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## Method for Drawing Continuous Fiber

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**Quick et al.**

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(45) **Date of Patent:** **Mar. 21, 2006**

(54) **METHOD FOR DRAWING CONTINUOUS FIBER**

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(60) Provisional application No. 60/203,048, filed on May 9, 2000.

(51) **Int. Cl.**  
**B21D 37/16** (2006.01)

(52) **U.S. Cl.** ..... **72/342.5; 72/286; 72/288; 72/342.1; 72/364; 72/378; 72/38**

(58) **Field of Classification Search** ..... **72/274, 72/278, 279, 282, 286, 288, 342.1, 342.94, 72/364, 377, 378, 700, 38, 342.5, 342.6**

See application file for complete search history.

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*Primary Examiner*—Ed Tolan

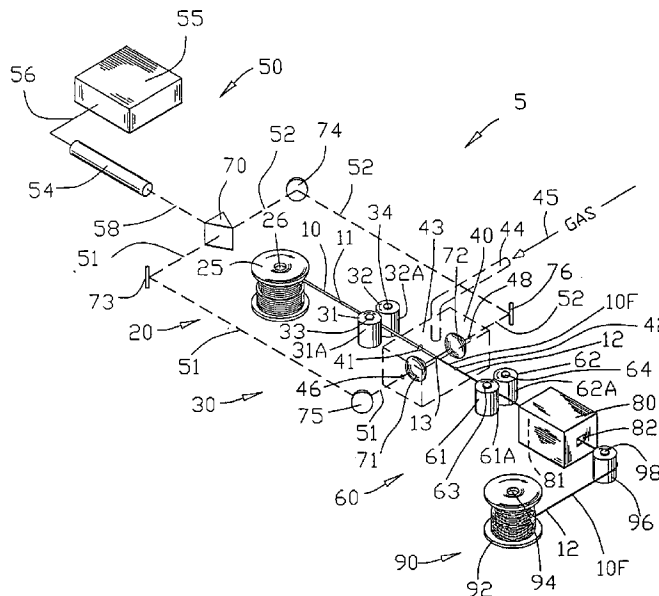
(74) *Attorney, Agent, or Firm*—Frijouf, Rust & Pyle P.A.

(57)

**ABSTRACT**

An apparatus and method is disclosed for drawing continuous metallic wire having a first diameter to a metallic fiber having a reduced second diameter. A feed mechanism moves the wire at a first linear velocity. A laser beam heats a region of the wire to an elevated temperature. A draw mechanism draws the heated wire at a second and greater linear velocity for providing a drawn metallic fiber having the reduced second diameter.

**4 Claims, 8 Drawing Sheets**



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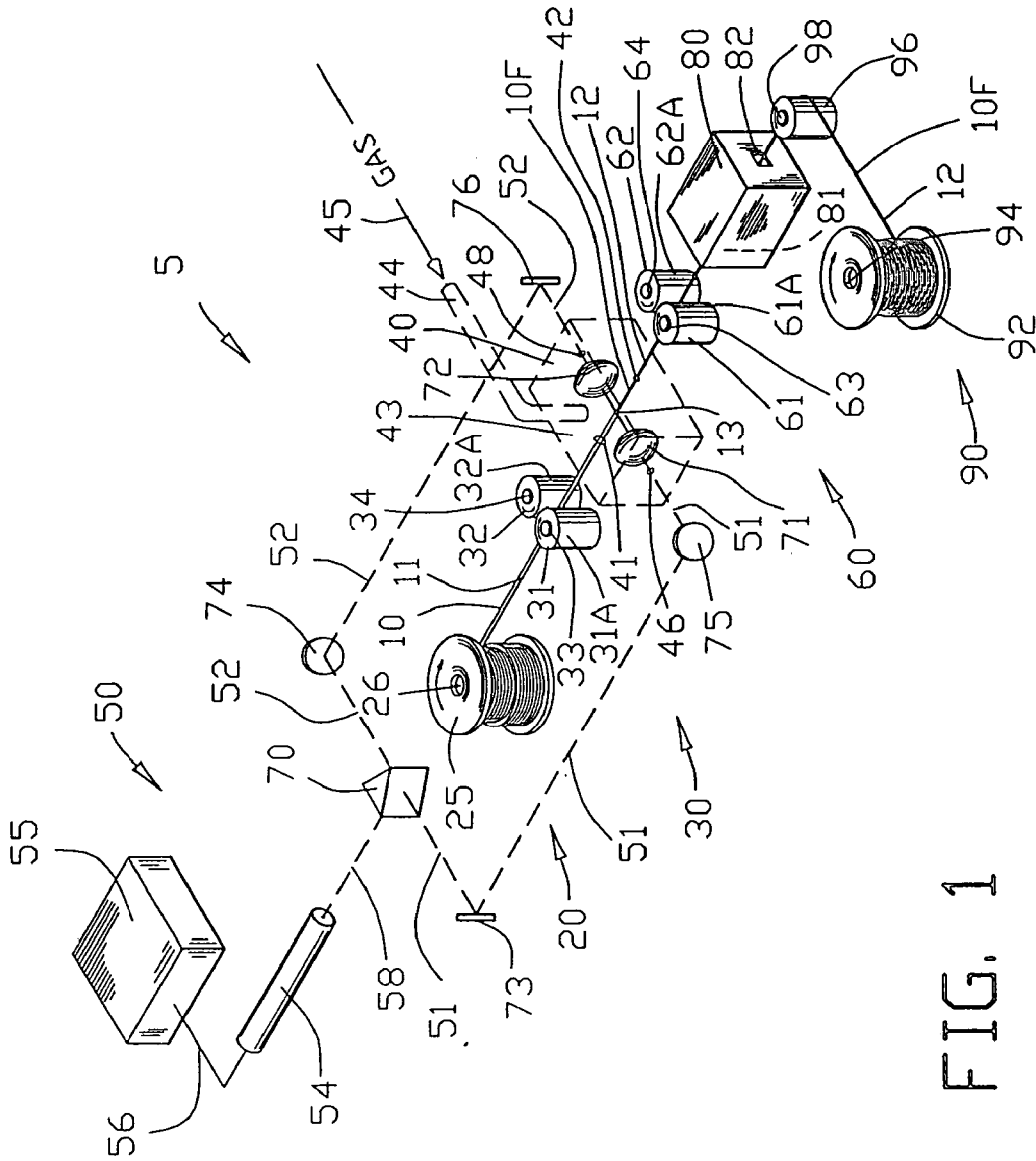


FIG. 1

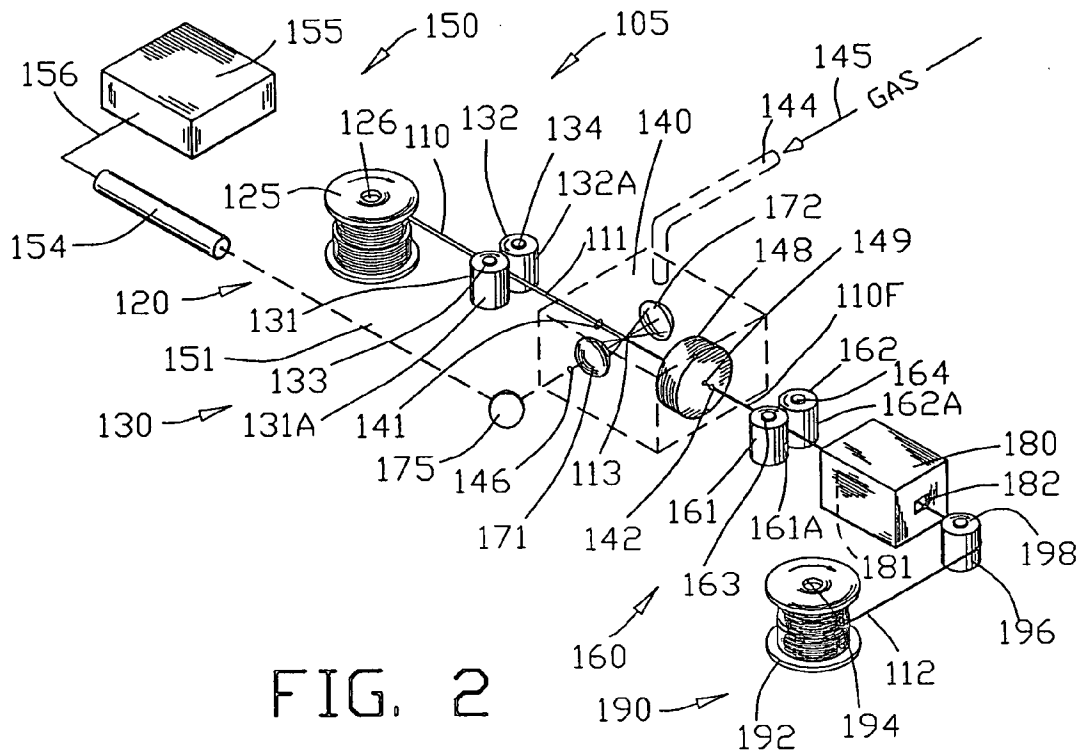


FIG. 2

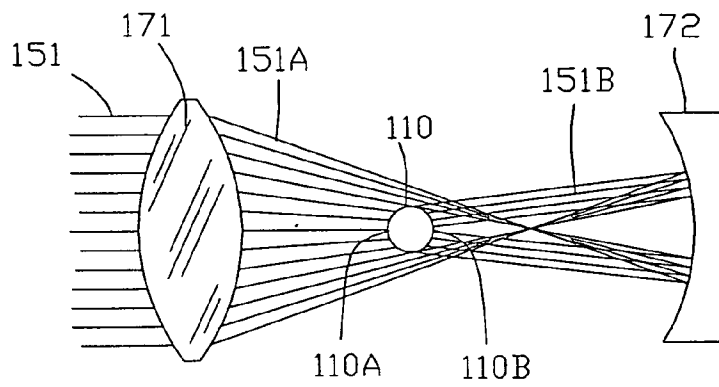


FIG. 3

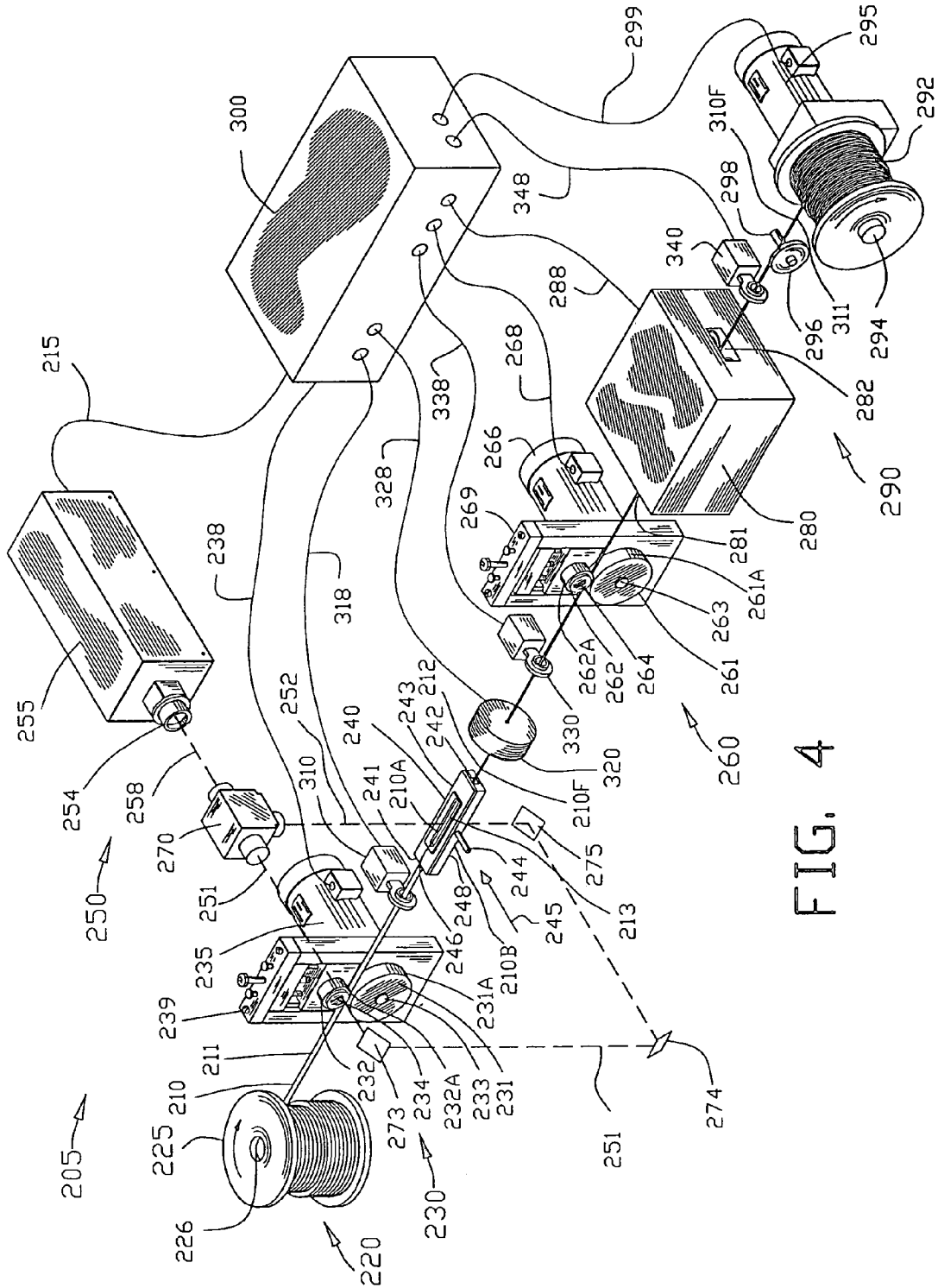


FIG. 4

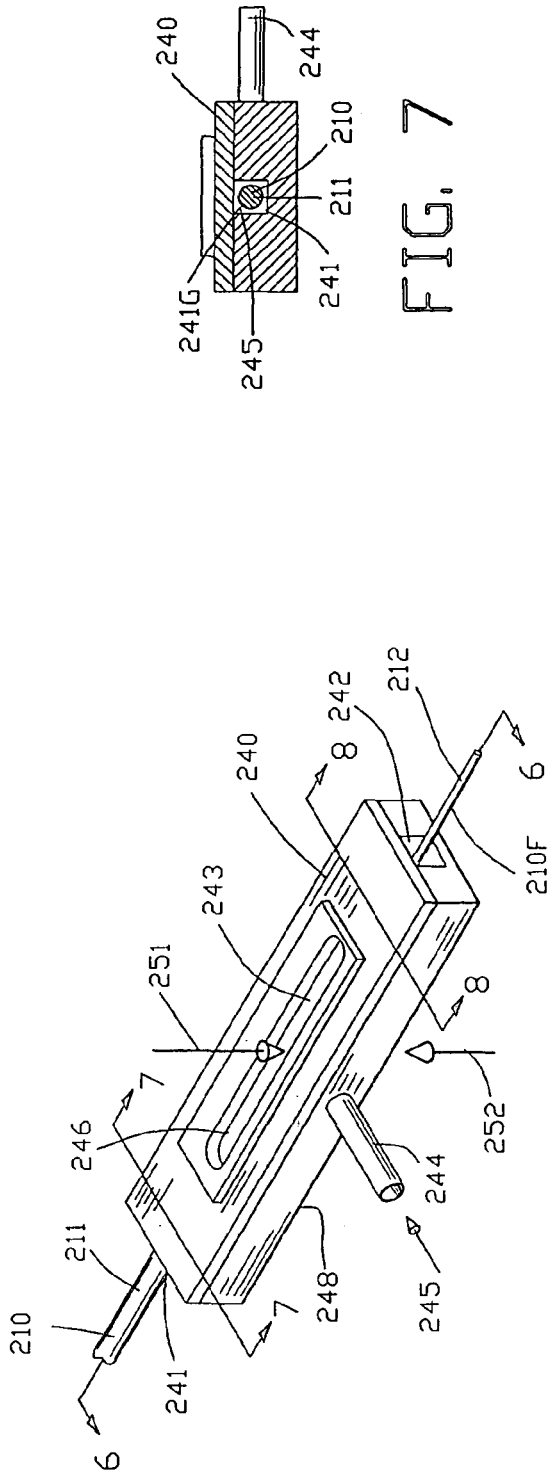


FIG. 5

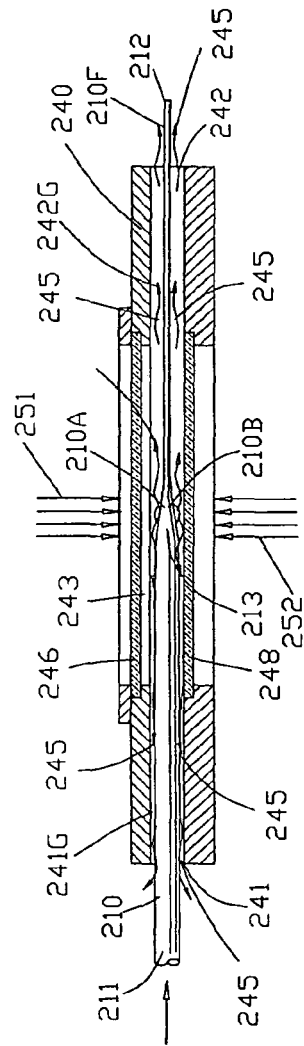


FIG. 6

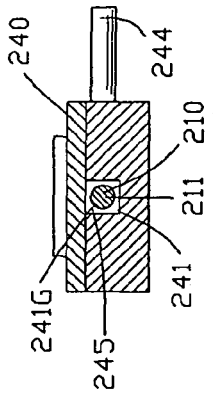


FIG. 7

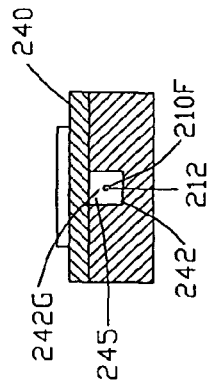


FIG. 8

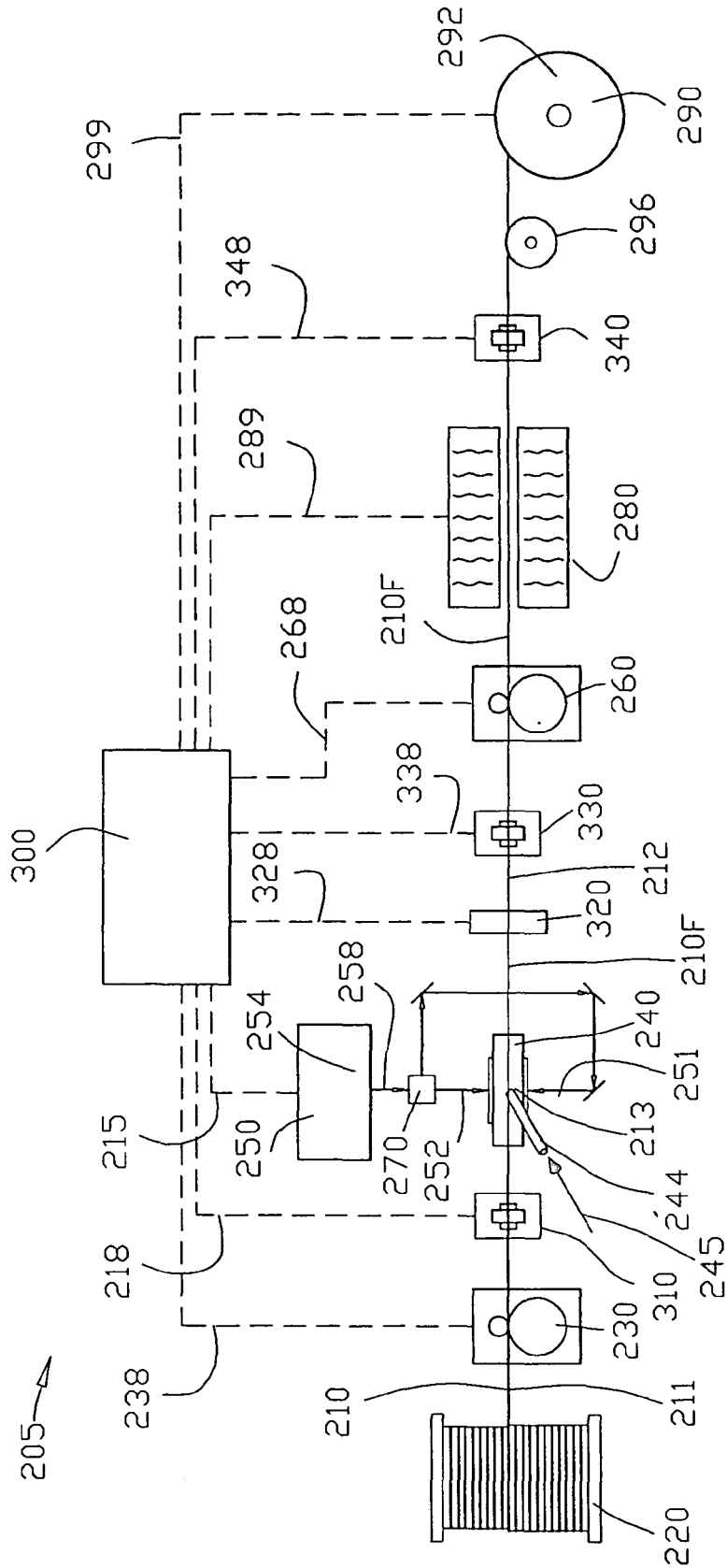


FIG. 9



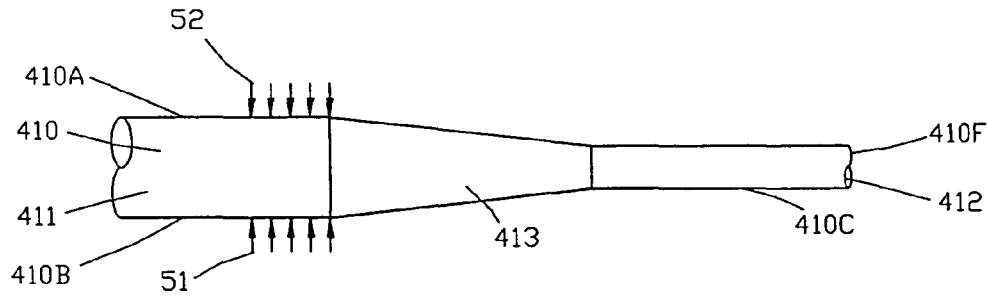


FIG. 10

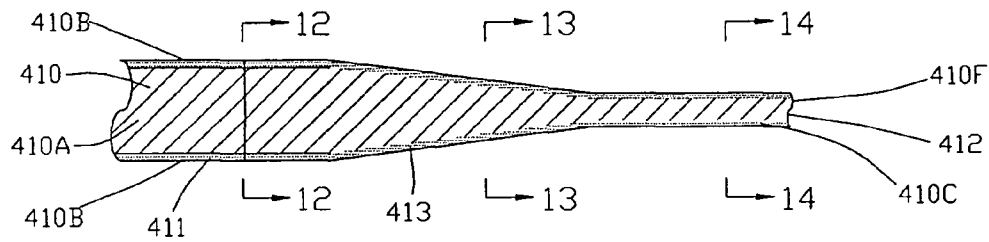


FIG. 11

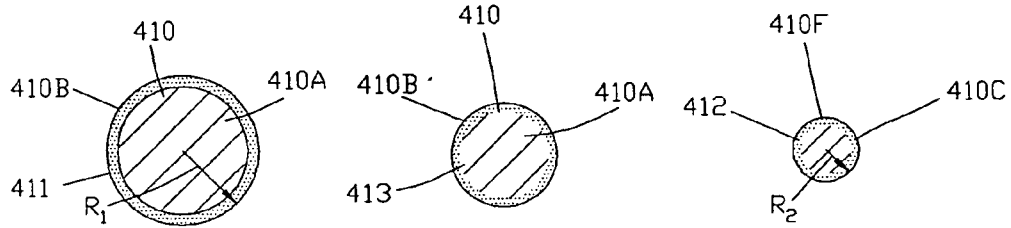


FIG. 12    FIG. 13    FIG. 14

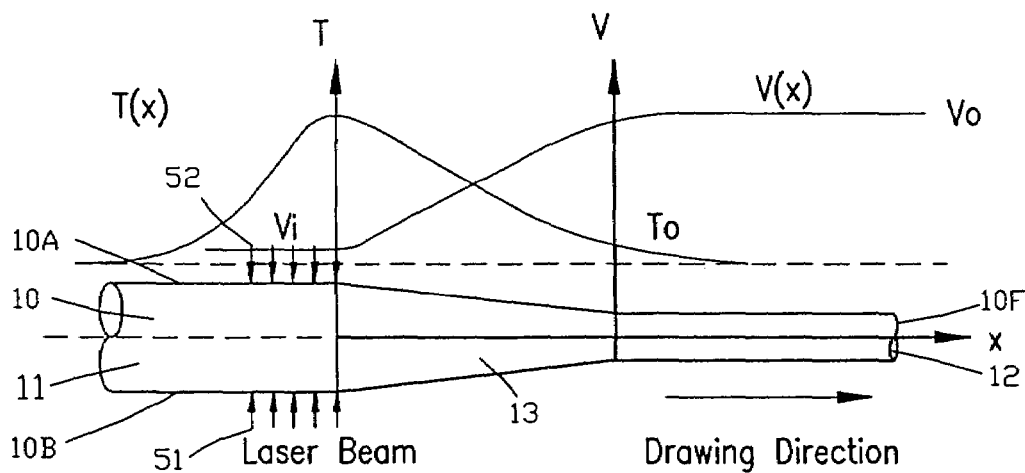


FIG. 15

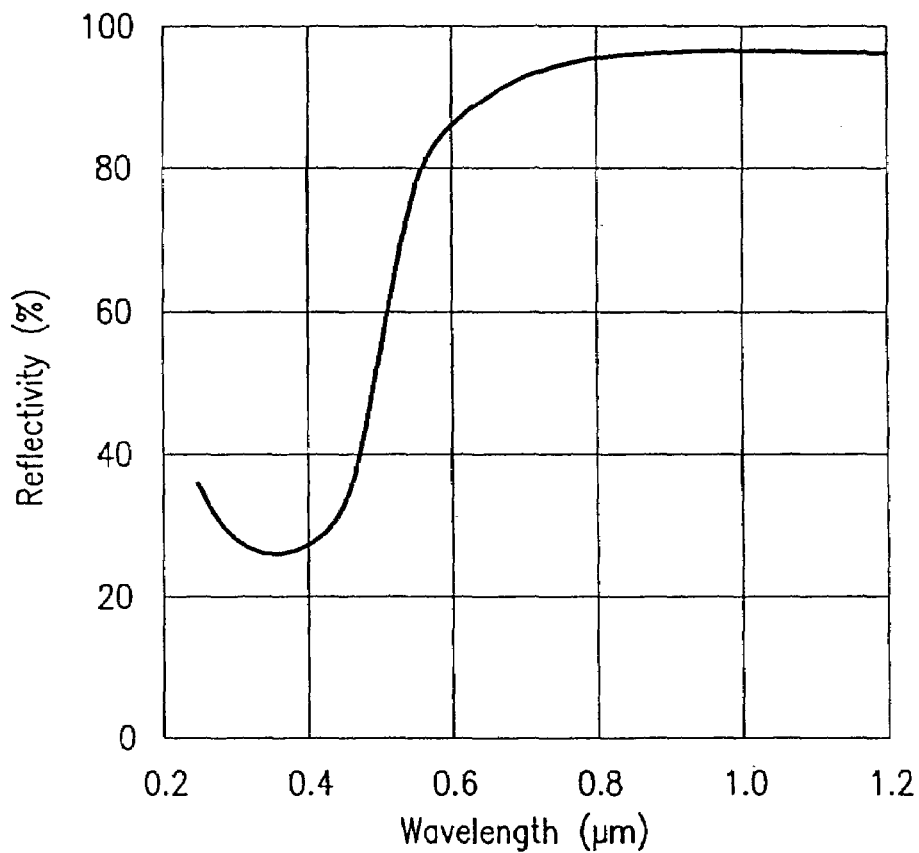


FIG. 16

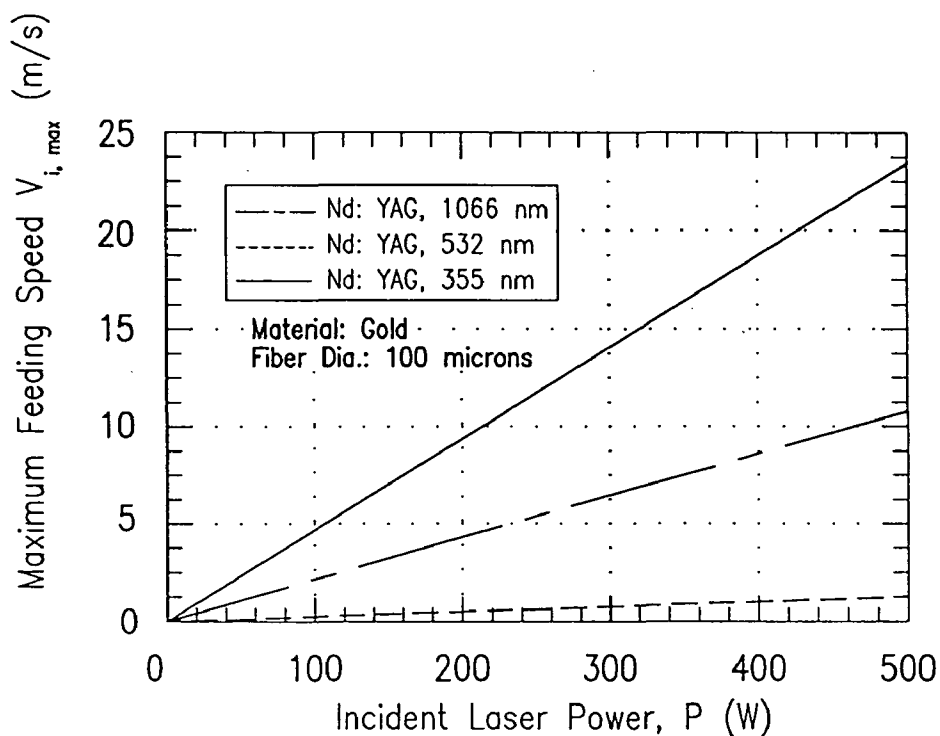


FIG. 17

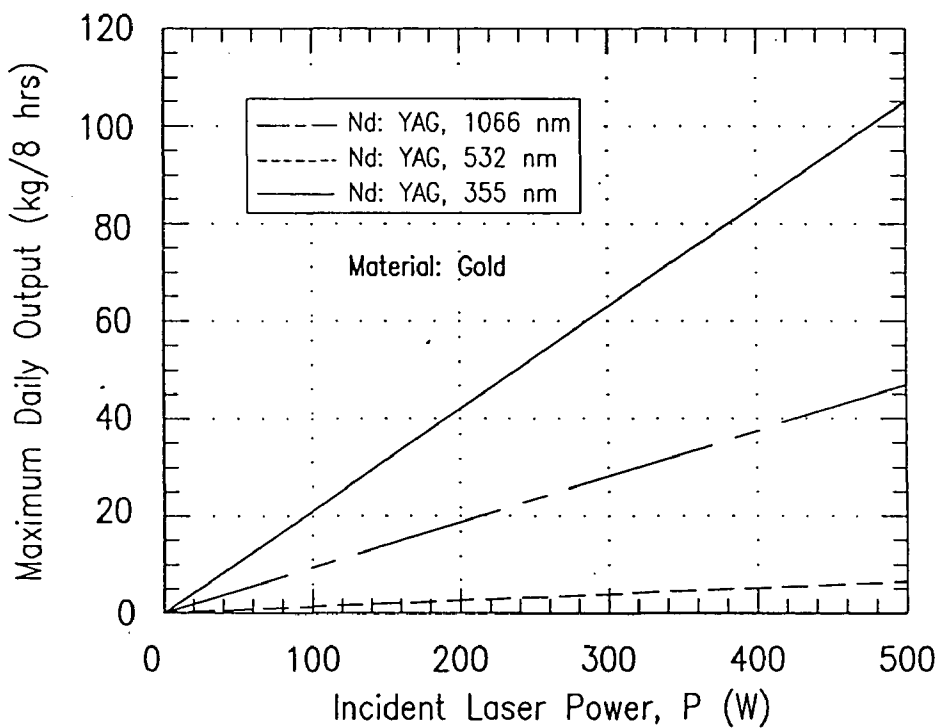


FIG. 18

## METHOD FOR DRAWING CONTINUOUS FIBER

### CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a division of parent application Ser. No. 09/851,517 filed May 8, 2001 now U.S. Pat. No. 6,732,562 issued May 11, 2004.

This application claims benefit of U.S. Patent Provisional application Ser. No. 60/203,048 filed May 9, 2000. All subject matter set forth in provisional application Ser. No. 60/203,048 is hereby incorporated by reference into the present application as if fully set forth herein.

### BACKGROUND OF THE INVENTION

#### 1. Field of the Invention

This invention relates to an apparatus and method for drawing continuous metallic fiber and more particularly to an apparatus and a method for heating and drawing wire for providing a drawn metallic fiber.

#### 2. Description of the Related Art

The art of metal working and metal forming have been well known for a great number of years. Metal may be deformed into various useful shapes by a multitude of apparatuses and methods. One particular form of metal working comprises the working and/or fashioning of metallic wire into fine metallic wire.

Metallic wires and more particularly fine metallic wires have found a wide variety of applications in modern military, industrial and consumer applications. Of the many processes of metal working that have been developed by the prior art, the process of wire drawing is considered one of the preferred processes to produce fine metallic wires. The process of wire drawing has proven to be an effective technique to reduce the diameter of metallic wire. A commercially feasible conventional wire drawing process is capable of producing metallic wire having a diameter of only 100 microns.

In a conventional wire drawing process, a metallic wire is passed through a wire drawing die for reducing the diameter of the metallic wire. In many cases, the metallic wire is passed through a series of wire drawing dies for producing the fine metallic wires. Unfortunately, the production of fine metallic wires by a wire drawing process remains a costly undertaking. In addition, the fine metallic wires may be contaminated by wire drawing dies during the conventional wire drawing process.

The drawing of ductile metallic wire may be accomplished by other drawing processes. One example of a non-conventional wire drawing process comprises the use of a laser to heat the ductile metallic wire. Laser radiation can be focused using a lens system to produce a small spot of high intensity heat energy. The high intensity heat energy may be used for drawing the ductile metallic wire in a non-conventional fashion. The following United States patents are representative of the uses of lasers for heating ductile metallic wire. Many of these United States patents employ complex systems to modify the shape of the laser beam to produce desired heating effects for the production of small diameter wires.

U.S. Pat. No. 3,944,640 to Haggerty et al teaches the method of forming fibers of refractory materials using a focused laser beam and optical system to create a heating zone. The laser beam is split into four beams focused on the refractory material.

U.S. Pat. No. 5,336,360 and U.S. Pat. No. 5,549,971 to Nordine teaches laser assisted fiber growth which includes small diameter fibers of zinc or tungsten of 10 to 170 micrometers. The fiber growth is achieved by movement of a metallurgical microscope stage. The laser beam has a focal point adjusted to coincide with the tip of the growing fiber. Producing an annular laser beam aligned with the axis of the fiber has proved to be an effective though more complex method to control laser energy.

U.S. Pat. No. 3,865,564 to Jaeger et al teaches the drawing of both clad and unclad glass fibers from preform using a laser beam having an annular cross section to soften the preform. The annular laser beam is directed along the axis of the fiber. A modulated control system is also discussed.

U.S. Pat. No. 3,981,705 to Jaeger et al teaches the use of a conical reflector to focus laser radiation in an annular configuration around a glass preform in drawing glass fibers.

U.S. Pat. No. 3,943,324 to Haggerty discloses an apparatus for forming refractory tubing that includes creating a heated zone using a laser. Various optical systems are illustrated for beam splitting and creating annular laser beam configuration.

U.S. Pat. No. 4,135,902 to Oehrlé teaches the use of an annular beam to form a melt zone on a fiber using an optical system which includes oscillating galvanometer controlled mirrors, fixed mirror, and a conical reflector to focus the annular laser beam at the surface of the fiber.

U.S. Pat. No. 4,215,263 to Grey et al teaches the use of a rotating reflector, annular mirrors, and a conical reflector to create an annular laser beam heating zone for drawing an optical wave guide wherein the annular laser beam does not intersect the axis of the blank wave guide.

U.S. Pat. No. 4,383,843 to Jyengar suggests use of an annular laser beam as a source for heating a preform from which a light guide fiber is drawn.

U.S. Pat. No. 4,547,650 to Arditty et al discloses an optical system utilizing a laser beam directed towards a spherical mirror then from an ellipsoidal mirror to direct the laser energy in a threadlike annular heating zone.

Although the aforementioned prior art provided a method of fine wire production, these prior art processes did have a major disadvantage and did not fulfill the needs of the wire drawing art.

Therefore, it is an object of the present invention to provide an apparatus and method for drawing continuous metallic fiber that overcomes the disadvantages of the prior art devices and provides a substantial contribution to the wire and metallic fiber production art.

Another object of this invention is to provide an apparatus and method for drawing continuous metallic fiber without the introduction of contaminants into the drawn continuous metallic fiber.

Another object of this invention is to provide an apparatus and method for drawing continuous metallic fiber and capable of accurately producing fine metallic fiber in commercial quantities.

Another object of this invention is to provide an apparatus and method for drawing continuous metallic fiber that is reliable and energy efficient.

Another object of this invention is to provide an apparatus and method for drawing continuous metallic fiber with reduced production costs over the prior art techniques and devices.

The foregoing has outlined some of the more pertinent objects of the present invention. These objects should be construed as being merely illustrative of some of the more prominent features and applications of the invention. Many

other beneficial results can be obtained by applying the disclosed invention in a different manner or modifying the invention within the scope of the invention. Accordingly other objects in a full understanding of the invention may be had by referring to the summary of the invention and the detailed description describing the preferred embodiment of the invention.

### SUMMARY OF THE INVENTION

A specific embodiment of the present invention is shown in the attached drawings. For the purpose of summarizing the invention, the invention relates to an apparatus for drawing a wire having a first diameter to provide a metallic fiber having a reduced second diameter comprising a feed mechanism for moving the wire at a first linear velocity. A laser beam heats a region of the wire and a draw mechanism draws the heated wire at a second linear velocity for providing a metallic fiber having a second diameter.

In a more specific of the invention, the laser beam heats the region of the wire to a visco-elastic temperature. The second linear velocity is greater than the first linear velocity. The feed and the draw mechanisms comprise a feed capstan drive and a draw capstan drive, respectively. The laser beam may comprise a beam splitter for dividing the laser output beam into a first laser beam and a second laser beam for impinging upon a first and a second side of the wire.

A chamber has an entry groove and an exit groove with the wire entering the chamber through the entry groove and with the drawn metallic fiber exiting the chamber through the exit groove. The chamber has a fluid inlet port for receiving a pressurized fluid atmosphere for enveloping the wire. The pressurized fluid atmosphere exits the entry groove and the exit groove for providing a fluid bearing for the wire within the entry groove and for providing a fluid bearing for the drawn metallic fiber within the exit groove. The pressurized fluid atmosphere exits the exit groove for cooling the drawn metallic fiber emanating from the heated region. The chamber has a window substantially transparent to the laser beam for heating the region of the wire within the chamber.

A first and a second sensor sense the first diameter of the wire and the second diameter of the metallic fiber, respectively. A control module is connected to the first and second sensors for controlling the first linear velocity and the second linear velocity for controlling the reduction of the second diameter from the first diameter.

The invention is also incorporated into the method of drawing a wire having a first diameter to a metallic fiber having a second diameter comprising the steps of feeding the wire at a first linear velocity. The wire is heated to a visco-elastic temperature region with a laser. The wire is drawn at second linear velocity to produce the metallic fiber having a reduced second diameter.

The foregoing has outlined rather broadly the more pertinent and important features of the present invention in order that the detailed description that follows may be better understood so that the present contribution to the art can be more fully appreciated. Additional features of the invention will be described hereinafter which form the subject matter of the invention. It should be appreciated by those skilled in the art that the conception and the specific embodiments disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention.

### BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and objects of the invention, reference should be made to the following detailed description taken in connection with the accompanying drawings in which:

FIG. 1 is an isometric view of a first embodiment of an apparatus for drawing continuous metallic fiber incorporating the present invention;

FIG. 2 is an isometric view of a second embodiment of an apparatus for drawing continuous metallic fiber incorporating the present invention;

FIG. 3 is an enlarged side view of a parabolic mirror system of FIG. 2;

FIG. 4 is an isometric view of a third embodiment of an apparatus for drawing continuous metallic fiber incorporating the present invention;

FIG. 5 is an enlarged view of a portion of FIG. 4;

FIG. 6 is a sectional view along line 6—6 in FIG. 5;

FIG. 7 is a sectional view along line 7—7 in FIG. 5;

FIG. 8 is a sectional view along line 8—8 in FIG. 5;

FIG. 9 is a block diagram of the apparatus for drawing continuous metallic fiber illustrated in FIG. 4;

FIG. 10 is a side view of illustrating the transformation of a composite wire into an metallic alloy;

FIG. 11 is a sectional view of FIG. 10;

FIG. 12 is a sectional view along line 12—12 in FIG. 11;

FIG. 13 is a sectional view along line 13—13 in FIG. 11;

FIG. 14 is a sectional view along line 14—14 in FIG. 11;

FIG. 15 is a graphical representation of a region of a wire heated by a laser to a visco-elastic temperature;

FIG. 16 is a graph illustrating the relationship of a laser wavelength versus the reflectivity of gold;

FIG. 17 is a graph illustrating the incident laser power for three distinct wavelengths of lasers versus maximum feeding speed to achieve proper drawing of a regions of a 100 micron gold metallic fiber heated to a visco-elastic temperature; and

FIG. 18 is a graph illustrating the incident laser power for three distinct wavelengths of lasers versus maximum daily output in kilograms per eight hours gold metallic fiber.

Similar reference characters refer to similar parts throughout the several Figures of the drawings.

### DETAILED DISCUSSION

FIG. 1 is an isometric view of a first embodiment of an apparatus 5 for drawing continuous metallic wire 10 incorporating the present invention. The apparatus 5 transforms the metallic wire 10 having a first diameter 11 into a drawn metallic fiber 10F having a second diameter 12. The apparatus 5 of the present invention is capable of reducing the metallic wires 10 into metallic fiber 10F having less than one-third of the diameter of the metallic wires 10 during a single processing technique. Through the use of multiple processing techniques, the apparatus 5 of the present invention is capable of reducing the metallic wires 10 having the first diameter 11 of 250 microns ( $\mu\text{m}$ ) into the drawn metallic fiber 10F having the second diameter 12 of 25 microns ( $\mu\text{m}$ ).

The apparatus 5 comprises a wire supply 20 including a feed spool 25 rotatably mounted on a feed spool spindle 26. The feed spool 25 contains a quantity of the wire 10 having the first diameter 11. The feed spool 25 is free to rotate about the feed spool spindle 26 with minimum drag.

A feed mechanism 30 comprises a first and a second feed roller 31 and 32 having first and second cylindrical surfaces 31A and 32A. The first feed roller 31 is driven by a first

roller shaft **33** in a clockwise direction (viewed from above). The second feed roller **32** is driven by a second roller shaft **34** in a counterclockwise direction (viewed from above). The first and second feed roller shafts **33** and **34** are driven by a feed motor (not shown) at a constant speed. Preferably, the feed motor (not shown) may be adjusted to vary the rotational speed of the first and second feed rollers **31** and **32**.

The metallic wire **10** is threaded between the first and second cylindrical surfaces **31A** and **32A** of the first and second feed rollers **31** and **32**. Preferably, the relative positions of the first and second feed rollers **31** and **32** may be adjusted to ensure proper engagement with the wire **10**.

The first and second cylindrical surfaces **31A** and **32A** engage with the metallic wire **10** to linearly move the wire **10** upon rotation of the first and second feed rollers **31** and **32**. The adjustment of the rotational speed of the first and second feed rollers **31** and **32** provides an optimum first linear velocity of the wire **10** through the first and second feed rollers **31** and **32**.

The apparatus **5** comprises a chamber **40** having an entry orifice **41** and an exit orifice **42**. The chamber **40** defines an interior region **43** interposed between the entry orifice **41** and the exit orifice **42**. A fluid inlet port **44** communicates with the chamber **40**. Preferably, a fluid **45** is introduced through the fluid inlet port **44** into the chamber **40**.

The wire supply **20** feeds the metallic wire **10** into the entry orifice **41** of the chamber **40**. The metallic wire **10** passes through the interior region **43** of the chamber **40**. The fluid **45** surrounds the metallic wire **10** passing through the interior region **43** of the chamber **40**. The chamber **40** defines a first and a second aperture **46** and **48**.

A laser system **50** generates a first and a second laser beam **51** and **52** for entering into the interior region **43** of the chamber **40** through the first and second apertures **46** and **48**. The first and second laser beams **51** and **52** heat the wire **10** for assisting in the transformation of the wire **10** into the drawn metallic fiber **10F**.

A draw mechanism **60** draws the metallic wire **10** to form the drawn metallic fiber **10F**. The drawn metallic fiber **10F** exits from the exit orifice **42** defined in the chamber **40**. The draw mechanism **60** comprises a first and a second draw roller **61** and **62** having first and second cylindrical surfaces **61A** and **62A**. The first draw roller **61** is driven by a first roller shaft **63** in a clockwise direction (viewed from above). The second draw roller **62** is driven by a second roller shaft **64** in a counterclockwise direction (viewed from above). The first and second feed roller shafts **63** and **64** are driven by a draw motor (not shown) at a constant speed. Preferably, the draw motor (not shown) may be adjusted to vary the rotational speed of the first and second draw rollers **61** and **62**.

The drawn metallic fiber **10F** is threaded between the first and second cylindrical surfaces **61A** and **62A** of the first and second draw rollers **61** and **62**. Preferably, the relative positions of the first and second draw rollers **61** and **62** may be adjusted to ensure proper engagement with the drawn metallic fiber **10F** without slippage.

The first and second cylindrical surfaces **61A** and **62A** engage the drawn metallic fiber **10F** to linearly move the drawn metallic fiber **10F** upon rotation of the first and second draw rollers **61** and **62**. The adjustment of the rotational speed of the first and second draw rollers **61** and **62** provides an optimum second linear velocity of the drawn metallic fiber **10F** through the first and second draw rollers **61** and **62**.

The second linear velocity of the drawn metallic fiber **10F** through the first and second draw rollers **61** and **62** is adjusted relative to the first linear velocity of the wire **10** through the first and second feed rollers **31** and **32** to ensure the proper drawing of the drawn metallic fiber **10F**.

The laser system **50** comprises a laser device **54** powered by a power supply **55** through a connector **56**. In this embodiment of the invention, the laser device **54** utilizes a short wavelength of light that will be absorbed by the surface of the metallic wire **10**. The specific characteristics of the laser device **54** will be described in greater detail hereinafter.

A laser output beam **58** emanates from the laser device **54** and enters a beam splitter **70**. The beam splitter **70** splits the laser output beam **58** into the first and second beams **51** and **52**. The first and second beams **51** and **52** exit in opposite directions from the beam splitter **70** and are reflected to a first and a second lens **71** and **72**.

The first laser beam **51** is reflected by planar reflectors **73** and **75** toward a chamber **40**. The second laser beam **52** is reflected by planar reflectors **74** and **76** toward the chamber **40**. The first and second laser beams **51** and **52** enter into the chamber **40** through the first and the second aperture **46** and **48** defined in the chamber **40** to impinge upon the first and second lens **71** and **72**. The first and second lenses **71** and **72** are shown mounted internal to the chamber **40**. The first and second laser beams **51** and **52** are focused by the first and second lenses **71** and **72** onto a first and a second side of the metallic wire **10** located in the interior region **43** of the chamber **40**.

The metallic wire **10** having the first diameter **11** enters the entry orifice **41** of the chamber **40**. A region **13** of the metallic wire **10** is heated by the first and second laser beams **51** and **52**. The fluid **45** blankets the region **13** of the wire **10** heated by the first and second laser beams **51** and **52**. In this example of the invention, the region **13** of the metallic wire **10** is heated to a visco-elastic temperature. The heating of the region **13** of the wire **10** to a visco-elastic temperature enables the metallic wire **10** to be drawn into the drawn metallic fiber **10F** without the use of a drawing die.

The first and second draw rollers **61** and **62** operate at the second linear velocity that is greater than the first linear velocity of the first and second feed rollers **31** and **32**. The first and second draw rollers **61** and **62** draw the region **13** of the wire **10**. The drawing of the region **13** of the wire **10** elongates the wire **10** having the first diameter **11** into the drawn metallic fiber **10F** having the second diameter **12**. The drawn metallic fiber **10F** exits the chamber **40** through exit orifice **42**.

The drawn metallic fiber **10F** enters an annealing oven **80** through an entry port **81**. The drawn metallic fiber **10F** passes through the annealing oven **80** and exits from an exit port **82**. The drawn metallic fiber **10F** is annealed within the annealing oven **80**.

A take-up mechanism **90** comprises a take-up spool **92** for receiving the drawn metallic fiber **10F**. The take-up spool **92** is rotated by a take up spool shaft **94** driven by take up spool motor (not shown). Preferably, take-up spool **92** is driven to maintain a slight tension on the drawn metallic fiber **10F**. A guide roller **96** freely rotates about guide roller spindle **98** to ensure the linearity and orientation of the drawn metallic fiber **10F** as the drawn metallic fiber **10F** traverses the annealing oven **80**.

The relationship between the first linear velocity of the first and second feed rollers **31** and **32** and the second linear velocity of the first and second draw rollers **61** and **62** in conjunction with the heat applied by the first and second laser beams **51** and **52** determine the amount of elongation

or drawing of the drawn metallic fiber **10F** from the wire **10**. This specific relationship will be discussed in greater hereafter.

The fluid **45** within the chamber **40** provides a controlled environment during the heating of the metallic wire **10**. The fluid **45** may be a gas or a vapor depending upon any desired chemical reaction to take place within the chamber **40**. Preferably, an inert gas is used as the fluid **45** when the chamber **40** is merely used to provide the controlled environment during the heating of the metallic wire **10**. The inert gas may be selected from the group consisting of nitrogen, argon or a nitrogen argon mixture. In the alternative, the inert gas may be virtually any inert gas.

A specialized fluid is used as the fluid **45** when the chamber **40** is used to provide a chemical reaction within the chamber **40**. The specialized fluid may be a reactive gas, a partially reactive gas, an organic gas or a vapor containing a metal organic compound. The type of metallic wire **10** and the type of specialized fluid **45** is determined by the chemical reaction desired by the user.

FIG. 2 is an isometric view of a second embodiment of an apparatus **105** for drawing continuous metallic wire **110** incorporating the present invention. The apparatus **105** comprises a wire supply **120** including a feed spool **125** rotatably mounted on a feed spool spindle **126**. The feed spool **125** contains the metallic wire **110** having the first diameter **111**.

A feed mechanism **130** comprises a first and a second feed roller **131** and **132** having first and second cylindrical surfaces **131A** and **132A**. The first and second feed rollers **131** and **132** are driven by a first and a second roller shaft **133** and **134** as set forth previously.

The metallic wire **110** is threaded between the first and second cylindrical surfaces **131A** and **132A** of the first and second feed rollers **131** and **132** to linearly move the wire **110** upon rotation of the first and second feed rollers **131** and **132** at a first linear velocity.

The apparatus **105** comprises a chamber **140** having an entry orifice **141** and an exit orifice **142**. The chamber **140** defines an interior region **143** interposed between the entry orifice **141** and the exit orifice **142**. A fluid inlet port **144** communicates with the chamber **140** for introducing a fluid **145** into the chamber **140**. The chamber **140** defines an aperture **146**.

In this example of the invention, a drawing die **148** is located within the chamber **140**. The drawing die **148** comprises a drawing aperture **149** for drawing the metallic wire **110** to form the drawn metallic fiber **110F**.

The wire supply **120** feeds the metallic wire **110** into the entry orifice **141** of the chamber **140**. The metallic wire **110** passes through the drawing aperture **149** of the drawing die **148** located within the interior region **143** of the chamber **140**. The fluid **145** surrounds the metallic wire **110** passing through the interior region **143** of the chamber **140**.

A laser system **150** generates a laser beam **151** for heating the wire **110** for assisting in the transformation of the wire **110** into the drawn metallic fiber **110F**. The laser system **150** comprises a laser device **154** powered by a power supply **155** through a connector **156**. The laser beam **151** emanates from the laser device **154** and is reflected into the chamber **140** through the aperture **146**.

The draw mechanism **160** comprises a first and a second draw roller **161** and **162** having first and second cylindrical surfaces **161A** and **162A**. The first and second draw rollers **161** and **162** are driven by a first and a second roller shaft **163** and **164** as set forth previously.

The metallic drawn metallic fiber **110F** is threaded between the first and second cylindrical surfaces **161A** and

**162A** of the first and second draw rollers **161** and **162**. The first and second cylindrical surfaces **161A** and **162A** engage the drawn metallic fiber **110F** to linearly move the drawn metallic fiber **110F** upon rotation of the first and second draw rollers **161** and **162** at a second linear velocity. The second linear velocity of the drawn metallic fiber **110F** through the first and second draw rollers **161** and **162** is adjusted relative to the first linear velocity of the wire **110** through the first and second feed rollers **131** and **132**.

FIG. 3 is an enlarged side view of a portion of FIG. 2. The laser beam **151** is reflected by a planar reflector **175** through the aperture **146** to a first lens **171** located within the chamber **140**. The first lens **171** focuses a first portion **151A** of the laser beam **151** onto a first side **110A** of the metallic wire **110**. A second portion **151B** of the laser beam **151** passes along side of the metallic wire **110**. The second portion **151B** of the laser beam **151** passes above and below the metallic wire **110** and impinges upon a parabolic reflector **172**. The parabolic reflector **172** focuses the second laser beam **151B** onto a second side **110B** of the metallic wire **110**.

The metallic wire **110** is heated by the first and second laser beams **151A** and **151B** focused on the first and second sides **110A** and **110B** of the wire **110**. In this example of the invention, a region **113** of the metallic wire **110** is heated to a temperature sufficient for enabling the drawing die **148** to draw the metallic wire **110** to form the drawn metallic fiber **110F**. Preferably, the region **113** of the metallic wire **110** is heated below a visco-elastic temperature.

The first and second draw rollers **161** and **162** operate at a second linear velocity that is greater than the first linear velocity of the first and second feed rollers **131** and **132**. The first and second draw rollers **161** and **162** draw the wire **110** through the drawing aperture **149** for drawing die **148**. The drawing of the wire **110** through the drawing aperture **149** for drawing die **148** elongates the wire **110** having the first diameter **111** into the drawn metallic fiber **110F** having the second diameter **112**.

The drawn metallic fiber **110F** is annealed in an annealing oven **180** as set forth previously. A take-up mechanism **190** comprises a take-up spool **192** for receiving the drawn metallic fiber **110F** from the annealing oven **180**.

FIG. 4 is an isometric view of a third embodiment of an apparatus **205** for drawing continuous metallic wire **210** incorporating the present invention. The apparatus **205** transforms the metallic wire **210** having a first diameter **211** into a drawn metallic fiber **210F** having a second diameter **212**.

The apparatus **205** comprises a wire supply **220** including a feed spool **225** rotatably mounted on a feed spool spindle **226**. The feed spool **225** contains a quantity of the wire **210** having the first diameter **211**.

A feed mechanism **230** comprises a first and a second feed roller **231** and **232** having first and second cylindrical surfaces **231A** and **232A**. The first feed roller **231** is driven by a first roller shaft **233** by a feed motor **235**. The speed of the feed motor **235** is adjusted by a control module **300** through a control cable **238** to provide optimum first linear velocity as will be further discussed.

The second feed roller **232** is an idler roller being rotatable on a second roller shaft **234**. A feed roller tension adjustment **239** is provided to enable optimum tension between first and second feed rollers **231** and **232** for engaging the wire **210** therebetween. The first and second cylindrical surfaces **231A** and **232A** engaged with the wire **210** to linearly move the wire **210** upon rotation of the first and second feed rollers **231** and **232**.

The wire **210** having a first diameter **211** traverses a feed diameter sensor **310** for measuring the first diameter **211** of the wire **210**. The feed diameter sensor **310** supplies a signal to the control module **300** through a cable **318** of the measured first diameter **211** of the wire **210**.

The apparatus **205** comprises a chamber **240** having an entry orifice **241** and an exit orifice **242**. The chamber **240** defines an interior region **243** interposed between the entry orifice **241** and the exit orifice **242**. A fluid inlet port **244** communicates with the chamber **240** for introducing a fluid **245** into the chamber **240**.

The wire supply **220** feeds the metallic wire **210** into the entry orifice **241** of the chamber **240**. The wire **210** passes through the interior region **243** of the chamber **240** with the fluid **245** surrounding the metallic wire **210**. The chamber **240** defines a first and a second aperture **246** and **248**. The specific structure of the chamber **240** will be described in greater detail hereinafter.

A laser system **250** generates a first and a second laser beam **251** and **252** for entering into the interior region **243** of the chamber **240** through the first and second apertures **246** and **248**. The first and second laser beams **251** and **252** heat the wire **210** for assisting in the transformation of the wire **210** into the drawn metallic fiber **210F**.

A draw mechanism **260** draws the drawn metallic fiber **210F** from the exit orifice **242** defined in the chamber **240**. The draw mechanism **260** comprises a first and a second draw roller **261** and **262** having first and second cylindrical surfaces **261A** and **262A**. The first draw roller **261** is driven by a first roller shaft **263** by a draw motor **266**. The speed of the draw motor **266** is adjusted by control module **300** through a control cable **268** to provide optimum second linear velocity as will be further discussed.

The second draw roller **262** is an idler roller being rotatable on a second roller shaft **264**. A draw roller tension adjustment **269** is provided to enable optimum tension between first and second draw rollers **261** and **262** for engaging the metallic fiber **210F** therebetween. The first and second cylindrical surfaces **261A** and **262A** engaged with the drawn metallic fiber **210F** to linearly move the metallic fiber **210F** upon rotation of the first and second draw rollers **261** and **262**.

The linear velocity of the drawn metallic fiber **210F** through the first and second draw rollers **261** and **262** is adjusted relative to the linear velocity of the wire **210** through the first and second feed rollers **231** and **232** by the control module **300** to ensure the proper drawing of the drawn metallic fiber **210F**.

The laser system **250** comprises a laser device **254** powered by a power supply **255**. A laser output beam **258** emanates from the laser device **254** and enters a beam splitter **270**. The beam splitter **270** splits the laser output beam **258** into the first and second beams **251** and **252**. The first beam **251** is reflected toward the chamber **240** by planar reflectors **273–275**. The second beam **252** is directed toward the chamber **240**. The first and second laser beams **251** and **252** enter into the chamber **240** through the first and second apertures **246** and **248** to impinge upon a first and a second side **210A** and **210B** of the metallic wire **210** located in the interior region **243** of the chamber **240**.

The wire **210** having the first diameter **211** enters the entry orifice **241** of the chamber **240** and a region **213** of the wire **210** is heated to a visco-elastic temperature by the first and second laser beams **251** and **252** focused on the first and second sides **210A** and **210B** of the wire **210**. The fluid **245** blankets the region **213** of the wire **210** heated by the first and second laser beams **251** and **252**.

The first and second draw rollers **261** and **262** operate at a second linear velocity that is greater than the first linear velocity of the first and second feed rollers **231** and **232**. The drawing of the region **213** of the wire **210** elongates the wire **210** having the first diameter **211** into the drawn metallic fiber **210F** having the second diameter **212**. The drawn metallic fiber **210F** exits the chamber **240** through exit orifice **242**.

The drawn metallic fiber **210F** enters an optional finishing die **320**. The optional finishing die **320** provides a very uniform second diameter **212** to the drawn metallic fiber **210F**. In addition, the optional finishing die **320** finishes the surface of the second diameter **212** of the drawn metallic fiber **210F**.

The optional finishing die **320** provides additional cooling of the drawn metallic fiber **210F**. The mass of the optional finishing die **320** transfers heat from the drawn metallic fiber **210F** for substantially reducing the temperature of drawn metallic fiber **210F**. Alternately, an independent temperature control and cooling system may be used.

The drawn metallic fiber **210F** having the second diameter **212** traverses a second diameter sensor **330** for measuring the second diameter **212** of the metallic fiber **210F**. The second diameter sensor **330** supplies a signal to the control module **300** through a cable **338** of the measured second diameter **212** of the metallic fiber **210F**.

The drawn metallic fiber **210F** enters an annealing oven **280** through an entry port **281**. The drawn metallic fiber **210F** passes through the annealing oven **280** and exits from an exit port **282**.

The drawn metallic fiber **210F** is annealed within the annealing oven **280**. The temperature of the annealing oven **280** is controlled by the control module **300** through a cable **288**. Alternately, an independent temperature control and cooling system may be used.

The annealed drawn metallic fiber **210F** having the second diameter **212** traverses a tension sensor **340** for measuring the tension applied to the metallic fiber **210F** by a take-up mechanism **290**. The tension sensor **340** supplies a signal to the control module **300** through a cable **348** for controlling the take-up mechanism **290**.

A take-up mechanism **290** comprises a take-up spool **292** for receiving the drawn metallic fiber **210F**. The take-up spool **292** is rotated by a take up spool shaft **294** driven by take up spool motor **295**. The spool motor **295** is controlled by the control module **300** through a control cable **299**. Preferably, take-up spool **292** is driven to maintain a slight tension on the drawn metallic fiber **210F**. A guide roller **296** freely rotates about guide roller spindle **298** to ensure the linearity and orientation of the drawn metallic fiber **210F** as the drawn metallic fiber **210F** traverses the annealing oven **280**.

The relationship between the first linear velocity of the first and second feed rollers **231** and **232** and the second linear velocity of the first and second draw rollers **261** and **262** in conjunction with the heat applied by the first and second laser beams **251** and **252** determine the amount of elongation or drawing of the drawn metallic fiber **210F** from the wire **210**. This specific relationship will be discussed in greater hereafter.

FIGS. 5–8 are enlarged views of the chamber **240** shown in FIG. 4. The entry orifice **241** and the exit orifice **242** include an elongated entry groove **241G** and an elongated exit groove **242G**. A fluid inlet port **244** introduces the fluid **245** into the interior region **243** interposed between the entry orifice **241** and the exit orifice **242** of the chamber **240**. The fluid **245** provides a positive pressure within the interior



region 243 of the chamber 240. The fluid 245 flows through the elongated entry groove 241G to be discharged from the entry orifice 241. Similarly, the fluid 245 flows through the elongated exit groove 242G to be discharged from the exit orifice 242.

The first and second laser beams 251 and 252 enter into the chamber 240 through the first and second apertures 246 and 248. Preferably, the first and second apertures 246 and 248 are covered with a first and a second window 246W and 248W that are substantially transparent to the first and second laser beams 251 and 252. The first and second laser beams 251 and 252 impinge upon the first and second sides 210A and 210B of the metallic wire 210 located in the interior region 243 of the chamber 240.

The wire 210 is heated to a visco-elastic temperature by the first and second laser beams 251 and 252 focused on the first and second sides 210A and 210B of the wire 210. The fluid 245 blankets the region 213 of the wire 210.

The fluid 245 flowing through the elongated entry groove 241G provides a fluid bearing between the wire 210 and the elongated entry groove 241G. The fluid 245 flowing through the elongated entry groove 241G centers the wire 210 within the elongated entry groove 241G as shown in FIG. 7.

The fluid 245 flowing through the elongated exit groove 242G provides a fluid bearing between the drawn metallic fiber 210F and the elongated exit groove 242G. The fluid 245 flowing through the elongated exit groove 242G centers the drawn metallic fiber 210F within the elongated entry groove 242G as shown in FIG. 8.

The fluid 245 flowing through the elongated exit groove 242G cools the drawn metallic fiber 210F within the elongated exit groove 242G. The elongated exit groove 242G acts as a cooling chamber with the cooling being effected by the fluid 245 flowing through the elongated entry groove 241G.

The fluid 245 flowing through the elongated entry groove 241G and the elongated exit groove 242G prevent contact of the metallic wire 210 and/or the metallic fiber 210F with the chamber 240. The non-contact of the metallic wire 210 and/or the metallic fiber 210F with the chamber 240 eliminates the possibility of contamination of the metallic wire 210 and/or the metallic fiber 210F.

FIG. 9 illustrates a block diagram of the third embodiment of the apparatus 205 for drawing continuous metallic wire 210 incorporating the present invention. A control module 300 is interfaced to the components of the apparatus 205 as set forth previously.

The wire 210 having the first diameter 211 is pulled from the wire supply 220 by the feed mechanism 230 and fed through the first diameter sensor 310. The control module 300 monitors the first diameter 211 from the first diameter sensor 310.

The wire 210 having a first diameter 211 enters chamber 240 filled with the fluid 245. The laser system 250 heats the region 213 of the wire to a visco-elastic temperature. The output of the laser system 250 is controlled by the control module 300.

The draw mechanism 260 operates at the second linear velocity that is greater than the first linear velocity of the feed mechanism 230. The first and second linear velocities of the feed mechanism 230 and the draw mechanism 260 are controlled by the control module 300. The control of the first and second linear velocities in combination with the control of the output of the laser system 250 controls the elongation or drawing of the metallic fiber 210F from the wire 210.

The drawn metallic fiber 210F enters the annealing oven 280 controlled by the control module 300. The drawn

metallic fiber 210 enters the tension sensor 340 for controlling the take-up mechanism 290.

The utilization of the control module 300 interfaced throughout the apparatus 205 enables process optimization by variation of the control module 300 algorithms. Any variables in the wire 210 (raw material) having a first diameter 211 are easily compensated during the process resulting in higher quality continuous metallic fiber 210F (product).

FIGS. 10-14 are various views of illustrating the transformation of a composite wire 410 into an metallic alloy or an intermetallic fiber 410F. The composite wire 410 comprises an inner wire component 410A and an outer component 410B. The outer component 410B may be applied to the inner wire component 410A by electroplating process, a sheathing process, a tube filling process or any other suitable process.

Preferably, an inner wire component 410A is form from a different material then the outer component 410B to form a desired metallic alloy or intermetallic material 410C. The composite wire 410 containing the inner wire component 410A and the outerwear component 410B are transformed by heating and drawing into an metallic fiber 410F having a surface formed from the metallic alloy or intermetallic material 410C.

In this example of the invention, the heating of the region 413 of the composite wire 410 provides two operations that occurring at the time. First, the composite wire 410 is heated to a visco-elastic temperature for allowing the drawing of the composite wire 410 to form the fiber 410F. Second, the composite wire 410 is heated to a temperature to diffuse the outer wire component 410B into the surface of the inner wire component 410A.

The process of forming the metallic alloy or intermetallic material 410C has been illustrated the formation of the alloy material 410C on the surface of the metallic fiber 410F. However, it should be understood that the process may be adapted to provide an interface diffusion or a homogeneous alloy.

FIG. 12 illustrates the composite wire 410 having a first diameter 411 defines by a radius  $R_1$ . FIG. 14 illustrates the drawn fiber 410F having a second diameter 412 defines by a radius  $R_2$ . The radius  $R_2$  of the drawn fiber 410F is approximately 0.4 the radius  $R_1$  of the composite wire 410.

The cross-sectional area of the composite wire 410 and the drawn fiber 410F may be given by the well known formula:

$$A = \pi R^2$$

where A is the cross-sectional area and R is the radius.

Since the radius  $R_2$  of the drawn fiber 410F is approximately one-third the radius  $R_1$  of the composite wire 410, the cross-sectional area of the drawn fiber 410F is sixteen percent (16%) the cross-sectional area of the composite wire 410. The process of the present invention provides a substantial savings when the process is application the making metallic fibers of precious metals such as gold, platinum and the like.

FIG. 15 illustrates the model geometry for the laser heated metallic fiber drawing process of the present invention. The first and second laser beams 51 and 52 intercept the first and second sides 10A and 10B of the wire 10 having a first diameter 11 to heat the region 13 of the wire 10 to a visco-elastic temperature. The wire 10 having the first diameter 11 is drawn or elongated to provide a metallic fiber 10F having a second diameter 12.

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FIG. 15 illustrates the metallic fiber temperature increases to a maximum at T and reduces to  $T_0$ . The metallic fiber velocity starts at  $V_1$  and increases to a final velocity  $V_0$ . As the visco-elastic temperature reaches a maximum the metallic fiber velocity begins to increase and temperature then begins to decrease. If incident laser power is exclusively utilized to heat the metallic fiber, then the product of the incident laser power and the absorptivity of the metallic fiber determine the maximum velocity achievable in the drawing process. Mass conservation ensures that the metallic fiber diameter is reduced as the square root of the ratio of the constant feed linear metallic fiber velocity to the constant draw linear metallic fiber velocity.

FIG. 16 illustrates the wavelength vs. percent reflectivity for gold. Absorptivity is strongly dependent on laser wavelength. Gold is highly reflective at wavelengths greater than 600 nm. The highest absorptivity occurs at less than 400 nm (approximately 25 percent reflectivity at 0.4 microns).

FIG. 17 illustrates maximum feeding speed in meters per second vs. incident laser power in watts for an Nd:YAG laser, frequency doubled and frequency tripled. The metallic fiber material is gold with a 100 micron diameter. The absorptivity for the Nd:YAG laser (1064 nm) is 3% for frequency doubled (532 nm) absorptivity increase to 32% and for frequency tripled, (355 nm) the absorptivity is 72%.

FIG. 18 illustrates the maximum daily output in kg per 8 hours vs. incident laser power in watts. The metallic fiber material is gold and the ND:YAG laser, frequency doubled and frequency tripled are also illustrated. For a frequency tripled Nd:YAG laser processing 100 micron gold metallic fiber, laser powers of 50, 100, and 200 watts would process 10.4, 20.8, and 41.6 kg per 8 hour day.

Preferably, the type of laser is selected on the basis of a wavelength of light that will be absorbed by the surface of the metallic wire 10 or any coating on the surface of a composite metallic wire 410. Conventional lasers such as Nd:YAG, EXCIMER or CO<sub>2</sub> lasers may be used with the present invention. Although the laser system has been shown to provide a first and a second laser beam, it should be understood that the apparatus of the present invention may utilize a single laser beam.

## EXAMPLE I

The process may be used for ductile metals including gold and gold alloys, platinum and platinum alloys, palladium and palladium alloys, nickel and nickel alloys and iron and iron alloys, titanium and titanium alloys, aluminum and aluminum alloys, copper and copper alloys. The process can also be used to process intermetallics and ceramic surface modified metal metallic fibers. The process also is suitable for rapid proto-typing of metal metallic fiber compositions and ceramic-metal metallic fiber compositions of various sizes and shapes.

## EXAMPLE II

The laser metallic fiber process can be used to directly make alloys by diffusion of a surface metal layer into a substrate wire metal concurrent with the deformation by the laser metallic fiber drawing process. In this example, 6–15% by weight Copper electro-plated or clad Nickel wire is prepared. Laser processing in the laser metallic fiber processing apparatus promotes the diffusion of copper into the adjacent nickel region resulting in a 50% by weight Copper-50% by weight Nickel alloy region approaching a Monel like composition. Like compositions are highly corrosion resistant to fluorides.

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## EXAMPLE III

In another example, a 6% by weight Gold electroplating on Nickel is processed in the apparatus to produce a gold-nickel surface alloy, for example 50% by weight gold and 50% by weight Nickel surface region concurrently with diameter reduction. These compositions provide jewelry optical quality appearance (14 Kt gold) and improve electrical conductivity.

## EXAMPLE IV

Intermetallic compositions can be obtained by a controlled conversion where a surface metal is diffused into a substrate wire metal. An aluminum plating, coating or clad is prepared on a nickel substrate. The aluminum diffuses into the nickel surface region concurrently with the composite diameter reduction by the laser metallic fiber drawing process. A 6–15% by weight Aluminum surface layer diffuses into the nickel wire substrate creating, for example, a 50% by weight Aluminum-50% by weight Nickel aluminate intermetallic surface region. Nickel can be replaced by Iron or Titanium to create Iron aluminides and Titanium aluminides.

## EXAMPLE V

Wear resistant and electrically conductive ceramic surfaces can be created on metals by the process of the present invention.

Processing titanium wire in a nitrogen atmosphere (N<sub>2</sub>) within the chamber during the laser heated drawing process creates a titanium nitride (TiN) surface coating that is electrically conductive and wear resistant.

Processing titanium wire in an oxygen atmosphere (O<sub>2</sub>) within the chamber during the laser heated drawing process creates a titanium oxide (TiO) surface coating.

Processing titanium wire in a methane atmosphere (CH<sub>4</sub>) within the chamber during the laser heated drawing process creates a titanium carbide (TiC) surface coating.

Processing titanium wire in a diborane atmosphere within the chamber during the laser heated drawing process creates a titanium boride (TiB<sub>2</sub>) surface coating.

## EXAMPLE VI

A small diameter ceramic pipe may be fabricated by the process of the present invention. For example, processing titanium wire in an oxygen atmosphere (O<sub>2</sub>) within the chamber during the laser heated drawing process creates a titanium oxide (TiO) surface coating. The metallic titanium wire is removed by a chemical or electrochemical process leaving the titanium oxide (TiO) surface coating in the form of a small diameter pipe.

## EXAMPLE VII

Various type of metal to metal diffusion can be created with the process of the present invention.

The controlled conversion of a surface metal coating is diffused into a substrate metallic wire. The conversion process may be controlled to provide (1) a surface alloy, or (2) an interface diffusion, or (3) a homogeneous alloy.

In the surface alloy, the surface metal coating is diffused only into the surface of the substrate metallic wire and the interior of the substrate metallic wire remains unchanged.

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In the interface diffusion, the surface metal coating is bonded to the substrate metallic wire by diffusion between the surface metal coating and the substrate metallic wire. The exterior of the surface metal coating and the interior of the substrate metallic wire remain unchanged.

In the homogeneous alloy, the surface metal coating is diffused through the substrate metallic wire.

## EXAMPLE VIII

Fibers with a catalytic active surface can be created with the process of the present invention.

A surface coating of a catalytic active material may be applied to the surface of a substrate metallic wire. The drawing fiber is formed with a surface coating of the catalytic active material. These catalytic active materials may include Platinum and Cobalt decomposed from metallo-organics during laser radiation.

The present apparatus provides an improved method and apparatus for providing continuous metallic fibers. The process eliminates the need for a bundled drawing and leaching process as required by the prior art. The present apparatus and method produces chemically clean metallic metallic fibers with no contamination. In many examples, the cross-sectional area of the metallic metallic fibers can be reduced by more than 75 percent. Greater reductions may be obtained through the use of multiple or serial processing steps.

The present apparatus provides for the production of continuous metallic fibers made of alloy materials. The process may be used for providing gold, gold alloys, platinum alloys, palladium alloys, stainless-steel and nickel and nickel alloys. The process also is suitable for rapidly prototyping of metallic fibers of various sizes and shapes.

Although the invention has been described in its preferred form with a certain degree of particularity, it is understood that the present disclosure of the preferred form has been made only by way of example and that numerous changes in the details of construction and the combination and arrangement of parts may be resorted to without departing from the spirit and scope of the invention.

What is claimed is:

1. A method of drawing a wire having a first diameter to a fiber having a second diameter, comprising the steps of:
  - feeding the wire into an entry orifice of a chamber at a first linear velocity;
  - introducing a pressurized fluid atmosphere into the chamber for enveloping the wire;
  - heating a region of the wire within an interior region of the chamber with a laser;
  - drawing the wire at second linear velocity from an exit orifice of the chamber for producing the fiber having a reduced second diameter;
  - discharging the pressurized fluid atmosphere from the chamber through the entry orifice and the exit orifices for providing an entry and an exit fluid bearing for the wire and the fiber; and

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cooling the fiber with the pressurized fluid atmosphere discharging from the exit orifice.

2. A method of drawing a precious metal wire having a first diameter to a precious metal fiber having a second diameter, comprising the steps of:

feeding the precious metal wire into an entry orifice of a chamber at a first linear velocity;

introducing a pressurized fluid atmosphere into the chamber for enveloping the precious metal wire;

heating a region of the precious metal wire within an interior region of the chamber with a laser;

drawing the precious metal wire at second linear velocity from an exit orifice of the chamber for producing the precious metal fiber having a reduced second diameter;

discharging the pressurized fluid atmosphere from the chamber through the entry orifice and the exit orifices for providing an entry and an exit fluid bearing for the precious metal wire and the precious metal fiber; and

cooling the precious metal fiber within the exit orifice with the pressurized fluid atmosphere discharging from the exit orifice.

3. A method of drawing a gold wire as set forth in claim 2, wherein the step of feeding the gold wire includes feeding the gold wire having the first diameter of approximately one hundred microns; and

the step of drawing the gold wire includes drawing the gold wire to have the second diameter of approximately twenty-five microns.

4. A method of drawing a composite wire having an inner wire component and outer wire component defining a first diameter to a metallic fiber alloy having a second diameter, comprising the steps of:

feeding the composite wire into an entry orifice of a chamber at a first linear velocity;

introducing a pressurized fluid atmosphere into the chamber for enveloping the composite wire;

heating a region of the composite wire within an interior region of the chamber for softening the composite wire and for diffusing the outer wire component into the inner wire component;

drawing the composite wire at second linear velocity from an exit orifice of the chamber for producing the metallic fiber alloy having a reduced second diameter;

discharging the pressurized fluid atmosphere from the chamber through the entry orifice and the exit orifices for providing an entry and an exit fluid bearing for the composite wire and the metallic fiber alloy; and

cooling the metallic fiber alloy with the pressurized fluid atmosphere discharging from the exit orifice.

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