A New Material for Balance Springs

Gideon Levingston looks at the thermal and magnetic properties of the conventional balance assembly, wheel and spring and suggests a new way of producing long term stability

THE ACCURACY of a mechanical watch is dependent upon the specific frequency of the oscillator composed of the balance wheel and balance spring. When the temperature varies, the thermal expansion of the balance wheel and balance spring, as well as the variation of the elasticity (Young's Modulus) of the balance spring, change the specific frequency of the oscillating system, disturbing the accuracy of the watch. Approximately three quarters of the variation can be attributed to thermal or magnetically induced changes in the balance spring.

Methods for compensating these variations are based on the consideration that the specific frequency depends exclusively upon the relationship between the torque of the balance spring acting upon the balance wheel and the moment of inertia of the balance wheel as is indicated in the following relationship

$$T = 2\pi\sqrt{\frac{I}{G}} \qquad (1)$$

T is the period of oscillation, ***I*** the moment of inertia of the balance wheel and, ***G*** the torque of the balance spring.

The moment of inertia of the balance wheel is a function of its mass ***M*** and its radius of gyration ***r***.

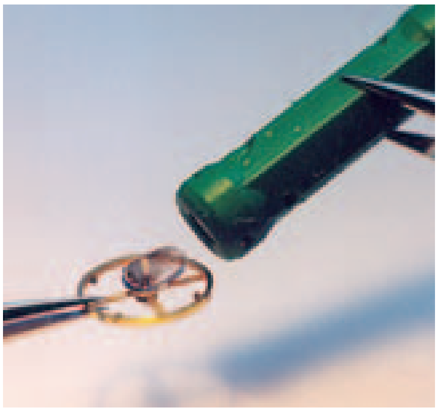
The torque of the balance spring is a function of its dimensions: length ***l***, height ***h***, thickness ***e***, and of its Young's Modulus ***E***. The length ***l*** of the balance spring (which may be helical or spiral) is the entire length, end to end. The relationship (1) is rewritten:

$$T = 2\pi\sqrt{\frac{12.M.r^2.l}{E.h.e^3}} \qquad (2)$$

Temperature variations influence ***T*** as a result of expansion and contraction of the balance spring and wheel. Dimensions ***l, h*** and ***e*** of the spring and ***r*** of the wheel, vary, but ***M*** remains constant.

We know how to compensate for the effects of expansion on ***l, h*** and ***e***. However the period of oscillation is still subject to variations of ***r*** and ***E*** in keeping with the relationship expressed by:

$$\frac{r}{\sqrt{E}} \qquad (3)$$



1. A current high-grade COSC-rated balance and spring in the presence of a child's toy magnet.

These two terms are not in a linear relationship.

It is necessary that this relationship should remain as constant as possible (so as to keep ***T*** constant, i.e. the oscillations are ***isochronous***).

This article describes a way of overcoming magnetic and thermal variation in watches. First the current problem is analysed by re-examining the present state of the art. Following this a proposed solution and a material choice, will be examined and demonstrated.

The Current State of the Art

Ferro nickel (Fe-Ni) metal spring alloys provide an approximate solution to the problem when the alloy is perfectly demagnetised. However, when the alloy is not perfectly demagnetised, the relationship is no longer constant: ***E*** changes.

Balance wheels currently employed in high grade chronometers are of a gold-copper or copper-beryllium (GLUCYDUR) alloys which have similar α (linear expansion) coefficients lying between +14 and +17 x 10^{-6}/°K.

These balance wheels expand isotropically with a rise in temperature as do all metal balance wheels except bi-metallic and ovalising balances which expand anisotropically. The change in the ***E*** value of the balance spring must therefore accommodate this, as is evident from the relationship (3).

The Fe-Ni alloys currently used for balance springs show an increase in both ***E*** and ***l*** for an increase in temperature across the normal ambient temperature range. These characteristics help to compensate each another. Whereas an increase in length is considered *normal* an increase in ***E*** is rare in materials, and is thus considered *abnormal.*

In summary, when the Fe-Ni balance spring gets hotter, instead of getting less elastic it gets more elastic (a positive or *abnormal* variation in ***E***). This compensates for both its dimensional change and the increasing diameter of the metal balance as it gets hotter and expands. Hence the term 'auto-compensating balance spring'. However this is true only up to a certain temperature, the Curie threshold (named after Pierre Curie) and concerns the increased dipole activity between the elements within the alloy as the threshold is approached.

The work of Charles Edouard Guillaume in the development of INVAR and other Fe-Ni low expansion alloys was a further development of Curie's investigations of magnetism in these alloys that are pivotal to the use of Fe-Ni alloys in balance springs and balance wheels.

De-magnetising has long been accepted as the solution to this problem, and as such is an imperative taught in watch schools. Unfortunately this is neither practical for every watch owner nor is it wholly effective.

What is not widely understood however is the relationship between temperature, magnetism and the useful positive variation of ***E*** in Fe-Ni alloys. It must be remembered that the external influences considered here are magnetism and temperature and their respective effects upon the spring and the balance.

If the spring behaves normally, i.e. ***E*** is negative as in a steel spring, then as the temperature increases the system will require that the workload of the spring is decreased. This is achieved by an inward-bending cut bi-metallic balance wheel where the value of the ***M*** multiplied by r^2 (equation 2) is decreased. Unfortunately, in this Guillaume system both balance and spring are susceptible to magnetism.

With a monometallic balance, when the temperature rises the work load on the spring gets greater. The balance wheel radius increases, its gyratory mass shifts further from its centre of rotation, and it requires greater effort on the part of the spring to keep it oscillating at the same

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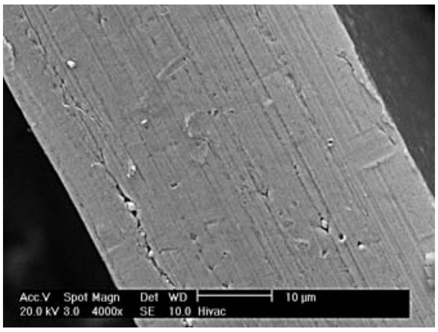


2. The thickness dimension view 'e' *(35 microns) of a new high quality chronometer balance spring, at 4000x magnification, showing inclusions from the rolling process and indications of the direction rolling.*

frequency. If the Fe-Ni spring has an *abnormal* (+ve) E tendency then it can compensate for this and all is well. If on the other hand its elasticity is subject to internal dipole changes triggered by a combination of temperature and magnetic effects, T will not remain constant and isochronism will be lost.

Examination of an Fe-Ni alloy at the microscopic level illustrates just how non-uniform this material actually is, **2**. The difficulties of producing finely alloyed metals to the very high specifications required in this field should not be underestimated. My examination and analysis of a high-grade balance spring shows how foreign matter can become impregnated in the processing of such materials to the detriment of the performance. The batch quality of the material is dependant upon its purity. Each batch is tested empirically and graded into a statistical spread of qualities.

Analysis using a scanning electron microscope, **3**, has shown that similar material is currently being used throughout the industry from high-grade watches to standard grade watches. The alloy in terms of its physical intrinsic properties performs in exactly the same manner.

The Problem

The Fe-Ni alloys currently used, despite their potential for compensation, only allow for the stability of T (the period of oscillation) over the ambient range up to 40°C – and only when the spring is perfectly demagnetised.

Any watch employing a Fe-Ni balance spring can be stopped by a sufficiently powerful magnet and any exposure to a magnetic field results in the absorption of magnetism in a cumulative manner. After a time the elasticity of the spring changes and isochronism is adversely affected.

Magnetic pollution from electric and electro-magnetic sources of all descriptions: computers, portable telephones, televisions, electric motors, toys etc, may all cause the alloy to absorb magnetism. In a magnetised Fe-Ni alloy the temperature limit for the usefully anomalous behaviour of E drops from 40°C to below 30°C, well below normal body temperature, and the spring loses its elasticity.

When a non compensating mono-metallic balance wheel of GLUCYDUR, or even gold and copper, expands, its greater gyratory mass cannot be compensated for by the spring. Where the alloy's physical properties require a balance wheel to have a linear expansion coefficient, α, around $+15\times10^{-6}$/°K, once beyond the magnetic and temperature limits the α coefficient of the balance intrinsically causes a change of rate, the balance wheel and balance spring do not conform to the relationship in (2) and the system is no longer isochronous. The watch, depending on the balance amplitude, will either gain or lose significantly. In fact a wristwatch chronometer subject to this effect may have as much as ± 10 seconds per day variation. The COSC certificate requires a tolerance of +5 to –7 seconds/day.

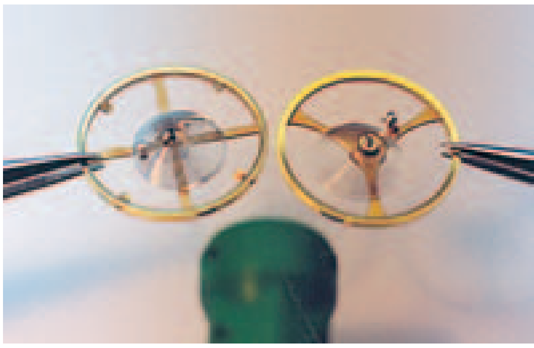
Furthermore, if a low positive α coefficient balance is coupled with the Fe-Ni spring this will neither compensate for the magnetised or non-magnetised condition of the spring nor for the thermal changes intrinsic to metal alloy springs in this oscillator arrangement. A low +ve α coefficient balance requires an appropriate low +ve variation in modulus.

If a non-magnetic balance spring material is used, its variation in E must be in keeping with the α coefficient of the balance variation in the relationship (2) or no further increment in precision will be gained.

Proposed Solution

Solutions need to be found if mechanical watches at the top end of the market are to retain their reputation in an environment increasingly subject to magnetic fields from computers, telephones and electric circuits as well as the earth's natural varying field forces.

The solutions must take into account the external influences of heat, cold and magnetism ***and*** their inter-relationship. A non-magnetically sensitive balance spring is one step in the right direction, it must however be thermally stable or it must be compensated by a balance wheel that can adjust for the intrinsic thermal characteristics of the spring.



4. Best chronometer and standard balance springs under the influence of a magnet.

A Solution

The non magnetic solution which I have been developing allows for the effect of magnetism to be ruled out completely at the same time that the material's remarkable thermal properties, very stable and slight modulation of E and very low creep, are exploited.

The internal friction of the material as known to Watch Timers (*Regleurs*) is another physical property very worthy of consideration as it has a consequence regarding balance amplitude in particular. The elastic damping coefficient (internal friction) of the materials considered is smaller than that of the Fe-Ni alloys currently employed, which means that the energy stored in the balance spring as a result of the impulse of the balance wheel is released in the returning arc of the oscillation in greater measure than is the case with the presently used metal alloys.

This means that loss of amplitude particularly between the vertical and horizontal positions, is reduced and that there is less total loss of the source energy stored. This increased increment of efficiency helps in maintaining long term stable rate.

As part of a post-graduate physics and material science research degree at the *Ecole de Mines de Paris* in the research and development centre Sophia Antipolis, I have investigated the use of various new composite materials, and found that a number of paths lie open for the solution to the outlined problem.

	Fe	Ni	Cr	Ti	Al	Mn	Si
Best Chronometer Balance spring alloy	50.84	38.23	8.47	1.29	0.37	0.45	0.36
Standard Balance spring alloy	50.19	38.79	8.75	1.02	0.42	0.45	0.38

3. Scanning Electron Microscope (SEM) analysis of Balance Spring alloys in high grade and standard grade mechanical watches.

The major considerations for the choice of an alternative material, apart from its magnetic insensitivity and change in E, must be its α coefficient and its density.

The density of the spring material as it dilates is the source of lateral gyratory forces on the balance pivots in their bearings as well as producing an inertia within the spring. This was understood by A-L Breguet and others and gave rise to Breguet's development of the overcoil to reduce these forces. So if the material density is decreased the need for the overcoil is also decreased as the lateral forces on the balance pivots are reduced.

In my opinion one of the optimum materials of choice is continuous carbon fibre: it is non magnetic, **5**, has high elasticity, low density, is thermally very stable in the ambient range and it has a very slight and negative linear α coefficient. It has been noted how important this is in equation (2). An increase in temperature results in a decrease in the length l of the balance spring (a shorter period of oscillation is provoked with a rise in temperature), which contributes to the compensation of a dilating balance wheel and also interacts with the thermo-elastic characteristic of the material producing a linear E variation which is minimal. The high tensile and flexural strength are also good and can both be varied by technical means.

In comparative dynamic materials analysis tests (DMA) using the standard Fe-Ni alloy as a reference material, I have compared my carbon fibre material at various frequencies from 0.32Hz – 10Hz (an 18,000 vph watch oscillates at 2.5 Hz) and have shown a marked improvement in thermal stability in the range 0 – 40°C. The DMA technique requires the material to be oscillated in flexion by a very finely balanced linear oscillator linked to a micro-force sensor which is connected to a computer. Data for the variation of E over the chosen temperature range at multiple frequencies is recorded as well as data on the damping of the material.

5. Continuous Carbon fibre composite balance springs (black) made by the author, with a standard ferro-nickel spring, in the presence of a magnetic field.

The thermal tests were run over the temperature range from 5° – 38°C which corresponds to the tests currently used for the COSC certificate. The variation of E is linear and minimal and the Young's Modulus damping(internal friction) of the material is low and stable throughout the temperature range. The magnetic influence is zero.

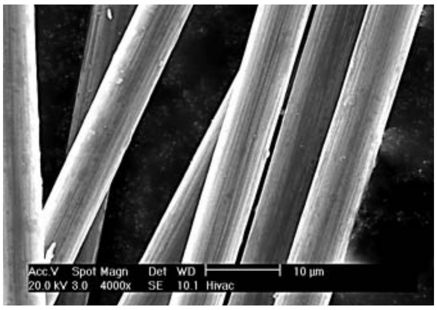
The Balance Wheel

The choice of a material which intrinsically limits the unwanted thermal, magnetic and energy loss effects is of prime importance but as the whole oscillator system must be taken into account the thermal characteristics of the balance wheel were also considered.

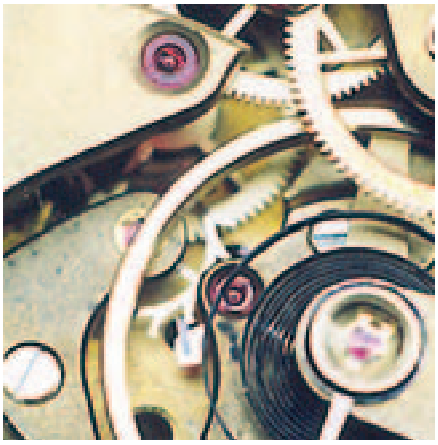
Appropriate values for the balance wheel α coefficient must be selected. For use with a carbon fibre balance spring a selection has been made from a range of low α coefficient materials which are non-magnetically sensitive. These include 99% fused quartz and certain silicates with α coefficients less than $+1.5\times10^{-6}$/°K, ten times less than current chronometer balance wheels. The net effect is to flatten the gradients of the curves for the variation E and r with temperature, so that the discrepancy is minimised in (3) over the desired temperature range. I have developed further residual compensation methods which allow for a parallel evolution in the two curves.

The use of ceramic material and the carbon family in all its forms, including diamond, has been claimed in the intellectual property rights I have filed in my international patent. The most efficient and cost effective solution is undergoing tests for potential industrial production.

The carbon fibre material used has proved itself over nearly forty years. Its present and continued use in the aerospace and aeronautical industry provides considerable evidence of its long term stability and reliability (high modulus polyacrylonitrile fibres were first developed by Rolls Royce and the Royal Aircraft Establishment). The use of polymer, ceramic and carbon matrix phases provide composites which are 'state of the art' and most remarkable. The material I have chosen is eminently suitable and has a proven track record.



6. Carbon fibre at 4000x magnification.



7. High quality deck watch fitted with the author's carbon composite balance spring.

Tests are currently being conducted using identical deck chronometers fitted with a flat spring, **7**, Further comparative tests using a pair of two day marine chronometers with helical springs are also being conducted as well as the integration of a flat spiral spring into an automatic wrist watch chronometer calibre.

The solution proposed is based upon the net advantages of the continuous carbon fibre based material which is non-magnetic. The high modulus and good flexion characteristics are excellent qualities for springs. The low negative α coefficient and low E variation and modulus damping minimise temperature influences on both the dimensions of the spring and its elasticity. The low creep and low density of the material allow for long term stability on the one hand and energy gains on the other.

In high quality watches where the energy delivered via the escapement to the oscillator has been perfected, essential further precision and stability can be gained. For the standard grade of watch the potential for substantial increase in performance is also waiting to be exploited. In overcoming the problems associated with magnetism and temperature, we can conclude from the characteristics of this new material proposal that it offers a potential solution to the industry, for whom the essential requirements for the mechanical oscillator are to give long term stable precision. ❒