The physical characeristics of historical iron music wire and a report on its replication as a viable modern product

Autor(en): **Birkett, Stephen**

Objekttyp: **Article**

Zeitschrift: **Publikationen der Schweizerischen Musikforschenden Gesellschaft. Serie 2 = Publications de la Société Suisse de Musicologie. Série 2**

Band (Jahr): **53 (2010)**

PDF erstellt am: **29.06.2024**

Persistenter Link: https://doi.org/10.5169/seals-858697

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

The physical characteristics of historical iron music wire and a report on its replication as a viable modern product

Stephen Birkett

Introduction

At the inaugural Lausanne Harmoniques conference in 2002 I proposed to embark on a major project to reproduce authentic historical iron music wire.[1] At that time I presented a review of the current state of affairs with respect to this most basic component of our clavichords, harpsichords, fortepianos, and their various cousins. In my challenge I proposed four tasks that I considered critical for a successful outcome:

1. Study the interactions between drawing parameters and the physical (elastic/plastic) properties of the wire;
2. Investigate the acoustic implications of wire properties and how these are influenced by drawing parameters;
3. Determine practical recommendations for appropriate drawing parameters for commercial production;
4. Estimate the economic viability of the product in the modern market.

These tasks reflect the technical, practical, aesthetic, and economic aspects of producing an authentic iron music wire and marketing it successfully. This article presents a review of the efforts taken to accomplish these goals, and some of the interim results obtained thus far.

Music wire, and, in particular, iron music wire, is one of the most difficult products to make. The physical characteristics of wire interact very closely with the design principles used for an instrument. Consequently it is important to have a material with the correct properties so as not to distort the aesthetic concept, and on the more fundamental level, simply to avoid encountering technical or practical problems with stringing. The historical builder's intuitive understanding of wire, combined with a pragmatic approach to design development, were sufficient to meet the day to day requirements of production, even in the large piano factories that became common in the nineteenth century.

1 S Birkett & P Poletti, 'Reproduction of authentic historical soft iron wire for musical instruments', in: T Steiner (Ed), *Instruments à claviers – expressivité et flexibilité sonore*, Actes des Rencontres Internationales harmoniques, Lausanne 2002. Bern: Peter Lang, 2004, pp259–272.

The modern builder of reproduction instruments, restorer of antiques, musician, or owner of an instrument that requires stringing, must tackle the problem of wire from a different perspective. In the case of a restoration with minimal alteration, or an accurate reproduction of an historical design concept, there is no freedom to adapt the instrument to meet the available wire. The problem here can be put simply: the ancient materials are no longer produced.

The most obvious approach to solving this dilemma would be to select an appropriate modern substitute that can replace the original wire when stringing an extant design. The validity of this solution then hinges on the interpretation of the extent to which the material can be considered 'appropriate'. Analysis suggests that determining this will involve many complex questions that consider the practical, mechanical, and acoustic relationship between wire characteristics and behaviour on the instrument.

The twentieth-century revival of historical instruments has seen an increasingly more sophisticated development in this regard. Initially, modern steel piano wire, widely available and inexpensive, was naively assumed to be 'appropriate' (even superior) because it so easily met (and exceeded) the simple requirement of not breaking in service. Experience with the more undesirable characteristics of this material on historical instruments presumably led to the (modern) theory[2] that wire should be 'critically stressed', that is utilized 'very close to its breaking strength to ensure good tone'; although why this should be so has never been satisfactorily explained, nor has it been adequately established, properly considering the characteristics of historical wire in relation to design, that this was indeed an acoustic goal of the historical builder. In response to this theory, lower strength (and consequently softer) stringing materials were developed based on processing existing commercial mild steel wire products as raw materials. The suitability of these materials for historical designs can also be questioned, as will be explained later.

An alternative approach to utilizing an existing commercial product is to follow the methods used by makers of instruments based on historical principles, and apply historical practices insofar as this is feasible. In other words, one could set out to reproduce the original wire itself. This is the approach I proposed in 2002.

2 G O'Brien, *Ruckers: A Harpsichord and Virginal Building Tradition*. Cambridge: Cambridge University Press, 1990, p18.

Technical background

For the benefit of the reader who is unfamiliar with the mechanics of materials[3] I will begin with a brief introduction to some important technical concepts that relate to the application of wire in stringing an instrument. Historical builders would have had a generally excellent intuitive and empirical understanding of the practical aspects of all this, even though they would not have used the modern terminology to describe it.

In the context of a stringed instrument, an installed wire tuned to a desired pitch is undergoing a *load* (or at a *tension*) that can be measured in kilograms (kg). This condition could be produced, for instance, by attaching a weight on the end of the string and allowing it to hang over the end of a monochord. Tension is an intuitive modern concept, much favored by organologists for analyzing ancient designs.[4] While tension has important implications for the mechanics of striking or plucking, and the magnitude and distribution of overall tension are important with respect to the structural integrity of an instrument, tension is not really very useful for understanding wire and how this interacts with string scale design.

It is well-known, and may be easily demonstrated with a monochord, that a larger wire diameter (*gage*) will require a higher tension to sound the same pitch. This situation is unified by the concept of *stress*, defined as tension per cross sectional area and measured in units of pressure (kg/mm^2, Pa, or psi and so on). Thus, if the diameter of a wire is doubled without changing the tension, the stress level will drop by a factor of four. For practical use in applications to stringed instruments wires are typically stressed at levels measured conveniently in MPa (million Pa).

The other two (instrument) design variables that determine pitch – speaking length and material density – are of less concern than stress when considering the tensile behaviour of wire. Two wires of the same material, and same length, will sound the same pitch if they are kept at the same stress level. Constant stress is the basis for the Pythagorean scale.

Wires which are stressed respond by stretching, that is their length is extended; alternatively a wire that is stretched can be considered to have responded by producing internal stress. Either viewpoint may be taken. Thus wrapping a wire on a tuning pin and tightening it against the fixed hitchpin end stretches it and produces a desired stress level. Alternatively, on a monochord a hanging weight attached to the end of the string can be viewed as applying a stress to which the wire responds by stretching.

3 Further details can be found in the many elementary textbooks on this subject, such as: FA McClintock & AS Argon (Eds), *Mechanical Behavior of Materials*. Reading MA: Addison-Wesley, 1966.

4 See, for instance: J Koster, 'The divided bridge, due tension, and rational striking point in early English grand pianos', *J. Amer. Musical Instrument Soc.* 23 (1997): 5–55.

In order to understand the relationship between stress and stretching it is important to be able to quantify the latter properly. An obvious attempt would be simply to use the measured change in length, but a longer string with the same stress will stretch more than a shorter one in absolute terms. Recognizing that the difference in stretch is proportional, we can use this to define the quantity called *strain*, which can be measured as the (unitless) percent change in length. We now have the two key concepts necessary to understand the tensile mechanics of a wire: stress and strain.

Two modes of stretching response occur in a stressed wire. *Elastic* response involves strain that is completely reversible, so removing the stress allows the wire to return to precisely its original state (length), and this process may be repeated any number of times. This can be contrasted with *plastic* strain, which occurs when a stress results in a permanent deformation of the wire, in which case removal of the stress leaves the wire longer than its original length. Many materials exhibit elastic strain in response to a range of stress levels and this relationship is (often) proportional or linear; the constant of proportionality for elastic stress/strain is called the *Young's modulus*, and values for metals are conveniently measured in units of GPa (10^9 Pa). As stress is raised a characteristic level is reached, called the *yield point* or *elastic limit*, at which plastic strain will begin to occur. The highest applied stress achieved for a material is called the *breaking stress* or (*ultimate*) *tensile strength* (UTS). In a tensile test, this will correspond to the end of uniform extension and the beginning of localized failure (called *necking*); on an instrument this will usually be initiated at a point such as a termination. After breakage, the plastic deformation of the sample can be measured to determine the permanent plastic strain at fracture, called the *elongation*, which is a measure of the ductility of the material.

The concepts described above are illustrated in the stress-strain curves shown in Figure 1.

In the above discussion no mention is made of time, yet this is an important factor for wires subject to a constant high stress level for extended periods on a musical instrument. Under such conditions a material may respond by continued gradual stretching, called *creep*; equivalently, the time response to constant strain (as in a tuned string) will be diminishing stress, called *stress relief*, observed as a drop in pitch. Materials may exhibit this phenomenon at stresses below the yield point.

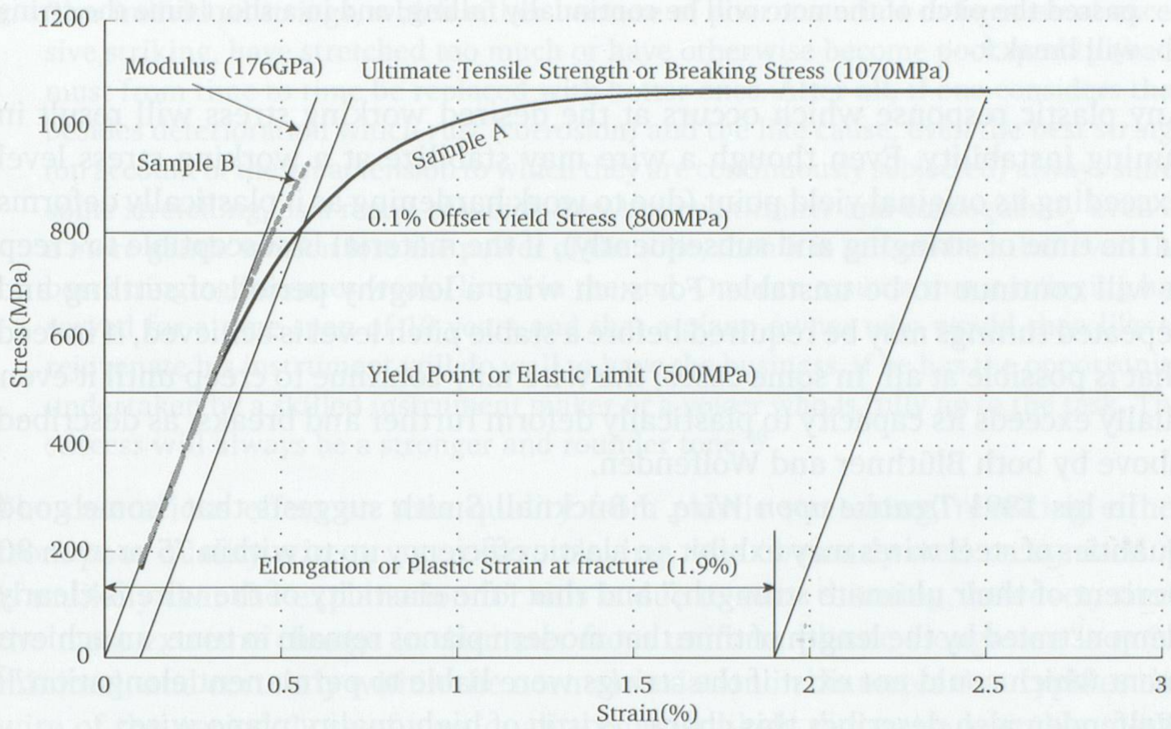

Figure 1. Sample stress-strain curves from tensile tests of two wire samples.

Music wire

Armed with the appropriate technical language, it can now be asked what are the tensile characteristics of ideal music wire?

The desirable properties will be qualitatively similar for all applications, differing only in degree, as they relate to the primary function of a stretched wire to vibrate at a fixed predictable frequency. In his *Lehrbuch*, the piano builder Julius Blüthner describes the state of music wire at the time (1886), and in particular the steel wire first produced in the 1850s by Moritz Pohlman of Nuremberg:

> Already in the first tests undertaken in 1859 … these strings showed a great elasticity roughly similar to the Miller ones. Moreover, the latter stretched much more and kept stretching until they broke, whereas the Pohlmann ones broke quickly and without any noticeable preceding stretching when heavy weights were attached. This consideration is of importance for the use of strings, since a string which stretches when there is increased tension does not hold the tone and is therefore unusable.[5]

Blüthner's comments were echoed by Samuel Wolfenden in 1927:

> It is very important that the tension should not exceed [the elastic limit of the wire], which is the stress at which a permanent elongation takes place … If this point is

5 J Blüthner & H Gretschel, *Lehrbuch des Pianofortebaues in seiner Geschichte, Theorie und Technik*. Weimar: Voigt, 1886, p89, trans: Birkett.

> passed the pitch of the note will be continually falling, and in a short time the string will break.[6]

Any plastic response which occurs at the desired working stress will result in tuning instability. Even though a wire may stabilize at a working stress level exceeding its original yield point (due to work hardening as it plastically deforms at the time of stringing and subsequently), if the material is susceptible to creep, it will continue to be unstable. For such wire a lengthy period of settling and repeated tunings may be required before a stable pitch level is achieved, if indeed that is possible at all. In some cases, the wire may continue to creep until it eventually exceeds its capacity to plastically deform further and breaks, as described above by both Blüthner and Wolfenden.

In his 1891 *Treatise upon Wire*, J Bucknall Smith suggests that "some good qualities of steel wires may exhibit an elastic efficiency up to within 75 or even 80 percent of their ultimate strength," and that "the elasticity of the wire is clearly demonstrated by the length of time that modern pianos remain in tune, an achievement which could not exist if the strings were liable to permanent elongation."[7] Wolfenden also describes this characteristic of high quality piano wire:

> The [plastic] stretch of first-class wire is not of large amount … in testing no very sensible elongation takes place, until just before the breaking-point is reached, when a quick run down occurs … sometimes of several lbs, followed by the snap. This I regard as creditable.[8]

These same characteristics are just as relevant to the earlier types of historical iron music wire. Resistance to plastic deformation and creep is invariably described as the critical factor for ideal music wire of any period. In his history of the Webster & Horsfall family wire manufacturers,[9] John Horsfall describes how the elimination of continental trade with England in the Napoleonic wars had forced piano makers such as Broadwood to find a new (English) source for wire in 1806. Despite this strong commercial market pressure, Joseph Webster deemed that none of his current wire production was suitable for pianos, because it was too ductile and suffered creep stretch under tension. Resistance to creep is also described as one of the most important characteristics of James Horsfall's newly invented patented steel wire in 1853, the innovation which made possible the modern piano.

The piano builders Johann Lorenz Schiedmayer and Carl Dieudonné describe quite clearly why plastic extension of music wire is undesirable:

6 S Wolfenden, *A Treatise on the Art of Pianoforte Construction*. Henley: Gresham Press, 1916 & 1927 Supplement (1975 reprint), p206. (1927 part)

7 J Bucknall Smith, *A Treatise upon Wire, its Manufacture and Uses*. London: Offices of "Engineering", 1891.

8 S Wolfenden, ibid., p9. (1916 part)

9 J Horsfall, *The Iron Masters of Penns 1720–1970*. Kineton: Roundwood Press, 1971.

> Also individual strings, which either because of poor materials or because of excessive striking, have stretched too much or have otherwise become poor quality (bad), must from time to time be replaced with better ones. After all, if one considers that, besides deterioration which rust (corrosion) and the like cause, even the best strings (on account of the great tension to which they are continuously subjected) always suffer some stretching, as a result of which they become thinner and consequently even at a more gentle tension lose the power of the tone, then it is self-evident that even the best stringing becomes weak (limp) in the end. One can assume that a stringing has served for a time span of 10 years and that a piano owner who would then like to rejuvenate his instrument will do well to have the business, if he has the opportunity, undertaken by a skilled instrument maker or a voicer who is fully up to the task. The success will always be a stronger and rounder tone.[10]

The deleterious effect on tone quality from plastic stretching, resulting either from poor quality wire or aggressive playing, was obviously well recognized. It is unlikely that the explanation for this is due to wire thinning, however, since the most extreme change in diameter from uniform plastic elongation is quite minimal, and certainly within the normal variation in diameter that typifies the wire of the period. Loss of tone quality is most likely due to undesirable metallurgical changes in the wire from plastic stretching. This suggests that the current standard stringing practice of using wire stressed to normal working levels beyond its yield point and allowing it to stabilize, will result in a compromised tone quality for the duration of its life on the instrument. After all, Dieudonné & Schiedmayer say unequivocally that such wires should be replaced to achieve a strong and round tone.

Breaking stress *per se* in relation to scale length is of little value in determining the suitability of a stringing material for use on a given instrument. This is because tensile strength, yield point, and creep resistance are independent properties, consequences of both the metallic alloy as well as the techniques used in drawing the wire. Even though adequate breaking stress is obviously necessary for an application, it is not sufficient, as seen by the various comments cited above. I would like to emphasize this point, as it is one of the key factors that was, and still is, overlooked by organologists and modern builders of historical instruments, although historical builders were well aware of it. In his 1810 patent specification Pleyel concludes, not with comments about breaking strength, but with the note that his "strings and wires made by these methods will stand in tune a tone and a half higher than the wire of Nuremberg."[11] In other words he is describing an enhanced yield point behaviour and resistance to creep as the most important and relevant property that differentiates his wire from the competition.

10 JL Schiedmayer & C Dieudonné, *Kurze Anleitung zu einer richtigen Kenntnis und Behandlung der Forte-Pianos* (A short instruction to achieve correct knowledge and handling of fortepianos). Stuttgart, 1824, p73, trans: Birkett.

11 Description of patent for wire drawing awarded to Ignace Pleyel, Paris, 1810. Editorial reports, *J. Franklin Institute* 6 (1830): 173–176.

Summarizing, the following may be taken as the critical tensile requirements for ideal music wire of any period:

1) There should be no plastic deformation in the desired range of working stress;
2) The yield point should be as close as possible to the breaking stress;
3) Plastic response prior to breaking should be minimal; and
4) The material should be creep resistant.

These tensile requirements can be established intuitively, and, as was common practice for the historical builder, wire samples may easily be evaluated empirically since the implications of tensile properties can be directly observed through changes in pitch using a monochord. Scaling design was adapted accordingly to create an appropriate desired range of working stress within the constraints of the available material, allowing a fairly conservative safety margin to accommodate the inevitable variation in material quality. It was the realm of the wire drawer to develop materials, processes, and drawing techniques which optimized the tensile characteristics. We can now consider how this was done by the historical iron music wire drawer.

Five centuries of ferrous wire

Despite the seemingly enormous range of wire that could have been used on stringed keyboard instruments over the past five centuries, it is perhaps surprising that there are really only three main types of ferrous wire that meet the tensile criteria above. It is useful to describe these in order to put our historical iron wire into perspective. Modern patented steel wire, introduced in 1853,[12] was widely utilized on pianos from about 1860 onwards. Before this, heat-treating was used to produce tempered steel music wires, with the critical metallurgical breakthrough taking place in 1823. Prior to these developments, steel wire was considered not suitable for pianos, on account of its tendency to stretch plastically, a property that proved very difficult to remove.

All instruments at least before 1823, or later depending on the geographical locations and inclinations of individual builders, must have used iron wire as the ferrous stringing material. This specialized product is the subject of our investigations. One of the most fascinating discoveries I can report is the extent to which some piano builders seem to have lagged in their adoption of the latest developments in wire technology. Thus, in some specific cases well into the

12 James Horsfall, British Patent No 1104, 18 May 1854. A summary of the patent claim is available in: *Patents for Inventions – Abridgments of Specifications Relating to Music and Musical Instruments A.D. 1694–1866*, London: Office of the Commissioners of Patents for Inventions, 1871, p206.

mid-nineteenth century, instrument scales may still have been designed for iron wire. In addition, it has become increasingly clear from studying historical wire samples, instrument designs, and our reproduction material, that all iron music wire, whether on the earliest harpsichords or latest fortepianos, was essentially the same material. In particular, these observations simplify the economic and practical aspects of production and marketing of a modern reproduction iron wire.

The historical processes used to make iron wire have been reasonably well-documented in a variety of sources.[13] It was necessary for our purposes to re-discover some missing details of these production processes and adapt them while keeping within the economic constraints pertaining to eventual marketing. As described in the challenge four years ago, even the alloy used as the raw material for iron music wire is not commercially produced nowadays. In fact, the greatest efforts are used in the modern steel industry to remove all traces of the critical essential element in the alloy (phosphorus) from their products, as its presence in steels is detrimental.

The sequence of operations[14] began with mining, the acquisition of an appropriate iron ore. This material was smelted to extract the iron, which was collected in long ingots called pigs. Those destined for wire production were further processed in a particularly hot forge, painstakingly collecting drops of molten material on the end of a long staff, in order to produce a raw material that was suitable for drawing. Workers who carried out this fining operation were highly regarded and received special compensation in recognition of the physical stresses it imposed. Failure to consider the significance of this critical step is a first point where the modern iron wire producer can come to grief. Next, the fined iron was hot worked to extend it into a bar, continuing until finger-size rods were obtained. Towards the end of the eighteenth century slitting and rolling mills were used to speed up this processing stage.

The rods were bundled and sent to the wire drawers who reduced the diameter further by repeatedly drawing them through a sequence of diminishing diameter tapered holes in a die plate. The first drawing operation, called ripping, required the intermittent application of a very heavy pulling force, administered by a variety of techniques over the different periods. After the wire was reduced to the size of a thick thread it was feasible to pull it through the die with a continuous force, using a drum with a handle, or, later, powered drums. As the desired gages of commercial interest were acquired these were polished, spooled, and sold to distributors for re-packaging and eventual sale to consumers, usually by weight. Music wire of the finest gages, such as is appropriate for harpsichords, required

13 For example: HW Paar & DG Tucker, 'The technology of wire making at Tintern, Gwent, 1566–c. 1880', *Historical Metallurgy* 11 (1977): 15–24; HR Schubert, *History of the British Iron and Steel Industry from c.450 BC to AD 1775*. London, 1957; M Goodway & JS Odell, *The Metallurgy of 17th- and 18th-Century Music Wire*. Stuvesant NY: Pendragon Press, 1987.

14 Illustrations of these processes may be found in Birkett & Poletti, 2002 (see note 1).

very special care, and was probably drawn by hand operation of small spindles on a bench. At this point the breaking tension of the wire is low enough that it can easily perish during the drawing with an inadvertent tug on the drawing handle. The critical importance of the fining operation previously mentioned also becomes apparent with harpsichord gages, as any impurities (inclusions) present in the material can become significant in relation to the diameter of the wire, thereby making it impossible to draw it further, even though the material itself is strong enough (see Figure 3).

Several intermediate annealings, heating the material to red hot followed by a slow cooling, were necessary to soften it and return the ductility required to continue the drawing operations. It is important to note that the final product must have been significantly cold-worked by drawing through many dies after the last annealing, in order that very little ductility remained, thereby achieving the desired tensile properties of music wire. The drawing process gradually raises the tensile strength of the wire, provided no further annealing is done, so that finer gages are considerably stronger than coarser ones. A much more important observation, which is critical for application to music wire, is that the yield point and breaking point get closer together the more the wire is drawn. This is the explanation for the much shorter scales that were used for pianos as compared to harpsichords with their thinner strings.

A focus on tensile strength, as is customary amongst modern organologists, can lead to false conclusions, such as:

> the observation that the typical iron string scaling in English grand pianos is significantly shorter than required by the limits of the wire's tensile strength, shows that the standards of scaling pianos for optimal tone, even at this relatively early period, were different from those applied to harpsichords. That is, in pianos the timbre of slacker strings was preferred.[15]

In reality, the thicker strings of pianos required a greater safety margin than that necessary with the thinner wires used on harpsichords, simply to reduce the chance of plastic deformation occurring under normal service. The more highly drawn fine wire gages respond elastically very close to the tensile strength of the material; however, this characteristic can only be achieved if the material is sufficiently ductile that it can be drawn through many dies without heating it again to anneal it. Alloy composition is critical to achieving this ductility. A material such as mild steel cannot be so heavily drawn or it will eventually become over-extended and break. Thus we can see that various factors have to come together in a very specific way if one can expect to obtain a high quality iron music wire, particularly if this is destined for harpsichord gages. Understanding which of these factors are important and devising means to achieve them with our reproduction wire proved to be difficult.

15 J. Koster, 1997, p35 (see note 4).

Replication of historical iron music wire

Complete reproduction of the historical production process is possible, in theory, but not feasible as it would far exceed the practical and economic constraints for a modern commercial product, let alone the effect on a research budget. The most obviously costly aspects are, of course, the historical heavy industries for smelting, casting, and refining the raw material. This problem has been addressed by adapting the processes so they can be carried out using the small-scale facilities of a modern metallurgical laboratory.

The starting point for producing the alloy consists of pure iron ingots into which phosphorus was introduced at one of two experimental levels (0.1% and 0.2%), values determined from the results of our analyses of many historical wire samples. Initially, ingots were cast from this material (Figure 2), in the hope that the purity of the original iron material would avoid the necessity of the fining stage. The resulting material could easily be drawn to piano gages, however it proved difficult to be able to obtain harpsichord wire from it consistently. When examined under the microscope (Figure 3) it is clear that the the historical wire was considerably more free of inclusions than our product, presumably the result of their painstaking fining operation. This observation has further raised our respect for the abilities of the historical artisan. We have recently been able to devise methods to eliminate the inclusions in our material, by using a vacuum casting system instead of casting the ingots in air. This technique eliminates the formation of oxides as the ingot cools, a well known problem in air casting operations.

Continuing in the metallurgical lab operations, the ingots are hot worked in the rolling mill to plate thicknesses (Figure 4), cut into strips using the bandsaw (acting as a 'cold ripping mill'), and swaged to extend them to 10 mm diameter rods.

Our drawing operations are based on the historical ones. Fortunately, dies proved not to be an issue; we have had good success with a sequence of standard commercial tungsten-carbide drawing dies, which we had made following a proposed historical reduction sequence of 18% per step, and half gages between them. A 3m long powered ripping bench capable of reducing 10mm diameter rods was constructed for the heavy drawing (Figure 5). After the wire is sufficiently reduced for continuous drawing it is moved to the drawing bench, which, as can be seen in Figure 5, is modelled on the design shown in the well-known Diderot drawing.

One of the operations that proved particularly frustrating was pointing, required at every step to reduce the size of the wire so it can be started in the next die. We have developed a good understanding of this procedure and constructed a pointing machine which is useful for a limited range of sizes. The finest gages have to be hand-pointed using files, not an easy operation on something that is hair-like in thickness. Again our respect for the historical artisan was further raised.

The reproduction historical iron wire produced as described above is called *P-wire*.

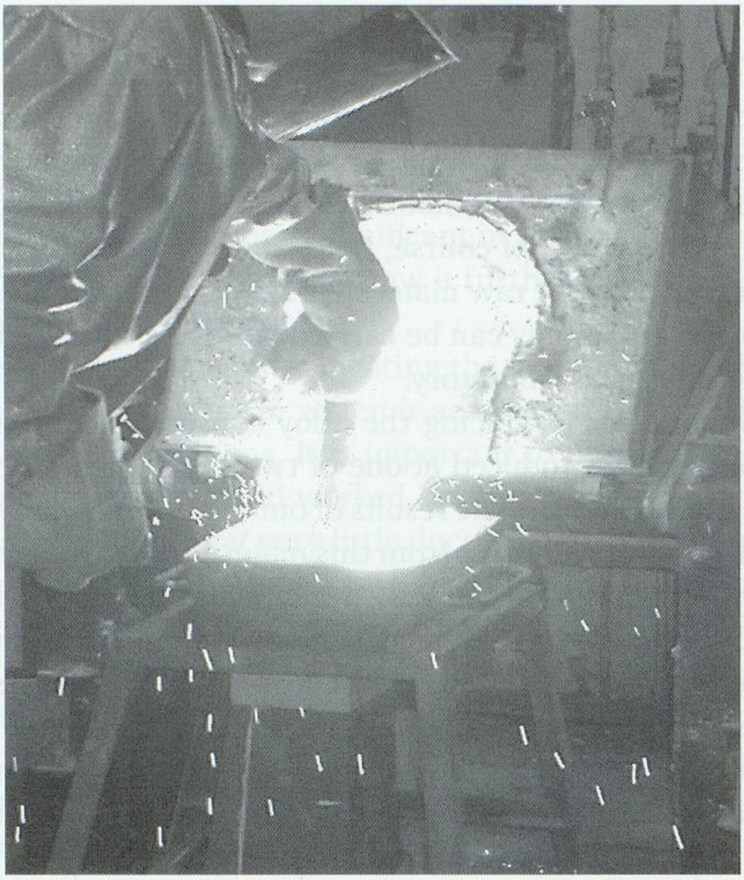

Figure 2. Casting ingots of pure iron and phosphorus.

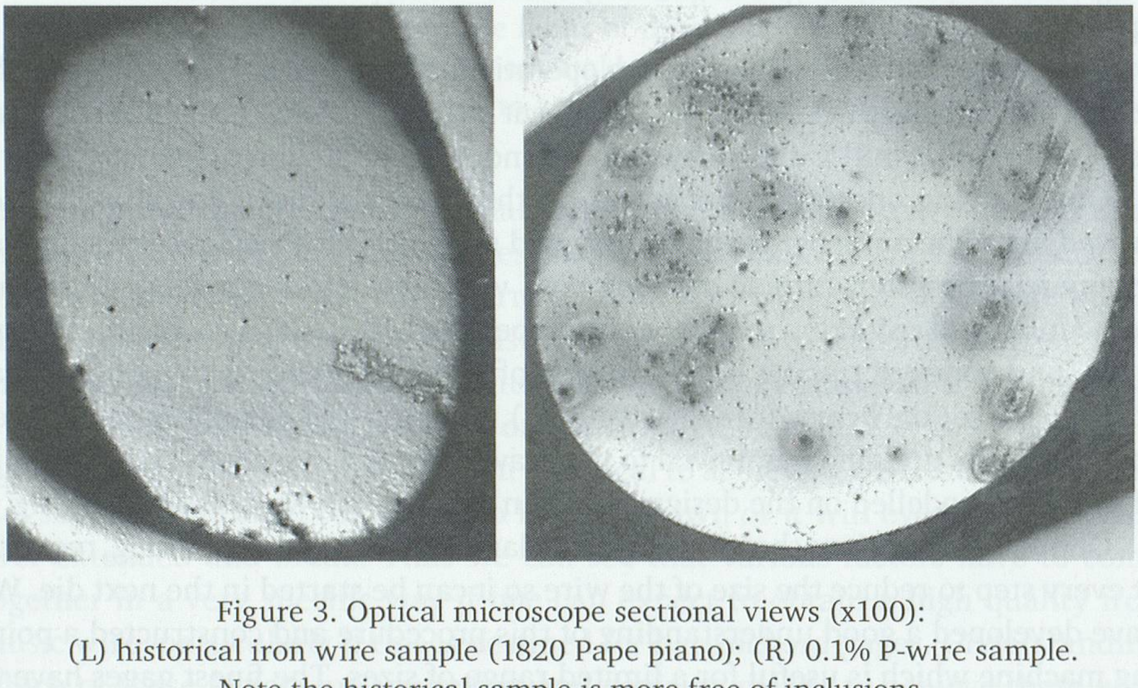

Figure 3. Optical microscope sectional views (x100):
(L) historical iron wire sample (1820 Pape piano); (R) 0.1% P-wire sample.
Note the historical sample is more free of inclusions.

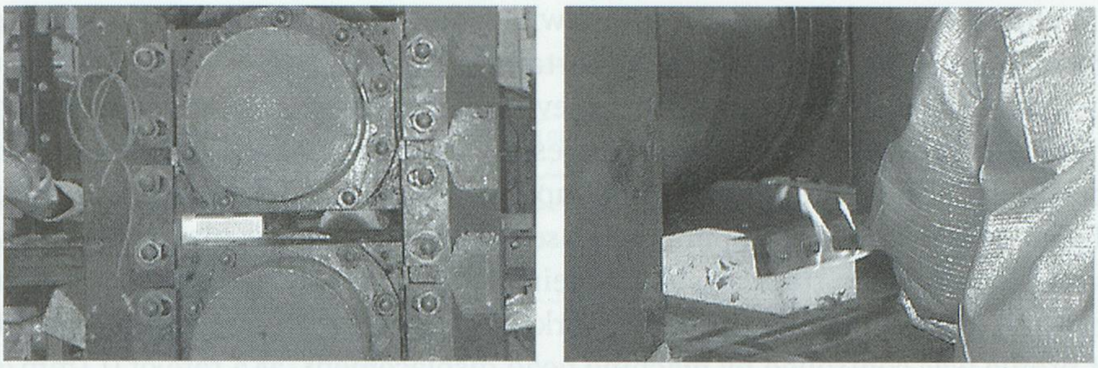

Figure 4. Hot rolling ingots to plate thickness; removing scale after rolling.

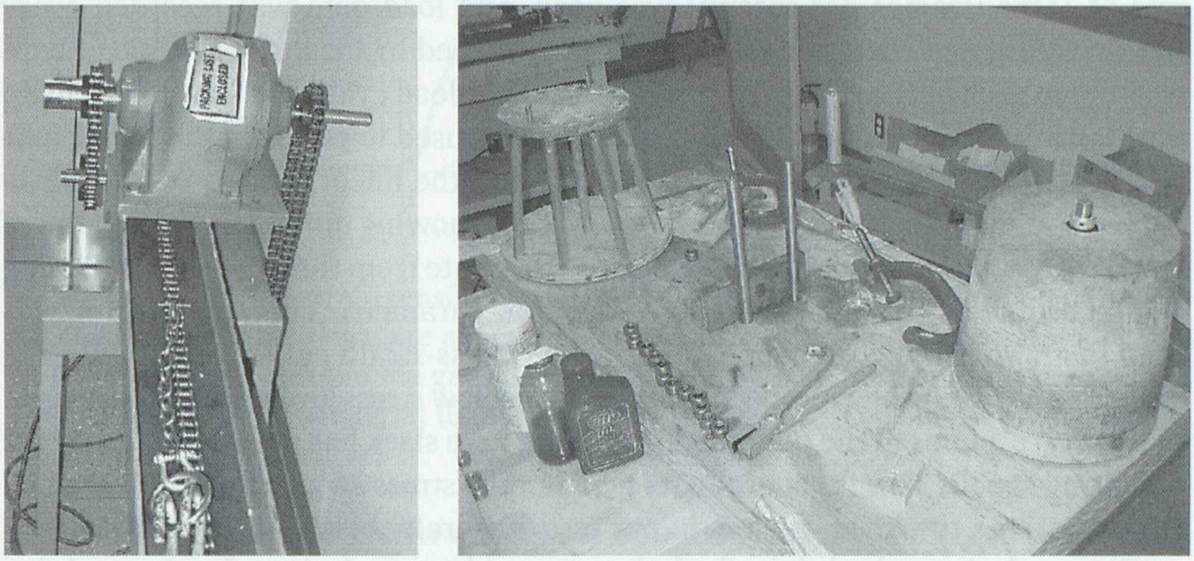

Figure 5. Powered ripping bench; hand-operated wire drawing bench (tungsten-carbide dies are seen in the foreground).

Historical iron wire compared to modern substitutes

Modern substitutes for historical iron music wire are well-known and have been available for some time (Rose, Gug, Voss, Paulello, Vogel, Zuckerman, and so on). Tensile tests were conducted to obtain complete stress-strain curves for these wires at two different diameters: (i) 0.34mm (gage 5), typical of the top treble notes in a late 18th century Viennese fortepiano (e.g. Stein, Schiedmayer); and (ii) 0.67mm (gage 2/0 or 3/0), typical of the region around d1 on an 1820s Viennese fortepiano (e.g. Graf or Fritz). Representative samples were tested: Rose wire Type A, B, and so-called 'special' versions of these, Sp A and Sp B; Voss; and Paulello Type II (intended for 1820–1840 pianos), as well as samples of our 0.1% P-wire, and an historical sample from a Fritz 1820 six octave piano.

Tensile testing of metal fine wires is particularly difficult on account of the very high resolution (0.001mm) for extension data required to calculate strain, combined with problems encountered in mounting specimens so as to avoid any effect from slippage or settling in the grips (which can give the appearance of plastic deformation). Consequently, it is important to provide details of the techniques which were used so the results can be evaluated properly. The tensile tests were carried out with an Instron 5547 micro-testing machine, and an independent video extensometer, thereby eliminating corruption of strain data from slippage. A nominal gage length of about 135mm was used, with six markers placed on the wire for subsequent video tracking, strain being calculated by averaging the distance between two independent pairs of markers to minimize noise in the data. The test profile was controlled by machine head displacement, at a rate of 0.1mm/s to 800MPa, with a subsequent unloading to 50MPa and reloading to 800MPa at this rate, and finally loading to breaking point at a rate of 0.2mm/s. A video sampling rate of 15fps (frames per second) was used, and load data was recorded every 100ms. Strain and stress datasets were synchronized by locating the time of wire fracture in each of them. The intermediate unload-load cycle was used to calculate the elastic modulus by linear fitting, and this was used to generate the initial (parallel) elastic line. Gage length was adjusted until the linear regions of the tensile curves visually coincided with this modulus line, showing quite clearly the onset of plastic deformation when the curve begins to deviate from that line, and providing a good estimate of the elastic limit. A final non-parametric curve smoothing was used to improve the visual appearance of the stress-strain curves.

In tensile testing of wire specimens the data at low stress levels is not meaningful as this corresponds to the period before all the wire slack has been taken up by the mounting spools. This is generally reflected in the stress-strain graph as a gradual curved start to the linear region, in our tests generally below about 200MPa.

The analysis method described above provides a technique for determining consistent estimates of the elastic limit, which can be difficult to locate precisely, as the change to plastic extension may take place quite gradually. An easier practical expedient that is often used in tensile testing is to locate an *offset yield stress* value at which strain has deviated by some pre-determined amount from the elastic line. Typical industry standards of 0.2% or 0.1% offset yield stress are, however, quite inadequate for characterizing the subtle performance of good music wire, which may well already have broken at an elongation less than 0.1%. It is essential in describing the tensile properties of music wire to test it in such a way that a good estimate for the actual elastic limit may be obtained directly from the stress-strain data.

Empirical wire testing, as was commonly and routinely done by historical builders, is easy compared to the quantitative tensile testing described above. Tensile strength may be determined simply by tuning a wire until it breaks, and the highest pitch sustained (with standardized parameters such as length and diameter) is a perfectly good measure of UTS. A builder could also have used a monochord, or simply hung weights on the end of a wire, to investigate yield behaviour and creep, again determining the highest pitch at which a wire was stable, in order to provide a basis for designing a stringing scale consistent with the available wire. The acid creep test for wire is, of course, employing it on an instrument.

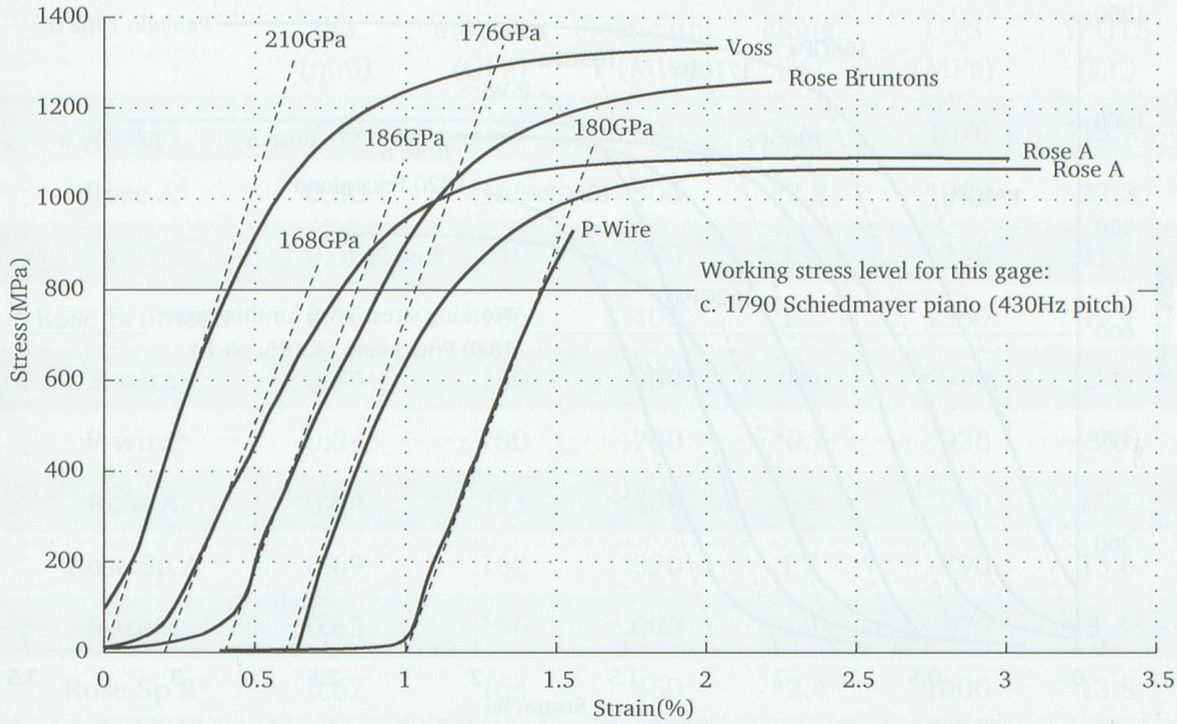

Figure 6. Stress-strain tensile curves from testing 0.34mm dia. wire samples. All elongations at breakage are approximately uniform except for the sample indicated in bold, which broke in the gage length (a test result is also shown from another sample of this material (0.49mm dia.) which did not break in the gage.)

Two representative stress-strain curves obtained from our tests are shown in Figure 1: Sample A exhibits tensile characteristics considered undesirable for music wire; Sample B provides a material that would be suitable for music wire, stable at stresses very close to its UTS. It should be noted that the higher tensile strength of Sample A is of no value in an application as music wire. Complete sets of tensile curves for each of the diameters tested have been combined and are given in Figure 6 and Figure 7.

These are presented with the origin of each curve shifted along the strain axis, the standard practice when multiple tensile curves are plotted for comparison. On each of the graphs, a typical working stress level for that gage iron wire on a piano is also indicated by a solid line. Even though the tensile strength of all the substitute wire types exceeds the required working stress levels of the target instruments, the yield behaviour of these stringing materials is generally poor. There is an early transition from elastic to plastic response and this occurs well within the intended working stress range (with a single exception). Moreover, all of these wires appear to be under-drawn, with the result that they exhibit a very large uniform elongation, expressed as a large region of plastic response, and making the material susceptible to creep. Most of the samples tested broke outside the gage length; consequently, the total plastic strain shown in the tensile curves for these will be a good approximation of the uniform elongation, that is plastic strain not including localized necking immediately prior to breakage.

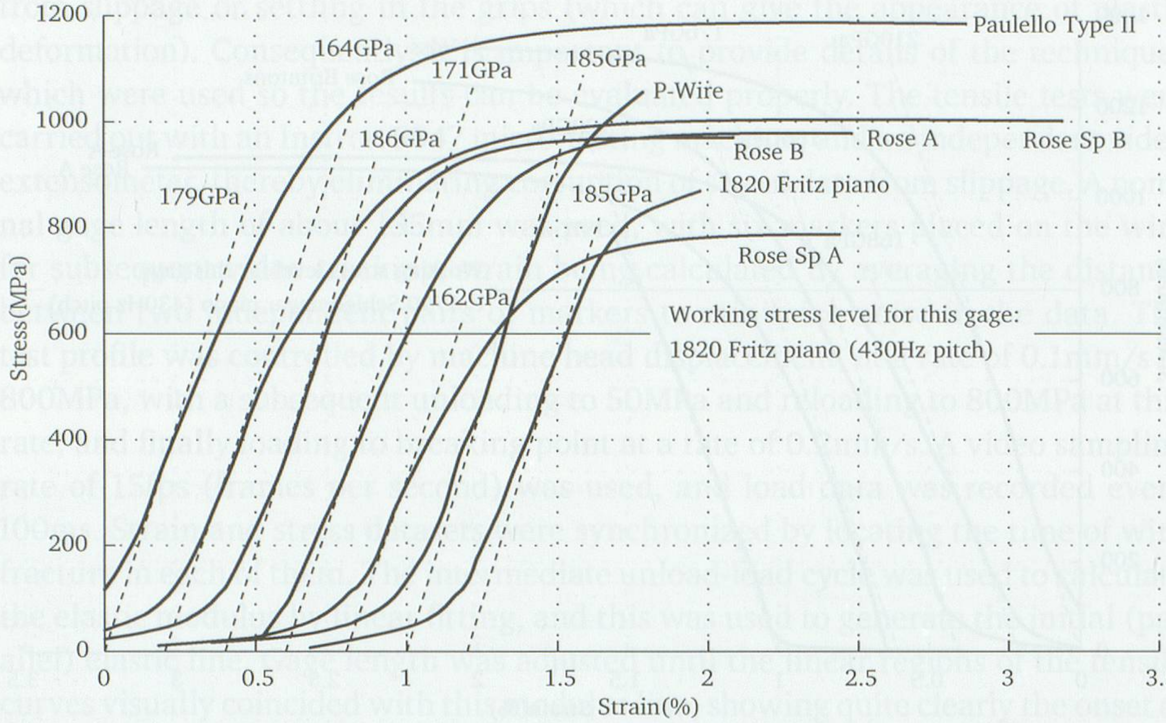

Figure 7. Stress-strain tensile curves from testing 0.68mm dia. wire samples. All elongations at breakage are approximately uniform except for the two samples indicated in bold, which broke in the gage length.

In contrast to the modern substitute wires, the P-wire samples, as well as the historical wire, operate well within the elastic zone at the intended stress levels, and, most important, the plastic zone is extremely short, giving optimized creep resistance.

Tensile parameters obtained for these wire tests are given in Table 1. Elongations for samples that broke outside the gage length are good estimates for total uniform elongation, since the extension data does not include extension in the necked region at breakage. In addition, the ratio of elastic limit to UTS has been calculated and expressed in semitones to demonstrate the extent to which plastic stretching dominates the response of all the modern substitute wire types.

There seems to have been no historical precedent, and no need, for different varieties of iron wire. In the course of the study it has become clear that a single product can be used for any pre-1823 iron strung instrument. The actual date at which builders changed their designs and incorporated the enhanced stress capabilities of steel wire varied, but, in many cases, it will have been considerably later than 1823. One of the most exciting discoveries of the project is the potential applicability of P-wire to mid-century instruments such as JB Streicher and Pleyel pianos to the end of the 1840s. These observations can be illustrated effectively by showing the relationship between gage diameters and intended working stress levels for a variety of instruments and periods (Figure 8).

	dia. (mm)	modulus (GPa)	elastic lim. Y (MPa)	elong. (%)	UTS (MPa)	Y/UTS (s.t.)
Rose A	0.49	176	500	1.9	1070	13.2
Rose A*	0.36	168	300	*2.2	1090	22.3
Voss	0.36	210	680	1.4	1330	11.6
Rose Bruntons	0.35	186	400	1.1	1260	19.9
P-wire	0.34	180	800	0.0	930	2.6
P-wire*	0.34	180	700	*0.1	930	5.0
Rose A	0.64	171	400	1.3	980	15.5
Rose Sp A	0.69	162	320	1.2	790	15.6
Rose B	0.65	186	600	1.2	970	8.3
Rose Sp B*	0.67	164	450	*2.4	1000	13.8
Paulello Type II	0.68	179	400	2.2	1190	18.9
P-wire	0.66	185	800	0.2	1060	4.9
1820 Fritz*	0.66	186	630	*0.3	870	5.6

Table 1. Tensile parameters obtained from testing wire samples. Specimens indicated by (*) broke in the gage; elongations for these are total. All other specimens broke outside the gage; for these the strain at breakage was used as a good estimate of total uniform elongation. The last column is the ratio of yield point stress to UTS expressed as semitones.

It should be clear that, apart from the later Erard 1859 which shows a discrete transition to steel wire, these scale designs all follow basically a common curve. The extra strength obtained from tensile pickup in the finer gages can be seen in the graph; less obvious, but of great practical importance, is the location of the elastic limit for the various gages, requiring a larger margin for thicker diameter wires. These facts were clearly understood and used in practice by historical builders.

Conclusions

The most important characteristics of ideal music wire are that it should go to pitch without breaking and be stable under working tensions. Historical iron wire achieved both strength and pitch stability through a unique alloy composition, as well as through adherence to a strict manufacturing process. The great

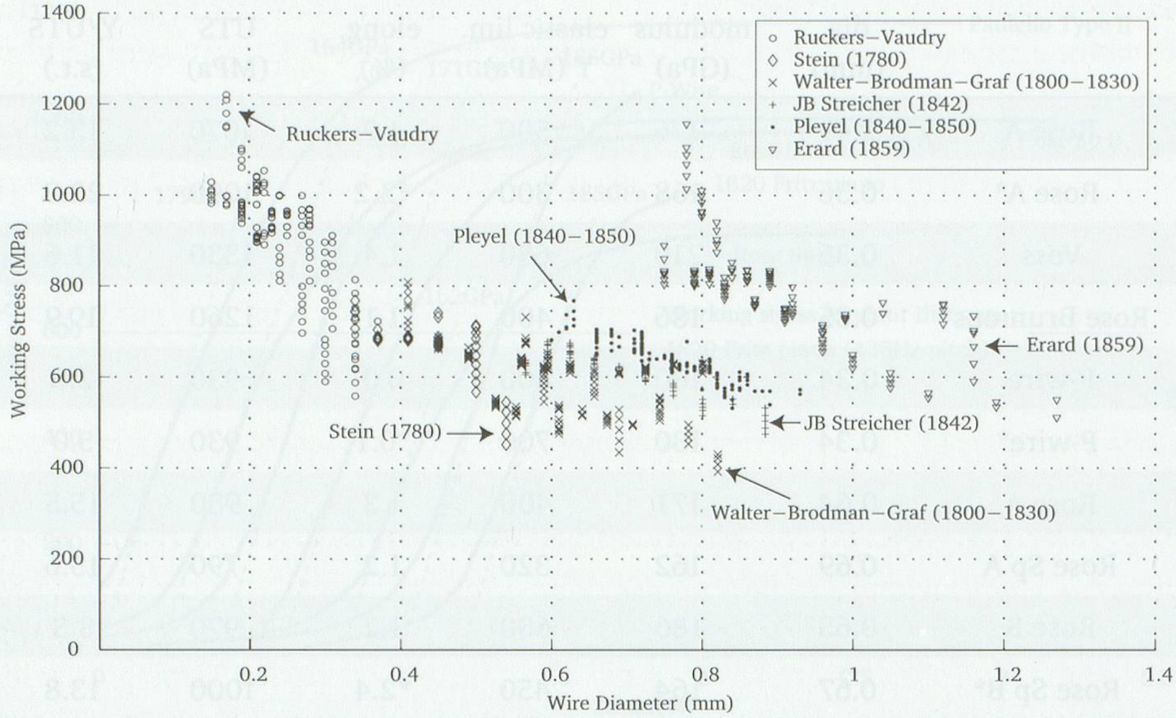

Figure 8. Working stress related to ferrous wire gage diameters on harpsichords and pianos.

similarity of this product between different geographical locales and over an extensive time period appears to be related to the very small margin between success and complete failure when making it. In short, there is really only one way to make iron music wire, the right way. This observation provides a means to unequivocally confirm that a wire sample from an historical instrument is indeed contemporary, provided one has sufficient material to permit the use of destructive chemical and mechanical testing.

The acquisition of an authentic iron music wire for harpsichords and fortepianos has proved an elusive goal. Four years ago I proposed to study the technical, practical, aesthetic, and economic aspects of reproducing such a product and marketing it successfully. As far as the technical and practical goals are concerned, we have successfully adapted historical methods so as to be able to produce a modern wire that possesses very similar tensile properties to those of historical iron wire. Moreover, the economics of production meet the constraints required for marketing a product at a reasonable cost so that it could be widely adopted. What remains to be done is to increase the capabilities of our production system, investigate distribution methods, and so on. In other words we have to take the wire from the laboratory to the marketplace.

The importance of achieving the critical mechanical properties for music wire is first and foremost a practical issue, and therefore highly relevant to instrument builders, restorers, and owners. It also relates to a more subtle point, in that the mechanical properties of the wire have a major influence on the tone quality derived from it in an instrument. This is the aesthetic goal in our list of four. Dieudonné and Schiedmayer clearly described the undesirable tonal effect due to plastic stretching of wire, yet the 'historically motivated' wire used to string most keyboard instruments today will have almost always undergone that process to some degree before it stabilizes, if indeed it ever does stabilize. A research investigation of the properties of P-wire is continuing, now with a focus on acoustics, how this behaviour is affected by metallurgical properties, including internal damping studies, and concluding with extensive testing on instruments.

Summary

The most important characteristics of ideal music wire are that it should go to pitch without breaking and be stable under working tensions. Historical iron wire achieved both strength and pitch stability through a unique alloy composition as well as through adherence to a strict manufacturing process. The close proximity between success and complete failure when making this material appears to have been responsible for its universal similarity regardless of geographical locale or period. In short, there is really only one way to make iron music wire, the right way. This observation provides an unequivocal means to confirm the veracity of historical samples, provided one has sufficient material to permit the use of destructive chemical and mechanical testing.

Despite these observations the reproduction of modern iron music wire for harpsichords and fortepianos has proved an elusive goal, for practical, technical, and economic reasons. By returning to historical manufacturing principles in a modern setting we have been able to develop a viable technique for the commercial production of iron wire that is indistinguishable from the historical product. We describe how this is done, and demonstrate how the wire meets the demands for ferrous stringing in any instrument design prior to the adoption of steel wire in the 19th century.

Résumé

Les qualités les plus importantes de la corde idéale pour instrument de musique seraient que cette corde soit capable de monter au ton sans se rompre et de rester stable, sous les tensions à l'oeuvre pour qu'elle garde le ton. La corde en fer d'époque atteignait tout à la fois la résistance et la stabilité du ton, grâce à la composition unique de son alliage ainsi que grâce à l'adhésion d'un procédé de fabrication strict qui ne tolérait pas de variation.

Le fait que la marge soit si étroite entre la réussite et l'échec total dans la fabrication de ce matériel semble être à l'origine de son uniformité universelle, indifférente à la localisation géographique ou de l'époque. En résumé, pour fabriquer

une corde à musique en fer, il n'y a réellement qu'une seule manière : la bonne. Cette observation fournit un moyen sans équivoque d'authentifier des échantillons d'époque, à condition bien sûr de disposer d'une quantité suffisante de matière pour permettre des tests chimiques et mécaniques qui vont entraîner la destruction des échantillons.

En dépit de ces observations, la reproduction de cordes en fer moderne pour clavecins et pianofortes n'a jamais réellement atteint son but, pour des raisons pratiques, techniques ou économiques. En reprenant les principes de la fabrication d'époque, adaptés au contexte d'aujourd'hui, nous avons pu développer une technique viable pour une production commerciale de cordes en fer qui sont indiscernables des cordes d'époque. Nous allons expliquer comment le but fut atteint et démontrer comment cette corde satisfait aux exigences requises pour un cordage en fer sur n'importe quel instrument conçu avant l'adoption des cordes en acier dans le courant du 19e siècle.