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Reproduction of Authentic Historical Soft Iron Wire for Musical Instruments

Stephen Birkett and Paul Poletti

Introduction

Many of the historical materials used in making early musical instruments had unique properties that are critical for accurate mechanical and/or acoustic behaviour. These include particularly those materials that are directly involved with sound production, such as wire (iron, brass, steels), gut, quills, leathers, cloths (felts, wool), and animal glues. Even though all of these materials have nominal modern counterparts these are in no sense equivalent and generally have very different physical properties from the historical ones. *Ad hoc* solutions to the problem of critical acoustic materials have led to a variety of modern substitutes, but these are generally compromised in some way as compared to their historical "equivalents". The differences can be attributed to: (i) the basic raw material itself; (ii) the specialized processing which transformed it into a practical material product; and (iii) the methods of using the product in applications in instruments.

The traditional approach to reproducing historical instruments, *viz.* a careful reconstruction of the designs and methods of the historical builders, has largely been successful when applied to instruments that were originally made in a crafts based tradition. However, following this approach to replicate a specialized historical product, such as soft iron wire, is not a viable proposition, as it would require Herculean efforts to duplicate the entire associated industry. The problem can still be addressed pragmatically without having to accept a compromised modern substitute material. This can be done by studying the manufacturing processes in order to develop an understanding of which steps were critical in achieving the desirable material properties. These manufacturing processes can then be successfully adapted to the modern technological context while recognizing the obvious prevailing economic constraints that ultimately determine what is feasible. Moreover – and this is a point that is often overlooked – having an exact replicate material is not sufficient for success, unless its correct use in the historical context has also been accurately determined.

Developing a modern replica for historical soft iron wire stringing material is a particularly challenging problem that needs to be addressed urgently, due to the rather unsatisfactory nature of the available materials and the potentially large impact such a product could make. The technology for making iron wire changed very little from the earliest medieval product (Paar & Tucker, 1977) to well into the nineteenth century (Pleyel, 1830). Consequently, essentially the same wire product is applicable for stringing quite a wide range of historical keyboard instruments from throughout this lengthy period, including virginals, spinets, harpsichords, clavichords, classical pianos, and early romantic pianos, both restored antiques and modern copies. A research project is currently underway at the University of Waterloo, in collaboration with the Materials Technology Laboratory of the Canada Centre for Materials and Energy Technology (CANMET), with the objective to develop an economically viable modern technique for replicating historical soft iron wire and to make recommendations for process and operating parameters applicable to commercial production.

Historical Iron and Steel Wire

It was not necessary for historical builders of stringed keyboard instruments to distinguish between iron and steel in their terminology, because steel wire in the modern sense was simply not available prior to about 1830. The question of whether "white wire" in a stringing schedule was intended to be iron or steel is therefore quite easy to answer, except perhaps in the transitional period around 1830 when some builders were still using soft iron and others had changed to an early steel.[1] During this period the instrument design may suggest a stronger wire type but steel wire was not automatically adopted by all builders, due to its expense, availability, personal aesthetic preference, and perhaps a sense of conservatism.

Modern steel music wire is the end product of a series of nineteenth-century inventions and manufacturing innovations which began with the 1823 discovery by Webster of the effects of manganese on the strength of iron wire. By the 1830s some of the more progressive piano builders had already adjusted their designs to take advantage of the increased strength of this Birmingham wire. Further increases in tensile strength[2] were obtained, until, toward the end of the nineteenth century, steel wire of essentially modern specification was being made and used by piano builders.[3]

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[1] Steel wire drawing is a separate and difficult problem which must be addressed for stringing pianos from the 1830s until the end of the nineteenth century. Early steels are very different from both soft iron and modern steel music wire.

[2] The breaking strength of a material when subjected to a tensile (stretching) force. Relative values for different wire samples can be compared in the workshop using a monochord to determine the pitch at which each breaks for a given reference length. (Absolute tensile strength is often expressed in MPa.)

[3] It is often stated that the modern piano became possible on account of the iron frame. In reality, the iron frame became necessary because of the increased tensions that became possible on account of the development of modern steel music wire.

During this period, there was a continuing, almost Olympian, competition between wire makers to demonstrate their prowess at making a stronger product, and to show this at the various industrial trade shows and exhibitions of the time. This focus on tensile strength diverted attention away from the considerable associated effects which were coincidentally being made on the tonal properties of music wire. High tensile steel piano wire exhibits a significantly different vibrational behaviour from the iron wire that was still being used at the beginning of the nineteenth century, as can be demonstrated by qualitative comparative assessment. For example, modern steel music wire has a noticeably more metallic sound, with more prominent, and more slowly decaying high overtones, than the sound of modern soft-drawn, low-carbon steel wire, which is currently the closest product available as a substitute for "historical iron wire". It is likely that similar, and possibly considerably larger, tonal differences would also be observed in a comparison between this substitute steel wire and authentic historical soft iron wire, which is known to have been totally carbon-free (Goodway & Odell, 1987). Since tone is a critical factor by which instruments are evaluated, the potential impact from making available commercially an authentic historical iron wire is likely to be very large.

Carbon steel music wire is noticeably more stiff than soft iron wire, as can be verified simply by handling the two products. An increase in inharmonicity, i.e. a sharpening of overtones due to the increased stiffness, is often given as an explanation for the brighter sound of steel wire. This is unlikely to be the reason for the perceived tonal differences, though, as can be shown by a comparative assessment of electronically generated sounds differing only in the level of inharmonicity. The cause of the metallic brightness of steel wire may indeed be related to its increased stiffness, however, but for quite a different reason than inharmonicity. In particular, a small increase in stiffness is also associated with a quite large decrease in internal damping, i.e. the dissipation of vibrational energy at the molecular level in the crystalline structure of the wire (Koester, 1940). This effect could certainly explain the perceived mellowness and pleasant sound of soft iron wire, especially considering that traditional historical manufacturing processes automatically resulted in a product with a significantly higher internal damping as compared to that of carbon steel wire (Goodway & Odell, 1987). This hypothesis is being investigated as part of the research project at the University of Waterloo.

Reproduction of Historical Iron Wire

The accurate reproduction of soft iron music wire is a complicated and difficult undertaking, yet one which may be successfully accomplished with some careful preliminary analysis and experimentation. Modern metal production methods are completely different from historical ones. The approach used so successfully by modern makers of historical instruments – duplicating the workshop techniques and use of materials of the ancient craftsmen – is not an option for making soft iron wire, since it is neither economically, nor practicably, feasible to re-create the entire industrial activity, from mine pit to smelting furnace, ingot-casting, fining, swaging, and wire manufacture (Rees, 1968). Moreover, the iron alloy which was the starting point for historical drawing of soft iron wire, though commonplace until at least 1830, has today become an "exotic" metal and is not available commercially. Modern steel would be a poor substitute, as it includes elements which conflict with the duplication of antique alloys, and these impurities are also difficult to remove from available commercial raw iron sources.

On a more positive note, a great deal is known about historical iron wire-drawing (Pleyel, 1830; Schubert, 1957; Thomsen & Thomsen, 1974; Paar & Tucker, 1977), and it ought to be possible to develop modern metallurgical production techniques which can effectively replace the heavy industrial processes. Moreover, the final stages of fine wire drawing are likely the only critical production steps in achieving a product with the desired physical properties, and these were relatively simple and inexpensive to operate, so it is quite feasible to re-create them exactly in a modern operation. On a practical level more information is required about the quantitative aspects of historical iron wire making, such as drawing speeds, annealing diameters, and so on, and appropriate information must be determined experimentally before genuine reproduction wire can be accurately duplicated.

Historical soft iron wire must have been a consistent product, in principle, because the essential aspects of its manufacture had to be quite strictly followed to avoid failure altogether and broken wire. The importance of this is demonstrated, for instance, by the disastrous start up problems encountered at Tintern in the sixteenth century (Rees, 1968; Paar & Tucker, 1977). Even so, variation in quality and physical properties can be expected, as this would have been affected by differences in the original ore used, or according to the expertise of the (often independent) workers involved with the intermediate steps, or indeed, the fine wire drawing process, itself a highly specialized trade.

The typical alloy composition has been determined for several samples of mid-eighteenth century harpsichord wire (Goodway & Odell, 1987). Further analyses are required for wire samples from pianos *ca.* 1800 and later, to confirm that no significant change in alloy composition occurred before the early steels of the 1830s. In contrast to modern high-carbon steel music wire, soft iron wire has a very high phosphorus content (~0.15%), which is considered highly undesirable in modern steel (0.003%), and essentially no carbon (traces vs 0.95%). Some basic preliminary investigation of the physical properties of this phosphoric iron material has already been done (Goodway & Fisher, 1988; Goodway, 1999; Stewart *et al*, 2000), but considerably more work is required before a thorough understanding is achieved, especially with regard to the interactions between manufacturing processes and the elastic/plastic properties of the wire product. These factors ultimately relate to both practical design issues (string scaling) and aesthetic musical ones (tone quality).

Thus the specific problems that must be addressed, in order to reproduce historical soft iron wire, are: (i) obtain an economically viable source for iron alloy of the correct chemical composition, (ii) devise modern processes which duplicate the products of the heavy industrial aspects of historical manufacturing of iron wire; and (iii) determine appropriate operating parameters for the process of drawing the fine wire. The first two of these problems may be addressed by application of modern metallurgical analysis and laboratory-controlled techniques to produce the appropriate iron alloy as a raw material and tranform it into coarse wire. As for the third problem, the relationships between drawing parameters and the physical properties of the wire produced must be quantified through experimentation. Meeting the pragmatic objective of reproducing the historical product does not require consideration of theoretical metallurgical explanations or mechanisms, although this may provide some useful direction in focusing the investigation.

The Historical Iron Wire Industry

The basic historical processes used for making soft iron wire (Figure 1) were remarkably consistent over a period of several centuries, the only real change being a gradual mechanization, introduction of water power, and an increased scale of production output. Historical sources provide good documentation, for example: Rudolf of Nuremberg 1350; Biringuccio 1540; documents associated with Tintern Abbey 1566–1860; Diderot 1758; and a patent application by Ignaz Pleyel 1810 (Schubert, 1957; Rees, 1968; Paar & Tucker, 1977).

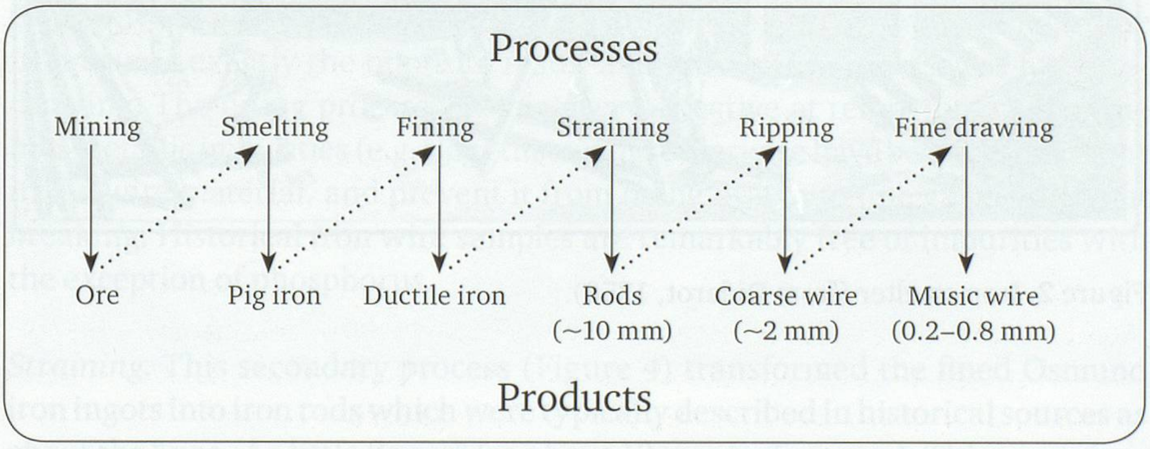

Figure 1. Historical industrial processes and intermediate products in iron wire manufacture.

Mining and smelting. The basic raw material – so-called *Osmund iron* – was produced from selected ores, which were smelted (Figure 2) and cast into long ingots called pigs (Figure 3). A specialty product was essential to ensure the subsequent successful production of a high quality iron wire with sufficient ductility[4] and strength to be drawn into fine gauges. This was achieved by following a smelting process that maximized the content of phosphorus, although this technique certainly was the result of experiential pragmatism (Vizcaino et al, 1998), rather than scientific knowledge, since the presence of phosphorus in iron was not known until 1784 (Smith, 1968).

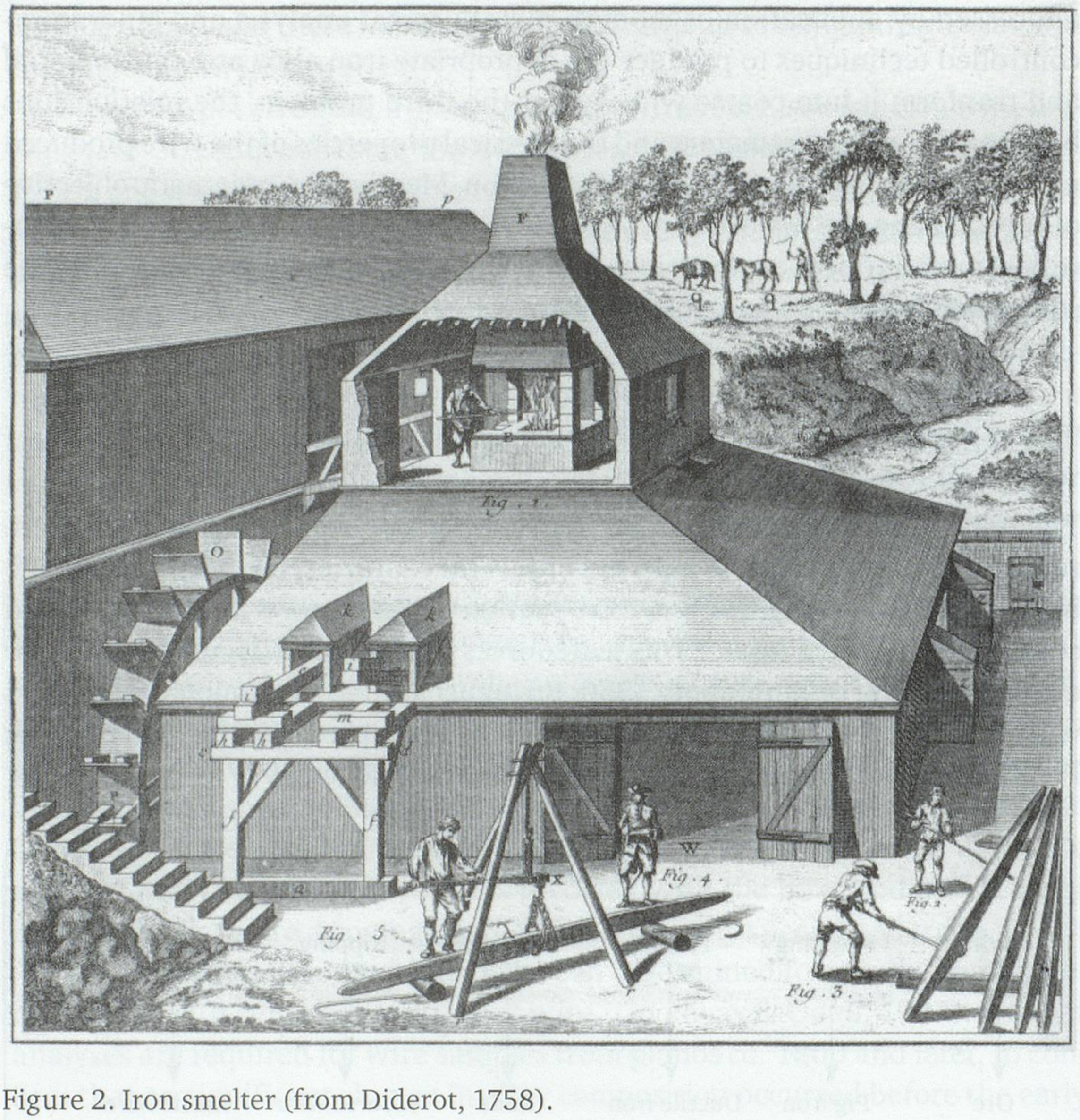

Figure 2. Iron smelter (from Diderot, 1758).

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[4] The property of metals that enables them to be mechanically deformed without fracture when cold. Usually measured by elongation and reduction of area in response to application of a given stress, such as occurs when drawn through a die in the wire-making process.

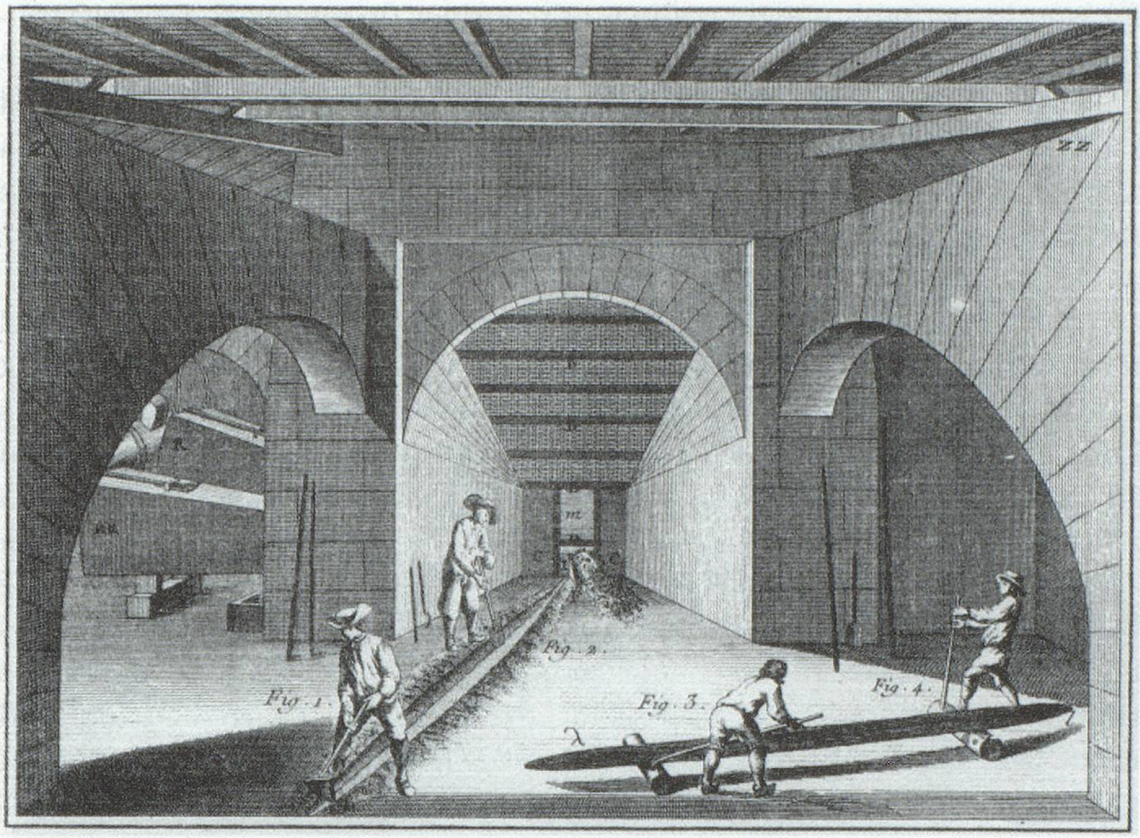

Figure 3. Casting of pigs (from Diderot, 1758).

Fining. In order to produce an iron product suitable for wire drawing a powerful decarburization and purification process was necessary. This laborious operation required a highly skilled worker who slowly collected small quantities of molten iron (about 10 kg at a time) on the end of a long staff. This material was passed repeatedly through the blast in a specially hot forge, with the result that the material was almost totally de-carburized, i.e. all the carbon was removed from it. This was critical for success, because phosphorus strengthens iron and enhances ductility only in the absence of carbon (Hopkins & Tipler, 1958; Goodway & Fisher, 1988; Stewart *et al*, 2000). Any carbon remaining in the iron causes exactly the opposite result and makes the iron useless for wire-drawing. The fining process was also very effective at removing most of the non-metallic impurities (e.g. slag) that would otherwise have become inclusions in the wire material, and prevent it from being drawn to fine gauges without breaking. Historical iron wire samples are remarkably free of impurities with the exception of phosphorus.

Straining. This secondary process (Figure 4) transformed the fined Osmund iron ingots into iron rods which were typically described in historical sources as about the “size of a little finger” (so about 10 mm in diameter). This procedure required several intermediate annealings (heating to red hot in a furnace with subsequent very slow cooling), waterings (soaking in water and/or lime baths for lengthy periods), and de-scalings or scourings (to remove the surface coating produced when annealing in air). The iron was gradually formed into the thin rods by hand-forging or swaging the hot metal with an especially light and rapid (water)-powered trip hammer. Some mechanization was introduced in the late eighteenth century to cut bars from flats (slitting mill), and to produce rods directly from bars (rolling mill with grooved rollers).

Ripping. The annealed iron rods were passed to the rippers to be transformed into coarse wire of thickness, as described in source documents, of a "great pack thread" (i.e. about 2 mm). The wire was drawn cold through a sequence of die holes with decreasing diameters, requiring further annealings, waterings and scourings. Many documentary sources confirm the use of water power from an early date for this heavy mechanical operation (Biringuccio, 1540; Paar & Tucker, 1977). The coarse wire product was annealed as a final treatment before being passed to the fine wire drawers. The diameter at this final annealing has a significant effect on the mechanical properties of the wire when drawn to the thin gauge sizes. It may well have changed over time, or a particular annealed coarse wire diameter may have been used to reflect the characteristic range of gauge sizes of wire destined for a particular application.

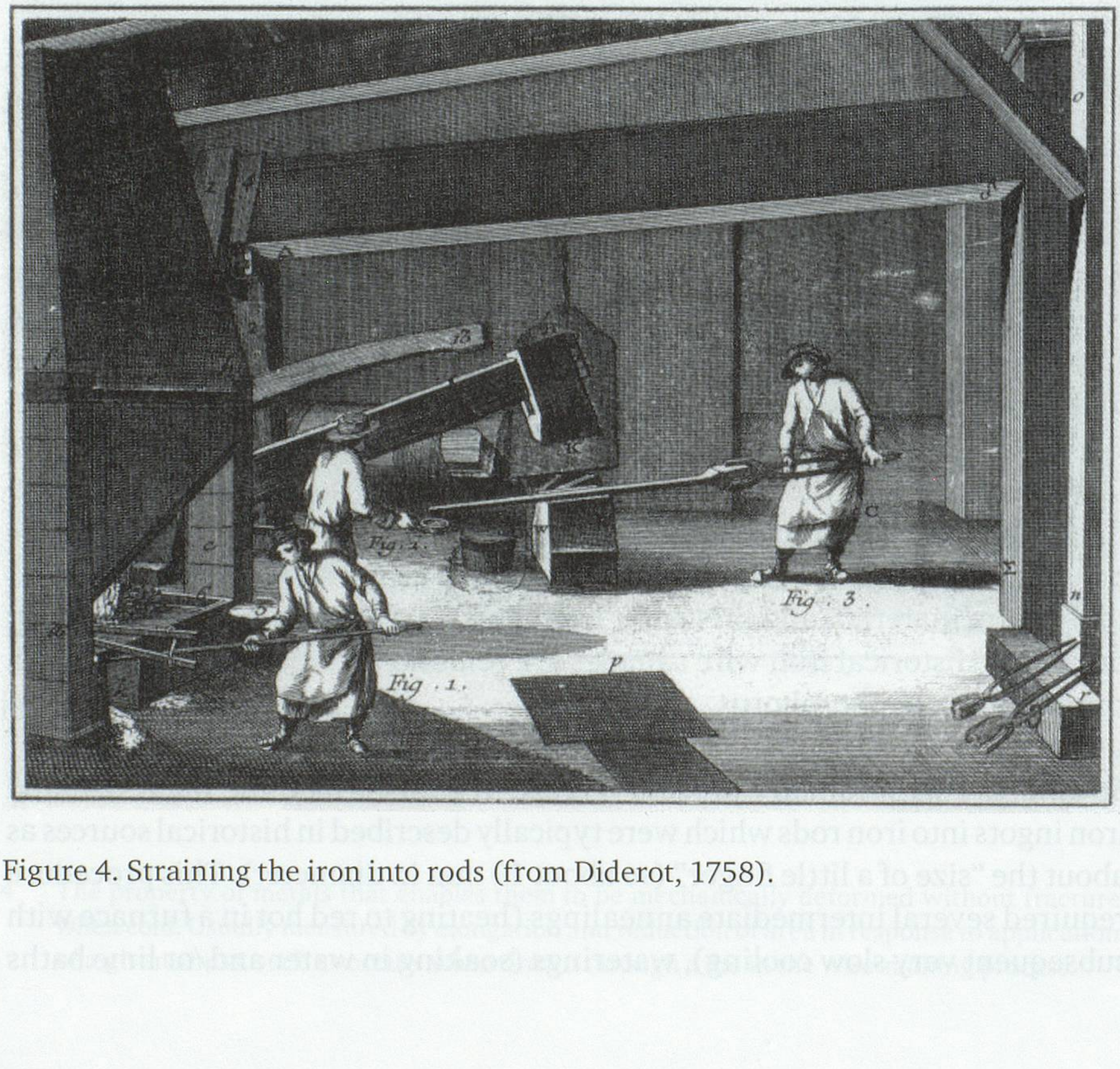

Figure 4. Straining the iron into rods (from Diderot, 1758).

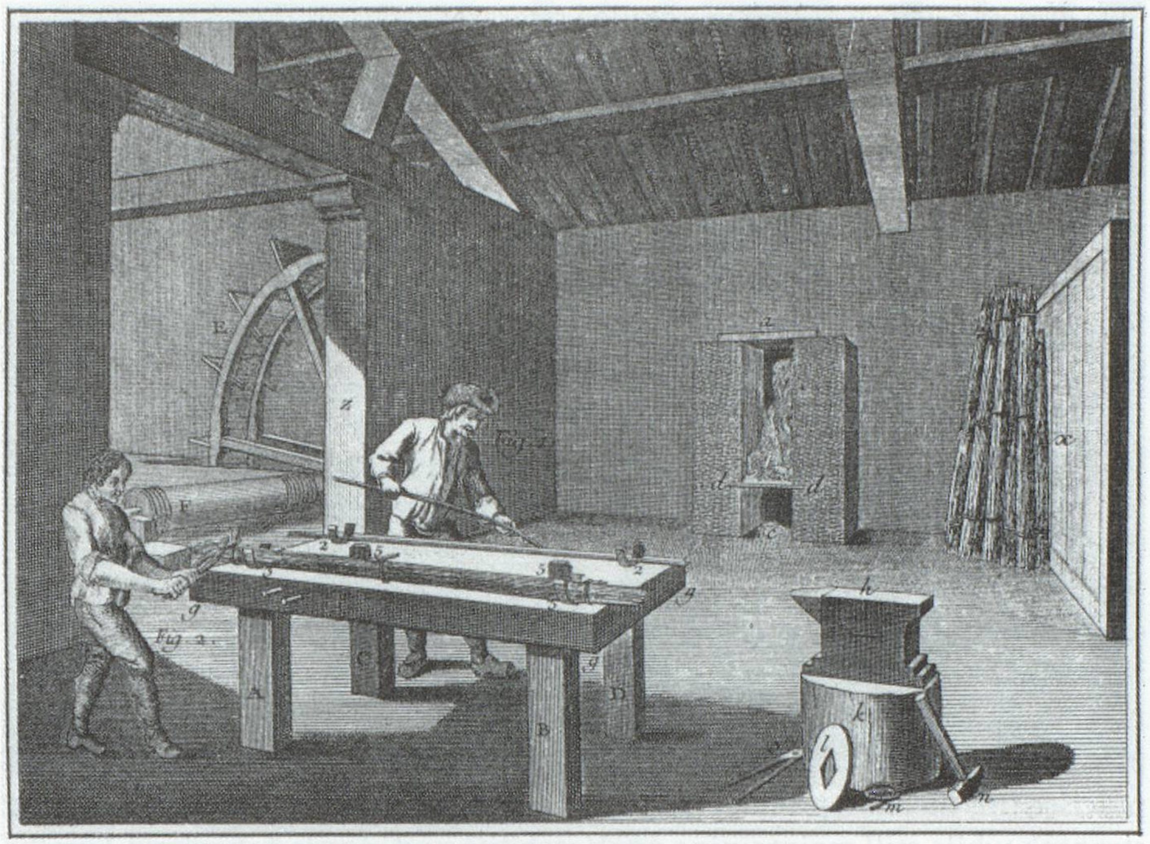

Figure 5. Bundling rods to pass to the ripper (from Diderot, 1758).

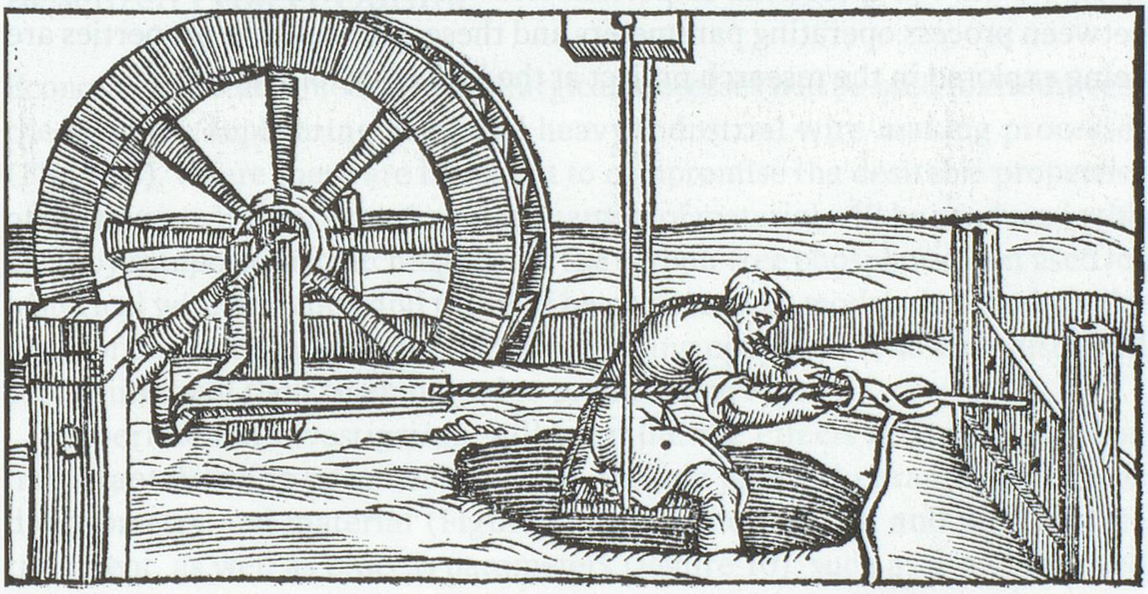

Figure 6. Ripping the iron rods to coarse wire using water power (from Biringuccio, 1540).

Fine drawing. This was a highly skilled operation that produced finished wire for applications. The wire was drawn by hand from one drum to another, passing through a sequence of holes of decreasing diameters (Figure 7). The final diameter of iron music wire historically ranged from about 0.20 mm to 0.80 mm, and gauge sizes were probably determined by proportional relationships between diameters (Poletti, 2000). In order to achieve the desirable mechanical properties in the finished wire it was critical to employ a very high final rate of reduction, typically at least 90%, and as large as 99%, with no annealing after the coarse wire received from the rippers.

The sequence of traditional processes described above resulted in a characteristic increase in tensile (breaking) strength due to strain hardening as the wire was repeatedly deformed in passing through the dies. This so-called tensile pickup, in which thinner wires are relatively stronger than thicker ones, was well-known to historical builders who took advantage of it in their scale designs (the lengths and diameters of strings). In addition, the typical very high reduction percentage of the final product enlarged the zone of elastic response, with yield strength[5] closer to breaking strength, and less chance of plastic deformation occurring in application when stringing an instrument. In practice this means a product that could be stressed quite close to its breaking strength while still maintaining pitch stability and elastic behaviour. Finally, the manufacturing processes also resulted in a reduction in the elastic modulus[6] of the wire material, with an associated increase in internal damping, an effect we have proposed has important tonal implications. The relationships between process operating parameters and these physical wire properties are being explored in the research project at the University of Waterloo.

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[5] Yield point is the load per unit of original cross section at which a marked increase in deformation occurs without increase in load. The elastic limit is the stress (load/area) at which the metal changes from elastic to plastic in behaviour, i.e. is permanently deformed. Working stress for music wire in an instrument must not get close to the plastic zone during playing.

[6] The (tensile) force which would be required to stretch a substance to double its normal length, on the assumption that it would remain perfectly elastic. The ratio of stress to strain within the perfectly elastic range. This parameter is a measure of the flexibility of the material.

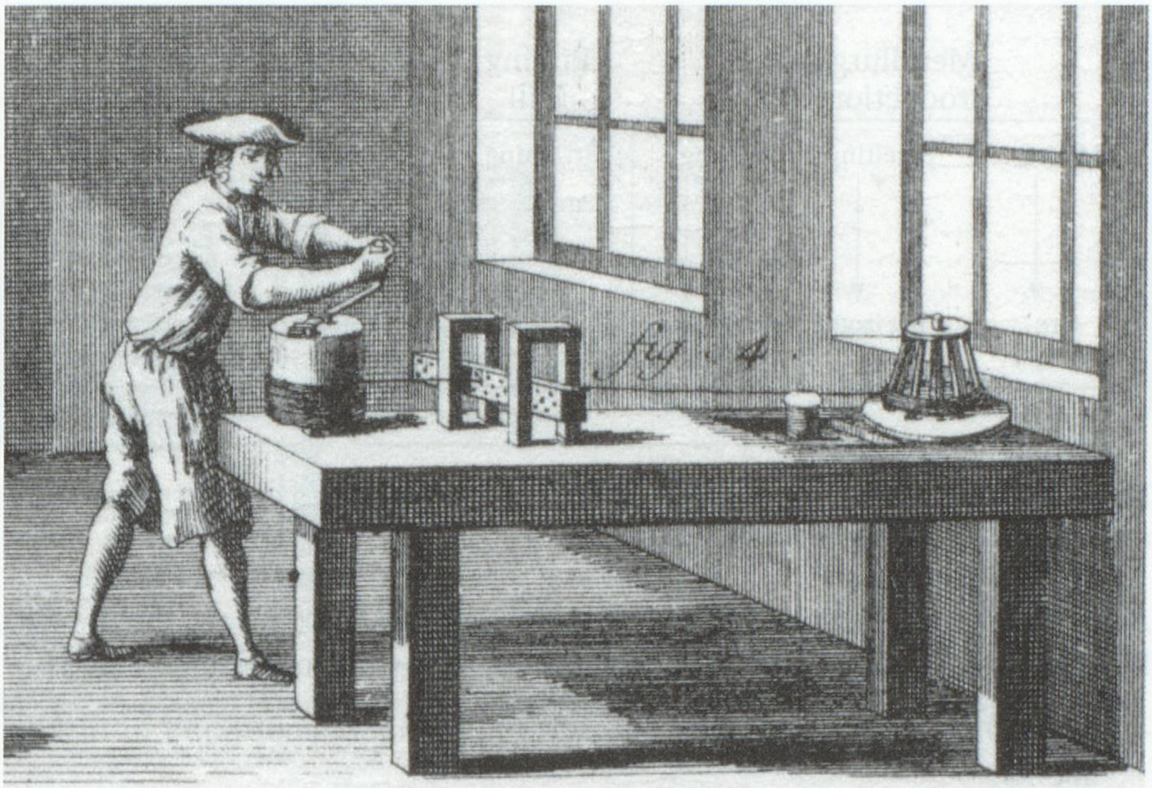

Figure 7. Fine wire drawing (from Diderot, 1758).

Research Project Outline

Economically viable modern metallurgical processes will be used to circumvent the need for duplicating historical heavy industrial wire-making processes (Figure 8), where these are likely not to compromise the desirable properties of the music wire. An experimental quantity of material will be produced with an alloy composition matching that of the carbon-free phosphoric iron used for historical wire drawing, and this will be processed by modern methods to the stage of annealed coarse wire. A wire drawing operation following historical procedures will then be employed to produce fine wire.

Experimental investigation will examine the effects of varying several important drawing parameters. These include physical parameters such as die geometry and material (Figure 9), lubrication media, and final surface treatment, as well as process parameters (Figure 10), such as drawing speed and force, incremental step size per reduction, and overall reduction amount since final annealing. Small batches of wire will be produced with controlled variations in these key drawing parameters, so that quantitative relationships may be established between them and the elastic and tensile properties of the wire. For example, the relationships between tensile pickup and yield point will be established as functions of diameter.

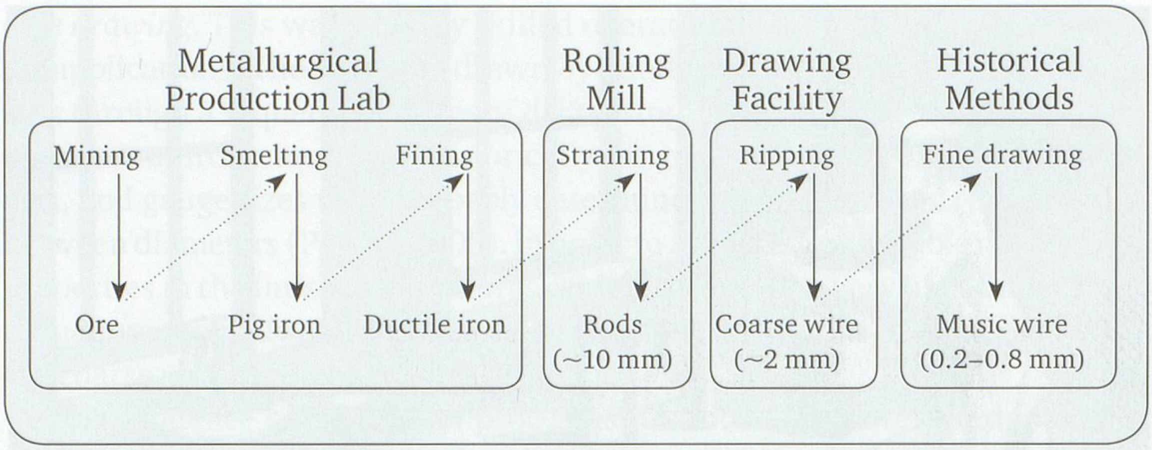

Figure 8. Proposed reproduction of historical iron wire replacing most historical industrial processes with modern processing.

As well as this scientific analysis of the drawing process, a quantity of wire will be produced and its musical application assessed by the following methods:

- Harmonic analysis of vibrating strings on a monochord and in instruments.
- Musicians, instrument builders, and lay people will be asked to make a qualitative assessment of instruments strung with the reproduction wire.
- Comparative tests with other types of modern wire, including steel music wire and modern low-carbon steel wire intended for historical instruments from different sources (e.g. Rose, Vogel, etc.).
- Wire samples will be offered to builders of stringed keyboard instruments for their critical assessment.

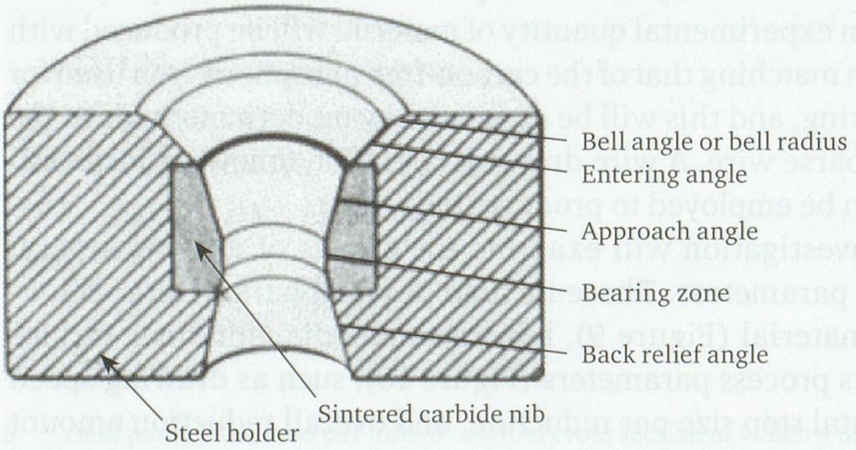

Figure 9. A modern wire-drawing die.

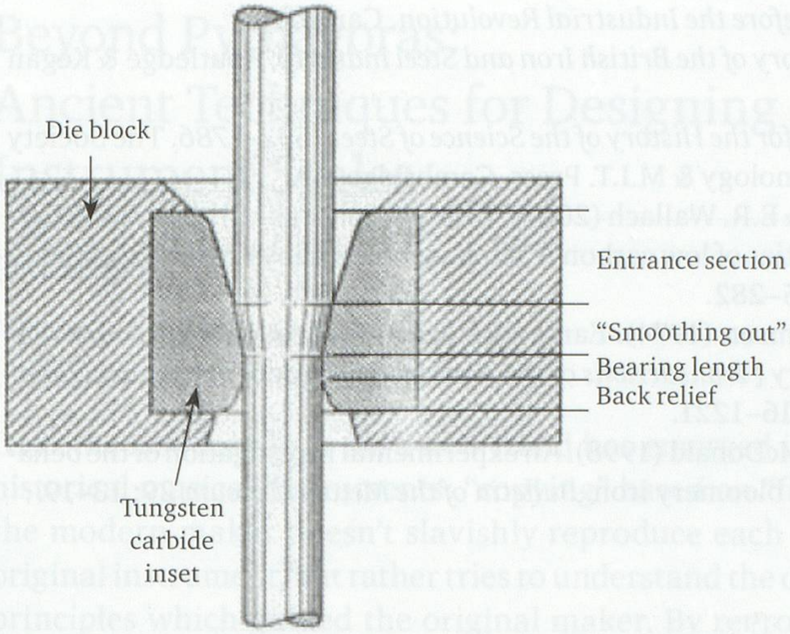

Figure 10. Typical arrangement for diameter reduction in the wire drawing process.

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