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Wiegand

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[45] **July 1, 1975**

[54] **METHOD OF MANUFACTURING BISTABLE MAGNETIC DEVICE**

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[21] Appl. No.: **481,226**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 247,356, April 25, 1972, Pat. No. 3,820,090, and a continuation-in-part of Ser. Nos. 173,070, Aug. 19, 1971, abandoned, and Ser. No. 137,567, April 26, 1971, abandoned, and Ser. No. 86,169, Nov. 20, 1970, abandoned, and a continuation-in-part of Ser. No. 5,631, Jan. 26, 1970, Pat. No. 3,602,906, and Ser. No. 5,632, Jan. 26, 1970, abandoned.

[52] **U.S. Cl.** .... **72/371;** 148/101; 340/174 ZB

[51] **Int. Cl.** **B21f 7/00;** B21f 45/00

[58] **Field of Search** ...... 72/371, 378; 148/101, 103, 148/31.57, 120; 340/174 PM, 174 ZB, 174 TW; 140/149

[56] **References Cited**

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Primary Examiner—Lowell A. Larson
Attorney, Agent, or Firm—Ryder, McAulay, Fields, Fisher & Goldstein

[57] **ABSTRACT**

A ferromagnetic wire is processed by being subjected to cycling torsional strain and longitudinal strain to provide a bistable magnetic wire switching device having permanently different shell and core magnetic properties. The product switches state in response to an appropriate threshold external field and does so without being held under external stress or strain.

18 Claims, 12 Drawing Figures

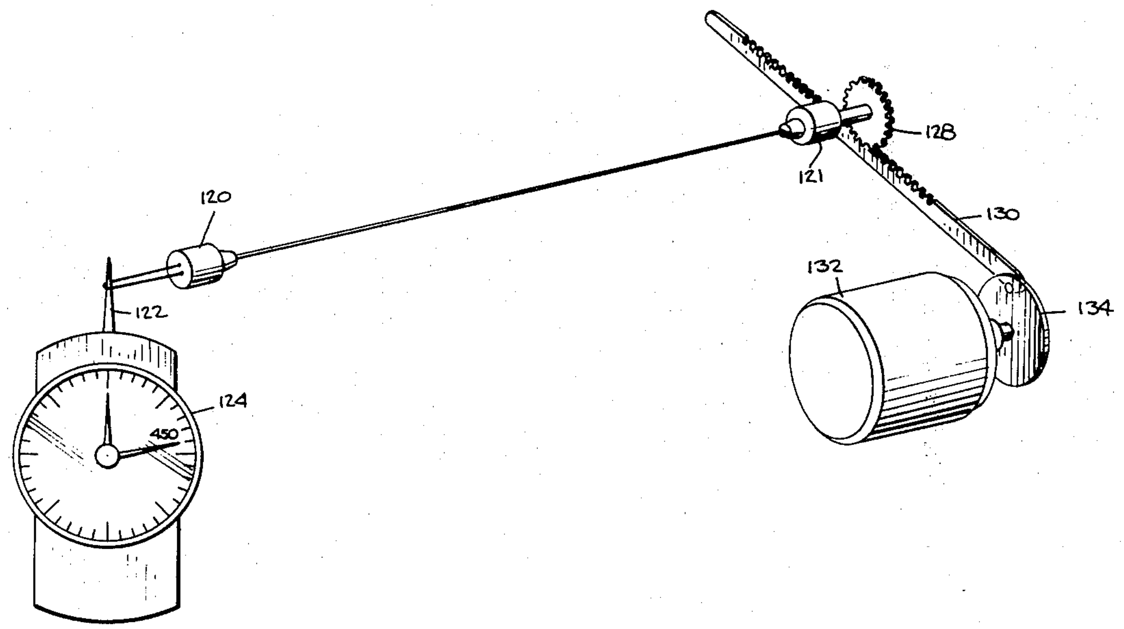


Fig. 1.

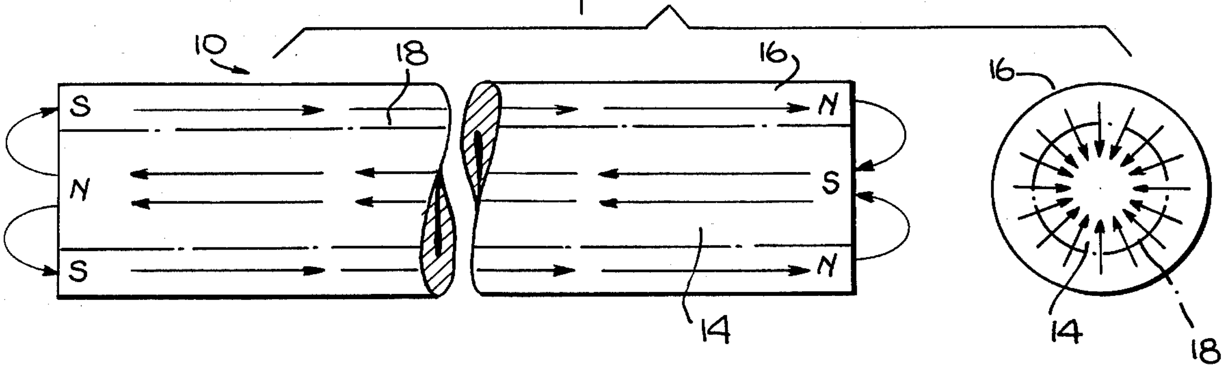


Fig. 2.

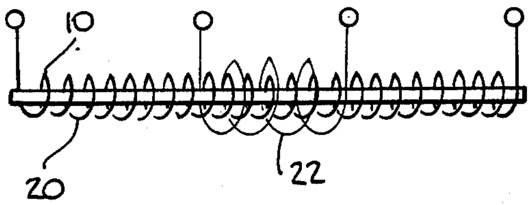


Fig. 3.

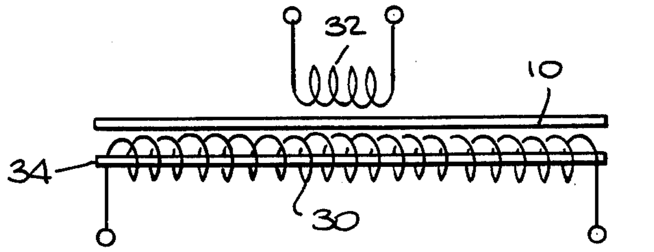


Fig. 4.

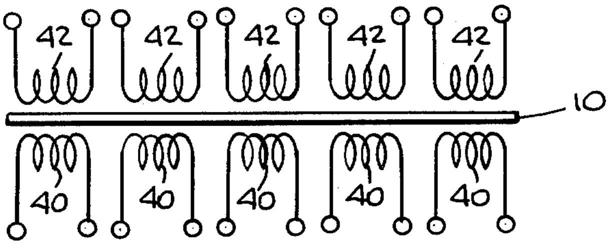


Fig. 5.

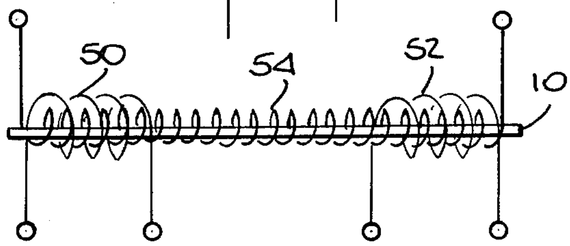
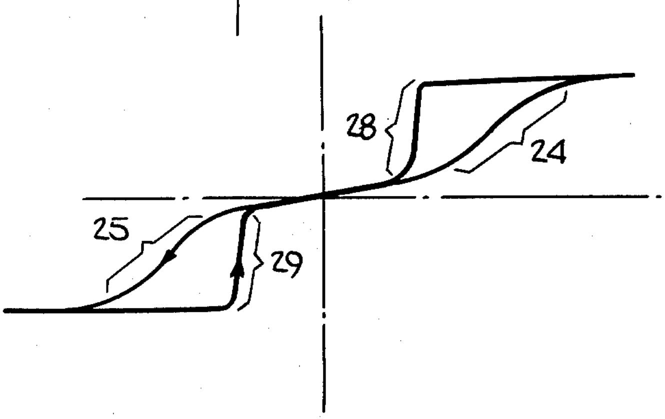


Fig. 6.



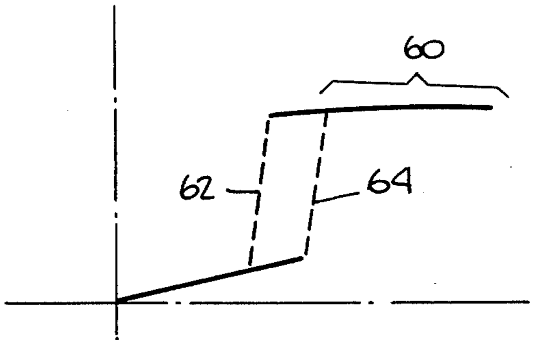


Fig. 6A.

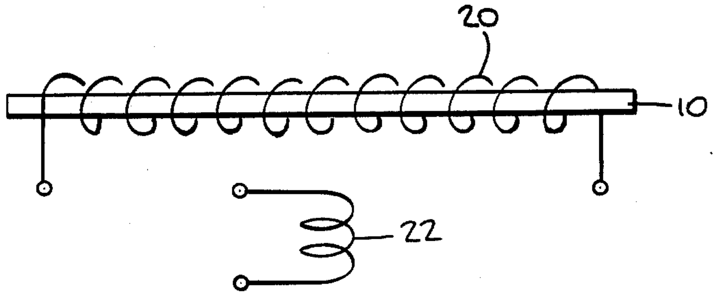


Fig. 2A.

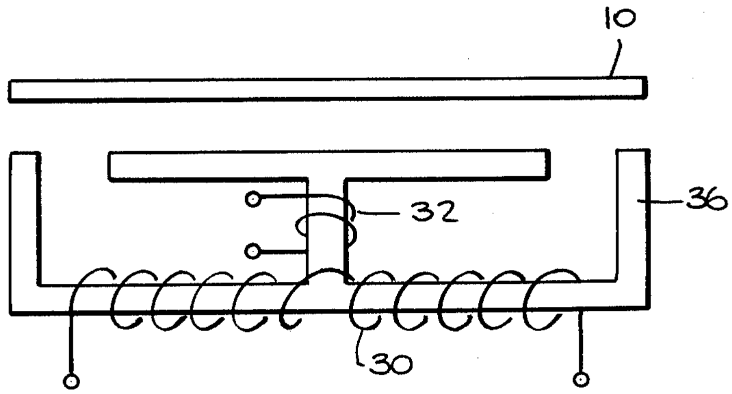


Fig 3A.

Fig. 7.

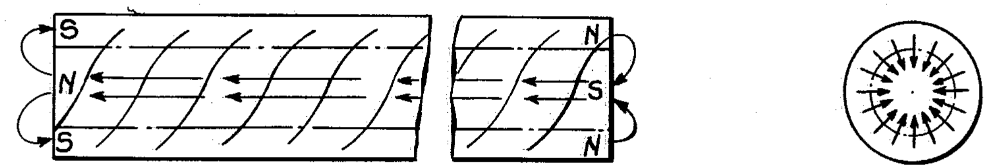


Fig. 9.

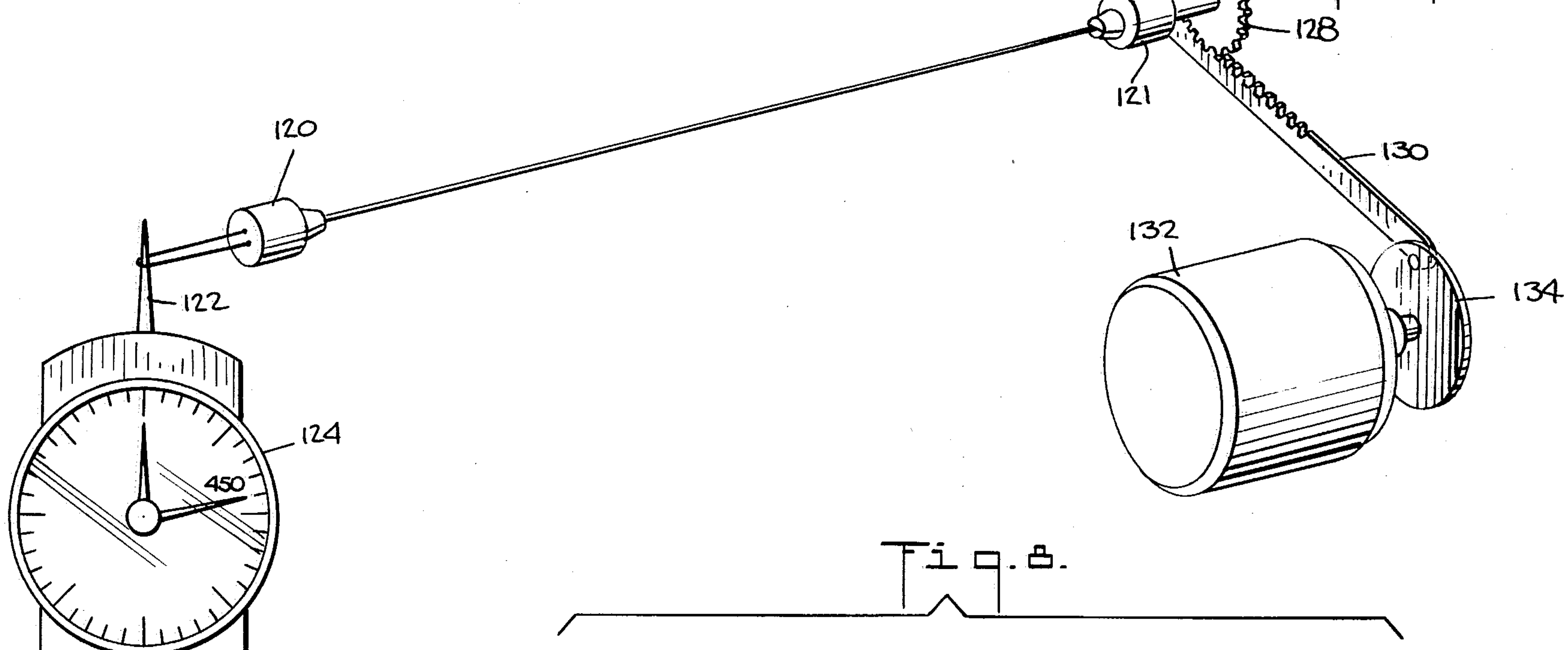
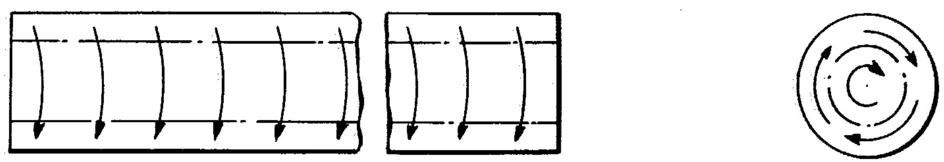


Fig. 8.



METHOD OF MANUFACTURING BISTABLE MAGNETIC DEVICE

This application is a continuation-in-part of co-pending application Ser. No. **247,356** filed by applicant on Apr. **25, 1972** and entitled "Bistable Magnetic Device", now Pat. No. **3,820,909,** and of the various now abandoned parent cases filed prior thereto, specifically Ser. No. **173,070** filed Aug. **19, 1971**; Ser. No. **137,567** filed Apr. **26, 1971;** and Ser. No. **86,169** filed Nov. **20, 1970.** This application is also a continuation-in-ppart of U.S. Pat. No. **3,602,906** issued Aug. **31, 1971** on an application filed Jan. **26, 1970,** Ser. No. **5,631,** and entitled "Multiple Pulse Magnetic Memory Unit" and of Ser. No. **5,632** filed Jan. **26, 1970** and entitled "Coded Magnetic Card and Reader". Ser. No. **5,632** was abandoned in view of the filing of a continuation-in-part case Ser. No. **189,027** filed Oct. **13, 1971** which issued on Jan. **1, 1974** as U.S. Pat. No. **3,783,249.**

The above referenced applications describe a magnetic device having two magnetic states and also describe the method for making the device which is described herein. The Patent Office required an election between the product invention and the method invention. Applicant elected the product invention. Accordingly, the present application would normally be a divisional application. However, applicant has further improved the method of manufacturing the device since filing the above referenced applications and files this application as a continuation-in-part in order to incorporate the preferred methods of manufacture as of the time of filing this application.

BACKGROUND OF THE INVENTION

The magnetic device described in the above referenced applications is a ferro-magnetic wire having core and shell portions with divergent magnetic properties. As taught in said applications a preferred way of obtaining these divergent magnetic properties is to apply a torsional force to the wire so as to circumferencially strain the wire. The wire is circumferencially strained in alternate clockwise and counterclockwise directions while maintaining axial tension on the wire. The result is a wire which, it is believed, because it has a relatively harder magnetic shell and a relatively softer magnetic core, has the property that once magnetized the shell becomes a permanent magnet and the core, being softer, will be magnetically captured by the shell to provide a return path for the lines of flux generated by the shell.

An alternate explanation of the phenomenon is one that assumes there is some axial flow of the shell relative to the core during the twisting operation because the twisting operation takes place while the wire is held under tension. Under this model, the axial flow or straining of the shell results in the application of a stress to the core. Then the torsional straining (twisting) is stopped and the axial tension removed, the resulting wire is one in which there is a permanent axial tension on the core exerted by the shell which is flowed.

When the wire described in the parent applications is subjected to an increasing external magnetic field, a threshold is reached where the external magnetic field suddenly and rapidly captures the core to provide a low reluctance path for its flux. If the polarity of the external field is opposite from that of the shell, then the flux from the shell must be completed in the space around the wire. A pick-up coil will produce a pulse in response to this sudden change in the flux pattern. The change in the flux pattern occurs in response to a threshold magnetic field intensity being achieved and is substantially rate insensitive. That is, the magnitude of the output pulse is independent of the rate at which the external field increases. Similarly, there is a reverse switch in magnetic field configuration and a reverse pulse generated in the pickup coil as the magnetic field decreases. Again, the pulse output is substantially independent of the rate at which the magnetic field decreases; all that is required is that the switching threshold be passed.

Accordingly the major purpose of the invention described and claimed herein is to provide a method for manufacturing the two state wire described in the above referenced patent application.

The magnitude of the output pulse is of critical importance in determining the value of the wire and in determining the scope of applications to which the wire can be commercially put. The larger the pulse, the less will be required in the way of electronic circuity associated with the pickup coil to distinguish the pulse from various background noise. The larger the pulse, the more repeatable will be any output condition that is to be iniated or recorded by the incidence of the pulse.

According, it is a major purpose of this invention to provide a method of fabricating the wire described in the above referenced patent applications with a switching response to a threshold external magnetic field that will produce a pulse having improved signal to noise ratio and having a larger peak magnitude.

It is a related and further important purpose of this invention to provide such an improved wire as will provide the kind of switching response to the threshold magnetic field that will produce a uniform and repeatable output pulse from a pick-up coil.

BRIEF DESCRIPTION OF THE INVENTION

In brief, it has been found that a preferred mode of manufacturing the wire to produce greater magnitude, more repeatable and more uniform output pulses is to use a fine grain nickle-iron alloy having a **10** mil (**0.010** inch) diameter. A one meter length of this wire is stretched four centimeters. The stretched wire is then held between two chucks at a constant tension of **450** grams. One of the two chucks is oscillated back and forth at a rate of **0.4** turns per centimeter of wire. Thus for the one metal length of wire, the chucks rotate **40** complete revolutions in one direction and then **40** complete revolutions in the other direction. This clockwise and counterclockwise rotation is repeated ten to fifteen times. The chucks are supported in a machine which maintains a constant tension of **450** grams as the rotation occurs. After this processing, the tension is removed and the one meter length of wire is cut into whatever lengths are desired (frequently about ½ inch each) for use in the various switching and pulse generating applications which have been developed for this wire.

Some variation in tension, number of turns per meter and number of cycles of clockwise and counterclockwise rotation are desirable as a function of wire diameter, wire chemical consistency, and wire application.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 illustrates an enlarged diagrammatic representation, including a longitudinal view and an end view, of an embodiment of a magnetic wire manufactured by the method of the present invention.

FIGS. 2, 2a, 3, 3a, 4 and 5 show enlarged diagrammatic representations of exemplary readout systems employing the magnetic wire of FIG. 1.

FIGS. 6 and 6a show M–H magnetization curves representing certain magnetic characteristics of the magnetic wire of FIG. 1.

FIGS. 7 and 8 show enlarged diagrammatic representations, similar to those shown in FIG. 1, of other embodiments of a magnetic wire manufactured by the method of the present invention.

FIG. 9 is a perspective representation of the equipment that may be used in manufacturing the magnetic wire device by the method of this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The wire described in the referenced patent applications is one which when magnetized has two magnetic states. When switching between these two magnetic states, at least a portion of the flux switches from a path external of the wire to a path internal to the wire or vice versa, so that a pick up coil wound around the wire will generate a pulse. The rate at which the flux switches when the wire changes state is so fast that the electrical pulse generated by the pick-up coil is a distinctive sharp usable pulse. Furthermore, this state switching occurs in response to an external magnetic field, having a proper direction, either increasing in magnetic field intensity to above a first threshhold or decreasing in magnetic field intensity below a second threshhold. The switching of the wire, thus, is responsive to a threshhold magnetic field applied to the wire. As a result, the magnitude of the output pulse is not rate sensitive in that it is not affected by the rate at which the external triggering magnetic field increases or decreases. The use of this bistable wire for generating this distinctive, non-rate sensitive output pulse has the further advantage that the process occurs without requiring any input electrical signals or current. Thus an external permanent magnet can be used as the source of the triggering magnetic field and all that is required is that the position between the bistable magnetic wire and the external permanent magnet be increased and decreased to provide the increase of external field over the first threshhold and the decrease of external field under the second threshhold. Even where the triggering magnetic field is generated by an electric current through a coil around the wire, there is no need for other electrical inputs at the switching device.

It is believed that this bistable magnetic wire operates as it does because of the intimate physical relationship between a magnetically harder shell zone and a magnetically softer core zone. It is believed that the holding of the core under tension by the shell occurs and may be an important factor in the magnetic switching phenomenon.

As described in the referenced patent application, a method for forming a wire of the type described is constituted by (a) drawing the wire to substantially the desired size while it is maintained at a suitable elevated temperature to form a wire with a desired fine grain, and (b) work hardening the wire in a manner which provides for hardening of the wire shell while maintaining the wire core relatively soft. For example, for forming a wire composed of 48% iron and 52% nickel, the wire is drawn from a relatively heavy gauge wire (e.g., 1 to 1½ diameter wire) by passing the wire through successive drawing stations which individually provide for a 20% reduction in the cross-sectional area of the wire at approximately 75 feet per minute. This is a standard wire drawing technique employed by the wire manufacturer.

By this first step of the manufacturing process, it is desired to form a wire with a fine grain not less than 6,000 grains and preferably with a grain size providing at least 8,000 grains per square millimeter and more desirably with a grain size providing 10,000 or more grains per square millimeter. It has been found that the effectiveness of the wire as a bi-stable switching device varies in some inverse relationship with the wire grain size and thus in some direct relationship with the number of grains per unit area. As grain size increases (from a grain size providing 10,000 grains per square millimeter) the effectiveness of the wire decreases fairly rapidly such that a wire with a grain size providing approximately 6,000 grains per square millimeter has substantially less effectiveness. As the grain size is reduced, the effectiveness of the wire is improved somewhat.

More specifically, it is believed that for a given wire diameter as the grain size is reduced the slope of the portion of the M–H curve corresponding to reversal of the core magnetism increases (becomes more verticle) and, therefore, the pulse is sharper. However, the resultant induced pulse width in the pick-up coil is reduced. Consequently, the optimum grain size depends upon the application in which the wire is used and for many applications the preferred grain size has been determined to be 10,000 grains per square millimeter for a 0.012 inch (12 mil) diameter wire.

Following the drawing operation, the wire is work hardened at room temperature to produce a relatively hard shell with relatively high retentivity and coercivity while maintaining a relatively soft core with relatively low retentivity and coercivity. In one early and experimental embodiment, it has been found that such results can be obtained by stretching the wire slightly (e.g., 2½% for an alloy of 48% iron and 52% nickel) and thereafter circumferentially straining the wire. The circumferential straining step can be performed by twisting the wire back and forth with or without retaining a permanent twist. For example, it has been found that good results are obtained by twisting the wire 10 turns per linear inch of wire in one direction and then untwisting the wire the same amount in the opposite direction and such that the wire is in a generally untwisted state when the work hardening process is completed. Alternatively, the twisting operation could be completed with the wire is a twisted state when for example a wire of the type shown in FIG. 7 is desired which provides a helical preference to a direction of magnetic flux.

Although a number of techniques and indeed a preferred technique for manufacturing the wire of the invention described and claimed in the above referenced patent applications has been described therein, further experimentation and development work has resulted in a very substantially improved wire and in a technique for manufacturing this improved wire. The wire is improved in that it provides (1) a greater output presumably because of the greater amount of the flux generated by the magnetized wire when switched and (2) a more repeatable and uniform wire in that each segment produced has characteristics substantially more similar to that of other segments than was previously the case.

A variety of different ferro-magnetic materials may be used for the wire of this invention. And it is believed that the material involved probably must have magneto-strictive qualities. The preferred wire is a fine grain structure; **10,000** grains being the grain count in one preferred embodiment. One wire employed has a **52%** nickel and a **48%** iron content and was **10** mils (**0.010** inches) in diameter. This type wire can be obtained as alloy No. **152** from the Driver-Harris Company.

A one meter length of wire has been used (only because it is a convenient length) for fabricating the bistable magnetic wire. In a second embodiment of this invention, this one meter length is then stretched by **4%** to a length of **104** centimeters. It is preferred to stretch the wire slowly and steadily so that an even stretching occurs over the length of the wire and so that any soft spots tend to harden rather than simply neck down and provide the only area where stretching occurs. It is believed that stretching tends to align the crystals in the wire in a longitudinal direction and to provide a somewhat longitudinal magnetic path that is easier to magnetize than is a radial path. In this fashion an anisotropy is built into the wire. The **4%** stretch is approximately one third of the amount of stretch that the wire will take until it breaks. Somewhat more stretching can thus be tolerated. Stretching up to six centimeters (**6%**) has been successfully employed while providing optimum results.

As shown in FIG. **9**, the wire, after it has been stretched, is held between two chucks **120, 121.** One of these chucks **120** is held to an arm **122** of a precision dynamometer **124.** The dynamometer **124** is adjusted to a tension of **450** grams so that the wire is held under a constant **450** gram tension. These dynamometers are of a type used in coil winding machinery and are a standard device. The other chuck **121** is mounted to a gear **128** which operates as the pinion of a rack and pinion combination. The rack **130** is rotated back and forth by a conventional eccentric mounting to a plate **134** driven by a motor **132.**

The rack **130** is moved in one direction to provide **40** turns on the one meter of wire held between the two chucks **120, 121** seen in FIG. **9.** With the rack **130** moving to the left, the wire is twisted about its axis in a counterclockwise direction. At all times the action of the dynamometer **124** maintaining the tension on the wire at a constant **450** grams. After **40** turns counterclockwise the rack **130** is caused to move to the right so that the wire is untwisted. This cycle of twisting counterclockwise and untwisting clockwise is repeated **15** times.

It is believed that the result of this process is to work harden the outer portion of the wire **10** while having a minimum effect on the inner portion of the wire. The result is a magnetically harder shell area and a magnetically softer core.

It is also believed that the maintaining of the constant **450** gram tension on the wire during this process tends to cause the worked portion (that is, the shell) to migrate somwhat in an axial direction. This slight longitudinal migration of the shell **16,** it is believed, tends to provide a permanent longitudinal tension on the core **14** and thus aids in the longitudinal anisotropy that facilitates the distinctive fast switching of the wire **10.**

After the cycling step, the wire is released from the chucks **120, 121** and cut into the desired lengths by means of shears. It is important that the wire be cut in a fashion that avoids pinching or squeezing the wire **10.** Radial compression of the wire tends to destroy the phenomenon on which this wire operation is based. Since compression of the ends can eliminate the switching effect for the length over which the ends are compressed, it is important that the wire be sheared without appreciable compression.

In a further embodiment of this invention, the same wire was employed but the initial stretch was **6%** instead of **4%** and thus the wire was stretched to **106** centimeters. In this further embodiment, the tension maintained during the twisting was **250** grams and the number of turns was **22** turns per meter instead of **40** turns per meter. Furthermore, the number of cycles of counterclockwise twisting and clockwise untwisting was **50** cycles instead of **15** cycles.

This further embodiment provided a wire having larger pulses where the wire segments that are employed in a switching device are in the order of **5** centimeters. The second embodiment (the **4%** pre-stretch example) appears to provide better wire where the length of wire segments employed are less than **3** centimeters. In any case, there is a range of stretching, tension, number of turns per meter and number of cycles which can be employed. The preferred or optimum results will be a function of trial and error in relationship to the particular wire involved and the particular end use of the wire.

In general terms, the following considerations should be kept in mind in determining the precise method employed in manufacturing this type of bistable magnetic wire.

A **10** mil (**0.010** Inch) diameter has been found to be optimum. Twelve mil diameter wire tends to produce a less distinctive, less sharp pulse. Eight mil wire tends to be too hard to control and provides less uniform results than does the **10** mil wire.

For the wire involved in these tests, a twisting of **22** turns per meter has been found to be a minimum optimum in that the amplitude of the output pulse in the wire product tends to decrease as the amount of the twisting in processing becomes less than approximately **22** turns per meter. As the number of turns per meter increases there is some increase of distortion in the output pulse from the wire product **10.** At approximately **60** turns per meter the output pulse distortion appears to be too great for most purposes.

The number of times the twisting and untwisting cycle is repeated has a limit in that too much cycling causes distortion. The twisting and the cycling both affect the amount of work hardening. Thus there is some trade-off between these two operating factors. The fewer the turns per meter, the more the number of cycles of twisting and untwisting to provide optimum results. But this trade-off is within a limited range.

It appears to be of value to maintain some circumferential component of some factor (perhaps anisotropy) in order to achieve an optimum switching effect. Thus, in the examples described above, the twisting is done on one side of a start position. But it is not certain as to how important this factor is. There are some experiments in which the twisting has been, say, 11 turns counterclockwise and 22 clockwise and 22 counterclockwise and cycled through such a procedure to provide usuable results.

When a ferromagnetic wire is treated in accordance with the method of this invention, a product is provided which apparently has a two magnetic phase characteristic or at least two portions or sets of portions having different magnetic characteristics. It is believed that the two portions are approximately a core and shell portion; the shell portion being coaxial with and surrounding the core portion. The difference between the shell and core portion is created by virtue of the fact that the wire is torsionally strained. The torsional straining means that the radially outer portions of the wire are strained more than are the radially inner portions of the wire. Indeed, from a geometrical point of view, the axis of the wire is untouched by the torsional straining process.

In addition to the torsional straining of the wire, there is an axial straining of the wire. In a preferred treatment technique, there is axial straining by virtue of the prestretching of the wire and further axial straining by virtue of a substantial tension being maintained on the wire while it is being torsionally strained.

The various experiments performed thus far indicate that a combination of axially straining and torsional straining is required to provide the end product of this invention. The particular manner in which a wire is treated is a function of the composition of that wire and more particularly of the hardness of the wire. However, in all cases, the wire involved is a ferromagnetic wire and apparently is one that has a substantial nickel content and thus generally has a magnetostrictive parameter.

In the above examples, pre-stretching (preferably 4 to 6%) is described. In wire that is substantially harder, pre-stretching may be impossible because it may break the wire. In such a case, the tension during torsional straining should be selected large enough to result in some elongation of the wire.

The Wire Product Provided

The method described above provides a ferromagnetic wire having a generally uniform chemical composition. The wire has a magnetic central portion (herein referred to as a core) and a magnetic outer portion (herein referred to as a shell) having different net magnetic characteristics and which cooperate to form an extremely effective magnetic switching device.

An embodiment 10 of such a magnetic wire is shown in FIG. 1 and comprises a drawn wire of a ferromagnetic material having a generally circular cross section. It is preferred that the wire has a true round cross section or as close to true round as can be reasonably obtained. The magnetic wire 10 may, for example, be ⅝ long, have a diameter of 0.012 inches and be made of a commercially available wire alloy having 48% iron and 52% nickel. The wire is processed to form a relatively "soft" magnetic wire core 14 having relatively low magnetic coercivity and a relatively "hard" magnetic wire shell 16 having relatively high magnetic coercivity. Accordingly, the shell is effective to magnetically bias the magnetic core 14.

The term "coercivity" is used herein in its traditional sense to indicate the magnitude of the external magnetic field necessary to bring the net magnetization of a magnetized sample of ferromagnetic material to zero.

The relatively "soft" core 14 is magnetically anisotropic with an easy axis of magnetization substantially parallel to the axis of the wire. The relatively "hard" shell is is also magnetically anisotropic with an easy axis of magnetization substantially parallel to the axis of the wire. In FIG. 1, the shell 16 is magnetized to form north and south poles at its opposite ends. The relatively "hard" shell 16 has a coercivity sufficiently greater than that of the relatively "soft" core 14 to couple the core to the shell 16 by causing the net magnetization of the core 14 to align in an axial direction opposite to the axial direction of the net magnetization of the shell 16 as indicated in FIG. 1. When the core 14 is thus coupled to the shell, the core 14 forms a magnetic return path or shunt for the shell 16 as shown by the flux lines illustrated in FIG. 1 and a domain wall interface 18 is formed in the wire 10 between the oppositely extending lines of flux therein. The domain wall interface 18 defines the boundary between the core and shell. For simplifying the understanding of the magnetic wire 10 this domain wall 18 boundary may be thought of as having a cylindrical shape as shown in FIG. 1 although it is believed that the domain wall interface occurs along a rather irregular and indefinite magnetic transition zone in the wire. The domain wall has a thickness in the order of one micron. Thus, for the purpose of simplifying the understanding of the operation of the wire 10, the core 14 and shell 16 may be considered to be contiguous, ignoring the extremely thin magnetic transition zone that is the domain wall interface when the magnetic core 14 is magnetically coupled to the shell 16.

The core 14 has a cross-sectional area which is preferably related to the cross-sectional area of the shell 16 so that the shell 16 is effective to couple the core 14 (so that the direction of the net magnetization of the core is opposite to the direction of the net magnetization of the shell 16 and thus the core 14 provides an effective return path for most of the magnetic flux of the shell 16). The core will be deemed, herein, to be captured by the shell when the FIG. 1 coupling arrangement exists.

The net magnetization of the shell may be in either axial direction. In the absence of an external field, the higher coercivity shell will then capture the core so that the net magnetization of the core will be opposite in direction to that of the shell.

An external field can be employed to overcome the effect of the shell and to cause the magnetization of the core to switch. For example, if a sufficiently strong bar magnet is brought close to the wire segment 10, in a parallel orientation to the wire 10 and with its magnetic field polarity in opposition to the polarity of the wire shell 16, this bar magnet will capture the core 14 to reverse the direction of the net magnetization in the core 14. The switching will occur when the field strength at the core 14 from the external bar magnet exceeds in absolute magnitude the field strength at the core 14 from the shell 16. The amount by which the bar magnet field strength must exceed the shell field strength will depend on the magnitude of the core magnetic anisotropy.

The net magnetization of the core 14 is switched either (a) when an external field in opposition to the shell field provides a strong enough bias on the core to capture the core from the shell or (b) when an external field in opposition to the shell is reduced in magnitude sufficiently so that the shell captures the core from the external field. In either case, this core net magnetization reversal occurs through the process of the nucleation of a magnetic domain at one, or both, ends of the wire core and propagation (that is, movement) of a "transverse" domain wall (not the cylindrical domain wall **18**) along the length of the wire. More explicitly, the transverse domain wall that is propagated during switching extends across the diameter of the core and is believed to be somewhat conical in shape. This somewhat conically shaped domain wall travels axially along the core during the process of switching and exists only during the process of switching. After this conically shaped domain wall has terminated, the domain wall **18** will either have been created (when the shell captures the core from an external field) or will have been eliminated (when an external field captures the core from the shell). It should be noted that when an external field in opposition to the shell has captured the core from the shell the direction of magnetic flux of the core will be essentially the same as the direction of the magnetic flux of the shell and thus in that state there will be no domain wall.

In general, the rate of propagation of the domain wall along the core **14** is a function of the composition, metallurgical structure, diameter and length of the wire **10** and of the strength of the magnetic field. The time involved for such nucleation and propagation is in general a function of the rate of propagation of the domain wall and the length of the wire **10.**

During this process where the net magnetization of the core switches, the contribution to the external field by the shell changes materially in magnitude and rapidly in time. The result is that an appropriately placed pick-up coil will detect (read) the core reversal through generation of a pulse in the pick-up coil.

When the shell captures the core from an external field, the net change in the external field will be due to the fact that the shell field will have a path through the core and thus will be vectorially subtracted from the external field, resulting in a larger net field at the pick-up coil. Similarly, when an external field captures the core from a shell, the magnetic field due to the shell will be completed external to the wire **10** and thus will be vectorially added to the external field, resulting in a smaller net field at the pick-up coil. The result is that the direction of the flux in the pick-up coil will differ depending upon which way the core magnetization is switched.

Also it has been found that for some applications (for example, as shown in FIGS. **2** and **3**) the wire can nucleate at only one end if the wire is more than some particular length. For example, a ferromagnetic wire composed of an alloy of **48%** iron and **52%** nickel and having a **0.012** inch diameter and processed as hereinafter described has such a maximum preferred length of approximately **0.625** inches (i.e., approximately **50** × diameter). The same wire excepting with a diameter of **0.030** inches has such a critical length of approximately **1.50** inches (i.e., approximately **50** × diameter).

Also, for example, a **0.550** inch length of the aforementioned **0.012** inch diameter wire has been found to be a useful size for the applications shown in FIGS. **2**, *2a*, 3 and *3a* and in one sample, the shell has been found to have a coercivity of approximately **23** oersteds and the core a coercivity that is estimated at approximately **8** oersteds. Operationally, this means that an external field of **23** oersteds is required to reverse the direction of net magnetization of the shell. It also means that when the core is captured by an external field, as the external field is reduced, the core is captured by the shell when the resultant field on the core drops below **8** oersteds.

FIGS. **2** through **5** illustrate readout systems which exemplify the operation of the magnetic wire **10.** In the readout system of FIG. **2** there is shown mounted in inductive relationship with the wire **10** a drive coil **20** shown encircling substantially the full length of the wire **10** and a pick-up or read coil **22** shown encircling a portion of the wire **10.** An alternate embodiment shown in FIG. *2a* has a pick-up coil **22** adjacent to the wire **10** and coiled normal to the orientation of the wire **10** and drive coil **20.** The drive coil **20** may be used to premagnetize the entire wire **10** in a desired axial direction. During the de-energizing of the drive coil **20** there is a reduced field intensity of the coil **20** at which the shell **16** captures the core **14** by reversing the net magnetization of the core **14.** Such core **14** capture takes place abruptly once the magnetic field intensity of the drive coil **20** is reduced sufficiently to permit nucleation of a magnetic domain wall in the core by the shell **16.** This reversing of the net magnetization of the core **14** by the magnetic flux bias of the shell **16** occurs abruptly and at a rate that is substantially independent of the rate at which the field intensity due to the drive coil decreases.

Upon re-energization of the drive coil **20** to provide a sufficiently high magnetic bias on the core in opposition to the magnetic bias due to the shell **16,** the direction of the net magnetization of the core will reverse. Thus alternate energization and de-energization of the drive coil **20** will cause the direction of the net magnetization at the core **14** to alternately switch as the core is alternately captured by drive coil **20** and by the shell **16.**

FIGS. **6** and *6a* illustrate the magnetization curve for the FIG. **2** embodiment. Specifically, these curves illustrate the net magnetization (M) of the wire **10** as a function of the magnitude of the field (H) due to the drive coil **20.** FIG. **6** illustrates the symmetric hysteresis curve in which the external biasing field H due to the drive coil **20** is swung over both positive and negative magnitudes. FIG. *6a* illustrates the hysteresis curve in the first quadrant that is generated when the external biasing field H is varied in magnitude but is always in one direction.

First, with reference to FIG. **6,** assume that the FIG. **2** embodiment starts out with an unmagnetized wire **10.** Then, as the external field H (due to the drive coil **20**) increases, the net magnetization M in the wire will increase in the expected S shaped fashion illustrated by the segment **24** of the curve. At saturation, the net magnetization M ceases to increase as external field strength H increases and the flat portion of the curve shown in FIG. **6** is obtained. If field strength is now reduced, the net magnetization M remains substantially constant at saturation until the shell captures the core. This capture of the core by the shell occurs very abruptly and results in a sharp immediate drop of the net magnetization of the wire **10** as indicated at **28** in FIG. **6.** Further decrease in the magnitude of the field H carries the M–H curve to the left until the direction of the field reverses. After the direction of the field H reverses, the net magnetization M in the wire **10** reverses. This reversal of field H direction and net magnetization M direction puts the curve in the third quadrant. An increasing negative value for the field H results in increasing negative net magnetization M producing the curve segment **25** until saturation occurs in a fashion quite analogous to that which occurs in the first quadrant. If the negative field magnitude is now decreased (that is, brought toward zero) the net magnetization of the saturated wire remains substantially constant at saturation until the external field H has an absolute magnitude of such a nature that the shell can now capture the core. At the point where the shell captures the core there is a sharp change in the net magnetization as indicated by the curve segment **29**.

In overall terms, the sections **24** and **25** of the FIG. **6** curve represent the magnetization of the entire wire **10** by the field while the segments **28** and **29** of the FIG. **6** curve represent the change in magnetization in the core which occurs because of the capture of the core by the shell. This capture occurs when the bias of the magnetic field generated by the drive coil **20** has been reduced to a point where the bias due to the shell overcomes the external field bias and the anisotropy of the core and the direction of net magnetization in the core switches.

With reference now to FIG. **6***a*, there is illustrated the situation that occurs when the current in the drive coil **20**, although it varies in magnitude, is always in the same direction so that the direction of the biasing field H is always in the same direction. For the purposes of the FIG. **6***a* illustration, the initial magnetizing of the wire **10** is not illustrated. Assuming that the wire **10** has been magnetized by a strong positive biasing field H, the net magnetization M will be in the saturation region **60**. As the biasing field due to the drive coil **20** is decreased in magnitude the net magnetization M for the wire **10** remains fairly constant at saturation. But when the bias of the external field (due to the drive coil **20**) drops sufficiently below the bias of the field due to the shell, the shell will capture the core. At this point, there is a sharp drop in the net magnetization M as indicated at **62**. After the shell has captured the core, further decrease of net magnetization M of the wire **10** providing that the direction of the external field is not reversed. An increase of the external field H after the shell has captured the core, will result in an increase in net magnetization M of the wire **10** up to a point where the external field captures the core. When the external field captures the core, there occurs an abrupt increase in the net magnetization M as indicated at **64**.

A comparison with FIGS. **6** and **6***a* is instructive. It should be noted that a change in net magnetization when the shell captures the core from the external field and when the external field captures the core from the shell results in an abrupt change in net magnetization (indicated at **28, 29, 62** and **64** in the curves). By constrast with core capture, when it is the shell that is being magnetized, the change in net magnetization is much less abrupt, as indicated at **24** and **25** of the FIG. **6** curve.

Thus, by means of this invention, an abrupt change in net magnetization is provided when the direction of magnetization of the core is reversed with the consequent result that the pulse generated within the pick-up coil **22** is a sharp, high amplitude, pulse.

In FIG. **3** there is shown a drive coil **30** and a pick-up coil **32**. The pick-up coil **32** is mounted in spaced relationship to the wire **10** (rather than encircling the wire **10** as shown in FIG. **2**). A suitable soft iron core **34** may be provided for the drive coil **30**. A signal is induced in pick-up coil **32** in the same manner as it is induced in pick-up coil **22** of the readout system of FIG. **2** even though the pick-up coil **32** is spaced (for example, **0.020** inches) from the wire **10**. Also, it has been found that the pick-up coil **32** (or the pick-up coil **22** in the readout system of FIG. **2**) may be located adjacent either end of the wire **10** (as well as centrally of the wire **10** as shown in FIGS. **2** and **3**) without substantially affecting the induced signal. The further form of the FIG. **3** embodiment is shown in FIG. **3a** where the drive coil **30** and pick-up coil **32** are wound normal to one another about perpendicular legs of a core **36** of high permeability. Such a core can be made from a **28** % iron — **72**% nickel alloy. The core **36** serves to direct and concentrate the flux field.

In FIG. **4** there is shown a multiple bit readout system comprising a plurality of drive coils **40** spaced along the length of the wire **10** (in which case it may be desired to employ a substantially longer wire **10** than those employed in the readout systems of FIGS. **2** and **3**) and a plurality of corresponding pick-up coils **42**. In such a readout system, each of a plurality of segments of the wire **10** are individually operated similar to the operation of the entire wire in the readout systems of FIGS. **2** and **3**. Thus, each of the drive coils **40** is operable to magnetize an adjacent segment of the signal wire **10** in either axial direction and be subsequently individually operated to momentarily reverse the magnetism in the core of the segment to induce a signal (or signals) in the corresponding pick-up coil **42**. The wire **10** may therefore be used as a memory storage element for storage of binary information in each of the segments of the wire, it being seen that each wire segment comprises a bi-stable magnetic shell and a non-destructive memory core and is self-resettable after being "read."

In FIG. **5** there is shown a readout system comprising a nucleating coil **50** at one end of the wire **10**, a pick-up coil **52** at the opposite end of the wire **10** and a propagating coil **54** extending substantially the full length of the wire. The propagating coil **54** may be used to premagnetize the wire **10** and thereafter used to propagate the domain wall of a magnetic domain in the core formed by the nucleation coil **50**. The pick-up coil **52** may be connected to suitable circuitry to produce a readout signal as the propagating coil **54** drives the domain wall across the pick-up coil **52** and/or upon the reverse magnetization of the core by the shell when the propagating coil **54** is de-energized.

As indicated, the magnetic wire may be formed from a commercially available wire composed of an alloy of iron and nickel. The magnetic wire could also be formed from other ferromagnetic compositions and for example, could be composed of iron and cobalt or iron, nickel and cobalt where a magnetic shell with higher coercivity and more rectangular hysteresis characteristics are desired. Where a magnetic wire having an anisotropic shell with an axial easy axis of magnetization is desired, it has been found that a wire of **48%** iron and **52%** nickel with a diameter of between **0.001** and **0.030** inches provides a satisfactory signal with a high signal-to-noise ratio and that such a wire with a diameter in the range of approximately **0.009** to **0.015** inches provides a signal with the highest signal-to-noise ratio. The latter size wire has therefore been found to be preferable in those applications where the time interval involved for "reading" the wire is relatively unimportant. In magnetic memory application of the wire (for example, in the memory system shown and described in U.S. Pat. No. **3,067,408** of William A. Barrett, Jr. dated Dec. **4, 1962** and entitled "Magnetic Memory Circuits") it is expected that a wire having a diameter of **0.001** inches or less would provide the best results.

Also, where the magnetic wire is to be employed as a magnetic memory element, it may be desirable in some applications (for example, as described in the aforementioned U.S. Pat. No. **3,067,408**) to form the shell of the wire with a permanent helical easy axis of magnetization as illustrated in FIG. **7** and in other applications (for example, as described in U.S. Pat. No. **3,370,979** of Arnold F. Schmeckenbecker dated Feb. **27, 1968** and entitled "Magnetic Films") to form the magnet shell of the wire with a circumferential easy axis of magnetization as illustrated in FIG. **8,** in which event the wire may preferably be formed of a suitable ferromagnetic material providing a magnetic shell with rectangular hysteresis characteristics.

What is claimed is:

1. The method of manufacturing a bi-stable ferromagnetic wire having first and second portions with differing magnetic characteristics including relatively low and high coercivity, respectively, comprising the steps of:

applying longitudinal tension to a ferro-magnetic wire, and

applying cycling torsional strain to said wire.

2. The method of claim **1** wherein said steps are applied simultaneously.

3. The method of claim **1** wherein said steps are applied sequentially, said applying tension step preceding said cycling step.

4. The method of claim **1** wherein said longitudinal tension is sufficiently great to permanently elongate said wire.

5. The method of claim **2** wherein said longitudinal tension is sufficiently great to permanently elongate said wire.

6. The method of claim **3** wherein said longitudinal tention is sufficiently great to permanently elongate said wire.

7. The method of claim **2** further comprising the step of:

releasing said longitudinal tension on completion of said cycling torsional strain step.

8. The method of claim **5** further comprising the step of:

releasing said longitudinal tension on completion of said cycling torsional strain step.

9. The method of claim **1** wherein:

said magnetizable wire has a composition containing a substantial amount of iron and a substantial amount of nickel, and has a diameter of substantially ten mils.

10. The method of claim **1** wherein said wire has a fine grain structure of at least approximately **10,000** grains per square centimeter.

11. The method of manufacturing a bistable magnetic wire switchable from a first state to a second state in response to an imposed magnetic field changing in value through a threshold, comprising the steps of:

holding a length of magnetizable wire at a predetermined tension, and

simultaneously twisting said wire about its axis a predetermined number of turns per unit of length in a first rotational direction and then in a return rotational direction,

repeating the cycle of twisting and untwisting a predetermined number of times, and

maintaining said predetermined tension substantially constant during said twisting.

12. The method of claim **11** further comprising the step of:

releasing said predetermined tension on completion of said cycling torsional strain steps.

13. The method of manufacturing a bistable ferromagnetic wire switchable from a first state to a second state in response to an imposed magnetic field changing in value through a threshold, comprising the steps of:

elongating a length of magnetizable wire a predetermined amount,

then holding said elongated length of magnetizable wire at a predetermined tension, and

simultaneously twisting said wire about its axis a predetermined number of turns per unit of length in a first rotational direction and then in a return rotational direction,

repeating the cycle of twisting and untwisting a predetermined number of times, and

maintaining said predetermined tension substantially constant during said twisting.

14. The method of claim **13** wherein:

said wire is elongated by an amount that is approximately equal to one-third of the amount that would cause said wire to break,

said predetermined tension is less than one kilogram,

said predetermined numbers of turns per unit of length is greater than **20** turns per meter and less than **60** turns per meter,

said predetermined number of times of repeating the cycle is at least **15** times and no more than **60** times.

15. The method of claim **13** further comprising the step of:

releasing said predetermined tension on completion of said cycling torsional strain steps.

16. The method of claim **14** further comprising the step of:

releasing said predetermined tension on completion of said cycling torsional strain stress.

17. The method of claim **13** wherein:

said magnetizable wire has a composition containing a substantial amount of iron and a substantial amount of nickel, and has a diameter of substantially ten mils.

18. The method of claim **17** wherein said wire has a fine grain structure of at least approximately **10,000** grains per square centimeter.

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