Engineering Failure Analysis 35 (2013) 164–177

Contents lists available at SciVerse ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Failure analysis of piano strings

Adelina Borruto [a,*], Giovanni Narducci [a], Mauro Buccitti [b]

[a] University of Rome "La Sapienza", Department of Chemical Engineering and Materials, Via Eudossiana 18, 00184 Rome, Italy
[b] Steinway Accademy diplome- Consevatory of Music. S. Cecilia Via dei Greci 17, Rome, Italy

ARTICLE INFO

Article history:
Available online 8 February 2013

Keywords:
Piano strings failure
Fatigue failure
Grand piano

ABSTRACT

In this paper we studied the failure cause of two types of piano strings. The numerous problems which make it difficult to quantify the string life are systematically analyzed. The strings in question, made of spring steel (cold drawn wires with different thickness), are bass strings and acute strings of a piano concert. SEM analysis and Energy dispersive X-ray analysis (EDS) were made.

Related questions were taken into account:

- the connection of the string at the "tuning pin";
- string wear produced in its anchor point "agraffe";
- the bending in the compression points;
- the environment where the piano is located, the relative humidity and the strings corrosion phenomena that might trigger stress-corrosion cracking;
- the surface finish of the cold drawn string. Besides these factors, it is necessary to consider the different tuning performed on a concert grand piano.

1. Introduction

The piano is a masterpiece of mechanical engineering and without a doubt it is the most complex stringed instrument in the world.

The invention of the modern piano is due to Bartolomeo Cristofori di Francesco (May 4, 1655 - January 27, 1731), an Italian manufacturer of musical instruments [1].

In this paper we study the failure causes of the piano strings, for this purpose it is useful preliminarily to describe how a piano is made and how the strings are positioned.

Fig. 1 shows a grand piano scheme highlighting the main elements.

Modern piano has six main elements: case, frame, soundboard, strings, action, pedals.

The *case* (Fig. 1(a)) is a wooden cabinet which houses the piano strung back and playing mechanism. The case must balance both the attractive and acoustic properties, in fact the quality of the wood with which the case is made plays an important role in determining the sound characteristics of the instrument.

The *frame* (Fig. 1(b)), also called *plate* or *harp*, support the high stress exerted by the strings [2]. The frame of a grand piano weighs about 180 kg.

The average modern piano has over 230 strings under a combined tension of 15 to 20 tons. A concert grand piano may have a combined string tension of up to 30 tons;

* Corresponding author. Tel.: +39 06 44585637; fax: +39 06 44585641.
E-mail address: adelina.borruto@uniroma1.it (A. Borruto).

1350-6307/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfailanal.2013.01.006

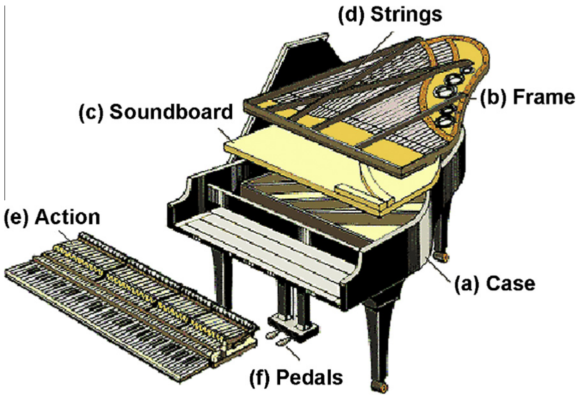

Fig. 1. Grand piano scheme and his principal elements.

The *tuning pins* (Fig. 2) are metal pins used both to anchor the strings and to vary the strain for tuning. These pins, through a hole in the frame, are planted for about half of its length in a solid block of wood called Somier (Fig. 3).

Tuning pin stability is ensured by contact between his outer surface and inner surface of the hole obtained in somier in which tuning pin itself is inserted.

The *soundboard* (Fig. 1(c)) is a thin piece of fine-grained spruce wood placed under the strings that reinforces the tone by means of sympathetic vibration.

The soundboard amplifies the vibrations of the strings.

Two soundboard bridges transfer the vibrations of strings along their lengths to the soundboard and support the down-bearing pressure of strings. This pressure must be supported also by the arch of the crown or the tone of the strings will drop.

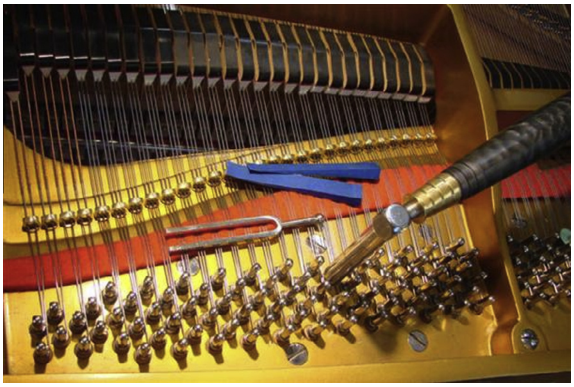

Fig. 2. Tuning pins.

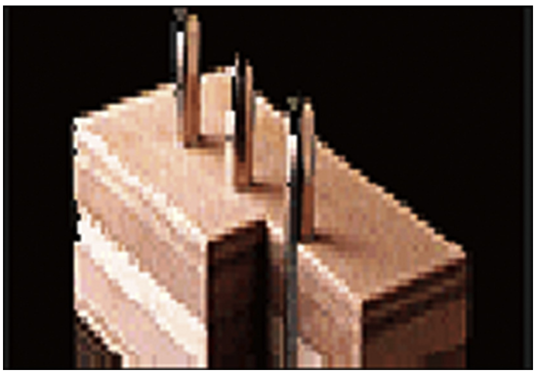

Fig. 3. Tuning pins into somier.

The *arc of the crown* is a soundboard convexity towards the bridges which is very important for the sound quality of the instrument.

Indeed, each manufacturer endeavor to calculate and implement the optimal value of such curvature: if it lacks the instrument would produce a hollow sound, if it is excessive the instrument would be fastidiously clarion.

The bridges are made from solid blocks of wood or laminated wood. Hard maple wood is used for pianos made in America, falcon wood (beech) is used in Europe.

Figs. 4 and 5 show respectively a soundboard with two bridges and the strings deformation on the bridge.

Fig. 6 highlights the position of the string fixed on the cast iron plate. One string end is wrapped around the tuning pin and the opposite end is fixed to the cast iron plate by an iron pin.

The *agraffe* (Fig. 7) is a critical element of the system because it causes the string failure by wear. The agraffe acts as a guide at the string end, near the tuning pin.

The agraffe can drive one, two or three strings together. This element not only control the string sound and length, but also the string vibration.

The good quality agraffe are generally made of brass but they can be painted or electro-plated. Usually the agraffe holes are flared. The agraffe lying plane must be perpendicular to the strings that cross the agraffe itself and its height is adjusted by means of thin brass thicknesses.

The vibrating part of a string, which produces the sound, corresponds with the stretch going from agraffe to bridge (Fig. 6).

Fig. 8 shows the vibration modes of a string [3].

Fig. 4. Soundboard and two bridges.

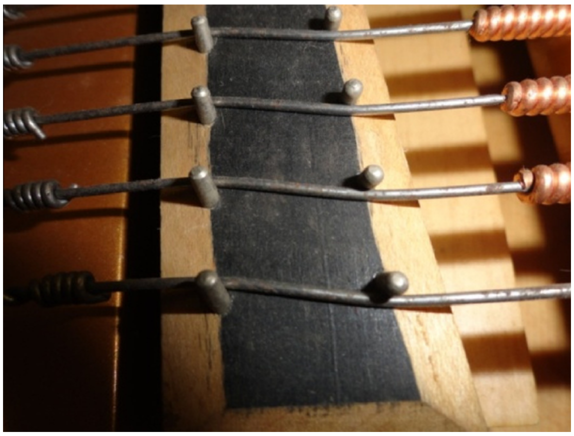

Fig. 5. Strings deformation on the bridge.

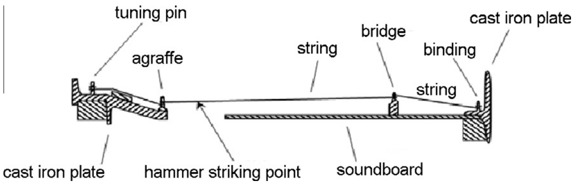

Fig. 6. Position of the string mounted on the cast iron plate.

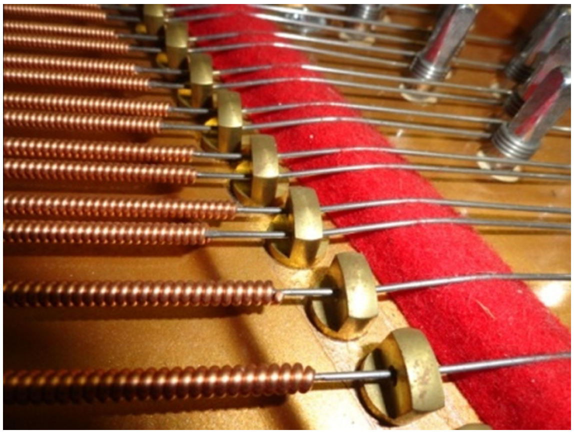

Fig. 7. Agraffe.

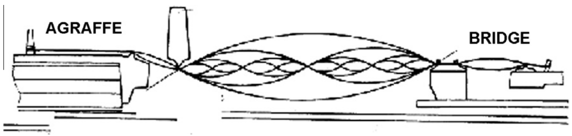

Fig. 8. Vibration modes of a string.

A sensitive vibration is not present in the lines between tuning pin and agraffe and between bridge and anchor pin (Fig. 6). In these two areas, due to the particular imposed path, the string is subjected to deformation.

When the tuner adjusts the string tension these two sections, blocked at one end, are subject to sliding.

The strings of the piano, *piano wire* or *music Wire*, (Fig. 1(d)) are made of high carbon content quenched steel (ASTM A228).

The piano wire is made by cold drawing with diameters ranging from 0.725 to 2.2 mm and has a tensile strength in the range 2000 to 2700 MPa.

The wire diameter must be kept strictly constant: variations greater than 8 μm produce sound falsifying in modern instruments.

Each note played on a piano is the result of a string, or a group of two or three strings, which vibrate at a specific frequency determined by the length, diameter, tension and the density of the string itself. A shorter, lighter string, under more tension, vibrates faster, and produces a higher-pitched sound (Tayor low) [4].

Generally, an average load of 90 – 100 kg is applied on the acute strings.

For each acute note there are 3 strings, for each upper bass there are two strings and for each lower bass there is one string. The highest notes are produced by thinner strings. If the high notes were produced by a single string, their sound would be overwhelmed by the sound of bass thicker strings.

The bass strings are made of a steel wire covered with a copper wire winding. The winding can weigh down the strings to make them vibrate at lower frequencies. The strings so formed can reach 6 mm in diameter. To save space and install longer possible lower bass strings in the case, in modern pianos these strings are arranged diagonally over the high notes strings.

The *action* (Fig. 1(e)) is the whole mechanism used to exert the impulsive stress on the strings to produce vibration.

For this purpose a keyboard is provided, consisting of several elements precisely denominated keys which are manipulated by the fingers [5].

Exerting pressure on a key is activated a sophisticated system of levers that moves an element covered with felt, called hammer, to strike the strings associated with the key pressed (Fig. 9).

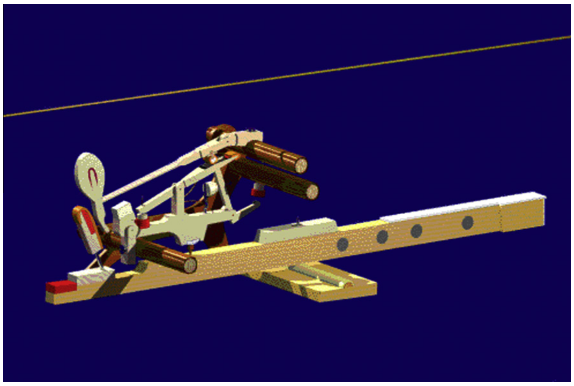

Fig. 9. Action.

The hammers rebound, allowing the strings to continue to vibrate at their resonance frequency. These vibrations are transmitted through a bridge to the soundboard that transmits the acoustic energy to the air.

When the key is released, a damper stops the string vibration.

The hammers of the piano strike the strings to 1/7 or 1/9 of their length (Fig. 6), in such a way to prevent the division into seven or nine portions of the string and consequent formation of the seventh and ninth harmonic that are the first harmonic dissonance.

2. Materials

As received materials and failed materials in opera were taken into account:

- brass agraffe;
- lower bass and acute strings.

2.1. As received materials

2.1.1. Agraffe

Fig. 10 shows a new brass agraffe having a single hole and Fig. 11 shows the hole surface finishing.

By examining the hole surface can be seen a high roughness due to a coarse-grained turning.

2.1.2. Strings

Figs. 12–14 show the surface state of a new commercial string. The string is made of piano wire ASTM A228. Many defects due to cold working can be seen. Fig. 13 shows the EDS analysis area and Table 1 shows the steel composition.

Fig. 14 shows a magnification of a string surface area.

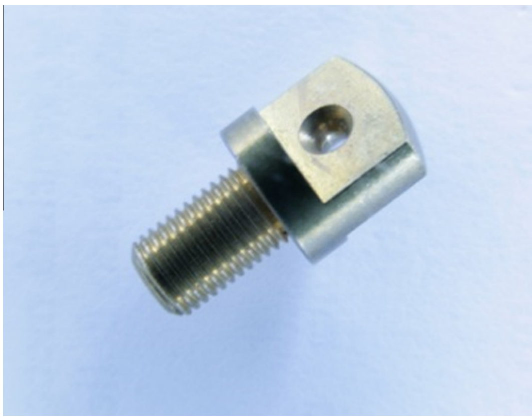

Fig. 10. Single hole agraffe.

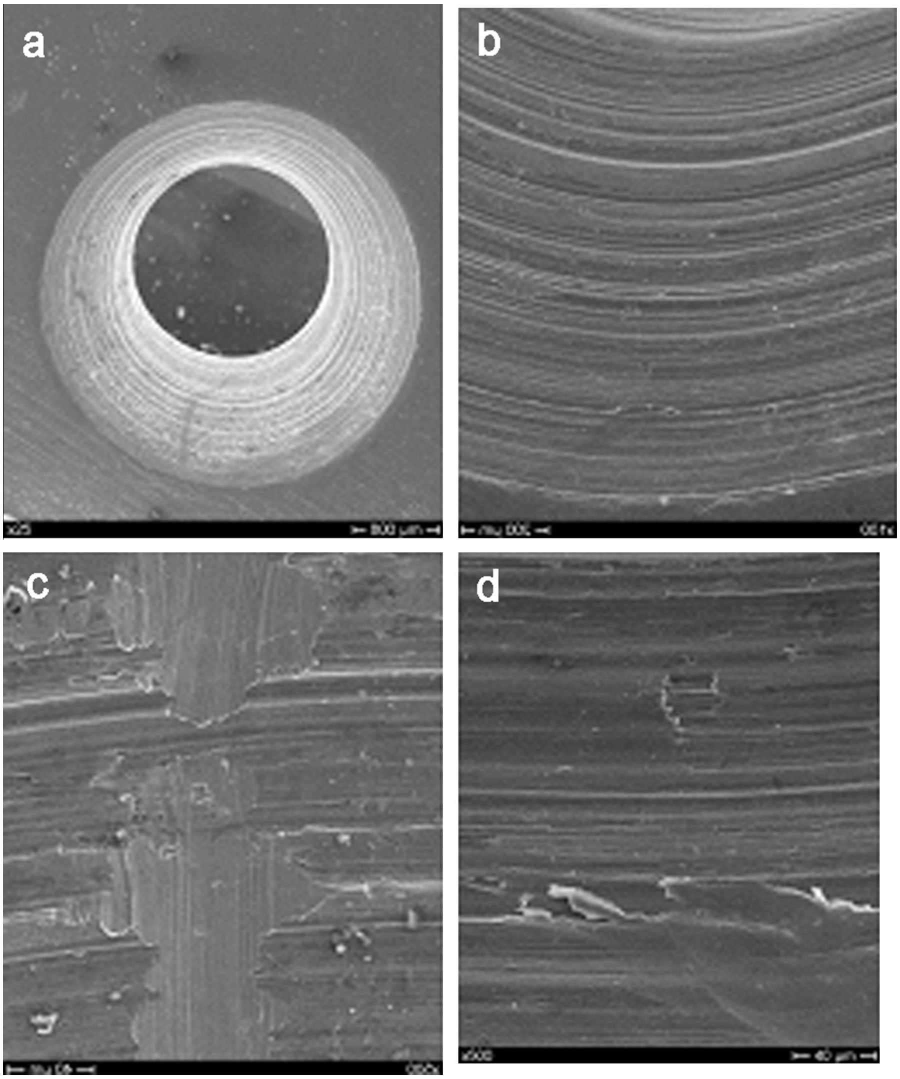

Fig. 11. Hole surface finishing – SEM: (a) 25×, (b) 100×, (c) 500×, (d) 500×.

2.2. Failed materials in opera

Failed acute and lower bass string from a grand piano concert were taken in account.

2.2.1. Lower bass strings

Figs. 15–19 show the fatigue fracture of a lower bass string occurred in the agraffe contact area.

Fig. 15 shows longitudinal view of the string. It is highlighted the deformation due to the crossing through the agraffe.

Figs. 16–18 show the string fatigue fracture surface. We can see (Figs. 18 and 19 and EDS analysis, Table 2), 30% of copper spread on the string. The copper coming from coating of the string.

2.2.2. Acute strings

Figs. 20–22 show the acute strings fatigue fracture. The string failed at the point of pressure holding the horizontal bar of the piano. The bar acts like an agraffe serving to hold firm the string. The bend we see corresponds to the overcoming of the bridge.

EDS analysis (Table 3) of the fracture surface (Fig. 20) show the typical composition of the string. The presence of impurities is due to corrosion, and dirt.

Figs. 21 and 22 show respectively the area of fracture initiation and its magnifications. Many defects can be seen due an incorrect mechanical processing on the string surface and cross grooves of wear due to the contact between the string and horizontal bar.

Fig. 12. Commercial string surface – SEM 100×.

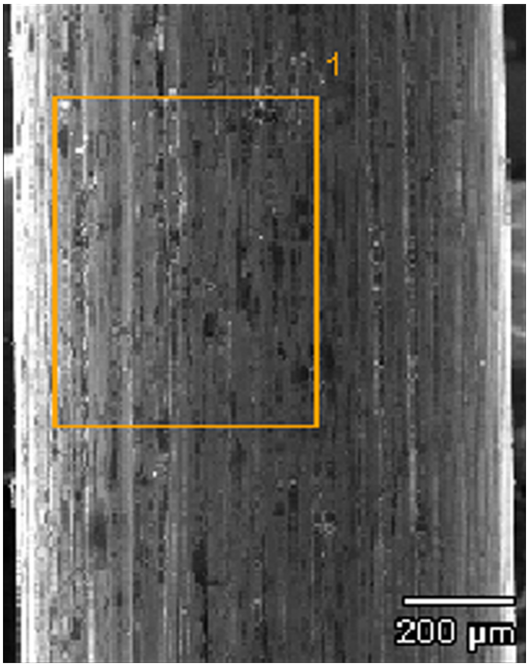

Fig. 13. Commercial string surface, EDS analysis area 100×.

3. Discussions and conclusions

The mechanisms leading to strings failure result from innumerable and interesting combinations of variables, some of which are:

- the bending in the compression points;

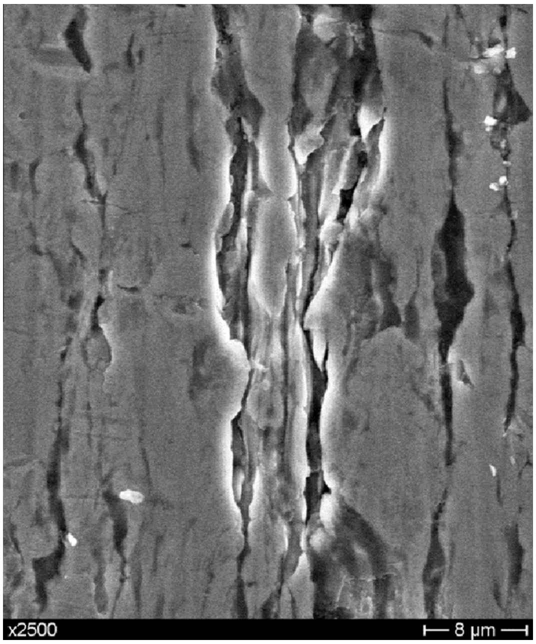

Fig. 14. Commercial string surface, SEM 2500×.

Table 1
EDS analysis. Energy dispersive X-ray analysis (wt%) (Fig. 13).

	Al	Si	K	Ca	Fe
pt1	0.39	0.12	0.21	0.23	99.05

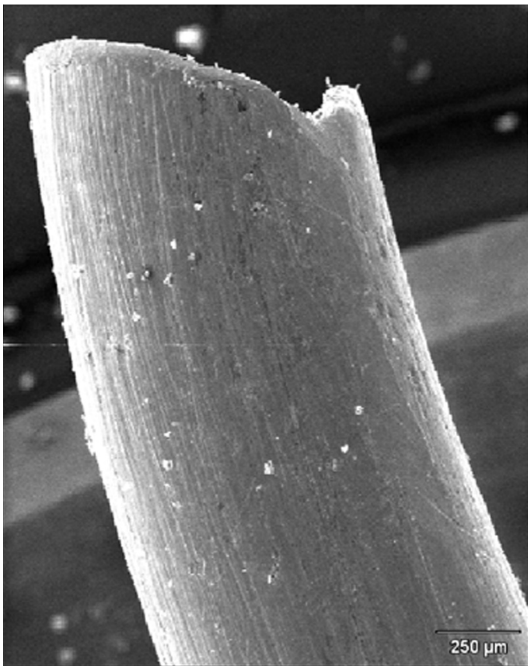

Fig. 15. Fatigue fracture of a lower bass string, SEM 60×.

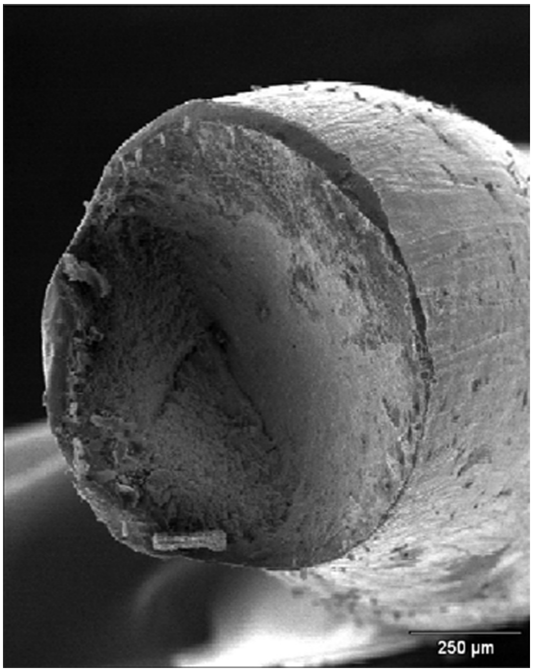

Fig. 16. Fatigue fracture of a lower bass string, SEM 80×.

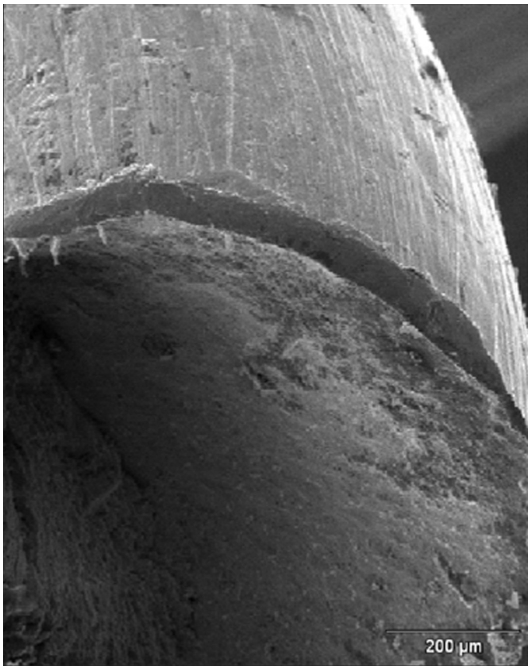

Fig. 17. Fatigue fracture of a lower bass string, SEM 120×.

- the connection of the string at the tuning pin;
- the string surface finish;
- the strings wear produced in its anchor point with agraffe;
- the environment where the piano is placed, the relative humidity and the strings corrosion;
- different tunings performed.

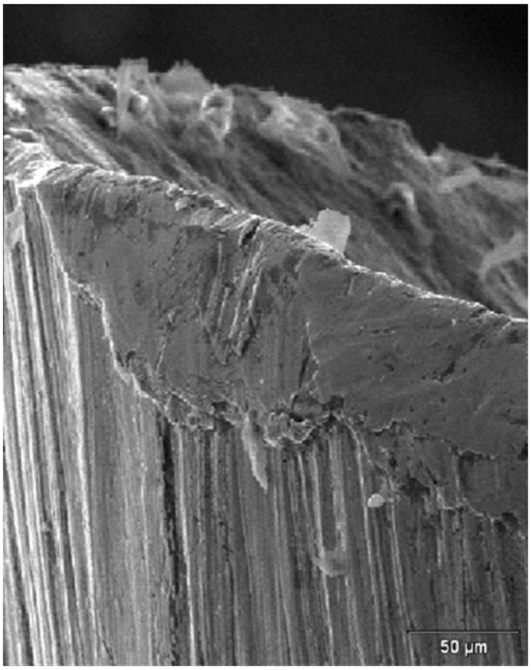

Fig. 18. Fracture surface, particular of a lower bass string, SEM 400×.

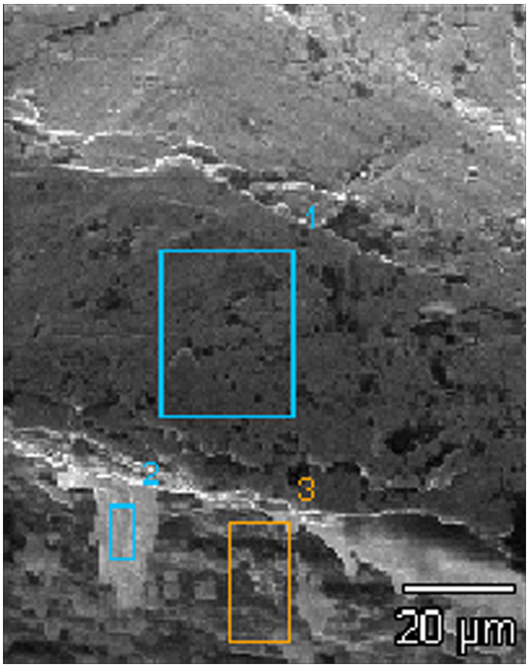

Fig. 19. Fatigue fracture of a lower bass string, EDS analysis area 100×.

The string, between the beginning and the end of its path, is subject to different deviations and deformations necessary to delimit the vibrating portion, see in this regard Figs. 5 and 7, respectively showing the string portion fixed to the pin end and passing through the bridge and the string segment wrapped around the tuning pin and passing through the agraffe. At the bridge and at the agraffe the string is subject to compression loads.

Each non-elastic bending imposed to the wire tends to harden it, exactly as a cold processing would on the steel if made in that area. The fibers on the convex side of the string (stretched fibers) are loaded over the yield point. So this area will be more brittle in comparison to other zones of the string.

Table 2
EDS analysis. Energy dispersive X-ray analysis (wt%) (Fig. 19).

	Si	Ca	Cr	Fe	Cu
pt1	0.63			99.37	
pt2		2.70	19.46	50.50	27.34
pt3		3.21	27.28	33.72	35.79

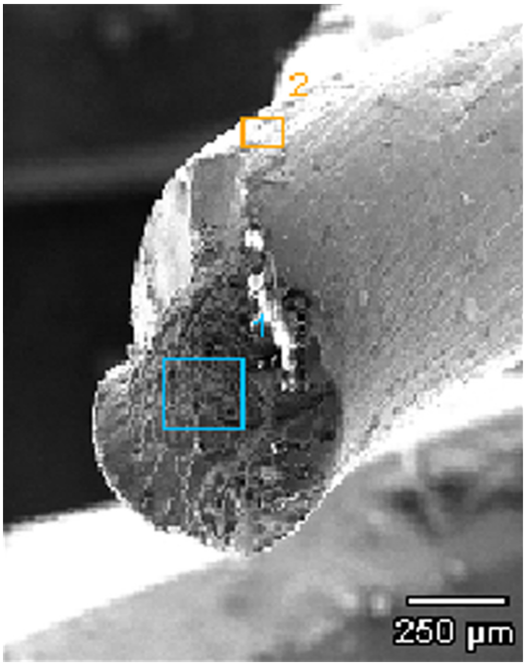

Fig. 20. Fatigue fracture of an acute string, EDS analysis area 70×.

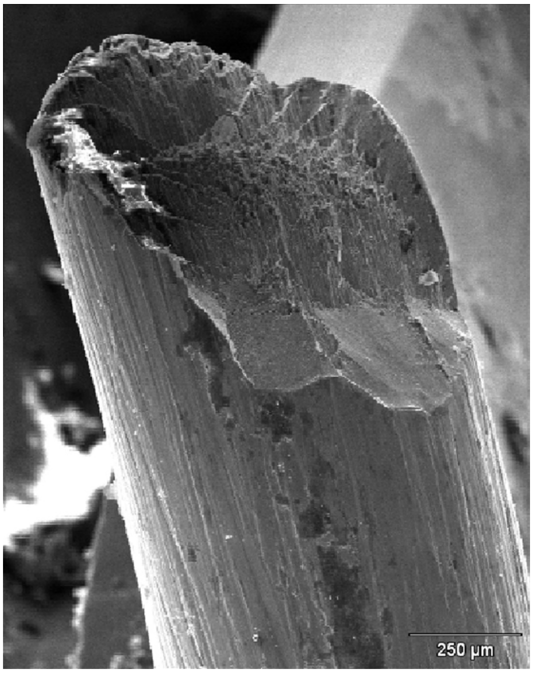

Fig. 21. Fatigue fracture of an acute string – SEM 80×.

Fig. 22. Fatigue fracture of an acute string, magnification of the fracture surface – SEM 800×.

Table 3
EDS analysis. Energy dispersive X-ray analysis (wt%) (Fig. 20).

	Mg	Al	Si	P	S	Ca	Cr	Fe
pt1				0.18			0.07	99.75
pt2	0.31	2.06	3.66		2.76	7.63		83.58

Another critical mechanism is in the point of tangency where the string starts to wind around the tuning pin. Repeated small tuning changes subject a short section of the string to alternate bending and straightening, which, even though slight, tend to work-harden the steel. This is why so many "old age" string failure occur at the tuning pin. It should be avoided to undergo the strings to unnecessary plastic bending due to incorrect twisting and excessive tension.

Each stress close to 70% of the tensile strength is dangerously close to the yield strength, although the acute strings necessarily are subjected to a load close to the yield strength.

Even the high-frequency reverse bending that occurs consistently in a strongly stretched vibrating string, particularly at the end where the transverse waves are reflected, is an high stress cyclic loading and many strings failure in opera should be considered fatigue failures.

As we observed in the results (Figs. 15–19 for the lower bass strings and Figs. 20–22 for the acute strings), fatigue failure is also determined by surface imperfections, such as defects by mechanical processing on the new string surface (Figs. 12–14).

Wear, that occurs in string-agraffe contact (Fig. 11) or in string-horizontal bar contact above the acute strings (Fig. 22), becomes very important for the probability of fracture, especially when the mechanical finishing is not adequate.

In fact, the tribological coupling between the outer surface of the string and the internal surface of the agraffe causes a strong abrasive wear with formation of brass debris that remain trapped between the contact surfaces, creating the three bodies wear phenomenon. Moreover, the known brass malleability against the very tough and jagged string surface brings as a consequence that these debris are spread on the string itself, with consequent exaltation of the phenomena.

Also, the presence of wear debris into the agraffe hole causes a buzzing sound.

The fatigue failure of the strings, as known, is accelerated by the corrosion phenomenon. It is necessary to check the environment in which the piano stays, the moisture conditions and very often the hazardous cleanings by very aggressive spray materials.

It is also necessary know the movements of the soundboard which are incisive for the tension of the strings and stress corrosion cracking.

In effect:

- *in wet environment*: the soundboard absorbs humidity in the air surrounding the piano, consequently swells upward. Corresponding the bridge increases the strings tension. In these conditions the string pitch (diapason) is too high (grows) in the acute region (Fig. 23);
- *in dry environment*: the soundboard withdraws and loses the inflection: the string tension on the bridge falls below a minimum value. In these conditions the acute string pitch (diapason) decreases (Fig. 24).

Unfortunately, because the strings lengths are all different, the pitch (diapason) does not increases or decreases in the same way, this leads to difference along the scale.

Another main issue is the tuning.

Every musician has a particular sensitivity to the sound of the instrument.

The pianist needs a special assistance from the tuner, for both the piano mechanics (consider the register of hammers that strike the string with different loads) and the tuning of the strings tension so to produce different vibratory motions.

The tuner, before carrying out any work, must carefully consider the various factors that influence his action, among which an important one is the environment.

As already said, it is the environment that affects the movements of the soundboard, and then the strings tension.

There is no piano that keeps the tuning when exposed to dramatic changes in humidity, which if unchecked can result in the failure of the soundboard and bridges.

The tuning system of a piano (Fig. 25) consists, as already anticipated in the introduction (Figs. 2 and 3), in tuning pin-tuning hummer coupling. Fig. 25 represents in detail the tuning pin-tuning hummer system.

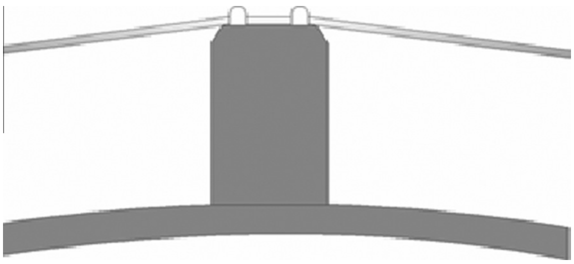

Fig. 23. Soundboard scheme in moisture environment.

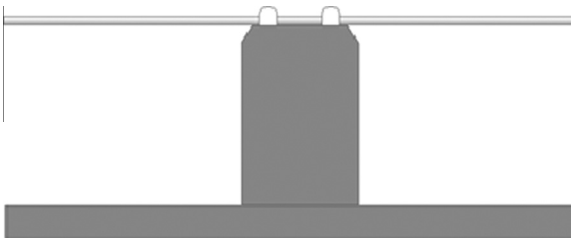

Fig. 24. Soundboard scheme in dry environment.

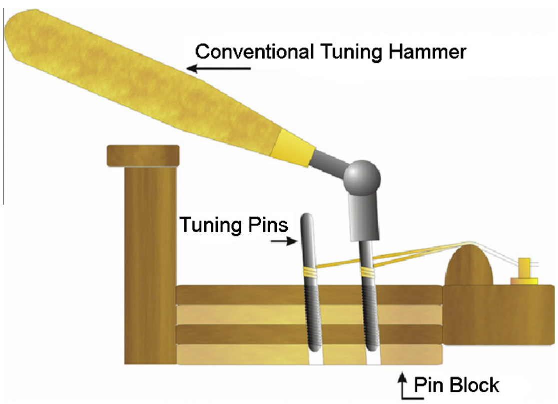

Fig. 25. Scheme of tuning pin-tuning hummer system.

This tuning system makes very difficult the task of the tuner to adjust mechanically the "pitch" of the strings. A fine tuning of a lower bass string (e.g. the lowest notes, length of 2012 mm, inner wire with a diameter of 1.7 mm) requires a tuning pin rotation resolution of 0.16°; a triple string (e.g. the highest notes with length of 50 mm, diameter of 0.8 mm) requires a rotation resolution of only 0.005°.

These fine resolutions are very difficult to achieve because of the non-linear friction strength that affect the tuning pin: 17 Nm are required to rotate a typical tuning pin [6]. This task becomes even more difficult when it is taken into account the variability of the torques required to rotate each tuning pin: friction characteristics vary widely from piano to piano by varying the somiere design [7], the tuning pin design [8] and, in a same piano, by varying the temperature over time.

A good tuning must also take into account the periodic stress exerted by the hammer on the strings, which determines the sound quality influencing the relationship dynamics-timbre.

Such stress can cause damage by periodic effort on the strings [9].

For all these reasons a concert grand piano should be tuned for each concert.

The piano tuner faces the complexity of mechanical and sound issues also trusting to his natural skills and experience which give much of the piano sound charm.

References

[1] Carter G. The piano book. Wensleydale Press; 2008.
[2] Davis JR. Cast irons/metallurgy and properties of ductile irons. ASM specialty handbook. ASM International; 1996.
[3] Fletcher NH. The non-linear physics of musical instruments. Rep Prog Phys 1999;62:723–64.
[4] Frova A. Fisica nella Musica. Zanichelli editore; 1999.
[5] Askenfelt A. Measuring the motion of the piano hammer during string contact. J STL-QPSR 1991;32(4):019–34.
[6] Gravagne N. Tuning pin torque & tuning that too tight pin. Piano Technicians J 1993:24–7.
[7] Larudee P. Tuning pin physics: Part 1. Piano Technicians J 2002:16–9.
[8] Larudee P. Tuning pin physics: Part 2. Piano Technicians J 2002:20–3.
[9] Conklin H. Tuning pin for pianos. US patent 4920847.