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Method for laser microwelding

Abstract

A weld (**3**) between a first material (**1**) and a second material (**2**), the first material (**1**) being a first metallic material, and the second material (**2**) being a second metallic material, the weld (**3**) has a width (**4**) between 0.5 mm and 7 mm, the weld (**3**) comprises at least one microweld (**8**), the microweld (**8**) forms a welding pattern (**5**) defined parallel to a surface (**6**) of the first material (**1**), and the microweld (**8**) has a characteristic feature size (**7**) of between 20 μm and 400 um.

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Background/Summary

FIELD OF INVENTION

(1) This invention relates to a method for laser microwelding. The weld may join one or more reflective materials. The weld may have a low ohmic resistance, a high shear strength, and a high peel strength.

BACKGROUND TO THE INVENTION

(2) The joining of bright metals such as gold, copper, aluminium, platinum and silver by laser welding in the near infrared spectrum (800 nm to 2500 nm) presents a challenge. This is because the surface of the bright metals is highly reflective with poor absorbance. To overcome the surface reflectivity and initiate coupling of the laser's energy into the metal surface, it is necessary to use laser beams with high power densities.

(3) The function of the laser beam on a bright material approximates a discreet function with a very narrow operating window from beam hold-off (reflection) and absorption. At first the surface reflects substantially all of the laser light. However, once the surface reflectivity is overcome by sufficient laser intensity, a melt of the surface is initiated. The reflectivity then almost immediately transitions from its original highly reflective condition of more than 80% reflectivity to a lower value, which for some metals, can be less than 50% reflectivity. This causes the melt pool on the surface to grow extremely rapidly. It is consequently very difficult to control.

(4) The challenge is increased when welding thin and low mass work pieces. High power densities are often detrimental, leading to over penetration of the laser beam, which results in unreliable joints. Conversely, if lasers are operated at lower power densities that are just above the absorbance limits, then the pulse duration has to be increased. Thermal heat sinking of the absorbed energy into the regions surrounding the weld can then cause overheating of the work piece, resulting in weak or absent welds.

(5) The present known preferred method of laser welding of copper and other bright metals such as gold and silver, involves the use of lasers that emit at visible green wavelengths. The most common lasers are frequency doubled 1064 nm lasers that emit at 532 nm. This is because the reflectivity of bright metals is lower at 532 nm than at near infrared wavelengths. The laser joining of bright metals with such lasers produces welds that are repeatable and consistent but at the cost of efficiency, complexity, and costs associated with frequency doubling. In some applications, it is necessary to combine a laser emitting at 532 nm with a second laser at 1064 nm in order to increase efficiency and productivity. Such dual wavelength systems require closed loop monitoring of the laser welding process using sophisticated beam monitoring and real time analysis in order to analyze and tailor the structure of the weld. Such diagnostic devices use video analysis of the back reflected light and the weld pool characteristics in order to provide feedback to a laser controller. These systems are complex and expensive.

(6) The use of green lasers has been adopted to perform weld joints of bright metals without specifically addressing the application of joining dissimilar metals. Conventional welding of dissimilar metals relies on specific control of the dilution of the metals at the interface and resulting thermal conditions to minimize mixing of the dissimilar metals which results in so-called intermetallics in the joint. Large intermetallic regions are prone to fracture from stresses acting on the joint, and the fracture propagates through the entire joint until failure.

(7) Laser welding with continuous wave and pulsed lasers is well known, with either a continuous weld front, or overlapping spot welds wherein the weld forms a continuous seam. Defects in the materials caused by the welding process create weaknesses, and are unacceptable in the majority of

applications. Pulsed welds are typically formed using microsecond and millisecond pulses. The pulse causes the material to melt which resolidifies to form the weld. When welding dissimilar materials, the weld interface can contain intermetallics, which are a compound formed from the two materials being joined, and are typically brittle and undesirable in nature. The weld can therefore preferentially fracture along this intermetallic layer under mechanical load.

(8) Forming low ohmic resistance welds between highly reflective materials has important applications in the electronics and electrical engineering industries, including in the manufacture of batteries, solar cells, semiconductor packaging, and electronic printed circuit boards. Various techniques are used, including laser welding. However the high reflectivity can require relatively expensive visible lasers. In addition, the welding equipment, process and the resulting welds do not meet current requirements of fast manufacturing speeds, low ohmic resistance, high shear strength, and high peel strength. Consequently, processes other than laser welding are often used.

(9) Laser welds in work pieces comprising one or more reflective metals, for example gold, copper, aluminium, platinum and silver, are often unreliable and weak. Laser welds in articles comprising dissimilar materials are typically brittle and undesirable in nature.

(10) There is a need for a method for laser microwelding bright and/or dissimilar metals and alloys that does not have reliability issues and it is an aim of the present invention to provide such a weld method.

THE INVENTION

(11) A weld made according to a method of the present Invention is between a first material and a second material, the first material being a first metallic material, and the second material being a second metallic material, and wherein the weld has a width between 0.5 mm and 7 mm, the weld comprises at least one microweld, the microweld forms a welding pattern defined parallel to a surface of the first material, and the microweld has a characteristic feature size of between 20 μm and 100 um,

(12) The weld made according to a method of the present invention has important applications in the electronics and electrical engineering industries. The ability to create welds in reflective metals using nanosecond fibre lasers, emitting in the 1 μm wavelength window, and with pulse energies of around 1 mJ, is new and unexpected. Moreover, the welds can have greater strength and reliability than prior art welds. The weld may be used in articles such for example as batteries, solar cells, semiconductor packaging, and electronic printed circuit boards.

(13) The weld comprises at least one microweld. The microweld forms the welding pattern. The welding pattern may be formed of a plurality of the microwelds. Alternatively, the welding pattern may be formed from a single microweld. The welding pattern may comprise a line in the form of a spiral. Alternatively or additionally, the welding pattern may comprise a plurality of hatch lines. The hatch lines may be in the form of a grid. The hatch lines may form a rectangular grid. The hatch lines may form a triangular grid. The welding pattern is preferably a two dimensional welding pattern.

(14) The first material and the second material may remain substantially unmixed in the weld. By “substantially unmixed” it is meant that the intermetallic content formed by the first material and the second material combined together in single co-mixed alloy phases comprises at most twenty percent, and preferably at most ten percent of the material of the weld. The intermetallic content at interfaces between the first material and the second material may be sufficient to achieve a joint with pre-determined mechanical properties and ohmic resistivity. The intermetallic content at interfaces between the first material and the second material may be small enough to avoid embrittlement such as caused by recrystallization.

(15) The weld may be substantially inhomogeneous. The weld may comprise discrete zones of the first metallic material and the second metallic material.

(16) The first material may have a reflectivity greater than 90% at an optical wavelength of one micron.

(17) The first material may have a different melting temperature than the second material.
(18) The microweld may comprise a hole formed in the first material. The first material may be contained within the second material. At least one of the first and the second material may have flowed into the hole. The first material may have a top surface and a bottom surface. The bottom surface may be closer to the second material than the top surface. The hole may have a width at the top surface and a width at the bottom surface, wherein the width at the top surface is wider than the width at the bottom surface. The hole may be a countersunk hole, and the microweld may resemble a rivet.
(19) The microweld may comprise a zone of the first material within the second material.
(20) Surprisingly, the weld provides a simpler solution for joining bright and dissimilar metals and alloys, producing consistent and predictive results on each joint formed by the weld. Arranging for one of the first and the second materials to flow into the hole without substantially mixing with the other material, helps prevent intermetallics from forming, and avoids the reliability issues associated with intermetallics such as brittleness and weak welds. Consistent and predictive results are obtainable with a range of alloys, including amorphous metal alloys, castings, sintered alloys, and injection formed alloys. They are also obtainable with refractory metals, including iridium, tungsten, molybdenum, niobium, and tantalum. Refractory metals are chemically inert, have a higher density and higher hardness than metals such as iron, copper, and nickel, and are characterised by melting temperatures above 2000° C. The increased surface area of the weld provides more contact area, which in turn reduces ohmic resistance. Reducing ohmic resistance is an important consideration for increasing efficiencies of batteries and solar panels. Examples of parts that may be connected include: electrical connections, such as copper to aluminium connections, inside batteries; low profile electrical connections between flexible circuit elements and thin-section busbars; metallic enclosures for medical electronic devices; electromagnetic interference and radio frequency shielding of electrical components; attaching leads, filaments, and wires to electrical connections and circuit boards; other electrical connections in consumer electronics such as mobile phones, laptop computers, televisions, and other consumer electronic devices; metallic labels and tags; silver, platinum, and gold parts in jewellery; and medical devices, sensors and other electrical circuits. Amorphous metal alloys are used in additive manufacturing, a form of three dimensional printing, wherein metal powders are sintered with a laser.
(21) The first material may comprise a metal selected from the group consisting of copper, aluminium, iron, nickel, tin, titanium, iridium, tungsten, molybdenum, niobium, tantalum, rhenium, silver, platinum, gold, and an alloy comprising at least one of the foregoing materials.
(22) The second material may comprise a metal selected from the group consisting of copper, aluminium, iron, nickel, tin, titanium, iridium, tungsten, molybdenum, niobium, tantalum, rhenium, silver, platinum, gold, and an alloy comprising at least one of the foregoing materials.
(23) Other metals for the first material and the second material may be employed. The first material and the second material may be the same or different.
(24) The width may be between 0.5 mm and 2.5 mm.
(25) The characteristic feature size may be a width of the microweld. The characteristic feature size may be between 40 μm and 100 um.
(26) Examples of articles that may include a weld made using a method of the invention include a smart phone, a mobile phone, a laptop computer, a tablet computer, a television, a consumer electronic device; a battery; a solar cell; an integrated electronic circuit component; a printed circuit board; an electrical connection; a low profile electrical connection between flexible circuit elements and thin-section busbars; a metallic enclosure for a medical electronic device; and an electrical connection in consumer electronics devices; metallic labels and tags; silver, platinum, and gold parts in jewellery.
(27) The present invention provides a method for laser microwelding a first material to a second material, which method comprises: placing a first metal part comprising the first material on a

second metal part comprising the second material; providing a laser for emitting a laser beam in the form of laser pulses; providing a scanner for scanning the laser beam with respect to a surface of the first metal part; providing an objective lens for focusing the laser pulses onto the surface; and providing a controller that is adapted to control the scanner such that the scanner moves the laser beam with respect to the surface,
(28) characterized by moving the laser beam with respect to the surface; focusing the laser pulses with a spot size and a pulse fluence that cause the formation of a weld comprising at least one microweld in the form of a welding pattern defined parallel to the surface; wherein the microweld has a characteristic feature size of between 20 μm and 400 μm; the laser pulses have pulse widths between 1 ns and 3000 ns; the first material is a first metal; the second material is a second metal which is different from the first metal; the weld is autogenous, and wherein the controller is operated to select a first laser signal to create a melt pool on the surface, a second laser signal to initiate welding of the first metal part to the second metal part, and a third laser signal to weld the first metal part to the second metal part to form the microweld; the first laser signal and the second laser signal comprise the laser pulses; and the third laser signal comprises either the laser pulses or a continuous wave laser beam.
(29) The moving of the laser beam with respect to the metal surface may be such that the weld has a width between 0.5 mm and 7 mm.
(30) The laser may be operated to form a plurality of melt pools in the first metal part and a plurality of heat stakes in the second metal part. Each heat stake may extend from a different one of the melt pools and may have a distal end. The method may include adapting the controller to space the focused spots apart by a distance that is small enough to cause the melt pools to overlap and that is large enough to ensure the distal end of the heat stakes are distinct and separate from each other in at least one direction.
(31) The controller may be operated to select a first laser signal to create a melt pool on the surface, a second laser signal to initiate welding of the first metal part to the second metal part, and a third laser signal to weld the first metal part to the second metal part to form the microweld. The first and the second laser signals may be same or different from each other. The first, second, and third laser signals may be provided in a single pass of the laser beam across the surface, or in a plurality of passes of the laser beam across the surface. The first and the second laser signals may be provided in a first pass of the laser beam across the surface, and the third laser signal may be provided in a second pass of the laser beam across the surface.
(32) The second laser signal may be selected to have a plurality of pulses characterized by a pulse width that is greater than 100 ps.
(33) The second laser signal may be selected to have a peak power which is substantially greater than a peak power of the third laser signal.
(34) At least one of the first, second and third signals may be selected to inhibit the formation of intermetallics.
(35) At least one of the first, second and the third signals may be selected to improve the smoothness of a surface of the laser weld.
(36) The welding process may be one that forms a key hole. The method may include providing a fourth laser signal which is selected to close the key hole.
(37) The first material may be substantially more ductile than the second material.
(38) The laser may be characterized by a beam quality M.sup.2 less than 4, preferably less than 2, and more preferably less than 1.3.
(39) The laser may be a nanosecond laser.
(40) The laser may be characterized by a wavelength between 1000 nm and 3000 nm.
(41) The laser may be a rare-earth doped fibre laser.
(42) The method may comprise forming a hole in the first material with the laser, melting at least one of the first and the second material with the laser, and flowing at least one of the first and the

second material into the hole.
(43) The first material and the second material may remain substantially unmixed in the weld.
(44) The hole may be formed by pulsing the laser such that at least some of the first material is injected into the second material.
(45) The hole may be formed by first forming a hole that does not penetrate through the first material, and then pulsing the laser such that at least some of the first material is injected into the second material.
(46) The first material may have a top surface and a bottom surface. The bottom surface may be closer to the second material than the top surface. The hole may have a width at the top surface and a width at the bottom surface, wherein the width at the top surface is wider than the width at the bottom surface. The hole may be a countersunk hole.
(47) The method may include a step of remelting at least one of the first material and the second material with the laser.
(48) The weld may comprise at least one void in at least one of the first material and the second material.
(49) The pulse repetition rate may be greater than 10 kHz, may be greater than 100 kHz, and may be greater than 200 kHz. The spot size, the pulse fluence, the pulse width, and the pulse repetition frequency may be selected such that at least one of the first material and the second material resolidifies between successive laser pulses thereby inhibiting the formation of an intermetallic phase in the weld. Selecting a pulse waveform that ensures that at least one of the first material and the second material is quenched rapidly substantially reduces intermetallic growth, and thereby avoids the reliability issues associated with intermetallics such as brittleness and weak welds.
(50) The spot size may be less than 100 μm. The spot size may be less than 60 μm.
(51) The first material may have a higher melting temperature than the second material.
(52) The first material may have a reflectivity greater than 90% at an optical wavelength of one micron.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings wherein:
(2) FIG. **1** shows a weld according to the present invention;
(3) FIG. **2** shows a weld in the form of a continuous spiral;
(4) FIG. **3** shows a weld in the form of rectangular hatching;
(5) FIG. **4** shows a weld in the form of rectangular hatching;
(6) FIG. **5** shows a weld in the form of triangular hatching;
(7) FIG. **6** shows a laser system for producing a weld according to the present invention;
(8) FIG. **7** shows a hole cut in the first material by the laser;
(9) FIG. **8** shows second material that has been melted by the laser;
(10) FIG. **9** shows the finished weld wherein the molten second material has flowed into the hole formed in the first material by the laser;
(11) FIG. **10** shows a hole that does not pass through the first material;
(12) FIG. **11** shows molten second material underneath the hole;
(13) FIG. **12** shows the finished weld wherein molten second material has flowed into the hole formed in the first material by the laser;
(14) FIG. **13** shows a weld being formed;
(15) FIG. **14** shows a weld having zones of the first material within the second material;
(16) FIG. **15** shows a laser system for producing a weld according to the present invention;

(17) FIG. **16** shows parameters of a pulsed laser waveform;
(18) FIG. **17** shows parameters of a focused laser spot;
(19) FIG. **18** shows two focused laser spots spaced apart;
(20) FIG. **19** shows two focused laser spots that are overlapping;
(21) FIG. **20** shows a stitched pattern of microwelds;
(22) FIG. **21** shows a laser system wherein a pulsed laser output is varied while making the weld;
(23) FIG. **22** shows a microweld being made using keyhole welding;
(24) FIG. **23** shows a cross section of a microweld;
(25) FIG. **24** shows a waveform that is used to close a keyhole;
(26) FIG. **25** shows a first material that is coated with a coating;
(27) FIG. **26** shows a first material welded to a second material, wherein the first and the second material comprise layers;
(28) FIG. **27** shows a prior art weld comprising intermetallics and a heat affected zone;
(29) FIG. **28** shows a weld according to the present invention comprising a heat affected zone;
(30) FIG. **29** shows a tab welded to a second metal part with a weld;
(31) FIG. **30** shows a graph of pulse fluence and absorbed energy density;
(32) FIG. **31** shows an example of a weld made according to a method of the present invention;
(33) FIG. **32** shows the results of a shear test of the weld shown in FIG. **31**;
(34) FIG. **33** shows two sheets of aluminium foil connected by copper foil using welds according to the present invention;
(35) FIG. **34** shows a weld formed of brass and copper;
(36) FIG. **35** shows evolution of pulse shape with pulse repetition frequency in a nanosecond pulsed fibre laser based on a master oscillator power amplifier configuration; and
(37) FIG. **36** shows two pulse waveforms having the same average power in the nanosecond pulsed fibre laser.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

(38) A weld according to the invention will now be described solely by way of example and with reference to FIG. **1**. FIG. **1** shows a weld **3** between a first material **1** and a second material **2**, the first material **1** being a first metallic material, and the second material **2** being a second metallic material, the weld **3** has a width **4** between 0.5 mm and 7 mm, the weld comprises at least one microweld **8**, the microweld **8** forms a welding pattern **5** (shown enlarged) defined parallel to a surface **6** of the first material **1**, and the microweld **8** has a characteristic feature size **7** of between 20 μm and 400 um.

(39) By parallel to the surface **6** of the first material **1**, it is meant either on the surface **6** in the vicinity of the weld **3**, or beneath the surface **6**, for example, below a weld pool. The welding pattern **5** is preferably a two dimensional welding pattern. By width **4** of the weld **3**, it is meant the smallest transverse dimension of the weld **3** on the surface **6**.

(40) The welding pattern **5** shown in FIG. **1** comprises a plurality of microwelds **8** in the form of a spiral. The characteristic feature size **7** of the microwelds **8** is the width or the diameter of the microwelds **8**. The arms **9** of the spiral are separated by a first separation **10**. The microwelds **8** are separated by a second separation **11** within the arms **9** of the spiral. The second separation **11** can be 50 μm to 450 μm. Preferably, the second separation **11** is between 50 μm and 200 μm. The spiral may be circular, or may be elongated such as in the form of a race track. Other patterns may also be used.

(41) The weld **3** can be in the form of the welding pattern **20** shown in FIG. **2**, which welding pattern **20** comprises a single microweld **21** that is in the form of a spiral **22**. The characteristic features size **7** of the microweld **21** is the width of the microweld **8**. The arms **9** of the spiral are separated by the first separation **10**.

(42) The welding pattern **5** may comprise a plurality of hatch lines **31** as shown in FIGS. **3**, **4** and **5**, each hatch line **31** comprising at least one microweld **8**. The welding pattern **5** may comprise a

perimeter ring **33** comprising at least one microweld **8** as shown in FIGS. **3** and **5**. Advantageously, the perimeter ring **33** can help to relieve stress in the weld **3**. The characteristic feature size **7** of the microweld **8** is the width of the microweld **8**. The hatch lines **31** may comprise a rectangular grid, as shown in FIGS. **3** and **4**, with individual hatch lines **31** being separated by the first separation **10** and by a third separation **32**. The hatch lines **31** may also form a triangular grid as shown with reference to FIG. **5**. Other grid patterns are also possible.
(43) The first separation **10** in FIGS. **1** to **5** can be in the range 20 to 2000 μm. The first separation **10** can be in the range 50 μm to 500 μm. Preferably the first separation **10** is the range 50 μm to 250 μm. More preferably the first separation **10** is in the range 50 μm to 125 μm.
(44) The third separation **32** in FIGS. **3** to **5** can be in the range 20 to 2000 μm. The third separation **32** can be in the range 50 μm to 500 μm. Preferably the third separation **32** is the range 50 μm to 250 μm. More preferably the third separation **32** is in the range 50 μm to 125 μm. The third separation **32** can be the same as the first separation **10**.
(45) The weld **3** can be made using the apparatus shown in FIG. **6**. The apparatus comprises a laser **61** coupled to a laser scanner **67** by beam delivery cable **69**. The laser **61** emits a laser beam **62** which is focused onto the surface **6** with an objective lens **68**.
(46) The laser **61** is preferably a nanosecond laser that emits at a wavelength of approximately 1060 nm. Various options for the laser **61** will be described later.
(47) By a nanosecond pulsed laser, it is meant a laser that can emit pulses having pulse widths in the range 1 ns to 1000 ns. Such lasers may also be able to emit shorter pulses, and longer pulses, and may also be able to emit continuous wave radiation. Such lasers are different from prior art millisecond lasers that are conventionally used for producing welds. Millisecond lasers generally form a weld by emitting a single pulse, and the welds that are formed by millisecond lasers have a very different visual appearance from the welds **3** of the present invention. Surprisingly, the welds **3** of the present invention can be formed in highly reflective metals and refractory metals, and by virtue of the shorter pulses that contain less energy, the welds **3** are extremely strong, even when using dissimilar metals, highly-reflective metals. At least one of the first material **1** and the second material **2** may cool down very rapidly between pulses, leaving insufficient time for intermetallic formation within the microweld **8**. Welds **3** can also be formed in combinations of metals, such as aluminium and stainless steel, in which strong, reliable and predictive welds have been difficult to achieve with prior art techniques.
(48) As shown in FIGS. **7** to **9**, the first material **1** and the second material **2** may be substantially unmixed in the microweld **8**. FIG. **7** shows a hole **71** that has been formed with the laser **61**. FIG. **8** shows molten second material **81** that has been melted with a laser. FIG. **8** shows the microweld **8** that is formed after the molten second material **81** has flowed into the hole **71** and resolidified. The flow may occur because of capillary action, by vapour pressure caused by the rapid expansion of vapourized material by the laser pulse, or by the Marangoni effect, which is the mass transfer along an interface between two fluids due to surface tension gradient. In the case of temperature dependence, this phenomenon may be called thermo-capillary convection (or Bénard-Marangoni convection).
(49) The weld **3** shown with reference to FIGS. **7** to **9** has a top surface **72** and a bottom surface **73**. The hole **71** has a width **74** at the top surface **72** which is wider than a width **75** at the bottom surface **73**. Importantly, such an arrangement can increase the peel strength of the microweld **8**. The hole **71** is a countersunk hole and the microweld **8** resembles a rivet. The width **74** may be less than 200 μm. The width **74** may be less than 50 μm. The width **74** may be less than 20 μm.
(50) FIG. **10** shows a hole **76** that does not penetrate through the first material **1**. The hole **76** can be formed by ensuring that the energy in the pulse is not sufficient to raise the vapour pressure in the first material **1** to a level in which the hole **76** penetrates to the bottom surface **73** of the first material **1**. This can be achieved by selecting the laser **61** such that it can deliver lower energy pulses such as pulses with lower peak powers, or pulse widths that are less than 20 ns. The scanner

67 can be used to scan the laser beam **62** on the first material **1** in order to obtain a predetermined shape of the hole **71**. For high reflectivity materials (for example, reflectivity greater than around 90% at 1 μm wavelength) picoseconds lasers (lasers that emit pulses having pulse widths between 1 ps and 1000 ps) may be used advantageously. FIG. **11** shows molten second material **81** that has been melted by the laser **61**. The laser **61** can then be pulsed such that the hole **76** now penetrates to the second surface **73**, creating the hole **71**, thus allowing at least some of the second material **2** to flow into the hole **71** as shown with reference to FIG. **12**. At least some of the first material **1** may be injected into the second material **2**, as shown by the zones **121** of the resulting microweld **8** shown in FIG. **12**. At least one void **122** may also occur in the second material **2**. The void **122** may assist the flow of the second material **2** through the hole **71** by vapour pressure.

(51) FIGS. **13** and **14** shown a microweld **8** formed with a laser **61** that has sufficient peak power to overcome the reflectivity of the first material **1**, and sufficient energy to form a key hole **133** in the second material **2**. Vapour pressure caused by the rapid heating of the first material **1** causes at least some of the first material **1** to be injected into the hole **71** or ejected from the hole **71**. This is shown by the material **131** being injected into the key hole **133** formed in the second material **2**, and the material **132** being emitted out of the hole **71**. The materials **131** and **132** may be in the vapour phase, fluid phase, solid phase, or a combination of at least two of the forgoing material phases. Molten second material **81** can then flow into the hole **71** as shown with reference to FIG. **14**. Zones **121** of the first material **1** and voids **122** may be present in the microweld **8**.

(52) The microwelds **8** shown with reference to FIGS. **1** to **5** can be one or more of the microwelds **8** shown with reference to FIGS. **9**, **12** and **14**.

(53) The microweld **8** may be substantially inhomogeneous. Unlike prior art welds, the microweld **8** may be substantially unmixed. By “substantially unmixed” it is meant that the intermetallic content formed by the first material **1** and the second material **2** combined together in single co-mixed alloy phases comprises at most twenty percent, and preferably at most ten percent of the material of the microweld **8**. The intermetallic content at interfaces between the first material **1** and the second material **2** may be sufficient to achieve a joint with pre-determined mechanical properties and ohmic resistivity. The intermetallic content at interfaces between the first material **1** and the second material **2** may be small enough to avoid embrittlement such as caused by recrystallization. Advantageously this avoids the problems of brittle or weak welds arising from intermetallics that can occur when forming a weld between dissimilar metals. The result is a weld **3** capable of joining bright and dissimilar metals and alloys, producing consistent and predictive results on each weld.

(54) The first material **1** may have a different melting temperature than the second material **2**. This enables one of the first and the second materials **1**, **2** to resolidify prior to the other material, and to flow, thus avoiding substantial mixing of the first and the second materials **1**, **2**. In order to optimize the performance of the microweld **8**, the parameters of the laser **61**, such as pulse width, pulse repetition frequency, pulse energy, and peak power can be adjusted. The first material **1** may have a melting temperature that is at least 50% higher or lower than a melting temperature of the second material **2**.

(55) The first material **1** may be defined by a Young's modulus which is less than a Young's modulus of the second material **2**. Advantageously, the first material **1** may be substantially more ductile than the second material **2**. This has advantages if the weld **3** is repeatedly strained since the microwelds **8** will be more resistant to metal fatigue.

(56) The first material **1** may have a reflectivity **145** greater than 90% at an optical wavelength **140** of one micron. The reflectivity **145** can be defined at 20 C.

(57) With reference to FIGS. **1** to **5** and **7** to **14**, the first material **1** can comprise a metal selected from the group consisting of copper, aluminium, iron, nickel, tin, titanium, iridium, tungsten, molybdenum, niobium, tantalum, rhenium, silver, platinum, gold, and an alloy comprising at least one of the foregoing materials. The alloy can be bronze, brass, a nickel titanium alloy, or an

amorphous alloy. The second material **2** can comprise a metal selected from the group consisting of copper, aluminium, iron, nickel, tin, titanium, iridium, tungsten, molybdenum, niobium, tantalum, rhenium, silver, platinum, gold, and an alloy comprising at least one of the foregoing materials. Other metals for the first material **1** and the second material **2** may be employed. The first material **1** and the second material **2** may be the same or different.
(58) Surprisingly, a weld **3** between bright and dissimilar metals and alloys has consistent and predictive qualities. Arranging for one of the first and the second materials **1**, **2** to flow into the hole **71** without substantially mixing with the other material, helps prevent intermetallics from forming, and avoids the reliability issues associated with intermetallics such as welds which are brittle and weak. The increased surface area of the weld **3** provides more contact area, which in turn reduces ohmic resistance. Reducing ohmic resistance is an important consideration for increasing efficiencies of batteries and solar panels.
(59) The width **4** may be between 0.5 mm and 2.5 mm. Preferably the characteristic feature size **7** is between 40 μm and 100 μm.
(60) The present invention also provides an article comprising at least one weld **3** according to the Figures disclosed. Examples of articles are smart phones, mobile phones, laptop computers, tablet computers, televisions, and other consumer electronic devices; batteries; solar cells; integrated electronic circuit components; printed circuit boards; electrical connections, such as copper to aluminium connections, inside batteries; low profile electrical connections between flexible circuit elements and thin-section busbars; metallic enclosures for medical electronic devices; and electrical connections in consumer electronics devices; metallic labels and tags; silver, platinum, and gold parts in jewellery.
(61) A method according to the invention for laser welding a first material **1** to a second material **2**, will now be described with reference to FIG. **15**. The method comprises: placing a first metal part **151** comprising the first material **1** on a second metal part **152** comprising the second material **2**, providing a laser **61** for emitting a laser beam **62** in the form of laser pulses **161**, providing a scanner **67** for scanning the laser beam **62** with respect to a surface **6** of the first metal part **151**, providing an objective lens **68** for focusing the laser pulses **161** onto the surface **6**, and providing a controller **153** that is adapted to control the scanner **67** such that the scanner **67** moves the laser beam **62** with respect to the surface **6**,
(62) characterized by moving the laser beam **62** with respect to the surface **6**, focusing the laser pulses **161** to form a focused spot **12** with a spot size **174** and a pulse fluence **176** (shown with reference to FIG. **17**) that cause the formation of at least one microweld **8** in the form of a welding pattern **5** defined parallel to the surface **6**; the moving of the laser beam **62** with respect to the metal surface is such that the weld **3** has a width **4** (shown with reference to FIG. **1**) between 0.5 mm and 7 mm. wherein the microweld **8** has a characteristic feature size **7** of between 20 μm and 400 μm.
(63) The laser radiation **62** is directed to the scanner **67** via an optical fibre **147** and a collimation optic **142**.
(64) The laser beam **62** is preferably moved in two dimensions with respect to the surface **6** such that the resulting welding pattern **5** is a two dimensional welding pattern.
(65) FIG. **15** shows the laser **61** emitting at a wavelength **140** and a beam quality **146** defined by an M.sup.2 value. The wavelength is shown as being 1060 nm and the beam quality **146** as being 1.6; this is intended to be non-limiting.
(66) The first metal part **151** can have a thickness **143** in a region of the weld **3** of no more than 5 mm. The thickness **143** may be less than 2 mm. The thickness **143** may be less than 1 mm. The thickness **143** may be less than 0.5 mm. The second metal part **152** can have a thickness **144** in a region of the weld **3** of at least 100 μm. The thickness **144** may be less than 0.5 mm. The first metal part **151** can have a reflectivity **145** greater than 80%. Other reflectivities are also possible.
(67) FIG. **16** shows pulses **161** defined by a peak power **162**, an average power **163**, a pulse shape **164**, pulse energy **165** (shown as the shaded area under the pulse), a pulse width **166**, and pulse

repetition frequency F.sub.R **167**. The average power **163** is equal to the product of the pulse energy **165** and the pulse repetition frequency **167**. The pulse width **166** is shown as the full width half maximum value (FWHM) of the peak power **162**. Also shown is a pulse width **168** measured at 10% of the peak power **162**. The pulse **161** comprises a pre-pulse **160** that can be followed by a lower power region **169**.

(68) FIG. **17** shows a spot **12** having a spot size **174** formed by focusing the laser beam **62** onto the surface **6**. The optical intensity **172** is the power per unit area of the laser beam **62**. The optical intensity **172** varies across the radius of the spot **12** from a peak intensity **179** at its centre, to a 1/e.sup.2 intensity **173** and to zero. The spot size **174** is typically taken as the 1/e.sup.2 diameter of the spot **12**, which is the diameter at which the optical intensity **172** falls to the 1/e.sup.2 intensity **173** on either side of the peak intensity **179**. The area **175** of the spot **12** is typically taken as the cross-sectional area of the spot **12** within the 1/e.sup.2 diameter. Pulse fluence **176** is defined as the energy per unit area of the spot **12** on the surface **6**. Pulse fluence is typically measured in J/cm.sup.2, and is an important parameter for laser welding because weld quality is highly influenced by the pulse fluence **176**.

(69) The laser **61**, the collimation optic **142** and the objective lens **68**, should be selected such that sufficient optical intensity **172** and pulse fluence **176** can be obtained to overcome the reflectivity of the surface **6**. The pre-pulse **160** can be used for overcoming the reflectivity of the first material **1**, and for forming the hole **71** shown with reference to FIGS. **7** to **14**. The lower power region **169** can be used to melt the second material **2**. The laser parameters shown with reference to FIG. **16** can be adjusted to optimize desired characteristics of the weld **3**. The optimum pulse fluence **176** for a particular weld varies between different materials and material thicknesses. The optimum pulse fluence **176** for welding a metal piece part can be determined through experimentation.

(70) The laser **61** in FIG. **15** can be operated to form a plurality of melt pools **19** in the first metal part **151** and a plurality of heat stakes **17** in the second metal part **152**. Each heat stake **17** extends from a different one of the melt pools **19** and has a distal end **154**. The method includes adapting the controller **153** such that the laser **61** and the scanner **67** cause the focused spots **12** to be spaced apart by a distance that is small enough to cause the melt pools **19** to overlap and that is large enough to ensure the distal end **154** of the heat stakes **17** are distinct and separate from each other in at least one direction **155**.

(71) By “distinct and separate from each other”, it is meant that the distal ends **154** of the heat stakes **17** do not form a substantially smooth weld in all directions; the heat stakes **17** may be at least partially separate from each other in at least one direction **155**. Alternatively, the heat stakes **17** may be at least partially separate from each other in all directions substantially parallel to the metal surface **6**. By “weld” it is meant a connection made by welding or joining.

(72) Successive focused laser spots **12** may be separated as shown in FIG. **18** such that the separation **181** between the centres of the laser spots **12** is greater than the spot size **34**. Alternatively or additionally, successive focused laser spots **12** may overlap as shown in FIG. **18** such that the separation **181** is less than the spot size **34**. If the laser spots **12** are separated as shown in FIG. **18**, then the heat stakes **17** can be distinct and separate from each other from each other in more than one direction **155**. If however the laser spots **12** overlap, as shown in FIG. **19**, then the resulting microwelds **8** can be linear welds such as shown in FIG. **20**. The pattern **5** can either be formed from a plurality of such microwelds **8** as shown, or be formed by a pattern **5** of a single microweld **8**. In the latter case, the heat stakes **17** are distinct and separate from each other in only one direction **155**. In FIGS. **17** and **18**, the focused laser spot **12** may represent a single laser pulse **161** or multiple laser pulses **161**, and the above discussion extends to the case in which the laser spot **12** is dithered to increase the characteristic feature size **7** of the microweld **8**.

(73) Each heat stake **17** is formed by at least one of the pulses **161**, the number of pulses **161** being dependent on the pulse fluence **176**. Ten to one hundred pulses **161** are typically used for a laser with 1 mJ pulse energy **165**. The distance **181** between the centres of the focused spots **12** will

approximate the distance **18** between the centres of the respective heat stakes **17**. The controller **153** can cause the scanner **67** to hold the focused spot **12** still during the formation of each of the heat stakes **17**. Alternatively, the controller **153** can cause the scanner **67** to dither the focused spot **12** during the formation of each of the heat stakes **17**, preferably by an amount less than the distance **18**. The distance **18** is typically 20 μm to 150 μm, and preferably 40 μm to 100 μm.

(74) The weld **3** can be a composite weld formed by the overlapping melt pools **19** and the heat stakes **17**. For clarity, FIG. **15** shows the focused spots **12** as black circles, and the weld **3** in cross section within a three dimensional depiction. The melt pools **19** are shown melted together without boundaries between them, and an interface is shown between the melt pools **19** and the heat stakes **17**. Metallurgical studies have demonstrated that both the melt pools **19** and the heat stakes **17** may comprise material that is from both the first material **1** and the second material **2**.

(75) Good mixing of the metals can be achieved, which can be advantageous when both the first and the second materials **1**, **2** are stainless steel. In this case there is generally no well defined boundary between the melt pools **19** and the heat stakes **17**.

(76) The distal ends **154** of the heat stakes **17** are shown as ending in a sharp point. However this is not necessarily so; the distal ends **154** may be substantially curved and may be fragmented such that they have more than one end.

(77) As shown with reference to FIG. **15**, the method may include the step of providing a shield gas **155** from a gas supply **156**, and applying the shield gas **155** over the weld **3**. Shield gases can be used to keep to prevent the weld **3** oxidising or to keep the weld **3** clean. The shield gas **155** can be argon, helium, nitrogen, or other gases commonly used in laser welding. The shield gas **155** may be mixtures of gases. The gas supply **156** may comprise a gas bottle, a nozzle, and a flow control regulator.

(78) The weld **3** has a substantially jagged surface at the distal ends **154** of the heat stakes **17**. This is in direct contrast with conventional welding practice in which a smooth distal end of the weld is thought to be advantageous. A weld line that is not smooth is believed to be a cause for concern in the prior art.

(79) The apparatus is preferably such that the laser pulses **161** are in synchronism with a control signal **157** used to control the scanner **67**. This may be achieved by applying a synchronisation signal into the controller **153**, or by adapting the controller **153** such that the controller also controls the laser **61**.

(80) The scanner **67** can be a galvanometric scan head. Alternatively or additionally, the scanner **67** can be a moveable two-dimensional or three-dimensional translation stage, or a robot arm. The scanner **67** is such that it can move the laser beam **62** in a first direction **158** and a second direction **159**. The scanner **67** and the objective lens **68** may be part of a processing optics known by persons skilled in the art. The processing optic may have additional optical elements like tiled mirrors, additional focus control and/or beam shaping optics.

(81) As shown in FIG. **21**, the method of the invention may comprise operating the controller **153** to select a first laser signal **201** to create the melt pool **19** on the metal surface **6**, a second laser signal **202** to initiate welding of the first metal part **151** to the second metal part **152**, and a third laser signal **203** to weld the first metal part **151** to the second metal part **152** to form the microweld **8**. The first, second and third laser signals **201**, **202**, **203** are depicted comprising the laser pulses **161**. Preferably, the controller **153** controls the laser **61** such that the first, second and third laser signals **201**, **202**, **203** are in synchronism with the scanner **67**.

(82) A first cross section **221** shows the melt pool **19** caused by absorption of the first laser signal **201** by the first material **1** during a first time period **204**. When welding reflective metals, the absorption of the metal can increase significantly when the melt pool **19** is created. To optimize the weld properties, it can therefore be important for the controller **153** to select the second laser signal **202** once the reflectivity **145** changes.

(83) A second cross section **222** shows the initiation of welding in a second time period **205**. The

second laser signal **202** has caused the melt pool **19** to extend through the first metal part **151** and into the second metal part **152**. The distal end **226** of the melt pool **19** is shown penetrating the second metal part **152**. The melt pool **19** will then begin to contain metal from both the first metal part **151** and the second metal part **152**. Alternatively or additionally, metal from the first metal part **151** may penetrate into the second metal part **152**. In either case, welding can be said to have been initiated. A key hole **133** is shown as being present. The key hole **133** was described with reference to FIG. **13**, and will be further described with reference to FIGS. **22** and **23**. The key hole **133** may not occur during the second time period **205** and may not occur at all. If the key hole **133** is present, then most of the laser beam **62** may be absorbed by the key hole **133**. When welding reflective metals, it may therefore be beneficial that at least one of the peak power **162** and the pulse energy **165** of the second laser signal **202** reduces with the increasing absorption of the laser beam **62** in order to limit eruptions occurring from the key hole **133**. If the welding process continues without the controller **153** changing to the third laser signal **203**, then there can be too much energy being absorbed by the first and the second metal parts **151**, **152**, which can result in violent eruptions of material from the key hole **133**, and consequently, rough surfaces that are undesirable, especially for such as jewellery and medical devices for insertion into humans.

(84) A third cross section **223** shows the first metal part **151** being welded to the second metal part **152** in a third time period **206** by the third laser signal **203**. This may occur in the same pass of the laser beam **62** across the surface **6** in which the first and the second laser signals **201** and **202** were applied, or in a subsequent pass. If the first material **1** is highly reflective, then the peak power **162** of the third laser signal **203** may be selected such that it is less than the peak power **162** of the second laser signal **202**; this has the effect of causing less violent eruptions of molten material from the key hole **133**. In certain circumstances, it may be preferred that the third laser signal **203** is a continuous wave signal. The melt pool **19** is shown as being larger than the melt pools **19** in the first and second cross sections **221**, **222**, but this is meant to be non limiting. The laser beam **62** is shown focused into the key hole **133**. The distal end **226** of the weld pool **19** is shown extending further into the second metal part **152**. The key hole **133** may not be present during the third time period **206**.

(85) Key hole welding is shown in more detail in FIG. **22**. In this process, the laser beam **62** not only melts the first and the second metal parts **151**, **152**, but also produces vapour. The dissipating vapour exerts pressure on the molten metal **225** and partially displaces it. The result is a deep, narrow, vapour filled hole called the keyhole **133**. Such a process may be involved in the formation of the microweld **8** and the heat stakes **17** (if present) in the apparatus and method of the invention.

(86) The method may be one in which the key hole **133** is surrounded by the molten metal **225**, and moves with the laser beam **62** in the direction **226** that the laser beam **62** is scanned. The molten metal **225** solidifies behind the keyhole **133** as it moves, forming the microweld **8**. The microweld **8** can be deep and narrow. The laser beam **62** is absorbed with high efficiency in the key hole **133** as it is reflected multiple times. As shown in FIG. **23**, the microweld **8** may have a depth **228** that is greater than its width **229**. The weld depth **228** can be up to ten times greater than the weld width **229**. Alternatively, the weld depth **228** can be greater than ten times greater than the weld width **229**.

(87) The heat stake **17** shown with reference to FIGS. **15** and **21** can form at least part of the microweld **8** shown in FIG. **23**. The width **229** can be the characteristic feature size **7** shown with reference to FIGS. **1** to **5** and FIG. **15**. By heat stake **17**, it is meant a weld that penetrates into the second metal part **152**. The heat stake **17** may resemble a spike penetrating the second metal part **152**. Alternatively, the heat stake **17** may be a deep penetration weld that may be linear or curved along its length. The first and second materials **1**, **2** may be mixed together in the heat stake **17**, or they may be substantially unmixed. Alternatively the heat stake **17** may mainly comprise the first material **1**.

(88) In certain cases, such as for example when welding materials having substantially different

melting temperatures, the key hole **133** may not close properly, leaving a void **122** in the weld **3**. This can be resolved by providing a fourth laser signal **240**, shown with respect to FIG. **24**, which laser signal **240** is selected to close the key hole **133**. The average power **153** of the fourth laser signal **240** may be reduced with time. In FIG. **24**, the fourth laser signal **240** comprises a plurality of pulses **161**, with a smaller pulse repetition frequency **167** than the pulse repetition frequency **167** of the third laser signal **203**. In addition, the peak power **162** is reduced with time. Other fourth laser signals **240** are also possible.
(89) Referring again to FIG. **21**, the microweld **8** is shown in cross section after it has cooled down. The microweld **8** is shown as comprising an optional heat stake **17** extending into the second metal part **152**. Also shown is material **132** on the surface of the weld **3**, and a void **122** within the second metal part **152**. The material **132** and the void **122** were previously described with reference to FIG. **13**. As described with reference to FIGS. **1** to **14**, pattern **5** can comprise a plurality of the microwelds **8** shown in FIG. **21**, or a single microweld **8** which forms the pattern **5**.
(90) The welding method can be improved or optimized with respect to one or more of the following criteria: (i) the elimination or reduction of the material **132**, (ii) the elimination or reduction of the voids **122**, (iii) reduction of surface roughness or the improvement of a surface of the weld **3**, (iv) reduction of time taken to form the weld **3**, (v) strength of the weld **3**, and (vi) reliability of the weld **3**. The optimization can be achieved through the selection of one or more of the first, second, third and fourth laser signals **201**, **202**, **203**, and **240**, the selection and focusing of the objective lens **68**, and the selection of scanning speeds of the scanner **67**. The optimization can be achieved through experimentation. For example, at least one of the first, second and third signals **201**, **202**, **203** may be selected to inhibit the formation of intermetallics. This should increase the strength and the reliability of the weld **3**. Parameters for optimizing welds in different materials and thicknesses **143**, **144** can be stored in the controller **153** and the laser **61**.
(91) The microweld **8** may be formed by a single pass of the laser beam **62** over the surface **6**, or in multiple passes of the laser beam **62** over the surface **6**. The first, second and third laser signals **201**, **202**, **203** may be provided in a single pass of the laser beam **62** as it forms the microweld **8**. Alternatively, the first and the second laser signals **201**, **202** can be provided in a pass of the laser beam **62** over the surface **6**, and the third laser signal **203** in another pass of the laser beam **62** over the surface **6**.
(92) In certain cases, it is important that the method for forming the weld **3** is as simple as possible, and preferably uses the same steps for different materials. In this event at least two of the first, second, third, and fourth laser signals **201**, **202**, **203**, and **240** can comprise pulses **161** having the same waveforms.
(93) The method of the invention described with respect to FIGS. **15** and **21** can comprise the steps described with reference to FIGS. **7** to **14**. The method can include forming the hole **71** in the first material **1** with the laser **61**, melting at least one of the first and the second materials **1**, **2** with the laser **61**, and flowing at least one of the first and the second materials **1**, **2**. The first and the second materials **1**, **2** may be flowed into the hole **71** The first material **1** and the second material **2** may remain substantially unmixed in the microweld **8** as shown in FIG. **8**. The hole **71** may be formed by pulsing the laser **61** such that at least some of the first material **1** is injected into the second material **2** as shown in FIGS. **12** and **13**.
(94) The step of forming the hole **71** may include cutting the first material **1**. By cutting, it is meant cutting or engraving. The step may include cutting the second material **2**.
(95) The steps of melting and flowing at least one of the first and the second materials **1**, **2** may be provided in an additional pass of the laser beam **62** over the microweld **8**.
(96) The step of forming the hole **71** may include forming a microweld **8** between the first material **1** and the second material **2**. However, the microweld **8** may not have the required strength, structure or appearance. The steps of melting at least one of the first and the second materials **1**, **2**, and flowing at least one of the first and the second materials **1**, **2** may improve the strength,

structure or appearance of the microweld **8**. Preferably some or all of the laser parameters described with reference to FIG. **16** are selected to inhibit the formation of intermetallics **281** in the microweld **8** when melting and flowing at least one of the first and the second materials **1**, **2**.
(97) The step of melting at least one of the first and the second materials **1**, **2** may include the step of operating the laser **61** such that the pulse fluence **176** preferentially melts one of the first and the second materials **1**, **2** in preference to the other one of the first and the second materials **1**, **2**. Preferentially melting one of the first and the second materials **1**, **2** can inhibit the formation of intermetallics **281**.
(98) The step of melting at least one of the first and the second materials **1**, **2** may include the step of operating the laser **61** with a pulse fluence **176** and a pulse repetition frequency **167** that melts both the first and the second materials **1**, **2**. Preferably, the pulse fluence **176** and the pulse repetition frequency **167** are selected such that at least one of the first and the second materials **1**, **2** solidifies between successive pulses **161**. This can inhibit the formation of intermetallics in the microweld **8**.
(99) The first material **1** may melt when exposed to a pulse energy **165** of 10 mJ or less. The pulse energy **165** may be 4 mJ or less. The pulse energy **165** may be 1 mJ or less. The pulse energy **165** may be 100 μJ or less. The pulse energy **165** may be 10 μJ or less. Thicker materials require larger pulse energies **165** than thinner materials.
(100) As shown in FIGS. **10** to **12**, the hole **71** may be formed by first forming the hole **76** that does not penetrate through the first material **1**, and then pulsing the laser **61** such that at least some of the first material **1** is injected into the second material **2**.
(101) The step of forming the hole **71** may include pulsing the laser **61** with at least one pulse **100** having a pulse width **166** defined by a full width half maximum value that is less than or equal to 100 ns. The pulse width **166** may be less than or equal to 10 ns. The laser **61** may be a nanosecond pulsed laser.
(102) The step of forming the hole **71** or the hole **76** may include pulsing the laser **61** with at least one pulse **161** having a pulse width **166** that is less than or equal to 20 ns. The pulse width **166** may be less than or equal to 1 ns. The pulse width **166** may be less than or equal to 100 ps. The pulse width **166** may be less than or equal to 10 ps. The laser **61** may be a picosecond pulsed laser. Preferably the laser **61** is such that it can emit both picosecond pulses (less than 1 ns) and nanosecond pulses (less than 1 μs). An advantage of having pulse widths **107** less than 1 ns is that less energy is provided in the pulse **161**, and this can assist cutting the hole **76** in the first material **3** without surface roughness or penetration through the first material **1**. Multiple pulses **161** may be employed to cut the hole **71** or the hole **76**.
(103) The laser weld **3** formed by the apparatus or the method of the invention may be autogenous, that is, no additional (filler) materials are added in forming the weld **3**.
(104) Referring to FIGS. **6**, **15** and **21**, the laser **61** can be a fibre laser, a solid state rod laser, a solid state disk laser, or a gas laser such as a carbon dioxide laser, or a combination thereof. The laser **61** may be a laser source with external optical modulators such as an acousto-optic modulator for creating the pulses **161**. The laser **61** may be a Q-switched laser, a modulated continuous wave laser, or a quasi continuous wave laser. The laser **61** is preferably a master oscillator power amplifier. The laser **61** is preferably able to output laser pulses **161** as well as a continuous wave output.
(105) The laser **61** may be defined by a beam quality M.sup.2 value **109** that is between 1 and 25. The M.sup.2 value **109** may be in a range 1 to 10, 1 to 5, or 2 to 5. Preferably the M.sup.2 value **109** may be in a range 1.3 to 2. The M.sup.2 value **109** may be less than 1.3.
(106) The laser **61** is preferably a rare-earth-doped nanosecond pulsed fibre laser, such as a ytterbium doped fibre laser, an erbium-doped fibre laser, a holmium-doped fibre laser, or a thulium doped fibre laser. These lasers typically emit laser radiation at the wavelength **140** in the 1 μm, 1.5 μm, 2 μm and 2 μm wavelength windows respectively.

(107) The laser **61** may be a laser that can emit the laser pulses **161** that have the pulse widths **166** between approximately 10 ps and 3000 ns, preferably in the range 100 ps and 1000 ns, and more preferably in the range 1 ns to 1000 ns. The laser **61** may also be able to emit a continuous wave laser signal. Preferably, the laser **61** has a wide variety of pulse shapes and pulse parameters that can be selected in order to optimize the properties and cost of producing the weld **3**. An example of such a laser is the nanosecond ytterbium-doped fibre laser, model SPI G4 70 EP-Z manufactured by SPI Lasers UK Ltd of Southampton, England. The laser emits at a wavelength **140** in the range 1059 nm and 1065 nm. Table 1 shows pulse parameter data for 36 waveforms (wfm0 to wfm35) that are selectable by the operator of the laser. Each waveform has a minimum pulse repetition frequency PRF**0** at which maximum pulse peak power is obtained, and a maximum pulse repetition frequency PRFmax at which the minimum pulse peak power is obtained. The maximum pulse energy Emax is obtained at the minimum pulse repetition frequency PRF**0**, and is not increased if the laser is operated below the minimum pulse repetition frequency. The peak power obtainable at the minimum pulse repetition frequency PRF**0** is the peak power that corresponds to Emax, and is shown in the right hand column.
(108) FIG. **35** shows how the pulse shape **164** varies with pulse repetition frequency **167** for waveform WF**0** shown in Table 1. As the pulse repetition frequency **167** increases, the peak power **162** reduces, and the full width half power (FWHP) pulse width **166** increases from approximately 20 ns at 10 kHz to approximately 220 ns at 560 kHz. The average power **163** is approximately 70 W for each pulse waveform, the pulse energy **165** reducing with increasing pulse repetition frequency **167**.
(109) TABLE-US-00001 TABLE 1 Pulse parameters of the laser used in Examples 1, 2, and 11 to 13. Max. Typ. Typ. pulse FWHM Pulse peak energy, pulse width width at power PRF0 PRFmax Emax at Emax 10% at Emax wfm (kHz) (kHz) (mJ) (ns) (ns) (kW) 0 70 1000 1.0 46 240 13 1 88 1000 0.87 45 220 10 2 95 1000 0.76 42 200 10 3 102 1000 0.71 40 175 10 4 105 1000 0.69 38 160 11 5 112 1000 0.64 40 145 10 6 119 1000 0.61 35 130 11 7 126 1000 0.57 33 120 11 8 130 1000 0.56 32 115 11 9 137 1000 0.53 35 105 10 10 144 1000 0.50 30 100 10 11 151 1000 0.48 36 90 10 12 158 1000 0.46 37 80 11 13 168 1000 0.43 26 65 10 14 179 1000 0.40 33 58 10 15 189 1000 0.38 27 60 10 16 200 1000 0.36 34 55 10 17 214 1000 0.34 34 50 10 18 228 1000 0.32 33 45 10 19 245 1000 0.29 32 40 10 20 266 1000 0.27 26 36 10 21 291 1000 0.25 26 33 10 22 315 1000 0.23 25 30 10 23 350 1000 0.21 23 26 10 24 403 1000 0.18 19 23 9 25 490 1000 0.15 16 20 9 26 600 1000 0.12 13 16 9 27 850 1000 0.08 9 10 8 28 1000 1000 0.07 9 10 7 29 70 900 1.0 72 270 8 30 70 800 1.0 75 295 8 31 70 600 1.0 85 320 7 32 70 600 1.0 90 350 7 33 70 600 1.0 95 380 6 34 70 600 1.0 100 420 6 35 70 500 1.0 110 470 6 36 70 500 1.0 115 520 5
(110) FIG. **36** shows the pulse shape **164** for two different pulse waveforms shown in Table 1 at the minimum pulse repetition frequency PRF**0**. The average power **163** is approximately 70 W for each pulse waveform.
(111) The laser can also provide a continuous wave (cw) laser beam **62**, which can be selected as the third or fourth laser signal **203**, **240**.
(112) The ability to weld highly reflective metals using nanosecond fibre lasers, emitting in the 1 μm wavelength window, and with pulse energies **165** of around 1 mJ, is new and unexpected.
(113) Referring to FIG. **21**, the second laser signal **202** may be selected to have a plurality of the pulses **161**. The pulse width **166** may be greater than 100 ps.
(114) The second laser signal **202** can be selected to have a peak power **162** that is substantially greater than the peak power **26** of the third laser signal **203**.
(115) The second laser signal **202** can be selected to have a pulse repetition frequency **167** which is substantially less than the pulse repetition frequency **167** of the third laser signal **203**. The average power **163** of the second laser signal **202** may be characterized by an average power which is substantially equal to the average power **163** of the third laser signal **203**. The third laser signal **203** may be a continuous wave signal; this can be advantageous when welding a reflective metal as it

avoids rapid absorption of pulse energy **165** that increases vapour pressure in the first material **1** and results in eruptions of material from the microweld **8**. The second and the third laser signals **202**, **203** can be applied in the same pass of the laser beam **62** over the first material **1**, or in different passes.

(116) The peak power **162** of the first laser signal **201** may be selected to have a peak power **162** that is greater than a peak power **162** of the second laser signal **202**. This can assist coupling of the laser beam **52** to the first material **62** as high peak power **162** is needed to overcome the reflectivity **145** of the first material **1**.

(117) The pulse energy **165** of the first laser signal **201** may be selected to a have a pulse energy **165** that is less than the pulse energy **165** of the second laser signal **202**.

(118) The pulse width **166** of the second laser signal **202** may be selected to be less than 2.5 ms, preferably less than 1 ms, and more preferably less than 100 ns.

(119) The pulse repetition frequency **167** of the second laser signal **202** may be selected to be greater than 1 kHz, preferably greater than 10 kHz, and more preferably greater than 100 kHz.

(120) The welding process that is optimised may be one that improves a smoothness of a surface **231** of the laser weld **3**. Alternatively or additionally, the welding process that is optimised may be one that increases the strength of the laser weld **3**. Alternatively or additionally, the welding process that is optimised may be one that reduces the time taken to form the laser weld **3**.

(121) As shown in FIG. **25**, the first material **1** may be coated with a coating **251**. The coating **251** may be a metal plating such as nickel or chrome, or may be a chemically-induced coating such as anodization. The coating **251** may be a polymer coating.

(122) The first metal part **151** may comprise multiple layers **231** as shown with reference to FIG. **26**. The multiple layers **231** may be folded sheets of the same metal, layers of the same metal, or layers of different metals. Alternatively or additionally, the second metal part **152** may comprise multiple layers **232**. The multiple layers **232** may be folded sheets of the same metal, layers of the same metal, or layers of different metals. The layers **231** may comprise the same metal as the layers **232**, or different metals. The weld **3** is shown joining the first metal part **151** to the second metal part **152**. The weld **3** is shown partially penetrating the second metal part **152**.

(123) FIG. **27** shows a laser weld **275** comprising a weld pool **270** between the first metal part **151** and the second metal part **152** using prior art techniques, including for example, laser welding with a green laser using a single high-energy pulse of 100 mJ or more, or welding with a quasi continuous wave fibre laser. The weld **275** has a similar overall size as the weld **3** shown in FIG. **1**. Consequently, the weld pool **270** is considerably larger than the microwelds **8** when molten shown with reference to FIGS. **1** to **5** and **7** to **14**, has a higher thermal mass, and will take a longer time to cool down. This results in metallic mixing. However if the mixing is not good enough, then this results in the formation of an associated boundary layer **271**, which when welding dissimilar metals, contains intermetallics that can be brittle. There is also an area around the weld pool **270** that is affected by the heat but where the metals have not flowed—the so-called heat affected zone (HAZ) **272**. The mechanical properties of the heat affected zone **272** can be substantially degraded as a result of thermal heat tempering, and should generally be minimized. The heat affected zone **272** is generally visible (eg after etching with acid) on both the top surface **273** of the first metal part **151** and the bottom surface **274** of the second metal part **152**.

(124) The boundary layer **271**, when welding steel to steel, can result in carbon formation along grain boundary interfaces, thereby providing a pathway for fracturing the weld **3**. Similarly, the boundary layer **271** when welding dissimilar metals may comprise intermetallics with a grain structure reflecting the cooling time from fusion to solidification. Such intermetallics are often brittle in nature, and therefore represent a weak point in the weld pool **270**. Thus the existence of the boundary layer **271** and heat affected zone **272** are not desirable in either the welding of similar metals or the welding of dissimilar metals.

(125) Whether the weld **275** is formed from similar metals or dissimilar metals, the mechanical

properties of the material comprising the weld **275** are likely to be weaker than the properties of the base materials that comprise the first metal part **151** and the second metal part **152**. Heat affected zones **272** are also of a concern if they affect the appearance or chemical composition of the first and second metal parts **151**, **152**.

(126) The problems associated with intermetallic layers **271** and heat affected zones **272** increase when welding thin sheet metals (less than 1 mm). Other issues concerning the time taken for welds to cool down include damage to coatings such as polymers on the first and second metal parts **151**, **152**.

(127) FIG. **28** depicts a top view of the weld **3** shown in FIG. **1**. Here the weld **3** is circular, achieved by rastering the laser beam **62** around on the metal surface **6**. A heat affected zone **281** is usually visible (possibly after chemical etching). However, with proper selection of the laser **61** and the laser pulse parameters shown with reference to FIGS. **16** and **17**, there is generally no heat affected zone visible on the bottom surface. This is because the microweld **8** has significantly less mass than the weld pool **270**, and consequently cools more rapidly. Similarly, there is little or no evidence of intermetallic layers **271** surrounding the microwelds **8**. These features provide great advantages over prior art welding techniques.

(128) Referring to FIGS. **16** and **17**, the method of the invention can be one in which the pulse repetition frequency **167** is greater than 10 kHz, and the spot size **174**, the pulse fluence **176**, the pulse width **166**, and the pulse repetition frequency **167** are selected such that at least one of the first material **1** and the second material **2** resolidifies between successive laser pulses **161** thereby inhibiting the formation of an intermetallic phase in the weld **3**. The pulse repetition frequency **167** may be greater than 100 kHz and may be greater than 200 kHz. The pulse repetition frequency **167** may be greater than 500 kHz.

(129) The spot size **174** may be less than 100 μm. The spot size **174** may be less than 60 μm. The first or the second material **1**, **2** may have a higher melting temperature than the other material. The first material **1** may have a reflectivity **145** greater than 90% at an optical wavelength **140** of one micron.

(130) The second metal part **152** shown in FIG. **29** may comprise a metal part **292** which is coated with a coating **293**. The coating **293** may be a metal plating such as nickel or chrome, or may be a chemically-induced coating such as an anodization. The first metal part **151** may be a tab **291** such as found in beverage cans. The tab **291** is shown welded to the second metal part **152** with the weld **3**.

(131) Beverage cans are often made from thin sheets of aluminium (the second metal part **152**) that are less than 250 μm in thickness. In a beverage can, the coating **293** would be a polymer coating usually applied before the weld **3** is formed. It is important that the method of forming the weld **3** does not degrade the coating **293**. The apparatus and method of the present invention achieves this by virtue of the microweld **8**, shown with reference to FIGS. **1** to **24**, as there is less heat generated in the second metal part **152** compared to a prior art weld.

(132) FIG. **30** shows a graph of pulse fluence **176** and absorbed energy density **303**, where the absorbed energy density **303** is the total pulse energy **165** absorbed by the first and the second metal parts **151**, **152** per unit surface area by the laser pulses **161**. In order to initiate the weld **3** shown with reference to FIGS. **1** to **5**, **7** to **15**, **18** to **24**, and **25**, it is necessary to use a pulse fluence **176** that is at least equal to the first pulse fluence threshold **301**. This is in order to initiate the melting of the metal surface **6**. Once the metal surface **6** has begun to melt, the remaining pulses **161** should have a pulse fluence **176** that is at least equal to the second pulse fluence threshold **302**. The second pulse fluence threshold **302** can be substantially less than the first pulse fluence threshold **301**. As each of the pulses **161** is absorbed, they contribute to the absorbed energy density **303**. The absorbed energy density **303** absorbed at each of the focused locations **16** should be at least equal to the first energy density threshold **304** at which the microweld **8** begins to penetrate the second metal part **152**, but less than the second energy density threshold **305** at which

the weld **3** becomes unacceptably brittle. If too much energy is absorbed by the weld **3**, there will be excessive heating of the first and the second materials **1**, **2**, resulting in sufficient time for intermetallics to form and a weak weld **3**. It can be seen that by varying the pulse parameters shown with reference to FIGS. **16** and **17**, the number of pulses **161**, and the distances **181** between focused spots **12**, there is a great controllability of the weld **3**, and moreover, greater control over its formation, and therefore mechanical properties, than prior art techniques. The preferred values will vary for different materials, and thicknesses of materials, and can be found by experimentation.

(133) The method described with reference to FIGS. **15** and **21** may include the step of remelting at least one of the first and the second materials **1**, **2** with the laser **61**. This can improve the cosmetic appearance of the weld **3**, and also improve physical characteristics such as shear strength, peel strength, porosity, and ohmic resistance.

(134) In Examples 1 and 2, provided below, the laser **61** was a nanosecond ytterbium-doped fibre laser, model SPI G4 70 EP-Z manufactured by SPI Lasers UK Ltd of Southampton, England. The laser **61** is the master oscillator power amplifier described with reference to FIGS. **35** and **36**. The beam quality **146** had an M.sup.2 value of approximately 1.6. The scanner **67** was a galvanometer-scanner model Super Scan II manufactured by Raylase of Munich, Germany with a 10 mm beam aperture (not shown). It can be controlled with a controller (not shown) such as a desktop computer with a Windows 8 operating system on which SCAPS scanner application software licensed by SCAPS GmbH of Munich, Germany. This can be used to program, operate, and store code for steering the laser beam **62**. The lens **68** was a 163 mm focal length F-theta lens.

(135) The above equipment can be used to form and translate the laser beam **62** onto the top surface **6** of the first material **1** with a focused spot having a spot size **174** (1/e.sup.2 diameter) of 40 μm and an area **175** of 1.256×10.sup.−5 cm.sup.2.

Example 1

(136) FIG. **31** shows an artistic impression of a cross-section through a weld **310** formed between copper having a thickness **143** of 100 μm and aluminium having a thickness **144** of 400 μm. The weld **310** was in the shape of the spiral, shown with reference to FIG. **2**, with a first separation **10** of 50 μm between the spiral arms **9**, and a diameter **4** of 1 mm. The width **74** of the hole **71** was approximately 5 μm to 20 μm. The weld **310** was formed using multiple pulses **161** from the laser **61**, which pulses **161** overlayed each other on the first material **1** by approximately 95% to 98% in area. The laser **61** has cut the first material **1**, which is copper, and the second material **2** (aluminium) has flowed into the hole **71**. At least some of the first material **1** has been injected into the second material **2**, as evidenced by the zones **121** that comprise the first material **1**. The zones **121** extend to approximately 300 μm to 400 μm into the second material **2**. Voids **122** are also present. A heat affected zone **281**, shown by the approximately triangularly-shaped dashed line of depth **311**, is present under the holes **71**. Only one of the heat affected zones **281** is shown for clarity. This heat affected zone **281** resembles a heat stake that is commonly seen when welding thermoplastic parts together.

(137) The weld **310** has excellent shear resistance, as evidenced by a shear test. FIG. **32** illustrates the failure mode when three welds **310** of the type shown in FIG. **31** were sheared. The first material **1** failed around the welds **310**, and not through the welds **310**, thus indicating that the welds **310** were stronger than the surrounding material. This is an unexpected result, and shows the importance of being able to flow the second material **2** into the hole **71** without forming characteristically brittle intermetallics.

(138) The weld **310** has surprisingly good shear resistance, and excellent ohmic resistance. This makes the welding process of the invention as described with reference to FIGS. **15**, **21** and **31**, suitable for joining sheets of first material **1** and second material **2** with welds **3**, wherein the weld **3** provides electrical contact between the first material **1** and the second material **2**. In the example of FIG. **33**, the first material **1** is copper, and the second material **2** is aluminium, a combination of

materials that is often found in batteries.
(139) Additional peel strength would be obtainable by increasing the countersinking of the hole **71** as shown in FIG. **7**.
Example 2
(140) FIG. **34** shows an artistic impression of a cross section of a weld **340** between a first material **1** copper and a second material **2** brass. The weld **340** was also formed in a similar spiral to the weld **310** shown with reference to FIG. **13**. It is surprising that the brass has flowed into the copper material to form the weld **340** with very little intermetallic mixing. The weld **340** is substantially inhomogeneous. The copper and the brass have flowed, but have not mixed together to form new homogeneous material phases. The material phases of the copper and the brass are largely unmixed, with the copper and the brass being in their original material phases. This is particularly surprising given that brass is an alloy of copper and zinc. There are zones **121** of the first material **1** contained within the second material **2**. There are also voids **122**. The resulting joint formed by the weld **340** has excellent shear strength.
Examples 3 to 10
(141) The laser **61** used in Examples 3 to 10 was a nanosecond ytterbium-doped fibre laser, model SPI G4 70 W HS-H manufactured by SPI Lasers UK Ltd of Southampton, England. The laser is substantially similar to the laser used in Examples 1 and 2, though with a poorer beam quality **146**, which was increased from approximately M.sup.2=1.6 to approximately M.sup.2=3. The spot size **174** was approximately 80 μm, which is approximately twice as large as obtained with the higher brightness laser used in Examples 1 and 2. Similar waveforms are provided with the laser as were described with reference to Table 1 and FIGS. **25** and **36**.
(142) Table 2 shows details of the welds **3** in Examples 3 to 10. The first metal listed in each example was the first material **1**, and the second metal listed was the second material **2**.
(143) The welding pattern **5** was the rectangular hatching of FIG. **3**. The first separation **10** and the third separation **32** were both equal to each other, and were varied between 0.2 mm and 2 mm. The optimum value was found to be approximately 0.5 mm in each of the Examples 3 to 10.
(144) The characteristic feature size **7** of the microweld **8** was the width of the microwelds, which was approximately 60 μm to 250 μm depending on the materials used.
(145) The width **4** of the welds **3** was between 1.5 mm and 5 mm, depending on the metals and their thickness. Larger widths were used on the thicker metals.
(146) Argon was used as the shield gas **155** in Examples 5 to 10. There was no shield gas used in Examples 3 and 4. The nickel alloy was an austenite nickel-chromium iron alloy that is sold under the trade name INCONEL 718. The stainless steel was a molybdenum-bearing grade, austenitic stainless steel under the trade name SS316.
(147) In Table 2, the first column shows the materials that were welded together. In each Example, the first metal stated was the first material **1**, and the second metal stated was the second material **2**. The thicknesses **143**, **144** of the first and second materials **1**, **2** are shown as the size in mm.
(148) In each Example, there were two passes of the laser beam **61** in the same pattern **5** shown with reference to FIG. **3**. The parameters of the first pass are shown in the first line of each Example, and the parameters of the second pass are shown in the second line of each Example. The parameters were varied to optimize the appearance and the strength of the welds **3**, and the optimized parameters are shown in the table.
(149) The first pass had a higher peak power **162** than the peak power **162** of the second pass. The first pass created holes **71** in the first material **1** as shown with reference to FIG. **8**. The holes **71** may also extend into the second material **2**. The first pass can also create a weld **3**. However most of the welds **3** created by the first pass could easily be broken, were in general not strong, and had poor appearance. The second pass melted at least one of the first and the second materials **1**, **2**. If the second material **2** melted in preference to the first material **1**, then the second material **2** flowed into the hole **71** as described with reference to FIG. **9**. However if the first material **1** melted in

preference to the second material **2**, then the first material **1** flowed into the hole **71**, which hole **71** may extend into the second material **2**. The result in each of the Examples 3 to 10 was a weld **3** that was substantially stronger than achieved with the first pass. It is believed that this is because the formation of intermetallics was inhibited. In addition, the second pass cleaned the surface **6** giving the weld **3** a smooth and clean appearance.
(150) In each of the Examples save for Example 9, the first pass had a peak power **162** of 13 kW at a pulse repetition frequency **167** of 266 kHz. For Example 9, the first material **1** was copper, and the first pass was performed with a slower scan speed and at a peak power **162** of 25 kW. A slower scan speed was also required in Examples 4 and 10 where the second material **2** was copper; copper has a high reflectivity **145**. It was not necessary to decrease the scan speed in Example 7. Without wishing to limit the scope of the invention, it is believed that this may be because titanium has a higher melting point than copper.
(151) The laser parameters used in the second pass were varied in order to optimize the strength and appearance of the welds **3**. Surprisingly, good welds could be produced with continuous wave signals in each case. However, a higher frequency waveform produced stronger welds in Examples 3 to 9. In Examples 4 to 9, the pulse repetition frequency **167** was 600 kHz, resulting in pulses **161** having approximately 44% of the pulse energy **165** than in the first pass. In Example 3, as a result of the lower average power used, the pulse energy **165** in the second pass was 32% of the pulse energy **165** of the first pass. It is believed that the lower pulse energies resulted in less vapour pressure being generated when the laser beam **62** was absorbed during the second pass. The second pass for Example 10 was made using a continuous wave signal having a peak power **162** equal to the average power **163** of 50 W. The scan speed was 20 mm/s, which was lower than the scan speed of 30 mm/s of the first pass. It was necessary to use a relatively slow scan speed (20 to 25 mm/s as compared to 75 to 80 mm/s) for the second pass in Examples 4, 9 and 10, all of which involved welding copper. The scan speed for the second pass was 80 mm/s when welding titanium to copper, Example 7.
(152) The welds **3** produced by Examples 3 to 10 have a very different appearance from prior art welds. By taking advantage of the variety of pulse waveforms obtainable from the laser, it was possible to obtain strong welds from materials, such as stainless steel to aluminium, that have hitherto been difficult to weld.
(153) TABLE-US-00002 TABLE 2 Process Parameters used in Examples 3 to 10 FWHM 10% Aver- Scan Pulse Pulse Peak age Size speed Width Width Power PRF Power Example (mm) (mm/s) (ns) (ns) (kW) (kHz) (W) 3. Aluminium 0.1 100 20 30 13 266 70 to Brass 0.3 80 12 10 8 600 50 4. Aluminium 0.1 30 20 30 13 266 70 to Copper 0.4 25 12 10 8 600 70 5. Stainless 0.15 100 20 30 13 266 70 Steel to 0.5 75 12 10 8 600 70 Aluminium 6. Titanium to 0.12 160 20 30 13 266 70 Aluminium 0.5 120 12 10 8 600 70 7. Titanium to 0.12 160 20 30 13 266 70 Copper 0.4 80 12 10 8 600 70 8. Aluminium 0.1 120 20 30 13 266 70 to Nickel alloy 0.5 40 12 10 8 600 70 9. Copper to 0.1 30 24 250 25 55 70 Nickel alloy 0.5 20 12 10 8 600 70 10. Stainless 0.15 30 20 30 13 266 70 Steel to Copper 0.4 20 CW CW 50 W CW 50
Example 11
(154) Other than as stated below, the welds described in Examples 11 to 13 were made using the same apparatus as used for Examples 1 and 2. With reference to FIG. **15**, the first material **1** was copper grade C110 with a 150 μm thickness, and the second material **2** was aluminium grade 5052 with a 500 μm thickness. Following experimentation to determine the peak power **162**, the pulse shape **164**, the pulse energy **165**, the pulse width **166**, and the pulse fluence **176**, it was decided to scan the laser beam **62** at a linear speed of 50 mm/s over the metal surface **6** and with the distance **181** (shown with reference to FIG. **18**) between successive of the focused spots **12** of 0.7 μm (measured centre to centre). This corresponds to the pulse repetition frequency **167** of 70 kHz. The appropriate control parameters were then fed into the controller **153** and the laser **61** set up accordingly, The laser beam **62** was repetitively pulsed at the pulse repetition frequency **167** of 70

kHz, and scanned over the metal surface **6** in the spiral **22** shown with reference to FIG. **10**. The spiral **22** was formed with a 50 mm/s linear speed. The total length of the spiral **22** was 15.8 mm, and was formed from the inside **22** to the outside **24** of the spiral. The diameter **4** of the weld **3** was 1 mm. The pulse width **166** was 115 ns at full width half maximum FWHM. The pulse width **169** was 520 ns at 10% of peak power **162**. Total pulse energy **165** was 1 mJ with an average power **163** of 70 W and a peak power **162** of 5 kW. Each laser pulse **161** had a peak power intensity of 3.98×10.sup.+8 W/cm.sup.2 with a pulse fluence **176** of 79.6 J/cm.sup.2. A shield gas mixture **155** was used of 50% Argon and 50% Helium. The gas supply **156** was a 6 mm diameter copper nozzle that was placed over the weld **3**. The gas was supplied through a flow control regulator at 10 cubic feet per hour. The weld **3** that was formed is of the type shown in FIGS. **2** and **15**. The heat stakes **17** form a continuous line along the spiral **22**, and are at least partially separated in a radial direction **25** across the spiral **22**, corresponding to the direction **155** shown in FIG. **15**. The weld pools **19** are continuous across the entire surface area of the weld **3**, though as shown in FIG. **15**, the surface of the weld **3** is not smooth. Observation of the welds **3** revealed aluminium colouring on the top surface **6**, indicating that the aluminium has melted and has flowed. The copper and aluminium have at least partially mixed in the weld **3**. The welds **3** were observed to be extremely strong for their size.

Example 12

(155) With reference to FIG. **15**, the first material **1** was copper grade C110 with a 150 μm thickness **143**, and the second material **2** was also copper grade C110 with a 150 um thickness **144**. After experimentation, it was determined that the same process parameters could be used as described with reference to Example 11. The resulting welds were observed to be extremely strong for their size.

Example 13

(156) With reference to FIG. **15**, the first material **1** was stainless steel grade 304 with a 250 μm thickness **143** and the second material **2** was grade stainless steel 304 with a 250 μm thickness **144**. Following experimentation to determine the peak power **162**, the pulse shape **164**, the pulse energy **165**, the pulse width **166**, and the pulse fluence **176**, it was decided to scan the laser beam **62** at a linear speed of 225 mm/s over the metal surface **6** and with the distance **181** (shown with reference to FIG. **18**) between successive of the focused spots **12** of 0.225 μm (measured centre to centre). This corresponds to the pulse repetition frequency **167** of 1 MHz. The appropriate control parameters were then fed into the controller **153** and the laser **61** set up accordingly, The laser beam **62** was repetitively pulsed at the pulse repetition frequency **167** of 1 MHz, and scanned over the metal surface **6** in the spiral **22** shown with reference to FIG. **2**. The spiral **22** was formed with a 225 mm/s linear speed. The spiral **22** was formed from the inside **22** to the outside **24**. The diameter **4** of the weld **3** was 1 mm. The pulse width **166** was 9 ns at full width half maximum FWHM. The pulse width **168** was 9 ns at 10% of the peak power **162**. Total pulse energy **165** was 7 μJ with an average power **163** of 70 W and a peak power **162** of 8 kW. Each laser pulse **161** had a peak power intensity **179** of 6.36×10.sup.+8 W/cm.sup.2 with a pulse fluence **176** of 5.6 J/cm.sup.2. A shield gas mixture **155** was used of 50% Argon and 50% Helium supplied thorough a low control regulator at 10 cubic feet per hour from a 6 mm diameter copper nozzle over the weld **3**. The weld **3** that was formed is of the type shown in FIGS. **2** and **15**. The heat stakes **17** extended from the weld **3** in the form a continuous line along the spiral **22**, and are at least partially separated in a radial direction **25** across the spiral, corresponding to the direction **155** shown in FIG. **15**. The weld pools **19** are continuous across the entire surface **6** of the weld **3**, though as shown in FIG. **15**, the surface of the weld **3** is not smooth. The top surface of the weld **3** resembled a traditional lap weld, with excellent mixing of the metals, but almost negligible heat affected zone **272** (shown with reference to FIG. **27**). However the extension of the heat stakes **17** from the weld **3** was substantially less than observed for the copper aluminium and copper welds of Examples 11 and 12 respectively. The welds **3** were observed to be extremely strong for their size.

(157) The present invention also provides a weld **3** according to the method of the invention.
(158) The present invention also provides an article when welded according to the method of the invention. Examples of articles are a smart phone, a mobile phone, a laptop computer, a tablet computer, a television, a consumer electronic device; a battery; a solar cell; an integrated electronic circuit component; a printed circuit board; an electrical connection; a low profile electrical connection between flexible circuit elements and thin-section busbars; a metallic enclosure for a medical electronic device; and an electrical connection in consumer electronics devices; metallic labels and tags; silver, platinum, and gold parts in jewellery.
(159) It is to be appreciated that the embodiments of the invention given above with reference to the Figures and the Examples have been given by way of example only and that modifications may be effected. Individual components shown in the Figures and individual values shown in the Examples may be used in other Figures and other Examples and in all aspects of the invention.

Claims

1. A method for laser microwelding a first material to a second material, which method comprises: placing a first metal part comprising the first material on a second metal part comprising the second material;" providing a laser for emitting a laser beam in the form of laser pulses; providing a scanner for scanning the laser beam with respect to a surface of the first metal part; providing an objective lens for focusing the laser pulses onto the surface; and providing a controller that is adapted to control the scanner such that the scanner moves the laser beam with respect to the surface, characterized by moving the laser beam with respect to the surface; focusing the laser pulses with a spot size and a pulse fluence that cause the formation of a weld comprising at least one microweld in the form of a welding pattern defined parallel to the surface; and operating the controller to form the microweld by selecting a first laser signal comprising a plurality of the laser pulses during a first time period to create a melt pool on the surface, then selecting a second laser signal comprising a plurality of the laser pulses during a second time period to initiate welding of the first metal part to the second metal part, and then selecting a third laser signal comprising either the laser pulses or a continuous wave laser beam during a third time period to weld the first metal part to the second metal-part; wherein the method is one that forms a key hole, the method further includes providing a fourth laser signal which is selected to close the key hole; wherein the microweld has a characteristic feature size of between 20 μm and 400 μm; the laser pulses have pulse widths between 1 ns and 3000 ns; "the first material is a first metal;" the second material is a second metal which is different from the first metal; the weld is autogenous; and wherein the laser pulses have a pulse energy of 10 mJ or less, the laser pulses have a pulse repetition frequency greater than 10 kHz, and the spot size is less than 100 μm.
2. The method according to claim 1 wherein the moving of the laser beam with respect to the surface of the first metal part is such that the weld has a width between 0.5 mm and 7 mm.
3. The method according to claim 1 wherein the laser is operated to form a plurality of melt pools in the first metal part and a plurality of heat stakes in the second metal part, wherein each heat stake extends from a different one of the melt pools and has a distal end, and the method including adapting the controller to space the focused spots apart by a distance that is small enough to cause the melt pools to overlap and that is large enough to ensure the distal end of the heat stakes are distinct and separate from each other in at least one direction.
4. The method according to claim 1 wherein the second laser signal is selected to have a peak power which is greater than a peak power of the third laser signal.
5. The method according to claim 1 wherein at least one of the first, second and third laser signals is selected to inhibit the formation of intermetallics.
6. The method according to claim 1 wherein at least one of the first, second and the third laser signals is selected to improve the smoothness of a surface of the weld.

7. The method according to claim 1 wherein the laser beam is characterized by a beam quality M.sup.2 less than 4.
8. The method according to claim 7 wherein the laser is characterized by a beam quality M.sup.2 less than 2.
9. The method according to claim 8 wherein the laser is characterized by a beam quality M.sup.2 less than 1.3.
10. The method according to claim 1 wherein the laser is a nanosecond laser.
11. The method according to claim 1 wherein the laser is characterized by a wavelength between 1000 nm and 3000 nm.
12. The method according to claim 1, which method comprises: forming a hole in the first material with the laser; melting at least one of the first and the second materials with the laser; and flowing at least one of the first and the second materials into the hole.
13. The method according to claim 12 wherein the first material and the second material remain substantially unmixed in the weld.
14. The method according to claim 12 wherein the hole is formed by pulsing the laser such that at least some of the first material is injected into the second material to form a zone comprising the first material surrounded by the second material.
15. The method according to claim 12 wherein the hole is formed by first forming a hole that does not penetrate through the first material, and then pulsing the laser such that at least some of the first material is injected into the second material to form a zone comprising the first material surrounded by the second material.
16. The method according to claim 12 wherein the first material has a bottom surface that is closer to the second material than the surface of the first metal part, the hole has a width at the surface of the first metal part and a width at the bottom surface, wherein the width at the surface of the first metal part is wider than the width at the bottom surface, and the method includes the step of flowing the second material into the hole.
17. The method according to claim 1 and including a step of remelting at least one of the first material and the second material with the laser.
18. The method according to claim 1, wherein the weld comprises at least one void in at least one of the first material and the second material.
19. The method according to claim 1 wherein the laser pulses have the pulse repetition frequency, the pulse repetition frequency is greater than 10 kHz, and the spot size, the pulse fluence, the pulse widths, and the pulse repetition frequency are selected such that at least one of the first material and the second material resolidifies between successive laser pulses thereby inhibiting the formation of an intermetallic phase in the weld.
20. The method according to claim 1 wherein the spot size is less than 60 μm.
21. The method according to claim 1 wherein the laser pulses have a pulse energy of 4 mJ or less, 1 mJ or less, or 100 μJ or less.
22. The method according to claim 1 wherein the laser pulses have a pulse energy of 1 mJ.
23. The method according to claim 1 wherein the laser is a fibre laser.
24. The method according to claim 1 wherein the laser is a fibre laser, the laser beam is characterized by a beam quality M.sup.2 less than 4, and the laser pulses have a pulse energy of 4 mJ or less, 1 mJ or less, or 100 μJ or less.