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MATERIALS PAPER: HIGH CARBON STEEL MUSIC WIRE

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ABSTRACT

More colloquially known as 'piano wire,' music wire is a versatile spring wire cold drawn from high carbon steel alloys, allowing for their use in numerous high-stress applications. High carbon steels are characterized by their high strength and toughness in comparison to their lower and medium carbon steel counterparts, establishing their use in cutting tools, rail steels, springs, etc. Many musical instruments utilize the plucking or hammering of wire strings to produce tones of different frequencies, and many of these strings are composed of metals like steel. Specifically, music wire of varying lengths and diameters are stretched across a pianoforte's cast iron frame, where hammers attached to piano keys hit them to produce sound. The introduction of steel music wire during the mid-to-late 1800s revolutionized how piano strings were made. This paper will explore the microstructure, heat treatments, and processing of high carbon steel before focusing on its application as music wire, specifically used in pianos.

Keywords: high carbon steel, music wire, piano wire, hypereutectoid steel, steel heat treatments

NOMENCLATURE

α-iron	Ferrite
γ-iron	Austenite
δ-iron	Gamma iron
BCC	Body-centered cubic
C	Carbon
$°C$	Celsius
FCC	Face-centered cubic
Fe_3C	Iron Carbide/Cementite
GPa	Gigapascal
L	Liquid alloy phase
Wt%	weight percent

1. INTRODUCTION

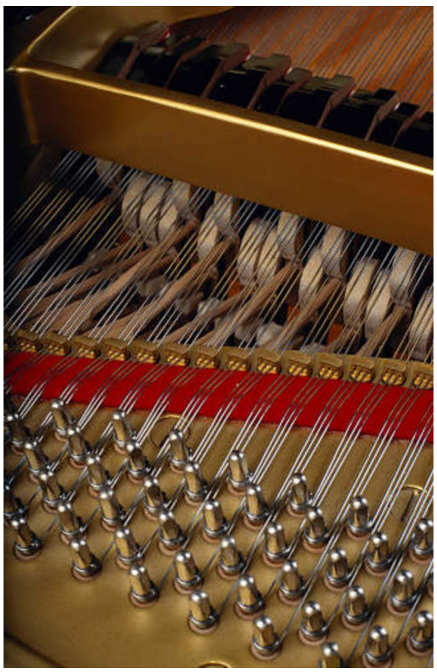
Steel is an iron-carbon alloy that is utilized in all facets of life, with applications in infrastructure, agriculture, car manufacturing, surgical tools, musical instruments, and more. The steel industry is steeped in history; archaeological evidence speaks of ferrous metallurgy occurring in Anatolia as early as 2000 BC and continues to portray its continuous development up until Englishman Henry Bessemer's steelmaking methods allowed for the inexpensive mass production of steel [1,2] .

Steels can be categorized based on various features, such as alloy content, application, heat treatment/microstructure, and more. In this paper, high carbon steel will be explored, and like the name indicates, it is a steel alloy with an elevated carbon-to-iron ratio, ranging from approximately 0.60 wt% to 1.4 wt% carbon. These high levels of carbon help yield the strongest, hardest, and least ductile carbon steel [3].

While it is often thought that high carbon steels are used in applications like tool and die steels, due to their resilience and ability to maintain a sharp edge, high carbon steels can also be cold drawn to form music wire.

Early appearances of wire-strung instruments date back to harps found in Ur, a Mesopotamian city founded around the 4th millennium BCE, marking the beginning of a musical revolution. One of the most important keyboard instruments emerged in during the 16th century: the harpsichord [4]. The harpsichord is generally composed of sets of strings that vibrate and produce tones through plucking. Antique music wires used in these instruments were generally composed of iron [5]. As harpsichords' designs progressed, and the invention of the *pianoforte* came with the turn of the 18th century, music wire design progressed as well. By the early 1800s, paralleled with the Industrial Revolution, piano makers in Europe began using steel wires (Figure 1 shows a closeup of piano wires) and yielded extraordinary results. The modern-day piano's design is not much different than the ones built in the late 1800s, bringing forth the question: what makes steel piano wires so attractive?

FIGURE 1: PIANO WIRE CLOSEUP [6]



2. STEEL MICROSTRUCTURE

Steel, an alloy of iron (Fe) and carbon (C), has a robust microstructure that is heat treatment and carbon content dependent. Figure 2, depicted below, is the Iron-Iron Carbide ($Fe - Fe_3C$) Phase Diagram, and can provide insight into the solid-state chemistry of steel and other ferrous alloys [3].

FIGURE 2: IRON-IRON CARBIDE PHASE DIAGRAM [7]

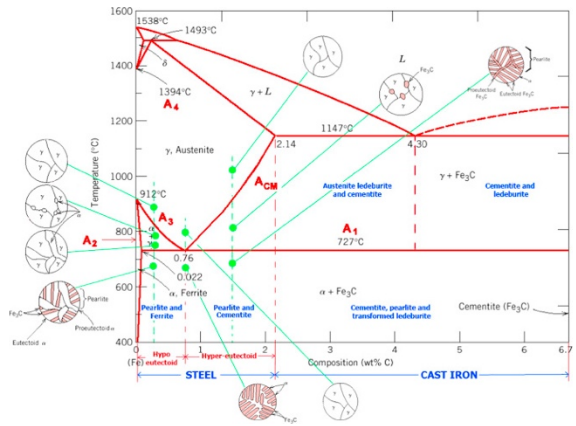


FIGURE 3: STEEL PORTION OF PHASE DIAGRAM [8]

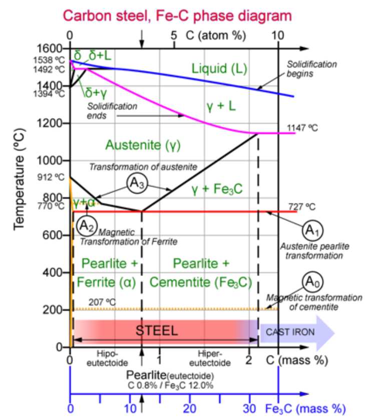
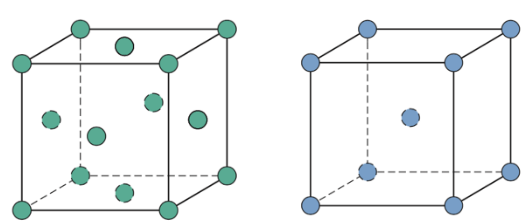


Figure 3, depicted above, magnifies in on the portion of the Iron-Iron Carbide Phase Diagram (Figure 2) representative of steel, with a carbon content range of approximately 0.022 to 2.11 wt% C [8].

2.1 Crystalline structures

Depending on temperature, two different crystal structures can appear in steel's microstructure: body-centered cubic (BCC) and face-centered cubic (FCC) crystal structures (shown below in Figure 4) [3].

FIGURE 4 : REDUCED-SPHERE UNIT CELL FOR FCC (LEFT) AND BCC (RIGHT) [3]



For a BCC crystal structure, lattice points (eg. atoms) are located at each corner and at the center of a unit cell (smallest division of crystalline structures). Whereas for a FCC crystal structure, lattice points are located at each corner and at the center of each face.

FIGURE 5: MICROSTRUCTURES FOR EQUILIBRIUM PHASE TRANSFORMATIONS IN HYPOEUTECTOID AND HYPEREUTECTOID STEELS [7]

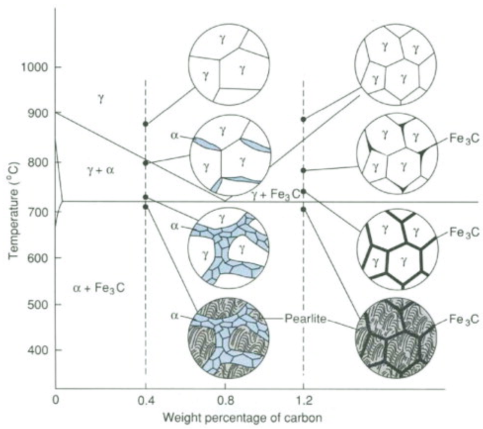


Figure 5 (shown above) depicts various microstructures resulting from isothermal reactions that will now be further explained.

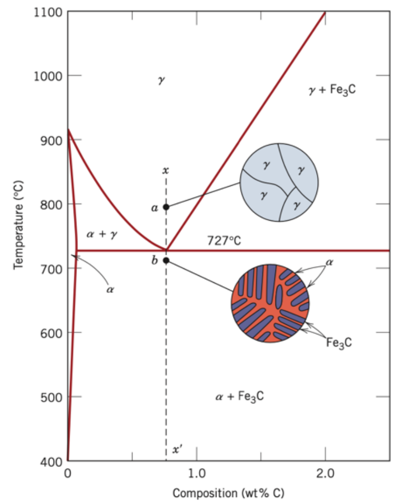
2.2 $L \rightarrow \gamma + Fe_3C$ transformation

There are three main isothermal reactions that occur in iron-carbon alloys, the first of which being the transformation from liquid phase to austenite (γ-iron) and iron carbide (Fe_3C). This eutectic reaction occurs at approximately 1147°C (shown in Figure 2) and yields austenite (FCC) with approximately 2.11 wt% C and iron carbide with approximately 6.69 wt% C [8].

2.3 $\gamma \rightarrow \alpha + Fe_3C$ transformation

The second isothermal reaction is a eutectoid one that transforms a solid reactant, austenite, into ferrite (α-iron) and cementite (a hard and brittle iron carbide) at approximately 727°C [8]. Ferrite, at room temperature, has a stable BCC structure [8].

FIGURE 6: IRON-CARBON ALLOY MICROSTRUCTURE ABOVE AND BELOW EUTECTOID TEMPERATURE [3]



This reaction yields significant changes to the microstructure, shown above in Figure 6. As the eutectoid steel is cooled below the eutectoid temperature (approximately 727°C), pearlite forms. Pearlite, named after its pearlescent appearance, consists of alternating layers of the two phases present: α-iron and cementite. The thickness of these layers is dependent on the cooling rate of the alloy: faster cooling rates yield finer layers [8]. Pearlite, physically, is somewhere between ductile and brittle [3].

2.4 δ-iron + L → γ transformation

The last isothermal reaction takes place at approximately 1495°C and transforms solid δ-iron and liquid alloy reactants into solid austenite [8].

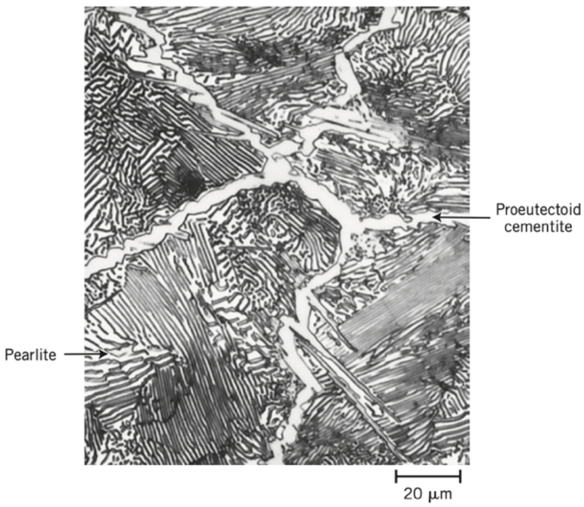
2.5 Hypereutectoid vs. hypoeutectoid steels

Hypereutectoid steels have a carbon content of more than approximately 0.8 wt% C (the eutectoid wt% C), whereas hypoeutectoid steels have a carbon content of less than 0.8 wt% C [7]. For hypoeutectoid steels, their microstructure consists mainly of ferrite and pearlite at room temperature, and for hypereutectoid steels, their microstructure is mainly pearlite and cementite [7].

2.6 Effects of high carbon content on steel microstructure

High carbon steel is characterized by its ability to achieve high strength and toughness through heat treatments, although it maintains a lower ductility in comparison to lower carbon steels. As we increase the carbon content (alpha + Fe_3C) region, the more cementite we get. Cementite, unlike ferrite, is a ceramic carbide, so our strength and hardness will increase but at the expense of ductility. High carbon steel's microstructure mainly consists of proeutectoid cementite and pearlite: an example of a 1.4 wt% C steel is shown below in Figure 7 [9]. Note the layered appearance of the pearlite, with white, hard, and brittle proeutectoid cementite located on the boundary grains. These cementite particles are very fine, spheroidal, and discontinuous [9].

FIGURE 7: PHOTOMICROGRAPH OF 1.4 % WT C STEEL'S MICROSTRUCTURE [3]



3. HEAT TREATMENT, PROCESSING, AND MANUFACTURING OF STEEL

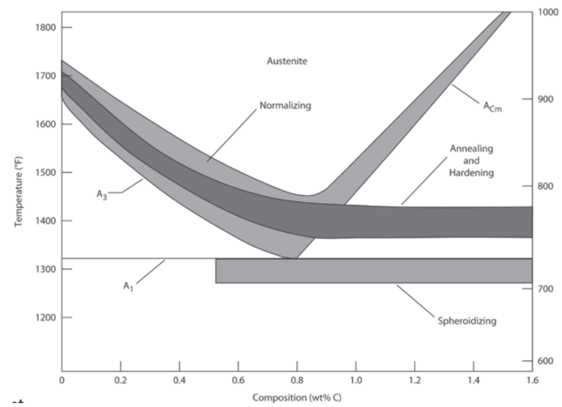
Heat treatment is often used to alter the mechanical properties of metals, such as hardness, strength, ductility, toughness, etc. There are several different heat treatment processes, and they are generally temperature time dependent: it is the temperature to which they are treated and the rate of cooling thereafter that affect the resultant metal structure. For the purposes of this paper, only heat treatments applicable to steel will be discussed, specifically annealing, hardening, and patenting as they are most applicable to the manufacturing of music wire.

3.1 Annealing

Annealing is used to restore a material's ductility and decrease its hardness through three stages: recovery, recrystallization, and grain growth [10]. This process is especially beneficial when cold-working metals, like steel, as it helps soften metals hardened through cold working processes.

The general annealing process for steel involves first heating the metal to a temperature, holding it there, and then cooling it back to room temperature [3]. According to a heat treatment guide by ASM International, for hypereutectoid steels, they should be heated to a temperature above the A_1 eutectoid temperature, shown in Figure 8 below, before being cooled via slow furnace [10].

FIGURE 8: STEEL HEAT TREATMENT TEMPERATURE RANGES [10]



Due to their microstructure, high carbon steels may sometimes be too hard to anneal using common methods and therefore can undergo spheroidizing. Spheroidizing involves heating the metal at a temperature just below the eutectoid and holding it there for up to 25 hours [3]. Spheroidizing will help break down steels' lamellar microstructure into what will eventually become tiny spheroids [10].

3.2 Hardening

Steels will undergo hardening to increase their mechanical hardness. Quenching is a hardening process that can be applied to ferrous alloys and involves an austenizing heat treatment and then a cooling treatment that allows amounts of austenite to transform into martensite [10]. To harden a ferrous alloy, it will undergo quenching in mediums such as air, oil, brine, etc . First, the steel will be heated to a temperature high enough for austenite crystalline particles to form. Then the steel will be cooled quickly back to room temperature (quenching), allowing for the austenite to be transformed into a brittle but strong martensite [10]. High carbon steels that undergo hardening will yield a higher hardness level as carbon plays a crucial role in physically hardening the steel.

Tempering can also be used after quenching in order to reach a specific range of hardness values, and involves reheating hardened steel to a lower temperature, and then cooling slowly [10].

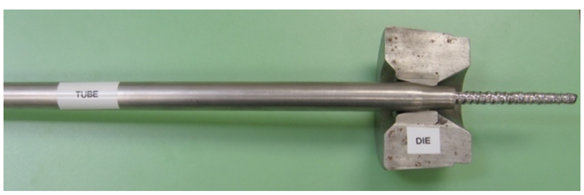
3.3 Wire Patenting

Another heat treatment method sometimes used to manufacture music wire is patenting. Patenting involves heating the steel to a high enough temperature to sufficiently form austenite. Then, rapid cooling is applied to help form ‘a uniform fine pearlite microstructure, ’strengthening the wire while leaving the iron intact [11]. The subsequent fine lamellar spacing between the ferrite and iron carbide particles will provide high ductility to the steel, as well as help it achieve a high tensile strength when cold drawn [12]. This heat treatment method can be applied as an intermediate heat treatment for cold drawing [11].

3.4 Cold Drawing

Music wire is manufactured through cold drawing. Cold drawing involves taking the high carbon metal and pulling it through a die (an example is shown below in Figure 9). The tensile force applied onto the metal as it exits the die reduces the cross section of the metal. Heat treatments can be applied before, during, and after cold drawing depending on what mechanical properties the steel needs to achieve.

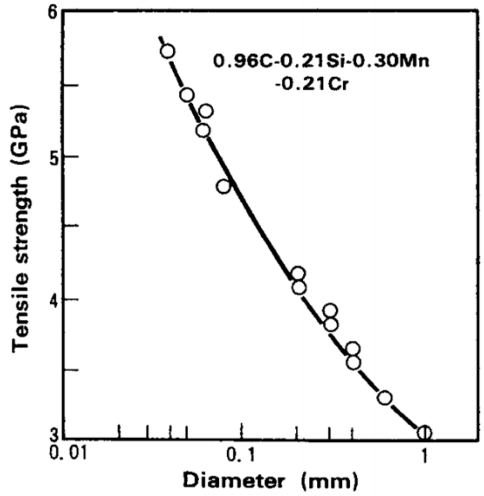
FIGURE 9: EXAMPLE METAL TUBE AND DIE [13]



3.5 Effects of Processing on Microstructure

Due to high carbon steels’ pearlitic and cementite microstructure, the resulting wires formed after cold drawing have the highest tensile strength in comparison to other steels [11]. Figure 10 below graphs tensile strength versus wire diameter for wire drawn pearlitic hypereutectoid steel wires and it is observed that tensile strengths of almost 6 GPa can be achieved.

FIGURE 10: TENSILE STRENGTH VS. WIRE DIAMETER FOR COLD DRAWN HYPEREUTECTOID STEELS [11]



As the steel is cold drawn, the cementite and lamellar pearlite layers will deform as well, with the longitudinal segments aligning themselves parallel with the direction of strain [11].

In an experiment conducted by scientists from Tsinghua University, Danish-Chinese Center for Nanometals, and Chongqing University to study the microstructure and strengthening mechanisms in cold-drawn pearlitic steel wire, researchers examined five steel samples subjected to various levels of strain [14]. The five levels were representative of the steps throughout the manufacturing process from non-drawn wire to fully cold-drawn. In Table 1 below, some of their results are presented comparing strain levels with the thickness of the ILS (interlamellar spacing), ferrite, and cementite layers. It is observed that the thickness of each of these layers drastically reduces throughout the cold-drawing process. The ferrite and cementite layers will also undergo slip deformations, along with ‘localized shear band formation throughout the pearlite lamellae’ [11].

TABLE 1: ILS AND THICKNESS OF FERRITE AND CEMENTITE THROUGHOUT COLD-DRAWING PROCESS [14]

ILS and thickness of ferrite (*F*) and cementite (*T*).

	Strain				
	0.00	0.68	1.51	2.67	3.68
ILS (nm)	89	70	55	28	20
F (nm)	70	56	45	23	18
T (nm)	19	14	10	5	2

The paper [14] suggest that the strength of high carbon steel cold drawn wire results from three strengthening mechanisms: boundary strengthening caused by the decreasing space between cementite lamellae layers; dislocation strengthening caused by the increasing of ferrite lamellae density dislocations;

and solid solution hardening caused by the increasing of the ferrite lamellae's carbon concentration [14].

4. DEVELOPMENT OF MUSIC WIRE

As mentioned earlier, the development of wire-strung instruments, mainly the piano, called for the need of music wire with higher tensile strengths.

A piano has approximately 230 music wires strung across an iron frame, with 88 total groupings that correspond to each of the 88 keys [15]. When a key is pressed, a hammer hits a complex mechanism that eventually vibrates the wires, producing tones of various frequencies based on the length and tension of the wires. Pictured below in Figure 11 is the aerial view of a standard modern Yamaha grand piano, where the strings are visibly strung across the copper-colored frame.

FIGURE 11: AERIAL VIEW OF YAMAHA GRAND PIANO [15]

While the modern piano utilizes high carbon steel music wires, early pianos from the 17th and 18th century used mainly iron and brass strings [16]. Although sufficient for those times, it was found that as the piano evolved into a larger and sturdier instrument (eg. adding more strings and an iron plate), the wires were subject to larger forces and vibrations that required the wires having greater tensile strengths [16]. Additionally, concerts were being played in grander halls and required wires that could produce a robust and loud sound.

In their paper [16], Giordano explores the evolution of music wire through comparing the piano wires from four pianos spanning 1890 to 1912. Table 2 below summarizes some of Giordano's findings, and a significant finding is the increased tensile strength from the iron wires used in an 1820 piano to the steel wires used in the 1912 Steinway [16].

TABLE 2: PIANOS INVOLVED IN STUDY AND THEIR RESPSECTIVE FINDINGS [16]

Piano	style	string radius (mm)	string length (m)	tension (N)	tension/area (Pa)	Approximate tensile strength of wire (Pa)
Anonymous (c. 1820)	6 octaves Viennese	0.29	0.31	140	5.1×10^8	1.0×10^9 (iron)
Stodart (c. 1820)	6 octaves English	0.27	0.33	150	6.6×10^8	1.0×10^9 (iron)
Streicher (c. 1850)	7 octaves Viennese	0.44	0.37	500	8.2×10^8	2.0×10^9 (steel)
Steinway M (c. 1912)	7-1/3 octaves Modern	0.495	0.39	690	8.9×10^8	2.5×10^9 (steel)

It is important to note that not every single piano string is composed entirely of steel. The lower bass strings tend to be wired with copper or have other various metal coatings to achieve their intended resonance [15]. This sheds light on an important balance that piano wires must achieve. Not only must they be mechanically sound and produce the tone they are supposed to, but they must also aim to create warm tones that are pleasant to the ear. This leads to a fine balancing act between mechanical components and the desired acoustics.

A common challenge piano designers face is selecting piano wire with tensile strengths that can suit the following criteria [16]:

1. Can provide enough tension to produce powerful and loud sounds
2. Can provide enough tension to withstand forces exerted on the wires from the playing and retuning
3. Has a wire diameter that is strong enough but does not increase the bending stress, which adversely affect the tone quality produced.

In order to determine tonal quality, or harmonicity (where sound frequencies are integer multiples of the fundamental frequency), sound physics and the mechanical properties of wires can be combined to form this equation [16]:

$$\alpha = \frac{\pi^2 E r^2}{32 \rho L^4 f_1^2} \tag{1}$$

where α is the inharmonicity parameter; E is the Young's modulus of the wire material; ρ is the string density; L is the string length; r is the string radius; and f_1 .is the fundamental frequency. While the physics behind this equation is beyond the scope of this paper, it is important to fully explore the parameters that need to be considered when developing music wire: how can the artistry of the sound produced be maintained while achieving ideal mechanical properties [16].

5. APPLICATIONS IN OTHER INDUSTRIES

Although named ‘music wire,’ it is, in the end, a versatile high carbon steel wire that serves important purposes outside of the music realm.

Music wire can be utilized in medical devices. An example would be using music wire as the base material for an intraluminal device that helps prevent pulmonary emboli through venal cava interruption [17]. Another popular usage of music wire is as a spring, due to its ability to withstand high tension and stress. More domestic uses include fishing lures to handheld tools.

6. CONCLUSION

This paper explored the general microstructure and heat treatments of steel before focusing on high carbon content steel, specifically its application as music wire in wire strung instruments such as the piano.

The development of steel paralleled the development of piano design, allowing for a powerful combination that has generally been left unchanged since the late 1800s.

This stagnancy in steel music wire development showcases how well it was mechanically manufactured to begin with, but also begs the questions: should other materials, such as carbon fiber which has a comparable tensile strength, be explored for piano wire? Or do the properties of steel allow for that perfect balance between mechanical abilities and tone quality?

While it would be interesting to test the limits of steel music wire design, it is indisputable that the modern-day piano, and other wire-strung instruments, are a true work of art and a testament to steels’ versatility and reliability.

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