to special consumer products (farm implements, barrel straps, chains) from blacksmiths who also had the capability of laminating it with even more expensive and rare steel for cutting edges [1-4,9]. Millwrights built water wheels, wind mills and mine hoisting machinery out of wood reinforced by iron straps attached by nails or cold riveted rods since nut-bolt pairs were hand made at much cost [1-3,10-12]. Wrought iron was essential because it had high ductility and strength in the longitudinal direction, due to the ductile iron grains; transverse cracks had a fibrous (silky) appearance (now referred to as dimpled) due to formation of voids at the slag [5,8-10]. In addition, bifurcation along slag stringers blunted cracks with longitudinal splitting, a failure behavior, some what like wood. The only mechanized forming equipment was tilt or helve type forging hammers (hinged at middle or end, raised by water-powered cam) [1-4,10]; light rolling and wire drawing were done by hand.

Wrought Iron (WI) by the Puddling Process

As the first stage of the metal industrial revolution, hard coke in plentiful supply from coal (replacing charcoal by A. Darby, 1750) permitted higher blast furnaces and stronger blast delivered from steam blowing-engines to increase the output and quality of pig iron at reduced cost [1-4]. As the second stage about 1780, H. Cort developed the puddling process, in which suitable pig iron (selected by fracture [9,10]) with slag and mill scale was melted in a reverberatory hearth (hot gasses from a separate fire box reflected from the roof) [1-5,10,13,14]. As air was forced into the liquid by stirring, skilled puddlers could gage the reduction in C producing 200 kg of sponge iron and slag in two hours. After rapid transfer to forging hammers, much liquid slag was ejected as fiery sparks, as elongated rectangular muck bars were produced, usually finished by rolling [1-5,10,13,14]. The muck bars piled together and wire bound were worked to consolidate them by hot pressure welding fluxed by slag; such lamination refined both phases and redistributed any defects. To improve quality, the bars were once more bundled and forge welded into billets or slabs of suitable dimensions as feedstock for rolling mills [1-5,10,13,14]. Large blooms could be created and manipulated by derricks for forging into large anchors and shafts for steam ship engines.

With inexpensive iron available, even with unmeasured mechanical properties, craftsmen expanded its application and developed the demand for a greatly increased range of shapes in dimensions beyond those of wood. To create larger structures (lighter, safer than brittle cast iron), hot driven rivets were developed, becoming the essential, dependable joining technique when nuts/bolts were costly and fusion welding unknown [1,6,11,15]. Driving about 250 rivets per shift required 4 men: i) to heat to cherry red (~1000ºC) in a forge, ii) to support the head end in the hole with a heavy maul and iii) two alternating nine pound hammer blows to upset the shank into a second head. Shrinkage from 800ºC cooling produced a clamping force that provided water tight joints for boilers and plate-rib ship hulls, conferring improved safety and efficiency [1,6,11,15]. Railroad rolling stock subjected to unprecedented speeds and repetitive stress suffered novel fatigue failures that some said arose from cold transformation to brittle mineral-like crystals (Fig.2)[1,8,11,12]. Railroad needs for river crossings gave rise to successful fabrication of long box girder spans (below) that supplanted overly flexible suspension bridges (eye-bar chain, Telford's Menai Bridge) [6,10,16].

The extensive capabilities of WI gave rise to a revolution of mechanical engineering into an era when machinery was built entirely of iron. Without defined WI mechanical properties, artisanal design was extended through experience with component service failure. In the factories, more powerful, accurate machines were powered by Watt's improved steam engines that benefitted from WI components [12]. One of the new manufacturers, M. Fairbrain, a Scott trained as a millwright in England, became a designer/builder of efficient factory power transmission systems (overhead shafts and belts) [1,11,12]. In the building of plate-rib iron ships, his testing determined the

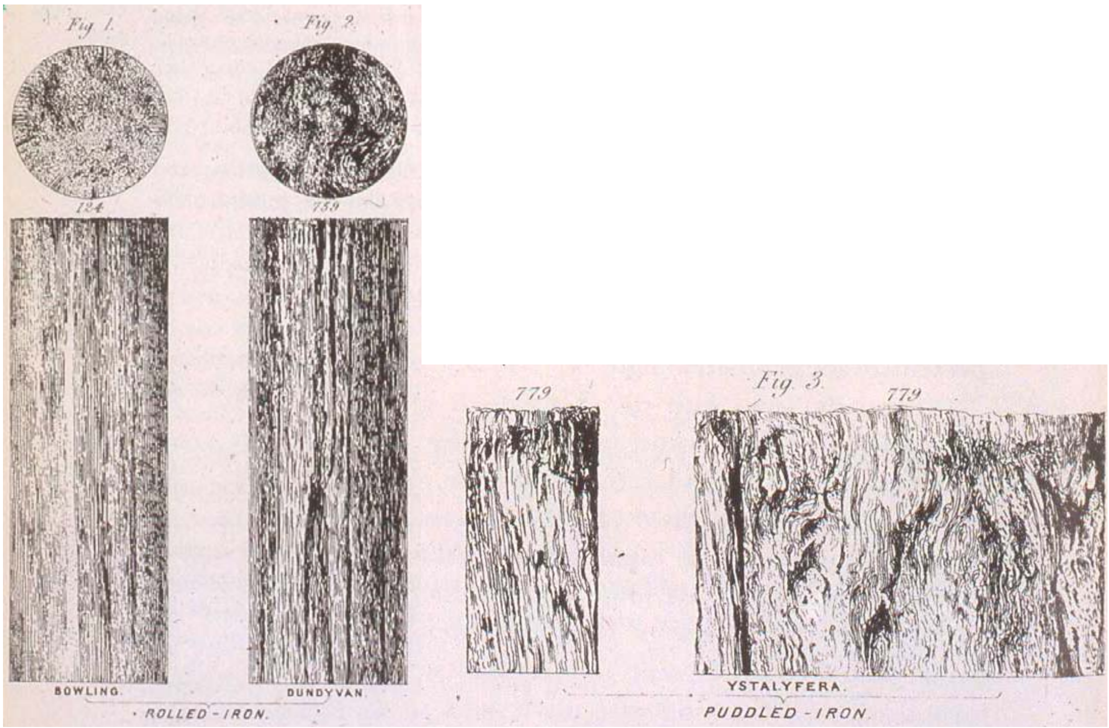

Figure 1. Etched microstructures of wrought iron showing slag stringers: a) elongated, parallel in rolled bars on left and irregular from primary hammering on right, as prepared by Kirkaldy about 1861, (after C.S. Smith, 1960 [9]).

optimum spacing and number of rows of rivets [1,11]. With R. Stephenson (railroads) large scale tests of plate-rib tubes optimized to a rectangle (reinforced top and bottom) that proved highly successful in both Britannia Bridge (over 100 years service) and Victoria Bridge (Montreal 1858) and helped establish beam theory [10,11,24]. He wrote a significant book on iron and steel manufacture, properties and application [1,11]. Other self-developed engineers improved techniques and metrology in machining, established universal standards for screw threads and wires [12], and designed building structures like the Crystal Palace (London). The worldwide railroad expansion 1825-65 depended on improved speed and safety derived from lighter, stronger rolling stock, rails with switches and bridges dependent on strong, ductile WI.

Scottish Iron/Steel Industry- Properties, Microstructures

The Scottish iron industry is described in a simplified perspective as a local-resource industry expanding, modernizing, and diversifying into a world producer. In 1759, J. Roebuck and English iron masters set up Carron Iron Works with local raw materials and good water power to drive cast iron blowing tubs (J. Smeaton, 1760); it had a good reputation notably for short bore cannon [12,14]. A subsidiary Clyde Iron Works (with two blast furnaces) and many rivals sprang up along the Clyde where in 1790 pits near Cambuslang produced 30,000 tons of coal (C) that did not coke well [14]. About 1810, D. Mushet discovered that raw pit coal could smelt black-band iron-stone containing 10-15% fine coal; this was applied at many works in Britain [12,14]. In 1828, J. B. Neilson, a Glasgow gas-works engineer, showed that hot blast could raise production rates as in a Clyde Iron Works furnace: 1811, 2,500 t/y iron (I) with $10.2t_C/t_I$, 1828, 5,900 t/y with $8t_C/t_I$ and 1832, 12,000 t/y with $2.1t_C/t_I$. Scottish iron production between 1830 to 1847 rose from 38 kt/y to 540 kt/y representing 27% of British output [1,13,14]. Coat-bridge town became a major center with 50 blast furnaces whose flames turned the night into day and created the highest pollution in Britain [13,14,17]. In Lanarkshire at the peak in 1870 with 40% of Scottish workers and 25% of steam power, some 90 blast furnaces produced about 600 kt/y (equaled in 1951 by output from 3 furnaces at Colville's Clyde Iron Works) [1,13,17]. By 1878 as local coal and ore were depleted, output fell to 14.5% of British production [13,14].

The Scottish pig iron had notably good castability so about 75% was exported throughout Europe [14]. The industry was slow to extend into wrought iron that never went to rails. Calderbank Iron Works rose to 6 blast furnaces and 60 puddling furnaces by 1880 to manufacture boiler and ships' plates with a reversing mill (closed 1887) [14]. Blochairn in Glasgow with 54 puddling furnaces produced about 33% of Scotland's ship plates and angles in 1872. Between 1871 and 1883 at Hallside and Blochairn in Glasgow, the Steel Co of Scotland constructed 26 Siemens open hearths (totaling 150t), first for rails and later for heavy angles, forgings and plate. With the 1848 arrival of rail connections, Motherwell became a center of puddling, forging and rolling. Colville's Dalzell Works founded with puddling in 1871 switched to 4 Siemens furnaces in 1880 [14,17,18]. In 1887 Clydebridge was started and expanded to six 40t and two 60t open hearths with associated rolling capacity but became effective only when taken over by Colville's [17,18]. About 1860, Bessemer converters were introduced unsuccessfully because the pig iron was not suitable but after 1885, output of four 10 ton converters was rolled for tin plate [14]. By 1880 Scotland produced 85 kt of Siemens steel and doubled that in the next year; in 1892, WI accounted for 300 kt and steel 675 kt [14]. Between 1914 and 1940, Colville's amalgamated many works, including Clyde Iron, Clydebridge and Steel Co. of Scotland with concentration near Motherwell [18]; such integration occurred much earlier in the USA. Colville's works Dalzell and Clydebridge have continued to produce and heat treat plate, becoming in mid 20th century part of British Steel and near its end of Corus Steel; on closing in 1977, Clyde Iron had poured 20Mt since 1888 [18]. Before addressing world conversion from WI to steel, development of testing to distinguish the properties is described.

As steel became more plentiful at about 50% premium in price and strength over WI, it became necessary to compare their properties accurately [1,8,11]. David Kirkaldy of R. Napiers foundry and shipyard, who tracked the performance of ships with different materials, studied mechanical properties of various grades of WI and of steel provided by many manufacturers. He developed accurate tension testing techniques for slow, fast and repetitive loading, measuring elongations and reductions in area [8,21-24]. The properties for WI were related to the uniform distribution and refinement of the slag stringers (Fig. 1), thus the first theory of TMP, properties and micro-structures. From plain and notched tensile specimens (Fig.2), he confirmed (with Fairbairn) that crystalline fracture was simply a different mechanism of crack propagation [8]. After publishing papers and a book (1861) [8], he turned to designing improved testing machines and setting up an independent laboratory that became a model around the world and operated for a century. Because of such facts (not opinions)[21.22], Lloyds Insurers approved reduced thickness by 20% in steel ship plate for greater capacity and life, Clyde building of commercial steel ships rose from 200 tons (out of 200kt) in 1871, to 75kt in 1881 and 145kt in 1884 [13,14]. In 1889 the great Forth Bridge (two spans, second longest cantilevers in the world, J. Fowler, B. Baker) utilized steel plate and rib technology (Brittania Bridge [10,16]) to create the principal members as circular tubes [25.26].

Mechanical shaping processes were increased in force, speed, shape intricacy and dimensional control by introduction of steam power and improved mechanical linkages [1-5,7,11,12,22]. Forging hammers changed to post or C-frame type with the hammer force controlled by a double-acting steam cylinder invented in 1838 by J. Nasmyth [5-7,12]. Rolling mills, although steam driven, depended on manual manipulation of the material; instead of being lifted over the top roll, the plate was raised less in a 3-high mill to be pulled back through the upper gap. The size of plates was limited to about 2 m x 0.5 m by the inadequate transfer equipment [1,10,16]. By pack rolling, up to 8 thin sheets could be produced for tin coating, or for food containers [5,6]. Grooved rolls were developed for rolling bars, rods for wire drawing, simple shapes and rails. Sheets could be

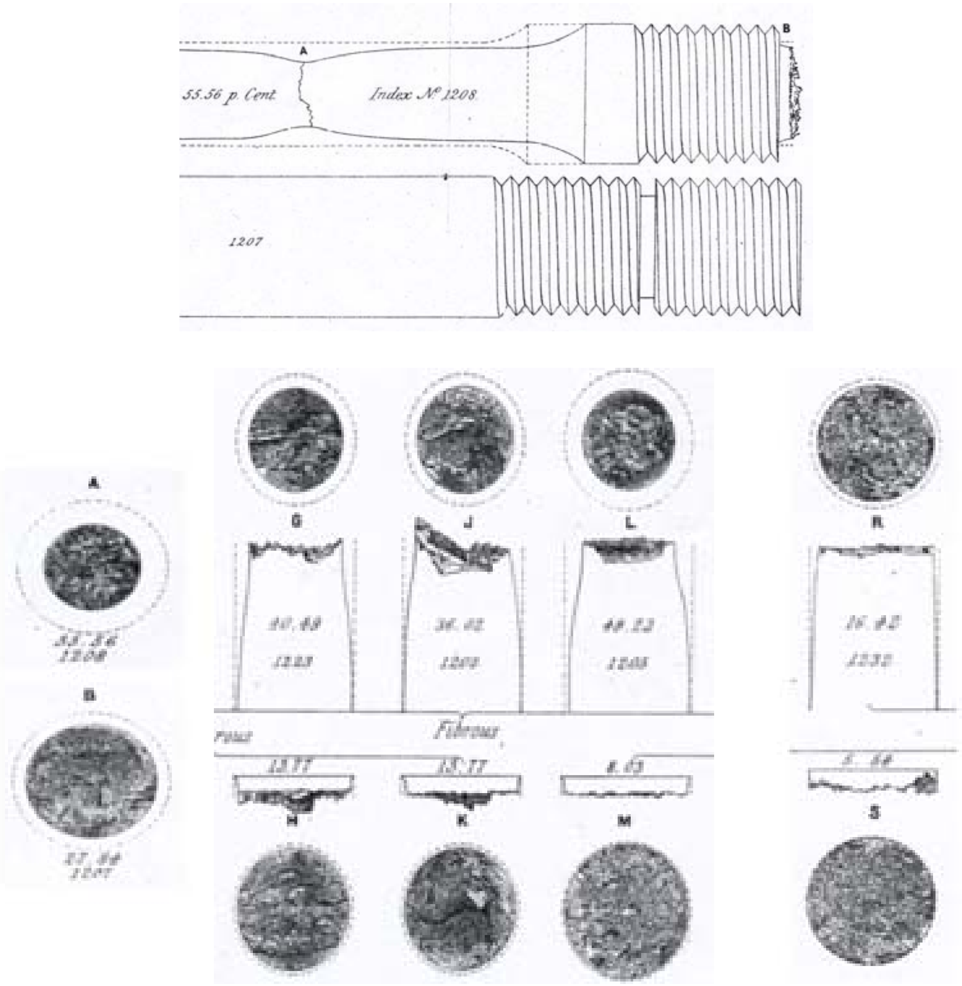

Figure 2. Differences in WI fracture behavior were exhibited on same bar (top, for $A_{1s}B_{1s}$) by first pulling notched part (B_{1n}) and, after machining to notch radius, the long smooth gage (A_{1s}). From the fractographs in similarly forged pairs (1,2), (3,4) and of variously cold worked bars (5), Kirkaldy refuted cold crystallization.
Long smooth gage (s)…………………………….... Notched (n)
A_{1s} with 56 %red was fibrous, softer (59 kpsi) …….B_{1n} was mainly fibrous with 29 %red (% reduction)
L_{2s} with 49%red, was harder (65 kpsi) ……………M_{2n} snapped, being highly crystalline with 13 %red …..
G_{3s} was 100% fibrous (40%red) …………………. H_{3n} was 96 fibrous (14 %red)
R_{4s} was only 12% fibrous (16 %red)……………... S_{4n} snapped, only 4% (6 %red).,
J_{5s}* was 100%fibrous…………………………..... K_{5n}* snapped with 22% fibrous….*see below
in $J_{5s}K_{5n}$* lightly cold hammered bar; in more hammered bars, both regions lower in reduction and fibrosity. Finally for 4 same-sourced long specimens, 3 with reduced smooth gage were elongated with 100% fibrous fracture and the 4th with center notch snapped with only 10%. (summarized results of Kirkaldy [8])

longitudinally slit and bent into angles. Heated straight narrow strips (skelp with beveled edges) were progressively curled into tubes with hot pressure butt welds from drawing through conical dies (bells) [5,27]; efficiency was raised by introducing continuous coiled steel strip and later by roll applied curling and closing pressure. Mannesman tube piercing (1865) failed on WI due to distributed slag stringers but succeeded industrially in 1885 on deoxidized steel with low voids [5,27].

Transition from Iron to Steel

Shortly after 1860, the age of steel dawned, as large scale production replaced small difficult methods such as cementation of solid WI in charcoal or crucible melting with suitable slag, alloying

Figure 3. Substitution on the 2 km (25span) Victoria bridge in 1898 of the steel truss spans (right spans) around the 1858 single-track tube (WI box-girder, left spans) was supported by a wider, higher construction frame (second span from right) directly resting on the piers; however, it could be rolled forward span by span, being supported on the tube [6] (Notman Photograph, McCord Museum, Montreal).

and charcoal [1-5]. Steel was stronger and harder but less tough, as Fe_3C content rose notably being greatly improved by quenching and tempering [7]. About 1865, in an extension of the puddling furnace, the Siemens-Martin open-hearth (Britain-France) used regenerative pre-heating with a clean burning fuel (as town gas) to keep the steel liquid [2-5]. The Bessemer-Kelly converter (Britain - U.S.A.), in which air was blown through the molten blast furnace pig, was effective for low P ore. Truly functional quality needed additions of an Fe-Mn-C alloy (R.F. Mushet) and a method to stop blowing at correct C content (G.F. Coronson) [3-5]. Finally about 1875, basic slag (and suitable refractories) was developed for high P ore by S.G. Thomas and P. Gilchrist. Because of 50% superior strength, steel had been used in many merchant ships by 1865, but the British Admiralty maintained that it was brittle. Bessemer himself countered with visual proofs of its high ductility in upsetting, tension, twisting, bending and cupping tests, both hot and cold [19]. The brittleness had been induced by WI workers inadvertently over heating to liquefy low melting impurities at the grain boundaries.

Steel production by the Bessemer process often was introduced into iron works equipped with forging and rolling equipment. While ingot casting practice had to be developed, the product was as large as bundles created from many forged and rolled WI bars. In the austenitic state, steels of high C content (even up to 1%) were as soft and ductile as WI; eutectoid steel rails (0.8C) could be rolled down to 720˚C, whereas wrought iron had to be shaped above 900˚C [5,7,20]. All primary hot working technology could be transferred from iron to steel. Rolling technology was advanced rapidly through 2-high, 3-high, 4-high, reversing and continuous types with innovations conceived, brought to plant effectiveness and transferred with improvements [5,7,14,20]. American industry expanded from 22kt in 1870 to 11Mt in 1900; often with optimized conditions so that productivity exceeded that of the British originators [5,7,20]. In Canada, rolling mills in Montreal for sheet and in Hamilton for rails progressed from WI to steel about 1880; two integrated steel mills mainly for rails were founded in 1901 [20]. In the world, annual steel production rose rapidly from 60kt in 1850 to 0.5Mt in 1870 and to 28Mt in 1900 (Britain 4.9Mt), while puddled iron fell from 3 to 0.5Mt (Table 1) [2,3,6].

Introduction of steel was slower in applications where the properties of WI gave satisfactory results (Table 2); while in shipbuilding, conversion was complete by 1890, for railroad axles during 1890-1910 and for cast charcoal-iron wheels during 1900 - 1910 [2,3,5,26]. In rails, where wear resistance was increased over iron by a factor of 18, steel had replaced all rails in service by 1890.

TABLE 1: WORLD PRODUCTION OF IRON AND STEEL [1,2,6]

	1850	1870	1880	1890	1900	1918
PIG IRON (COKE BLAST FURNACE)	4.8 Mt#				39 Mt	
BRITAIN	2.4 Mt				10 Mt	
GERMANY	2.4 Mt				10 Mt	
USA					13 Mt	
(% PUDDLED)		(*70%)		(*5%)		
CHARCOAL (CAN.)	5 kt ##	10kt	(1885, 4. kt)		18 kt	0 kt
COKE, (CANADA)		0kt	(1885, 20 kt)		80 kt	3 Mt
PUDDLED IRON	3 Mt				0.5 Mt	
BRITAIN	0.5 kt					
CANADA						
STEEL			(1873)		28 Mt	87Mt
BRITAIN	60 kt	0.5Mt	(0.65 Mt)		4.9 Mt	11 Mt
GERMANY	12 kt				8.0 Mt	
USA	0.2 kt	22kt	(0.2 Mt)		11 Mt	50 Mt
CANADA**					0.1 Mt	1.9 Mt
** CANADA: 1910~0.5MT, 1938~1.2MT, 1945 2.9MT, 1960 5MT, 1970 11MT						

\# Mt, million metric tons (mega tons) ## kt, thousand metric tons (kilo tons)

TABLE 2: APPLICATIONS TRANSFER FROM WROUGHT IRON TO STEEL [1,2,6]

	RAILS	AXLES	WHEELS	SHIPS	BRIDGES	BUILDINGS
STEEL BEGINS	1865* 1878†	1890	1900	1860	1870	1888
WROUGHT IRON ENDS	1890	1910	1910	1890	1890	1900‡
*Pearlitic, steel 18 x life of iron, †Bessemer North America, ‡1889 Eiffel Tower 300m						

In the first 12-story skyscraper with a structural skeleton, Bessemer steel was substituted after 6 floors of WI so that weight saving permitted addition of 2 more floors. Nevertheless in 1889, wrought iron was used throughout the Eiffel Tower. In 1898, the single-track WI tubular girder Victoria Bridge was replaced with Pratt trusses (double track, twin roadways); the 4x greater load required only doubled weight of Bessemer steel from U.S.A [6,19]. In bridges (American Society of Civil Engineers against it because of brittleness in a frost), steel was utilized for the highly compressed tubular arches of the first bridge across the Mississippi (J. Eads, 1874, St. Louis), and in the main chords of a cantilever bridge across the Niagara gorge [6,26]. The first all steel bridge in USA was a cantilever across the Mississippi in 1878; and for Canada in 1884 on the CPR transcontinental in Fraser Gorge [6]. In 1916, the world's longest cantilever at Quebec utilized 50% Ni steel to reduce weight [25,26].

Conclusion

The transition in hot mechanical shaping from wrought iron to steel was achieved through the efforts of craftsmen without knowledge of the microstructural mechanisms that defined optimum processing today. Instead of being worked at 600 to 700ºC as would ferritic alloys, WI was shaped at 1000-1100ºC where the silicate impurities were highly plastic and served as a flux for pressure welding. Such hot forming provided ideal ductility for ingot steel as austenite to facilitate break down of the cast structure. Moreover, steel flourished because it could fill all the WI markets with improved performance. The competition between the two materials encouraged accurate determination of mechanical properties and their relationship to microstructures and processing as initiated by David Kirkaldy who went on to develop improved testing systems that spread throughout world industry. It took almost a century before the scientific knowledge developed into thermomechanical processing such as controlled rolling of steel.

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