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Methods and Systems for Controlling and Determining Size and Quality of Weld Nuggets

Joerg Simon

Zeqin Liang

Viktor Hibert

Mathilde Guerin

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METHODS AND SYSTEMS FOR CONTROLLING AND DETERMINING SIZE AND QUALITY OF WELD NUGGETS

BACKGROUND

[0001] During a spot welding process, weld nuggets created at a spot welded joint between two adjacent materials may be checked for quality and size. Generally, to assess the quality and size of weld nuggets, the welded joint must be broken apart. Two common methods for testing weld nuggets include a chisel test and a peel test. Both of these methods are destructive and require breaking apart the two welded materials to access the weld nugget for assessment. Since non-destructive techniques for checking or controlling the quality of the spot weld are lacking, weld schedules are often used to create spot welds and they typically indicate some details of a welding discharge to create a suitable weld nugget and minimize the need for destructive analysis. In spite of the weld schedule, however, various factors can result in a weld nugget of unsuitable characteristics, such as size.

LIST OF FIGURES

[0002] FIG. 1 provides a schematic illustration of a welding system according to the present disclosure.

[0003] FIG. 2A provides a schematic illustration of a destructed weld nugget showing size and quality characteristics.

[0004] FIG. 2B provides a schematic illustration of a destructed weld nugget showing size and quality characteristics.

[0005] FIG. 2C provides a schematic illustration of a destructed weld nugget showing size and quality characteristics.

[0006] FIG. 2D provides an example image of a sectioned weld nugget.

[0007] FIG. 3 provides a schematic illustration of a welding system according to the present disclosure.

[0008] FIG. 4 provides an illustrative graph showing an exemplary current applied by a welding system according to the present disclosure.

[0009] FIG. 5 provides an illustrative graph showing an exemplary voltage applied by a welding system according to the present disclosure.

[0010] FIG. 6 provides an illustrative graph showing an example resistance curve according to the present disclosure.

[0011] FIG. 7 provides an illustrative graph showing an amount of power applied by a welding system according to the present disclosure.

[0012] FIG. 8 provides an overview of an example method for joining two or more aluminum alloy products according to the present disclosure.

[0013] FIG. 9 provides an overview of an example method for non-destructively determining a size of a weld nugget according to the present disclosure.

[0014] FIG. 10 provides an illustrative graph showing amounts of energy applied by a welding system for different spot welds and weld nugget diameters characterized using a destructive analysis technique.

[0015] FIG. 11 provides another illustrative graph showing amounts of energy applied by a welding system for different spot welds and weld nugget diameters characterized using a destructive analysis technique.

[0016] FIG. 12 provides an illustrative graph showing amounts of energy applied by a welding system for different spot welds and weld nugget diameters characterized using a destructive analysis technique.

[0017] FIG. 13 provides another illustrative graph showing amounts of energy applied by a welding system for different spot welds and weld nugget diameters characterized using a destructive analysis technique.

DETAILED DESCRIPTION

[0018] Described herein are systems and techniques for joining two or more aluminum alloy products by spot welding and for non-destructively determining the size and quality of a weld nugget created during joining of two or more aluminum alloy products. The systems and techniques described herein may evaluate and/or monitor the welding discharge, which may correspond to a flow of electricity (i.e., electric current) between electrodes and the products to be joined, to determine and/or control a total amount of energy applied for generation of a spot welded joint. For example, the amount of current applied and the voltage at which the current is applied may be used to determine the instantaneous power applied and may, when monitored as a function of time, be used to determine the total energy applied during generation of a spot weld.

[0019] It has been determined that total energy applied during generation of a spot weld provides a useful metric for evaluation of a weld nugget created during spot welding of aluminum alloy products. In some cases, the total amount of energy applied directly correlates with a quality characteristic of the weld nugget. For example, the size (e.g., diameter) of a weld nugget may directly correlate with the total amount of energy applied for generation of a spot welded joint. Using energy as a quality metric, the welding discharge may be controlled on the fly and in real time during spot welding to ensure that a weld nugget generated during spot welding is of a suitable size, for example. As another example, a welding discharge used to spot weld aluminum alloy products may be monitored to evaluate the total energy applied and provide a measure of the size of the resultant spot weld, providing a useful means for evaluating weld nuggets in a non-destructive way.

[0020] Additionally, monitoring the energy of a welding discharge used to spot weld aluminum alloy products may provide a useful metric for evaluation of electrode degradation and prediction of the end of the tiplife. For example, the failure of an electrode or tiplife end can be determined by the additional energy generated under the same welding schedule. By evaluating electrode degradation the electrode can be redressed before impacting the quality of the spot weld. Thus, the systems and techniques provided herein may ensure spot weld quality and welding stability.

[0021] Aspects and features of the present disclosure may be used with any suitable metal, such as steel, aluminum, magnesium, titanium, and their alloys. For example, the present disclosure may be especially relevant for aluminum alloy products. Specifically, desirable results may be achieved when joining or welding aluminum alloys such as 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys, in any combination. For example, certain aspects and features of the present disclosure may allow for a 7xxx series aluminum alloy and a 6xxx series aluminum alloy to be joined together by means of a weld nugget created between the 7xxx series aluminum alloy and the 6xxx series aluminum alloy. The size and quality of the weld nugget may be determined using the non-destructive systems and techniques described herein. In another example, certain aspects and features of the present disclosure may allow for more efficient and reliable joining or welding of two or more aluminum alloy products as compared to current joining or welding methodologies. For example, the systems and techniques of the present disclosure may allow for real-time monitoring and control of weld nugget growth or for subsequent characterization of weld nuggets after creation.

Definitions and Descriptions:

[0022] In this description, reference is made to alloys identified by AA numbers and other related designations, such as “series” or “7xxx.” For an understanding of the number designation system most commonly used in naming and identifying aluminum and its alloys, see “International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys” or “Registration Record of Aluminum Association Alloy Designations and Chemical Compositions Limits for Aluminum Alloys in the Form of Castings and Ingot,” both published by The Aluminum Association.

[0023] As used herein, a plate generally has a thickness of greater than about 15 mm. For example, a plate may refer to an aluminum product having a thickness of greater than about 15 mm, greater than about 20 mm, greater than about 25 mm, greater than about 30 mm, greater than about 35 mm, greater than about 40 mm, greater than about 45 mm, greater than about 50 mm, or greater than about 100 mm.

[0024] As used herein, a shate (also referred to as a sheet plate) generally has a thickness of from about 4 mm to about 15 mm. For example, a shate may have a thickness of about 4 mm, about 5 mm, about 6 mm, about 7 mm, about 8 mm, about 9 mm, about 10 mm, about 11 mm, about 12 mm, about 13 mm, about 14 mm, or about 15 mm.

[0025] As used herein, a sheet generally refers to an aluminum product having a thickness of less than about 4 mm. For example, a sheet may have a thickness of less than about 4 mm, less than about 3 mm, less than about 2 mm, less than about 1 mm, less than about 0.5 mm, or less than about 0.3 mm (e.g., about 0.2 mm).

[0026] As used herein, the meaning of “room temperature” can include a temperature of from about 15 °C to about 30 °C, for example about 15 °C, about 16 °C, about 17 °C, about 18 °C, about 19 °C, about 20 °C, about 21 °C, about 22 °C, about 23 °C, about 24 °C, about 25 °C, about 26 °C, about 27 °C, about 28 °C, about 29 °C, or about 30 °C. As used herein, the meaning of “ambient conditions” or “ambient environment” can include temperatures of about room temperature, relative humidity of from about 20% to about 100%, and barometric pressure of from about 975 millibar (mbar) to about 1050 mbar. For example, relative humidity can be about 20%, about 21%, about 22%, about 23%, about 24%, about 25%, about 26%, about 27%, about 28%, about 29%, about 30%, about 31%, about 32%, about 33%, about 34%, about 35%, about 36%, about 37%, about 38%, about 39%, about 40%, about 41%, about 42%, about 43%, about 44%, about 45%, about 46%, about 47%, about 48%, about 49%, about 50%, about 51%, about 52%, about 53%, about 54%, about 55%, about 56%, about 57%, about 58%, about 59%, about 60%, about 61%, about 62%, about 63%, about 64%, about 65%, about 66%, about 67%, about 68%, about 69%, about 70%, about 71%, about 72%, about 73%, about 74%, about 75%, about 76%, about 77%, about 78%, about 79%, about 80%, about 81%, about 82%, about 83%, about 84%, about 85%, about 86%, about 87%, about 88%, about 89%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, about 100%, or anywhere in between. For example, barometric pressure can be about 975 mbar, about 980 mbar, about 985 mbar, about 990 mbar, about 995 mbar, about 1000 mbar, about 1005 mbar, about 1010 mbar, about 1015 mbar, about 1020 mbar, about 1025 mbar, about 1030 mbar, about 1035 mbar, about 1040 mbar, about 1045 mbar, about 1050 mbar, or anywhere in between.

[0027] All ranges disclosed herein are to be understood to encompass any and all subranges subsumed therein. For example, a stated range of “1 to 10” should be considered to include any and all subranges between (and inclusive of) the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more, e.g., 1 to 6.1, and ending with a maximum value of 10 or less, e.g., 5.5 to 10. Unless stated otherwise, the expression “up to” when referring to the compositional amount of an element means that element is optional and includes a zero percent composition of that particular element. Unless stated otherwise, all compositional percentages are in weight percent (wt%).

[0028] As used herein, the meaning of “a,” “an,” and “the” includes singular and plural references unless the context clearly dictates otherwise.

Systems and Methods for Joining Metal Products

[0029] Aspects of the present disclosure relate to systems and methods for joining two or more metal products together, such as two or more aluminum alloy products. During joining of aluminum alloy products by spot welding, for example, a weld nugget may be generated between adjacent segments of the aluminum alloy product. To assess the quality of the spot weld, the size and quality of the weld nugget is used. Generally, to determine the size and quality of the weld nugget, the joint between the two adjacent aluminum alloy products must be broken to access the weld nugget. The size of the weld nugget typically indicates the quality of the spot weld, specifically the diameter of the weld nugget is a primary measurement used to assess the quality of the spot weld. Thus, access to the weld nugget to take measurements is traditionally required for quality testing.

[0030] Welding aluminum alloy products, including by resistance-based welding techniques like spot welding, is generally thought to be more challenging than welding other types of materials because of the low resistivity / high electrical conductivity of aluminum alloys and the presence of oxides occurring as part of or on the surface of the aluminum alloy. Aluminum oxides have high electrical resistances which can make it difficult to weld aluminum-based materials, such as aluminum alloy products. In addition to higher thermal conductivity and mixed resistivity properties, aluminum alloy products have low densities compared to steel. This may mean that aluminum products require higher welding currents over a shorter duration of time when compared with steel. Thus, welding aluminum alloy products often requires higher demands on welding equipment because of the mixed electrical resistance characteristics, lower density, and higher thermal conductivity.

[0031] Certain aspects of the present disclosure may relate to systems and techniques for real-time monitoring of welding system equipment. For example, real-time monitoring of the electrode tip life may be provided. Electrode tip life is a relevant concern when welding aluminum alloy products because eroded tips can result in weld nuggets having low shear strengths. Low shear strengths mean that welded joints are likely to shear or break under a low-threshold of stress. Every time an electrode is used in a welding process, the electrical flow through the tip causes the tip to erode and degrade. Thus, monitoring the tip life of an electrode is useful to ensure the quality of the produced weld nugget. An electrode can be considered to have reached the end of its effective life when it produces a weld with a shear strength that drops below a certain percentage of an initial value or when the electrode starts sticking to the surface of the products being joined. That is, to determine the end of tip life, a weld nugget with an inadequate quality may first be created. However, techniques and embodiments disclosed herein may allow for tip life and condition to be evaluated before creation of an inadequate quality weld nugget.

[0032] FIG. 1 schematically illustrates a welding machine 100. Welding machine 100 may be operable to join two or more aluminum alloy products together. For example, welding machine 100 may be operable to weld two or more aluminum alloy products together. For example, welding machine 100 may be operable to join two or more, three or more, or four or more aluminum alloy products together. Various welding techniques may be performable on welding machine 100. For example, welding machine 100 may be configured to perform resistance spot welding (RSW), resistance projection welding, resistance butt welding, flash butt welding, or resistance seam welding.

[0033] Welding machine 100 may include a pair of electrodes 102A and 102B. Electrodes 102A and 102B may be positioned to receive two or more metal products, such as aluminum alloy products 106 and 108. In certain embodiments, welding machine 100 may include more than two electrodes. For example, welding machine 100 may include three electrodes or multiple pairs of electrodes 102A and 102B. Electrodes 102A and 102B may include tips 104A and 104B, respectively. Tips 104A and 104B may be separate components from electrodes 102A and 102B; however, for some embodiments, tips 104A and 104B may be part of electrodes 102A and 102B. In some embodiments, tips 104A and 104B may be configured to generate a welding discharge. In other embodiments, electrodes 102A and 102B may be configured to generate a welding discharge. To facilitate the flow of electricity required to generate the welding discharge, tips 104A and 104B may be made from a material having high electrical conductivity. For example, tips 104A and 140B may include tungsten (e.g., W, WL10, or WL20), molybdenum (e.g., Mo or TZM), copper, copper-chromium-zirconium, copper-chromium, or any other suitable material. In certain embodiments, electrodes 102A and 102B may be solid or monolithic electrodes, while in other embodiments, electrodes 102A and 102B may be back-cast, multi-part, or insert electrodes. Optionally, electrodes 102A and 102B may be or comprise the same material as tips 104A and 104B.

[0034] Aluminum alloy products 106 and 108 may comprise, consist of, or consist essentially of aluminum or aluminum alloy materials. For example, aluminum alloy products 106 and 108 may be 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys, in any combination. In some embodiments, aluminum alloy products 106 and 108 may be the same aluminum alloy, while in other embodiments aluminum alloy products 106 and 108 may be different aluminum alloys. In some cases, a non-aluminum product may be joined along with aluminum alloy products 106 and/or 108. For example, aluminum alloy products 106 and/or 108 may be joined to a steel product (not shown). In embodiments, aluminum alloy products 106 and 108 may be aluminum alloy sheets. However, in other embodiments, aluminum alloy products 106 and 108 may be aluminum alloy plates, shates, extruded aluminum alloy products, or cast aluminum alloy products (e.g., slabs).

[0035] Welding machine 100 may include power source 110. Power source 110 may be a power supply that is configured to supply electrodes 102A and 102B with electricity, and may also be referred to as a current source and/or voltage source. For example, power source 110 may include one or more of batteries, a generator, an AC or DC power outlet, a high-frequency inverter, or the like. In embodiments, power source 110 may be configured to provide a current. For example, power source 110 may be configured to supply from 5,000 to 65,000 amperes or more, such as from 5,000 to 10,000 amperes, from 10,000 to 20,000 amperes, from 20,000 to 30,000 amperes, from 30,000 to 40,000 amperes, from 40,000 to 50,000 amperes, from 50,000 to 65,000 amperes or more than 65,000 amperes. Power source 110 may be configured to supply a constant current despite fluctuations in voltage supply or changes in resistance between the electrodes 102A and 102B through aluminum alloy products 106 and 108. Alternatively, power source 110 may adapt the current supplied to keep the applied voltage constant. Optionally, power source 110 may be configured to allow both voltage and current to vary according to a desired output scheme. Power source 110 is shown in electrical communication with electrodes 102A and 102B by communication line(s) 112.

[0036] Electrodes 102A and 102B may be operable to generate a welding discharge. The welding discharge may correspond to a flow of electricity (i.e., electric current) from or to each of electrodes 102A and 102B to or from a corresponding aluminum alloy product. For example, the welding discharge may be generated by current flowing from electrode 102A to and through aluminum alloy product 106, and through aluminum alloy product 108 to electrode 102B. The resistance of aluminum alloy products 106 and 108 to the flow of electricity applied by electrodes 102A and 102B, respectively, may regulate or modulate the welding discharge and resistively generate heat. The welding discharge may heat portions of aluminum alloy products 106 and 108 within the vicinity of and/or proximal to tips 104A and 104B, causing portions of aluminum alloy products 106 and 108 to melt.

[0037] In embodiments, welding machine 100 may include a force actuator 114. Force actuator 114 may be a pneumatic or other mechanical actuator that is configured to apply force to electrodes 102A and 102B. During the joining process, electrodes 102A and 102B may hold aluminum alloy products 106 and 108 together. In some embodiments, electrodes 102A and 102B may hold aluminum alloy products 106 and 108 under pressure before, during, and/or after the joining process. For example, after receiving aluminum alloy products 106 and 108, electrodes 102A and 102B may apply pressure to aluminum alloy products 106 and 108 with the force supplied by force actuator 114. After applying pressure, electrodes 102A and 102B may generate the welding discharge, causing a portion of aluminum alloy products 106 and 108 to melt corresponding to weld nugget 120. After aluminum alloy products 106 and 108 melt in the vicinity of electrodes 102A and 102B, electrodes 102A and 102B may optionally apply even more pressure to the melted portions during extended heating and/or cooling of weld nugget 120. Force actuator 114 may be operably coupled to electrodes 102A and 102B. For example, force actuator 114 may be in mechanical or pneumatic communication with electrodes 102A and 102B via communication line 116. In embodiments, the location of weld nugget 120 between first aluminum alloy product 106 and second aluminum alloy product 108 may be referred to as a spot welded joint.

[0038] FIGs. 2A, 2B, and 2C provide schematic illustrations of example weld nuggets 200A, 200B, and 200C, respectively, in deconstructed form showing size and quality characteristics. In embodiments, weld nuggets 200A, 200B, and 200C may be the same as weld nugget 120 after destructive separation of the aluminum alloy products 106 and 108 for analysis. Weld nuggets 200A, 200B, and 200C may illustrate aspects of the joint between adjacent aluminum alloy products. The application of pressure and a welding discharge to adjacent aluminum alloy products may create a section of molten aluminum alloy that quickly cools and solidifies. The resulting round joint is commonly known as a nugget and is herein referred to as a weld nugget. Weld nuggets 200A and 200B illustrated in FIGs. 2A and 2B, respectively, depict exemplary weld nuggets in deconstructed form having satisfactory quality (e.g., meeting quality standards). In contrast, weld nugget 200C provided in FIG. 2C, illustrates a weld nugget in deconstructed form having unsatisfactory quality. Weld nuggets 200A and 200B may be created using the systems and methods according to the present disclosure, whereas deconstructed weld nugget 200C may be created using conventional systems and techniques.

[0039] Each of weld nuggets 200A, 200B, and 200C are depicted as including a base 222A, 222B, and 222C, respectively, and a body 224A, 224B, and 224C, respectively. Body 224A, 224B, and 224C may correspond to a raised portion of the deconstructed weld nugget 200A, 200B, and 200C that may extend above the base 222A, 222B, 222C after deconstruction. Bases 222A, 222B, and 222C may correspond to a cutaway section of one of the aluminum alloy products joined by the welding process. Specifically, bases 222A, 222B, and 222C may correspond to portions of the aluminum alloy product that are adjacent to portions that melted during the welding process and solidified as weld nuggets 200A, 200B, and 200C are cooled. Deconstructed weld nuggets 200A, 200B, and 200C may have reciprocal portions (not shown) on the opposite side of bodies 224A, 224B, and 224C corresponding to the other joining aluminum alloy product. For ease of illustration, the reciprocal portions for deconstructed weld nuggets 200A, 200B, and 200C are not shown. For example, in a process joining aluminum alloy products 106 and 108 together by creation of a weld nugget, base 222A may correspond to aluminum alloy product 106 and a reciprocal portion, opposite to base 222A, may correspond to aluminum alloy product 108. In embodiments, the surfaces of bases 222A, 222B, and 222C from which bodies 224A, 224B, and 224C, respectively, protrude may be flush with the surface of the aluminum alloy products.

[0040] FIGs. 2A and 2B may illustrate deconstructed weld nuggets 200A and 200B having satisfactory quality. The size and uniformity of a weld nugget may be used to determine the quality of a weld. Thus, to determine the quality of the weld, multiple measurements of the weld nugget may be taken. Measurements that may be used to assess weld quality may include first diameters (D1) 201A and 201B, second diameters (D2) 202A and 202B, and thicknesses (t) 203A and 203B, as illustrated in FIGs. 2A and 2B respectively. In some embodiments, first diameters 201A and 201B, and second diameters 202A and B may be taken 90 degrees from each other, respectively. In other embodiments, first diameters 201A and 201B and second diameters 202A and 202B may be taken from the shortest diameter point and longest diameter point of bodies 224A and 224B, respectively. Using first diameters 201A and 201B and second diameters 202A and 202B, a minimum average diameter of weld nuggets 200A and 200B, respectively, may be determined. Optionally, more than two diameters may be measured and/or used when determining the minimum average diameter. In embodiments, the minimum average diameter may take into account a ratio of first diameters 201A and 201B to second diameters 202A and 202B, respectively. As illustrated in FIGs. 2A and 2B, a ratio of first diameters 201A and 201B to second diameters 202A and 202B for both weld nuggets 200A and 200B, respectively, may be close to 1:1 or 1. In various embodiments, a desirable ratio between first diameters 201A and 201B and second diameters 202A and 202B, respectively, may be 1:1, 0.9:1, 0.8:1, 0.75:1, 0.6:1 or 0.5:1.

[0041] A size and quality of a weld nugget may be determined based on a minimum average diameter. The minimum average diameter may also be referred to herein as a diameter. The diameter may correspond to a minimum average diameter required to meet performance and quality standards (e.g., minimum sheer strength). The diameter used for a particular joint may be dependent on the material composition of the aluminum alloy products. For example, as illustrated in FIGs. 2A and 2B, the diameter (i.e., the minimum average diameter determined based on first diameters 201 and second diameters 202) may be larger for weld nugget 200A and smaller for weld nugget 200B. The diameter for weld nugget 200A may be suitable for particular aluminum alloys or combinations of alloys, for example, because the joined aluminum alloy products may be 1xxx series aluminum alloys which may require larger diameters to meet quality or strength standards. In contrast, the diameter for weld nugget 200B may be suitable for other aluminum alloys or combinations of alloys, because the joined aluminum alloy products may, for example, be 6xxx series aluminum alloys which require smaller diameters to meet quality or strength standards. The diameter used for a particular application may be determined based on the material composition of each of the aluminum alloy products being joined and the application of the resulting joined product.

[0042] In embodiments, weld nuggets 200A and 200B may be created between adjoining aluminum alloy products having the same material composition. For example, both weld nugget 200A and weld nugget 200B may be created between two 6xxx series aluminum alloy products. However, in this example, due to the specific application for the joined aluminum alloy products, weld nugget 200A may be required to be larger to meet stricter quality or joint strength standards. For example, the joined aluminum alloy products corresponding to FIG. 2A may require a sheer strength that is greater than the sheer strength required of the joined aluminum alloy products corresponding to FIG. 2B. As such, the welding process to generate weld nugget 200A may require a higher amount of energy applied to the aluminum alloy products than the welding process required to generate weld nugget 200B. As illustrated by a comparison between FIG. 2A and 2B, a larger amount of energy applied during a joining process may result in a larger weld nugget. In FIG. 2A, a larger amount of energy may be applied resulting in weld nugget 200A being larger. In FIG. 2B, a smaller amount of energy may be applied resulting in weld nugget 200B being smaller. In other words, by increasing the amount of energy applied during the joining process, an increase in the size of the weld nugget may be achieved. In embodiments, increasing the amount of energy applied may include increasing the current applied, increasing the voltage applied, and/or increasing the duration that a welding discharge is applied.

[0043] FIG. 2C illustrates weld nugget 200C in deconstructed form for an undesirable quality weld. As illustrated, weld nugget 200C may have first diameter (D1) 201C and second diameter 202C. Similar to first diameters 201A and 201B and second diameters (D2) 202A and 202B, first diameter 201C and second diameter 202C may be measured 90 degrees from each other. However, in some embodiments, first diameter 201C and second diameter 202C may be measured at the shortest diameter point and the longest diameter point of body 224C. Unlike weld nuggets 200A and 200B, the minimum average weld diameter determined for weld nugget 200C may be unsatisfactory, indicating that weld nugget 200C does not meet quality standards. In embodiments, the ratio of first diameter 201C to second diameter 202C may indicate an unsatisfactory weld quality. For example, the ratio of first diameter 201C to second diameter 202C may be 0.75:1, 0.6:1, 0.5:1, 0.4:1, or any ratio indicating a failure to meet quality standards. In embodiments, even if the ratio of first diameter 201C and second diameter 202C is similar to the ratios illustrated for weld nuggets 200A and 200B, weld nugget 200C may still fail to meet quality standards. For example, weld nugget 200C may still fail sheer strength tests or other quality tests.

[0044] In embodiments, the thickness (t) 203A, 203B, and 203C of weld nuggets 200A, 200B, and 200C may be used to determine weld quality. As noted above, bases 222A, 222B, and 222C may be flush with the surfaces of aluminum alloy products joined together. In such embodiments, thicknesses 203A, 203B, and 203C of weld nuggets 200A, 200B, and 200C may be the same as thickness of bodies 224A, 224B, and 224C, respectively, as illustrated.

Thicknesses 203A, 203B, and 203C may be used to assess weld quality by indicating the depth of the weld or extent of the weld into each of the aluminum alloy products. In embodiments, thickness 203A, 203B, and 203C may also indicate the extent that the adjoining aluminum alloy products are melted and solidified as single continuous material. If thicknesses 203A, 203B, or 203C are too small, this may indicate that only a surface portion of the aluminum alloy products melted during the welding processing to create the weld nugget. Such weld nuggets may be susceptible to shearing, plug fracturing, or other mechanical failures. In some embodiments, however, bases 222A, 222B, and 222C may be interior in the aluminum alloy products joined together, and thus the thicknesses 203A, 203B, and 203C of weld nuggets 200A, 200B, and 200C, respectively, may be less than the total thickness of the aluminum alloy products. If thicknesses 203A, 203B, or 203C are too small, this may indicate that an insufficient portion of the aluminum alloy products melted during the welding processing to create the weld nugget.

[0045] In some cases, rather than separating adjacent aluminum alloy products for destructive analysis of a weld nugget, the weld nugget may be sectioned to allow for a view (e.g., a cross-sectional view) of its internal structure. FIG. 2D provides an example image of a sectioned weld nugget, showing the internal structure where the aluminum alloy products melted and resolidified. Advantageously, cracks, inclusions, and other defects may be readily seen under a sectioned analysis and a total thickness of the weld nugget may be readily determined. Depending on the sectioning position and orientation, lateral dimensions may or may not represent a minimum or maximum diameter of the weld nugget.

[0046] Turning now to FIG. 3, an illustrative depiction of welding system 300 is shown. Welding system 300 may include welding hardware 330 and control system 340. In embodiments, welding system 300 may be a resistance spot welding system. Welding system 300 may be operable to join two or more aluminum alloy products, such as aluminum alloy products 106 and 108, together and create a weld nugget.

[0047] Welding hardware 330 may include force actuator 314, power source 310, and electrodes 302A and 302B. In embodiments, welding hardware 330 may be the same as welding machine 100. For example, force actuator 314 may be the same as force actuator 114, power source 310 may be the same as power source 110, and electrodes 302A and 302B may be the same as electrodes 102A and 102B. Electrodes 302A and 302B may include tips 304A and 304B. Similar to welding machine 100, welding hardware 330 may be operably configured to join two or more aluminum alloy products together, such as aluminum alloy products 306 and 308. Aluminum alloy products 306 and 308 may be the same as aluminum alloy products 106 and 108, or may be different products such as an aluminum alloy product and a non-aluminum alloy product such as steel. In embodiments, welding system 300 may be configured to join more than two aluminum alloy products or other metal products. For example, welding system 300 may be configured to join 3, 4, 5, or more aluminum alloy products together.

[0048] Power source 310 may be in electrical communication with electrodes 302A and 302B in order to supply electricity to electrodes 302A and 302B by communication line 312. With the supplied electricity, electrodes 302A and 302B may generate a welding discharge. In embodiments, the welding discharge may apply energy to aluminum alloy products 306 and 308. In embodiments, electrodes 302A and 302B may apply energy to aluminum alloy products 306 and 308 through electrode tips 304A and 304B. The applied amount of energy may create weld nugget 320 between aluminum alloy products 306 and 308. Power source 310 may include sensing components that allow for monitoring of a current and/or voltage applied during a welding discharge, such as for purposes of determining an applied power (e.g., in watts) or an applied energy of welding discharge (e.g., in joules or in watt-seconds).

[0049] Force actuator 314 may be in operable communication with electrodes 302A and 302B by communication line 316. For example, force actuator 314 may be mechanically coupled to electrodes 302A and 302B such to move electrodes 302A and 302B. In embodiments, electrodes 302A and 302B may be operable by force actuator 314 to hold and apply a force to aluminum alloy products 306 and 308.

[0050] In embodiments, welding system 300 may include control system 340. Control system 340 may access or include one or more databases or data stores that are stored locally as part of control system 340 or welding system 300, using one or more non-transitory processor-readable mediums, which can include memories, hard drives, or solid-state drives, or remote database or data stores, such as network accessible databases or data stores. For example, control system 340 may include memory 344. For example, memory 344 may include weld schedules, firmware, or other information used by control system 340 to control force actuator 314 and power source 310 in the application of force and/or a welding discharge by electrodes 302A and 302B.

[0051] Control system 340 may include various computerized components, such as one or more processors 342, communication buses, displays, input/output systems, or the like. The one or more processors 342 used as part of control system 340 may include one or more specific-purpose processors that have various functionality hardcoded as part of the one or more processors, such as an application-specific integrated circuit (ASIC). Additionally, or alternatively, one or more general-purpose processors may be used, as part of control system 340, that execute stored instructions that cause the general-purpose processors to perform specific-purpose functions. Therefore, software and/or firmware may be used to perform at least some of the functions of control system 340. Further details regarding the functioning of control system 340 is provided in relation to FIG. 8 and FIG. 9.

[0052] In embodiments, a welding control interface (not shown) may be present to facilitate communication between control system 340 and welding hardware 330. For example, a welding control interface may translate instructions or signals from control system 340 to power source 310 or force actuator 314. Feedback from welding hardware 330 (e.g., an amount of energy, current, voltage, time, and/or force applied to aluminum alloy products 306 and 308) may be provided to the welding control interface for use by control system 340. In some embodiments, the welding interface may further be used to receive user input, which may, for example, specify target properties for a spot weld (e.g., diameter, thickness), identification of an alloy specification (e.g., AA designation), and/or intended application of the joined product.

[0053] Control system 340 may be in communication with welding hardware 330 by one or more communication lines 348. In embodiments, control system 340 may be in operable communication with force actuator 314 and/or power source 310 directly via communication lines 348. Communication lines 348 may correspond to data or signal lines between control system 340 and force actuator 314 and/or between control system 340 and power source 310. For example, control system 340 may transmit signals, via communication lines 348, that are received by force actuator 314 and cause force actuator 314 to apply pressure, stop application of pressure, or modulate application of pressure to aluminum alloy products 306 and 308 via electrodes 302A and 302B. For example, control system 340 may send a force signal to force actuator 314 to perform one or more force operations (e.g., direct electrodes 302A and 302B to apply pressure to aluminum alloy products 306 and 308).

[0054] In another example, control system 340 may send a control signal to power source 310 to supply electrodes 302A and 302B with electricity. For example, control system 340 may transmit signals, via communication lines 348, that are received by power source 310 and cause power source 310 to initiate, continue, stop, or modulate a welding discharge to aluminum alloy products 306 and 308 via electrodes 302A and 302B. In some cases, communication lines 348 may transmit signals from power source 310 to control system 340, which may correspond to or be representative of a current applied as part of a welding discharge, a voltage applied as part of a welding discharge, and/or a resistance between electrodes 302A and 302B, such as may be determined using one or more sensing components. In turn, control system 340 may modulate a control signal transmitted to power source 310 to control or modulate a welding discharge based on information contained in the signals representing the sensed current or voltage or resistance.

[0055] Control system 340 may control an instantaneous power supplied by power source 310, and thereby control the amount of energy applied by electrodes 302A and 302B to aluminum alloy products 306 and 308 over time. For example, control system 340 may control an amount of current or voltage applied by electrodes 302A and 302B by controlling an output of the power source 310 to electrodes 302A and 302B. Electric current may be supplied to electrodes 302A and 302B via communication line 312 to generate a welding discharge applied to aluminum alloy products 306 and 308. To ensure that a quality weld is created, control system 340 may control the amount of energy applied to generate weld nugget 320 with a target diameter, such as may be specified according to a particular welding schedule, according to user input, or according to application specifications. In exemplary embodiments, control system 340 may control the current applied by electrodes 302A and 302B. Alternatively or additionally, control system 340 may control the voltage applied by electrodes 302A and 302B. Alternatively or additionally, control system 340 may control the duration of time that the energy is applied by electrodes 302A and 302B. -

[0056] In embodiments, control system 340 may also or alternatively determine a size of weld nugget 320 by determining the amount of energy applied to aluminum alloy products 306 and 308. In this manner, control system 340 may manage the amount of energy applied and/or determine a size of weld nugget 320 during the joining process by monitoring and/or controlling an amount of energy applied.

[0057] In embodiments, welding system 300 may be communicatively coupled with one or more external sources. For example, a network interface may also be present as part of control system 340 to facilitate communication between control system 340 and various sources. For example, a network interface may be configured to wirelessly communicate with a cellular network or other wireless network, such as a wireless local area network (WLAN). Using a wireless network, control system 340 may communicate with a cloud-based server system or other type of external server systems. Presence of a network interface may be useful for updating firmware, weld schedules, and/or materials property information, for example, stored in memory 344.

[0058] Turning now to FIGs. 4-7, exemplary graphs of dynamic operating conditions during a process of joining two or more aluminum alloy products are provided. Starting with FIG. 4, graph 400 illustrates an amount of current applied by a welding system during a joining process according to an embodiment as disclosed herein. Graph 400 depicts current curve 410, representing an amount of current applied by a welding system during a joining process. For example, current curve 410 may depict an amount of current applied by welding system 300, specifically welding hardware 330, to aluminum alloy products 306 and 308 to create weld nugget 320. In embodiments, current curve 410 may depict the amount of current applied by welding machine 100 to aluminum alloy products 106 and 108 to create weld nugget 120.

[0059] To create current curve 410, a welding process may be performed using a welding system and the amount of applied current monitored as a function of time. For ease of explanation, welding system 300 is used for exemplary purposes. Current curve 410 may illustrate a current applied by electrodes 302A and 302B to aluminum alloy products 306 and 308. Power source 310 may supply electrodes 302A and 302B with electricity from which electrodes 302A and 302B apply the current. In embodiments, power source 310 may supply a mid-frequency or medium frequency direct current (MFDC). In such embodiments, alternating current (AC) power may be supplied to welding system 300 and then converted into an inverted higher frequency power direct current (DC) output or a DC current may be supplied directly to welding system 300, such as by power source 310. MFDC may be preferential for welding because of the constant supply of power available, which can reduce power fluctuations during the joining process.

[0060] At the beginning of a joining process, the current applied may exponentially or otherwise increase starting from time zero. As shown, an operating amount of current applied may be approximately 35 kiloamperes (kA). In embodiments, the operating amount of current applied may range from 5 to 10 kA, 10 to 20 kA, 20 to 30 kA, 30 to 40 kA, 40 to 50 kA, 50 to 65 kA, or above 65 kA. The operating amount of current applied may correspond to a current applied by the welding system to the aluminum alloy products to join them together or may correspond to a maximum current applied during the welding process. In embodiments, a control system, such as control system 340, may determine an amount of energy (e.g., in joules (J) or watt-hours (W-h) or watt-seconds (W-s)) applied or to be applied to the aluminum alloy products to create a weld nugget having a desired size and quality. In embodiments, an amount of energy to be applied by the welding system may be determined based on the material composition of each of the aluminum alloy products being joined and/or a desired size and quality of the weld nugget. For example, if two 6xxx series aluminum alloy products are being joined together, the control system may determine a target weld nugget characteristic. The target weld nugget characteristic may specify the size and quality of weld nugget required to adequately join the two 6xxx series aluminum alloy products together. In embodiments, size and quality of a target weld nugget may be determined separate from the material composition of the aluminum alloy products. For example, the size and quality of the target weld nugget may be determined based on the application of the resulting joined aluminum alloy products.

[0061] Once a target weld nugget characteristic is identified, an amount of energy to be applied based on the material composition and/or application of the aluminum alloy products being joined and the target weld nugget may be determined, for example. In embodiments, the welding system may determine an amount of energy to be applied to the aluminum alloy products. Then the welding system may apply the welding discharge, such as while monitoring the amount of energy, current, and/or voltage applied to the aluminum alloy products, to create a weld nugget meeting the target weld nugget criteria. When the appropriate amount of energy is applied, the welding discharge may be terminated, for example.

[0062] As illustrated in FIG. 4, after current curve 410 reaches an operating amount of current, here 35 kA, the welding system may maintain the current for the duration of the joining process. In embodiments, the duration of time that the current (or voltage or energy) is applied may range from 1 milliseconds (ms) to 1 second, such as from 1 ms to 50 ms, from 50 ms to 100 ms, from 100 ms to 150 ms, from 150 ms to 200 ms, from 200 ms to 300 ms, from 300 ms to 500 ms, or from 500 ms to 1 second, etc. In various embodiments, the welding system may fluctuate or modulate the amount of current applied. For example, if three aluminum alloy products are to be joined together, the welding system may determine that a higher amount of current is required at the beginning of the joining process based on the material composition of the two exterior products. In some cases, the operating voltage may be maintained at a constant level or at an approximately constant level (e.g., within 5% or 10% of a target level). To maintain a constant level, an applied voltage may be varied during the welding discharge, such as in response to a changing resistance between the electrodes as the discharge occurs.

[0063] FIG. 5 illustrates voltage graph 500 depicting a voltage that may be applied by a welding system during a joining process according to an embodiment as disclosed herein. Graph 500 depicts voltage curve 510 representing a voltage applied by a welding system. For example, voltage curve 510 may depict a voltage applied by welding system 300, specifically welding hardware 330, to aluminum alloy products 306 and 308. In embodiments, voltage curve 510 may depict the voltage applied by welding machine 100 to aluminum alloy products 106 and 108.

[0064] As shown, at the beginning of a welding process, the voltage applied may be low, but quickly increase (e.g., exponentially) to an operating voltage. For example, as illustrated in graph 500, an operating voltage applied may be 24 volts (V) and the welding system may reach the operating voltage within 20-40 milliseconds after the joining process begins. In embodiments, the operating voltage applied may range from 1 to 10 V, 10 to 20 V, 20 to 30 V, 30 to 40 V, 40 to 50 V, or above 50 V. Voltage curve 510 may correspond to the voltage applied by the welding system to aluminum alloy products during a welding discharge to join the aluminum alloy products together. Voltage curve 510 may be generated by monitoring the voltage applied by a power source, for example. The voltage applied for a welding discharge may in some embodiments, in part, be determined based on the material composition and/application of each of the aluminum alloy products being joined and the size and quality of a target weld nugget.

[0065] In embodiments, a direct current voltage may be used for the joining process. In such embodiments, the welding system may adapt the voltage supplied to keep the applied current constant. Depending on the evolution of the dynamic resistance of the stacks generated by the welding discharge, the voltage may fluctuate. Application of a constant current may increase the quality of the weld nugget, reduce overall welding time, and reduce overall energy consumption by the welding system. Accordingly, maintaining the current applied at a constant, or within a threshold range, may be desirable. To achieve a constant current, the welding system may continuously change the amount of voltage applied, as illustrated by feature 512 in FIG. 5. Voltage curve 510 illustrates an example dynamic adaptation of the voltage being applied by the welding system to the aluminum alloy products with feature 512.

[0066] During the joining process, the aluminum alloy products may exhibit a variable resistance to the flow of current across them, which may depend on their composition and temperature, quality of electrical contact between aluminum alloy products and/or between the aluminum alloy products and the electrodes or tips, the pressure or force applied by the electrodes or tips, or the like. In embodiments, where the joining process includes a resistance spot welding operation, the resistance to the flow of the welding discharge between the aluminum alloy products may generate heat, ultimately resulting in generation of the weld nugget. FIG. 6 illustrates an exemplary resistance graph 600. Resistance graph 600 illustrates a resistance between electrodes in a welding system during a joining process according to an embodiment as disclosed herein. For example, resistance curve 610 may depict a resistance between electrodes 302A and 302B in welding system 300 during a welding discharge. As shown, at the beginning of a welding process, the amount of resistance during the welding discharge may be high, but quickly decrease to an operating resistance or minimum resistance, which may be achieved once the aluminum alloy products 306 and 308 are physically joined by a small weld nugget, representing electrical and mechanical continuity between the aluminum alloy products 306 and 308. When the joining process initiates, the aluminum alloy products may be in a solid state. As the welding discharge is applied by the welding system, the resistance of the aluminum alloy products to the flow of the welding discharge (e.g., current) may generate heat, which may at least partially melt portions of the aluminum alloy products, which may then cool and become a weld nugget joining the aluminum alloy products. Since resistance may be inversely proportional to voltage and directly proportional to current, changes in resistance may change or impact the voltage and/or current applied, or vice versa. In embodiments, the welding system, specifically the control system or the power source, may adapt the voltage to maintain the current being applied at a constant rate as the resistance of the aluminum alloy products changes.

[0067] An exemplary steady state resistance during a joining process may be 0.075 milliohms (mΩ). In various embodiments, the resistance during a welding discharge may range from 0.01 mΩ to 0.05 mΩ, 0.05 mΩ to 0.075 mΩ, 0.075 mΩ to 0.1 mΩ, 0.1 mΩ to 0.2 mΩ, 0.2 mΩ to 0.5 mΩ, or 0.5 mΩ and above. Since resistance, current, and voltage may all be related to one another under Ohm's law, the resistance during the welding discharge may be related to an amount of energy applied by the welding system. That is, once the welding system determines the amount of energy that should be applied to create a weld nugget with target characteristics (e.g., based on the material composition of the aluminum alloy products being joined, etc.), the welding system may determine the amount of current, a voltage, and/or a discharge duration to be applied based on the resistance, which may be modified as the resistance changes dynamically.

[0068] FIG. 7 illustrates an exemplary power graph 700. Graph 700 may depict a power of a welding discharge during a joining process according to an embodiment as disclosed herein. Graph 700 includes power curve 710. Power curve 710 may depict an amount of power applied by a welding system during a joining process. For example, power curve 710 may depict an amount of power applied by welding system 300, specifically welding hardware 330, to aluminum alloy products 306 and 308 to create weld nugget 320. In embodiments, power curve 710 may depict the amount of power applied by welding machine 100 to aluminum alloy products 106 and 108 to create weld nugget 120. The energy applied may be determined by multiplying the applied power by the application time, for example. The energy applied may correspond to a cumulative amount of energy applied during a joining process, and may be represented by area or energy 715, corresponding to the area under power curve 710 on graph 700. The energy may be used by the welding system to determine whether the weld nugget meets the target weld nugget size and quality, when to terminate a welding discharge, and/or the size or quality of a weld nugget.

[0069] In embodiments, the welding system may be able to trace the development of the size of the weld nugget as it is being created based on power curve 710 and/or the energy 715 from time 0 to a duration of the joining process. For example, if the joining process operates for 100 ms, then the welding system may determine the size of the weld nugget as currently developed from time 0 to 100 ms by taking the area under power curve 710 from 0 to 100 ms and determining the energy 715 for that portion of the joining process. In embodiments, the amount of power applied may be directly proportional or correlated to the size of the weld nugget. For example, a lower amount of power applied may correspond to a smaller weld nugget size. Conversely, a higher amount of power applied may correspond to a larger weld nugget size. As the welding system increases the amount of energy applied to the aluminum alloy products, the larger the size of the weld nugget may become.

[0070] As illustrated, an exemplary amount of power applied during a joining process may be from 0 kilowatt to about 1000 kilowatts (W), or more. An amount of power applied during a joining process may be determined based on one or more or two or more of an amount of current applied, an applied voltage, and a resistance between the electrodes. In various embodiments, the amount of power applied during a welding discharge may range from 0 kW to 10 kW, from 10 kW to 25 kW, from 25 kW to 50 kW, from 50 kW to 100 kW, from 100 kW to 250 kW, from 250 kW to 500 kW, from 500 kW to 1000 kW, or greater than 1000 kW.

[0071] As noted above, an amount of energy applied, indicated by energy 715, may be determined by taking the area under power curve 710. In other words, energy 715 may include a cumulative amount of power applied over the total amount of time that the welding discharge is applied. As illustrated by FIG. 7, an exemplary amount of energy applied during a joining process may be approximately 1.90 kW-s or 0.53 W-h. In various embodiments, the amount of energy applied during a welding discharge may range from 0.01 W-h to 10 W-h, such as from 0.01 W-h to 0.05 W-h, from 0.05 W-h to 0.1 W-h, from 0.1 W-h to 0.25 W-h, from 0.25 W-h to 0.50 W-h, from 0.50 W-h to 1.0 W-h, from 1.0 W-h to 2.5 W-h, from 2.5 W-h to 5 W-h, from 5 W-h to 10 W-h, or greater.

[0072] FIG. 8 provides an overview of a method 800 for joining two or more aluminum alloy products according to embodiments disclosed herein. In embodiments, method 800 may correspond to a joining process carried out by a welding system, such as welding system 300. For example, a control system may be employed, such as control system 340 that includes a processor that is configured to carry out aspects of method 800 during a joining process according to machine or processor executable instructions. At block 810, two or more aluminum alloy products are positioned between a pair of electrodes. For example, with reference to FIG. 3, aluminum alloy products 306 and 308 may be positioned between electrodes 302A and 302B.

In some embodiments, electrode tips 304A and 304B may be contacting one or more surfaces of aluminum alloy products 306 and 308.

[0073] At block 820, method 800 includes applying a force to the aluminum alloy products. The force may be applied by electrodes 302A and 302B, in particular electrode tips 304A and 304B. The force may be generated by a pneumatic, electrical, or mechanical actuator, such as force actuator 314, causing electrodes 302A and 302B to squeeze or clamp towards each other, compressing the aluminum alloy products positioned between the pair of electrodes. In some embodiments, applying the force may occur before a welding discharge is generated between the pair of electrodes. In other embodiments, applying the force may occur during generation of a welding discharge. Optionally, applying the force may occur after a welding discharge is generated. For example, the force may be applied after portions of the aluminum alloy products have already melted due to the welding discharge. In some cases, the force may be applied to the aluminum alloy products after the welding discharge ceases and the force may be removed after the weld nugget reaches a solidification temperature. Optionally, the force applied may vary as a function of time and, in particular, may vary before, during, and/or after the welding discharge.

[0074] At block 830, a welding discharge may be generated to create a weld nugget. The welding discharge may be generated between the pair of electrodes. For example, the welding discharge may be generated between electrodes 302A and 302B, in particular between electrode tips 304A and 304B. The welding discharge may be generated by flowing a current between the electrodes through the aluminum alloy products. Due to the heat generated by resistance of the aluminum alloy products to the flow of current, portions of the aluminum alloy products proximal to or between the electrode tips may begin to melt and, upon cooling, create a weld nugget.

[0075] Generating a welding discharge to create a weld nugget at block 830 may include applying a current over a duration of time at block 832. Applying a current over a duration of time may include a power source supplying a current to the pair of electrodes. The pair of electrodes, in particular the electrode tips, may apply the current to the aluminum alloy products. In some embodiments, the current applied to the aluminum alloy products may be maintained constant or applied at a constant level during at least a portion of the welding discharge. To maintain a constant current, a voltage may be adapted. In various embodiments, block 832 may include applying a voltage over a duration of time. As shown in FIG. 4, an applied current may vary from an initial low value to an operating or approximately constant value.

[0076] As the welding discharge is applied to the aluminum alloy products, an amount of energy applied may be determined at block 840. In embodiments, a welding system, such as welding system 300, may determine the amount of energy applied. The amount of energy applied may be determined based on the duration of time that the welding discharge is applied, such as by monitoring an applied current, an applied voltage, and/or a resistive load between the electrodes. For example, if the welding discharge is applied for 100 ms, then the amount of energy applied may be a cumulative amount of the power applied for the 100 ms of the joining process. The power applied may be determined, for example, by monitoring the current applied during the 100 ms, by monitoring the voltage applied during the 100 ms, and/or by monitoring the resistance between the electrodes during the 100 ms. In embodiments, a welding system may determine an amount of energy applied continuously or at specified time increments. For example, the welding system may determine the amount of energy applied every 10 ms. In this manner, the welding system may monitor and/or control the creation of the weld nugget in real-time during a live joining process.

[0077] In some embodiments, when the amount of energy applied during a welding discharge reaches a threshold or target energy level, then the welding discharge may be ceased. At block 842, the material composition of each of the aluminum alloy products being joined may optionally be determined. In one example, the determination may be according to received user input. Optionally, a target weld nugget quality (e.g., size) may be determined, such as according to received user input. Based in part on the material composition of the aluminum alloy products, at block 844 a threshold energy level may be determined. For example, at block 842, welding system 300 may determine or receive input indicating that aluminum alloy products 306 and 308 are both 6xxx series aluminum alloy products. At block 844, the welding system 300 may determine that because both aluminum alloy products 306 and 308 are 6xxx series aluminum alloy products, a certain amount of energy is required to create a target weld nugget. A target weld nugget may be a weld nugget meeting quality standards. For example, a target weld nugget may be a weld nugget that has a particular diameter, a weld nugget that is not prone to plug failure or pull-out failure, a weld nugget that has sufficient shear strength, and/or meets other weld standards required of the desired application. In one example, the welding system may query a database, lookup table, or one or more weld schedules to determine a target or threshold energy amount useful for generating a weld nugget of a certain size for the combination of aluminum alloys used. Once the amount of energy to create the target weld nugget is determined, then the threshold energy level may be set. The threshold energy level may be the same as the amount of energy required to create the target weld nugget. In various embodiments, the threshold energy level may be slightly more or slightly less than the amount of energy required to create the target weld nugget. For example, it may be determined that by exceeding the amount of energy required to create the target weld nugget by 10 percent, the created weld nugget exceeds quality standards or is useable in a variety of applications.

[0078] At block 850, the welding discharge may be controlled based on the determined threshold energy level. For example, the welding discharge may be throttled down (e.g., stopped over a relatively short amount of time) as the accumulative energy applied approaches the threshold energy level. That is, the voltage or current applied to the aluminum alloy products during the welding discharge may be reduced as the accumulative energy applied reaches within 10 percent of the threshold energy level. In other embodiments, controlling the welding discharge may include immediately terminating the welding discharge, as indicated at block 852. At block 852, the welding system may determine that the amount of energy applied to the aluminum alloy products equals the threshold energy level determined at block 844. Once the welding system determines that the amount of energy applied equals the threshold energy level, the welding system may stop applying the welding discharge. This may mean that the electricity supplied to the pair of electrodes from the power source is stopped. In various embodiments, a relay may trip to impede the flow of electricity from the pair of electrodes to the aluminum alloy products. In some embodiments, the welding discharge may be stopped once the amount of energy applied exceeds the threshold energy level. In some cases, a control system may transmit a control signal to a power source to stop the flow of electricity to the electrodes.

[0079] Turning now to FIG. 9, an overview of a method 900 for non-destructively determining a size of a weld nugget according to an embodiment is provided. In embodiments, method 900 may correspond to a joining process carried out by welding system 300. For example, control system 340 may include a computer program product that is configured to carry out method 900 during a joining process. At block 910, a welding discharge may be applied to two or more aluminum alloy products. For example, a welding discharge may be applied to aluminum alloy products 306 and 308 by electrodes 302A and 302B, in particular electrode tips 304A and 304B. At block 912, applying a welding discharge may include applying a current to the aluminum alloy products over a duration of time. In some embodiments, applying a welding discharge may include applying a voltage to the aluminum alloy products over a duration of time. In some cases, the current may be maintained at a constant rate. In such cases, the voltage may be adapted to maintain the current at a constant rate. In other embodiments, applying the welding discharge may include applying a power to the aluminum alloy products over a duration of time. In such embodiments, a cumulative amount of energy may be applied to the aluminum alloy products.

[0080] At block 920, an amount of energy applied may be determined. For example, welding system 300 may determine an amount of energy applied by electrodes 302A and 302B to aluminum alloy products 306 and 308. An amount of energy applied may be determined based on an amount of power supplied by the pair of electrodes to the aluminum alloy products over the duration of the joining process. Optionally, the amount of power supplied by the electrodes may be determined by monitoring one or more of an applied current, an applied voltage, or a resistance between the electrodes. Optionally, the power may be computed by taking the product of the current and the voltage. Optionally, the power may be computed by taking the product of the square of the current and the resistance. Optionally, the power may be computed by taking the square of the voltage and dividing by the resistance.

[0081] At block 930, a size of the weld nugget created during the joining process may be determined. The size of the weld nugget may be determined using the amount of energy applied. The amount of energy applied may directly correlate to the size of the weld nugget. For example, an increase in the amount of energy applied may result in an increase in size of the weld nugget. At block 932, the material composition of each of the aluminum alloy products being joined may be determined. For example, welding system 300 may determine the material composition of each of aluminum alloy products 306 and 308, such as by receiving input indicating a composition of the aluminum alloy products. Exemplary material compositions of aluminum alloy products may include 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys. The size of the weld nugget may optionally be dependent on the material composition of the aluminum alloy products. In some cases, an analytical formula may be applied to the power or energy supplied to determine the weld nugget size. Optionally, a table, database, or weld schedule indicating empirically determined weld nugget sizes for applied energy amounts for a particular set of aluminum alloys may be queried to determine the size of the weld nugget. In the case where an applied amount of energy is not directly available in such a table, database, or weld schedule, the sizes of the nearest applied energy values may be used to interpolate an expected size for the applied energy amount. The method 900 exemplified by blocks 910, 920, and 930 and optionally blocks 912 and 932 may be useful for determining a size of a weld nugget in the absence of a control system that may be used to further control the application of a welding discharge. For example, if simply generating a spot weld according to a weld schedule, the present methods may be useful for determining whether the weld nugget meets size specifications by monitoring or measuring the applied current, voltage, and/or resistance between the electrodes during the welding discharge.

[0082] If a control system is available, the welding may be subjected to more control. In some embodiments, at block 940, a threshold energy level may be determined. The threshold energy level may be determined based, at least in part, on the material composition of the aluminum alloy products being joined. In various embodiments, the threshold energy level may be based, alternatively or additionally, on the application of the resulting joined aluminum alloy product. For example, if the joined aluminum alloy products are to be used in the aerospace or automotive industry, a higher threshold energy level may be used than if the joined aluminum alloy products are to be used in the household product industry. In some cases, the application of the joined aluminum alloy products may implicate a target size and quality of the weld nugget. Because the size and quality of the weld nugget may directly correlate to the amount of energy applied to the aluminum alloy products, the determination of the amount of energy to apply may require a determination of a target size and quality of the weld nugget. If the determined size of the weld nugget is smaller than desired, the welding discharge may be permitted to continue for additional time.

[0083] Determining the threshold energy level at block 940 may include determining a target diameter of the weld nugget, at block 942. As discussed with respect to FIGs. 2A to 2C, a diameter of the weld nugget may be an average between two or more diameter measurements. In some cases, the diameter measurements may be taken at the two largest diameter points of the weld nugget. The target diameter may indicate the diameter of a desired weld nugget suitable for a particular application. The target diameter may be received as user input. The target diameter may be retrieved from a database or lookup table based on a particular application and/or compositions or dimensions of the aluminum alloy products to be joined. In some cases, the target diameter may also indicate the quality of a weld nugget. Once a target diameter of a weld nugget is determined, the amount of energy to apply to the aluminum alloy products to create a weld nugget having the target diameter may be determined, such as according to a weld schedule, database, or lookup table identifying the amount of energy as a function of weld nugget size. Optionally, the target diameter may be determined by receiving input indicating the target diameter.

[0084] At block 950, the welding discharge may be controlled. In embodiments, the welding discharge may be controlled using the determined amount of energy applied. In particular, the welding discharge may be controlled using the determined target diameter. That is, the welding discharge may be controlled to create a weld nugget between the aluminum alloy products having the target diameter. In embodiments, the power source may be manipulated such to control the welding discharge. Controlling the welding discharge may include throttling a current or voltage of the supplied electricity to the pair of electrodes from the power source. In embodiments, controlling the welding discharge may include throttling an amount of power applied by the pair of electrodes to the aluminum alloy products.

[0085] In various embodiments, controlling the welding discharge may include stopping the welding discharge. At block 952, the welding discharge may be stopped based on a determined amount of energy applied. For example, welding system 300 may determine that a cumulative amount of energy applied to the aluminum alloy products has reached a threshold energy level. Once welding system 300 determines that the amount of energy applied to the aluminum alloy products equals or exceeds a threshold energy level, welding system 300 may stop the welding discharge. Stopping the welding discharge at block 952 may include stopping a current, voltage, or power application to the aluminum alloy products.

Methods of Using the Disclosed Aluminum Alloy Products

[0086] The aluminum alloy products described herein, including joined aluminum alloy products, can be used in automotive applications and other transportation applications, including aircraft and railway applications, or any other desired application. For example, the disclosed aluminum alloy products can be used to prepare automotive structural parts, such as bumpers, side beams, roof beams, cross beams, pillar reinforcements (e.g., A-pillars, B-pillars, and C-pillars), inner panels, outer panels, side panels, inner hoods, outer hoods, or trunk lid panels. The aluminum alloy products and methods described herein can also be used in aircraft or railway vehicle applications, to prepare, for example, external and internal panels.

[0087] The aluminum alloy products and methods described herein can also be used in electronics applications. For example, the aluminum alloy products and methods described herein can be used to prepare housings for electronic devices, including mobile phones and tablet computers. In some examples, the aluminum alloy products can be used to prepare housings for the outer casing of mobile phones (e.g., smart phones), tablet bottom chassis, and other portable electronics.

EXAMPLES

[0088] As discussed above, in embodiments, the amount of energy applied may correlate to the size and quality of the weld nugget created during the joining process. FIGs. 10 and 11 provide exemplary data showing energy applied and weld nugget diameter, as determined through destructive analysis. To generate the data for FIG. 10, two AA6111 sheets were spot welded together at multiple points, with each successive spot weld being applied using more energy. To generate the data for FIG. 11, two AA8999 sheets were spot welded together at multiple points, with each successive spot weld being applied using more energy. Following completion of all spot welds, the joined sheets were sectioned and each spot weld was analyzed to determine a weld nugget diameter. The data in FIGs. 10 and 11 show that for lower total amounts of energy applied, smaller weld nugget diameters were achieved, while for greater total amounts of energy applied, larger weld nugget diameters were achieved.

[0089] FIGs. 12 and 13 provide additional data showing energy applied and weld nugget diameter, as determined through destructive analysis. To generate the data for FIG. 12, two AA5182 sheets were spot welded together at multiple points, with each successive spot weld being applied using a different amount of energy. To generate the data for FIG. 13, two AA6170 sheets were spot welded together at multiple points, with each successive spot weld being applied using a different amount of energy. Following completion of all spot welds, the joined sheets were sectioned and each spot weld was analyzed to determine a weld nugget diameter.

The data in FIGs. 12 and 13 show that increases or decreases of total amounts of energy from spot weld to spot weld generally track with the increases or decreases of weld nugget diameters, at least up to a point.

[0090] The data on FIGs. 12 and 13 also show that the tip of the electrode may erode or degrade after extended use. After repetitive uses the total amount of energy applied may, in some cases, diverge from the weld nugget diameter. In some cases, the weld nugget diameter may exhibit a linear relationship with respect to the amount of energy applied when the tip of the electrode is in an acceptable condition and the relationship may change when the electrode is in a degraded or unacceptable condition. With respect to FIGs. 12 and 13, the portion of the plots highlighted in green may correspond to the tip being in an acceptable condition and the portion of the plot highlighted in red may correspond to the tip being in a degraded or unacceptable condition. The scattering or divergence of the total amount of energy applied indicates that the electrode may be eroding or degrading and weld quality suffering, indicating that the tip needs replacing. In some cases, analysis of one both of the number of spot welds and the total cumulative energy delivered by the tip may be used to identify when an electrode tip needs to be replaced, redressed, or reconditioned in order to provide spot welds of an acceptable or suitable condition. In some cases, methods or systems described herein may determine a total number of spot welds generated by the tip since being in a new, redressed, or reconditioned state and the total cumulative energy delivered by the tip since being in a new, redressed, or reconditioned state and, using the total number of spot welds and/or the total cumulative energy delivered by the tip, determine that the tip may need to be replaced, redressed, or reconditioned or could benefit from replacement, redressing, or reconditioning. Optionally, a notification may be delivered or generated indicating that tip replacement, redressing, or reconditioning may be desirable, needed, or useful. In some cases, determining that the tip needs to be replaced, redressed, or reconditioned or could benefit from replacement, redressing, or reconditioning may include comparing one or more reference or threshold values to the total number of spot welds generated by the tip since being in a new, redressed, or reconditioned state, the total cumulative energy delivered by the tip since being in a new, redressed, or reconditioned state, or a value derived from the total number of spot welds generated by the tip since being in a new, redressed, or reconditioned state and the total cumulative energy delivered by the tip since being in a new, redressed, or reconditioned state. For example, the value derived may correspond to a weighting factor applied to the energy delivered, with the weighting factor based on the sequence number of the spot weld.

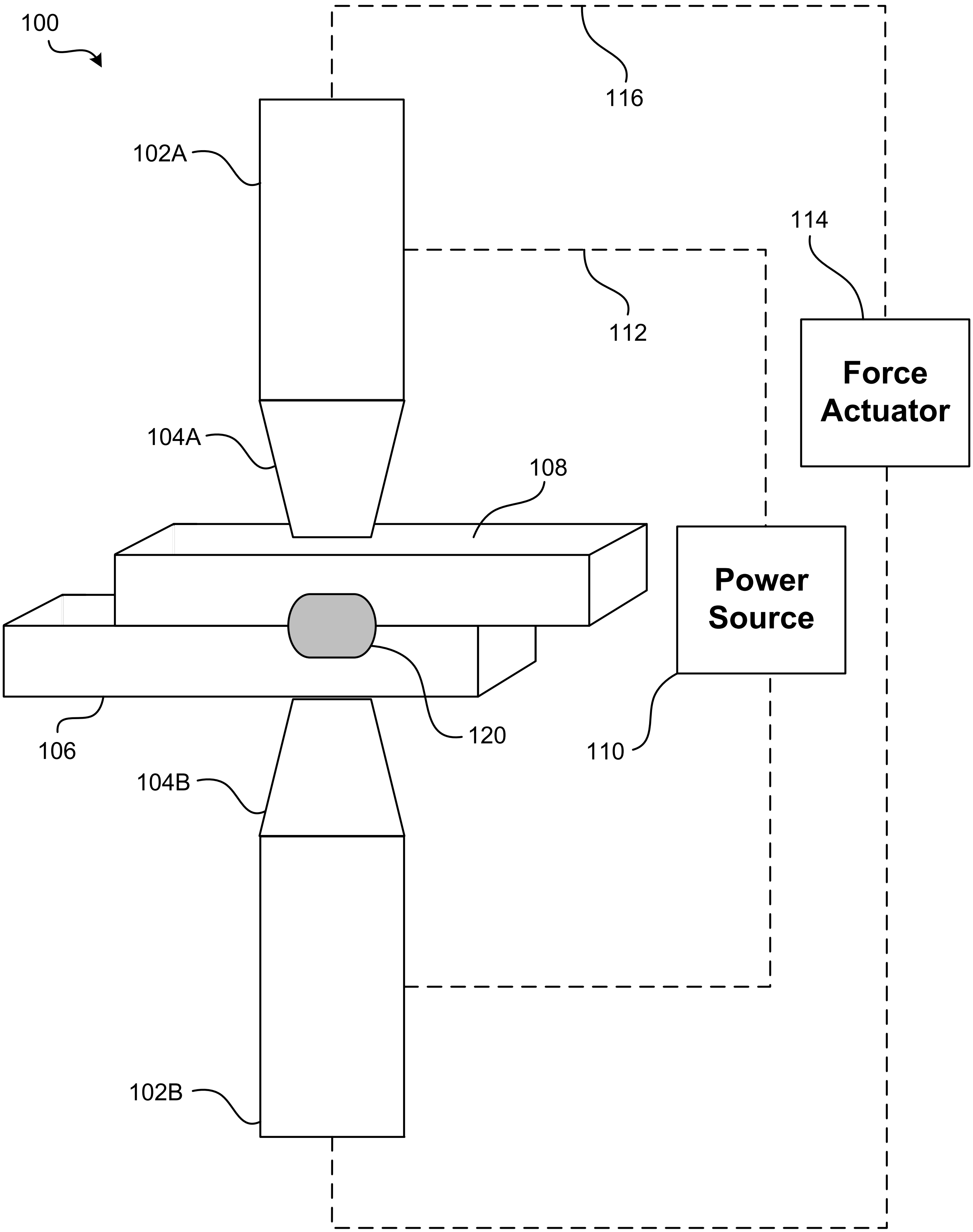
100
116
102A
114
112
Force
Actuator
104A
108
Power
Source
120
106
110
104B
102B

FIG. 1

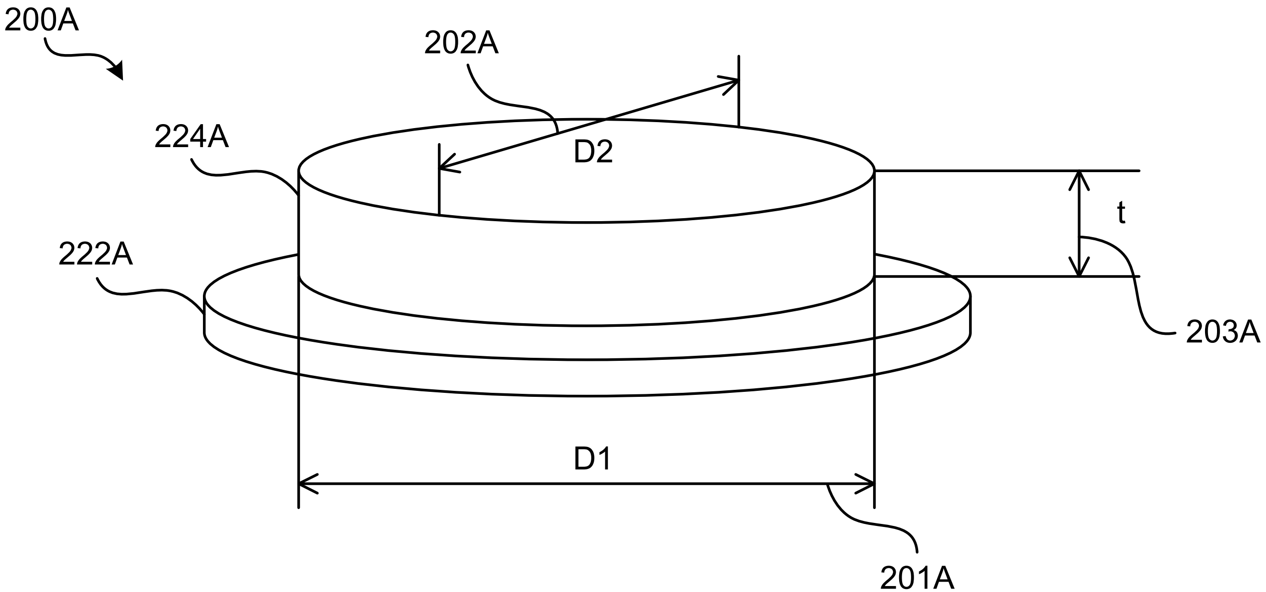
200A
202A
224A
D2
t
222A
203A
D1
201A

FIG. 2A

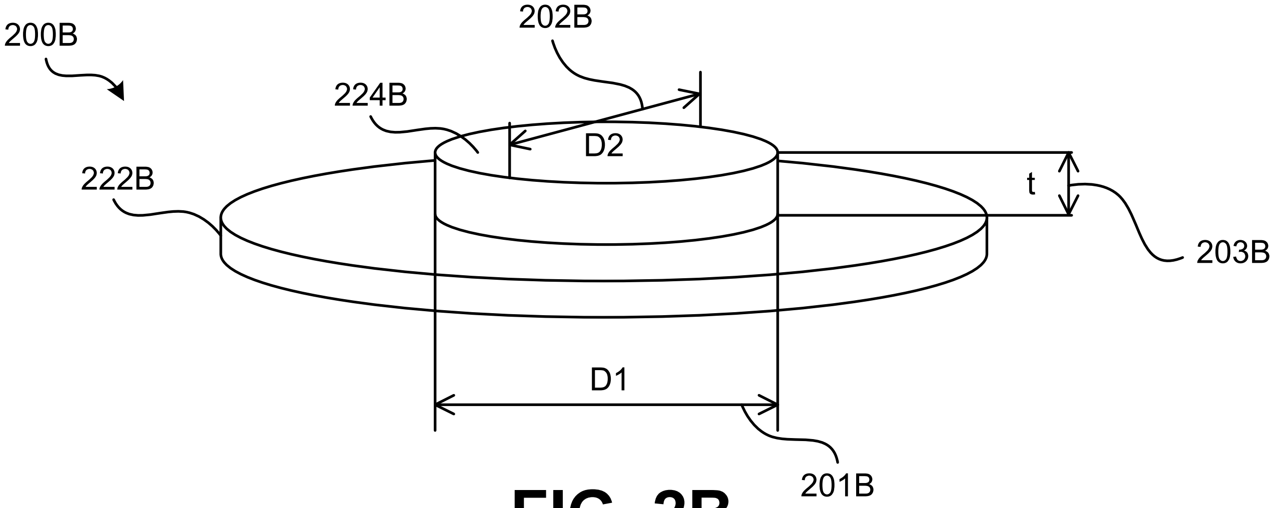
200B
202B
224B
D2
222B
t
203B
D1
201B

FIG. 2B

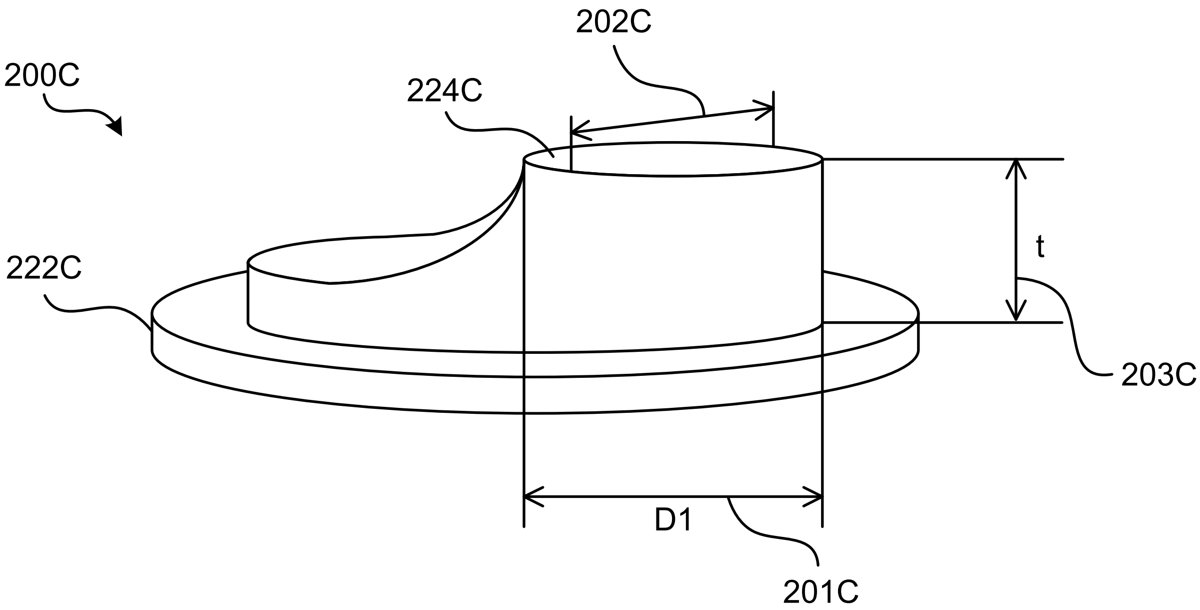

FIG. 2C

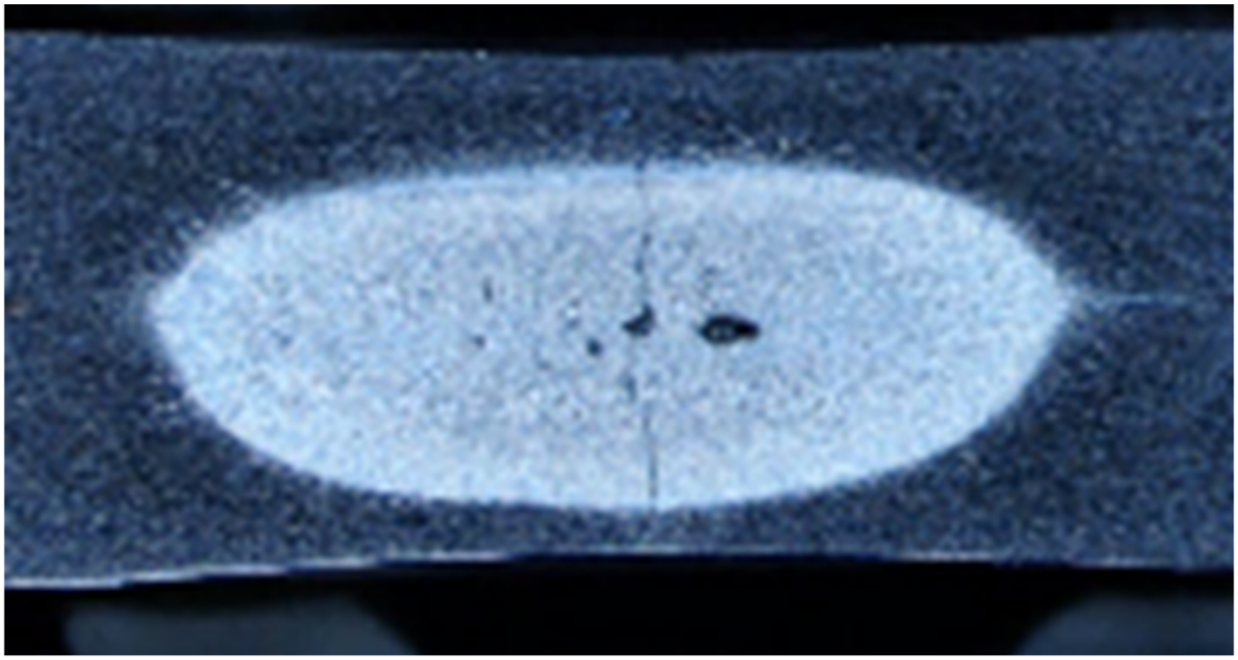

FIG. 2D

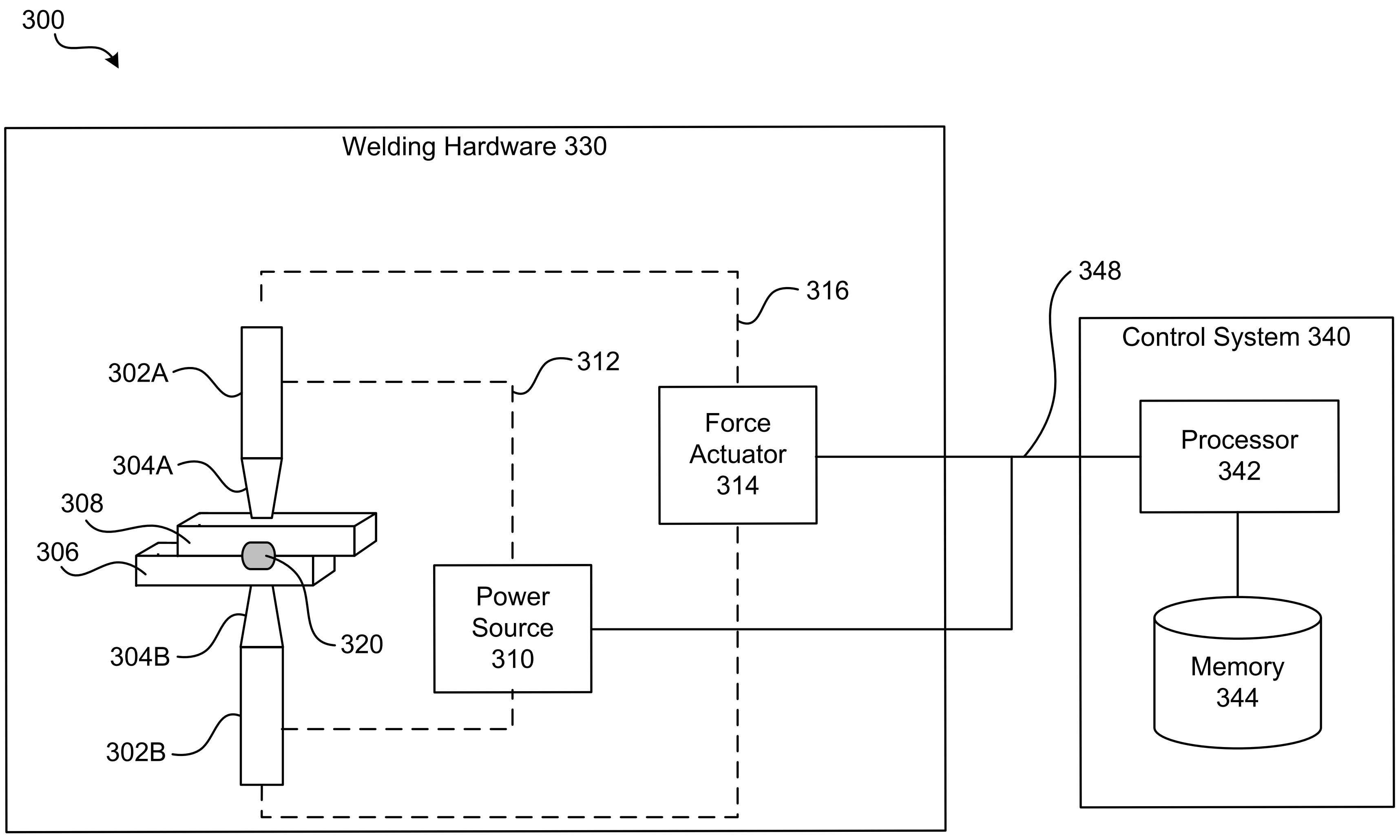
300
Welding Hardware 330
316
312
302A
304A
308
306
320
304B
302B
Force
Actuator
314
Power
Source
310
348
Control System 340
Processor
342
Memory
344

FIG. 3

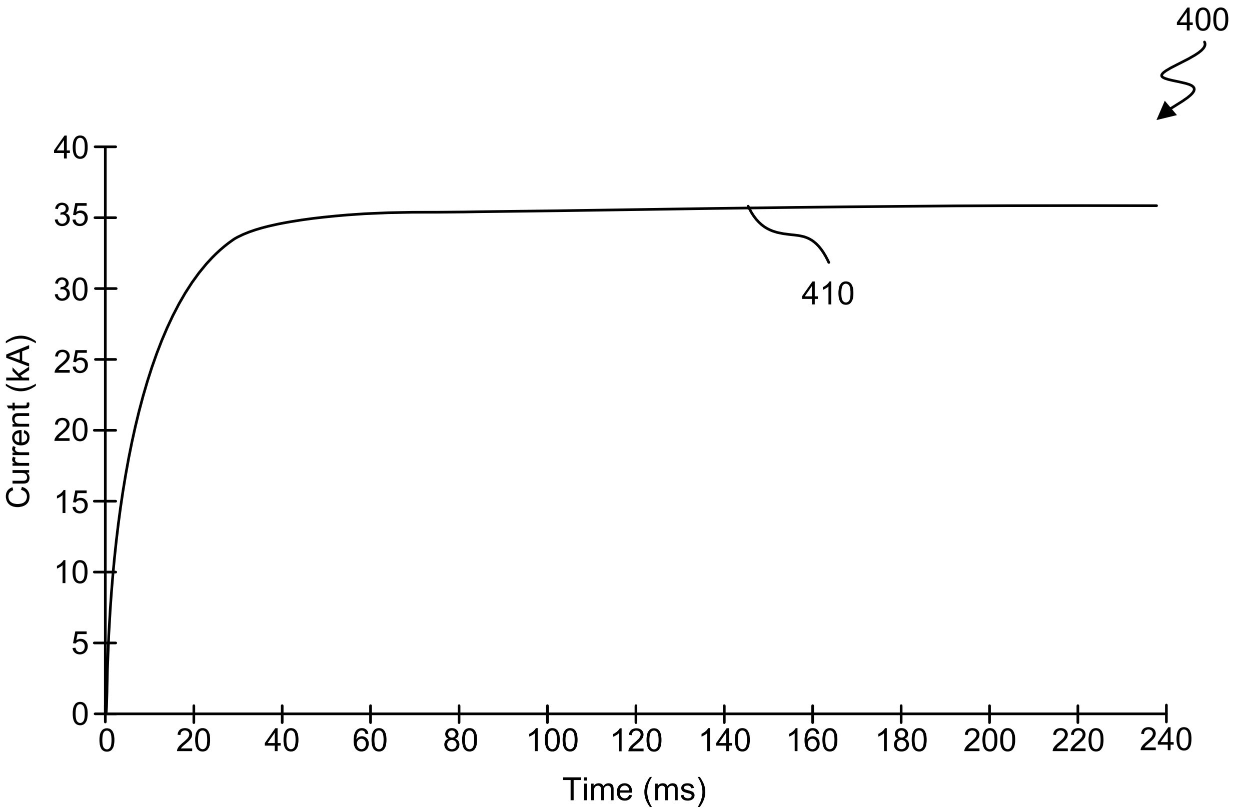
400
410
Current (kA)
0
5
10
15
20
25
30
35
40
Time (ms)
0
20
40
60
80
100
120
140
160
180
200
220
240

FIG. 4

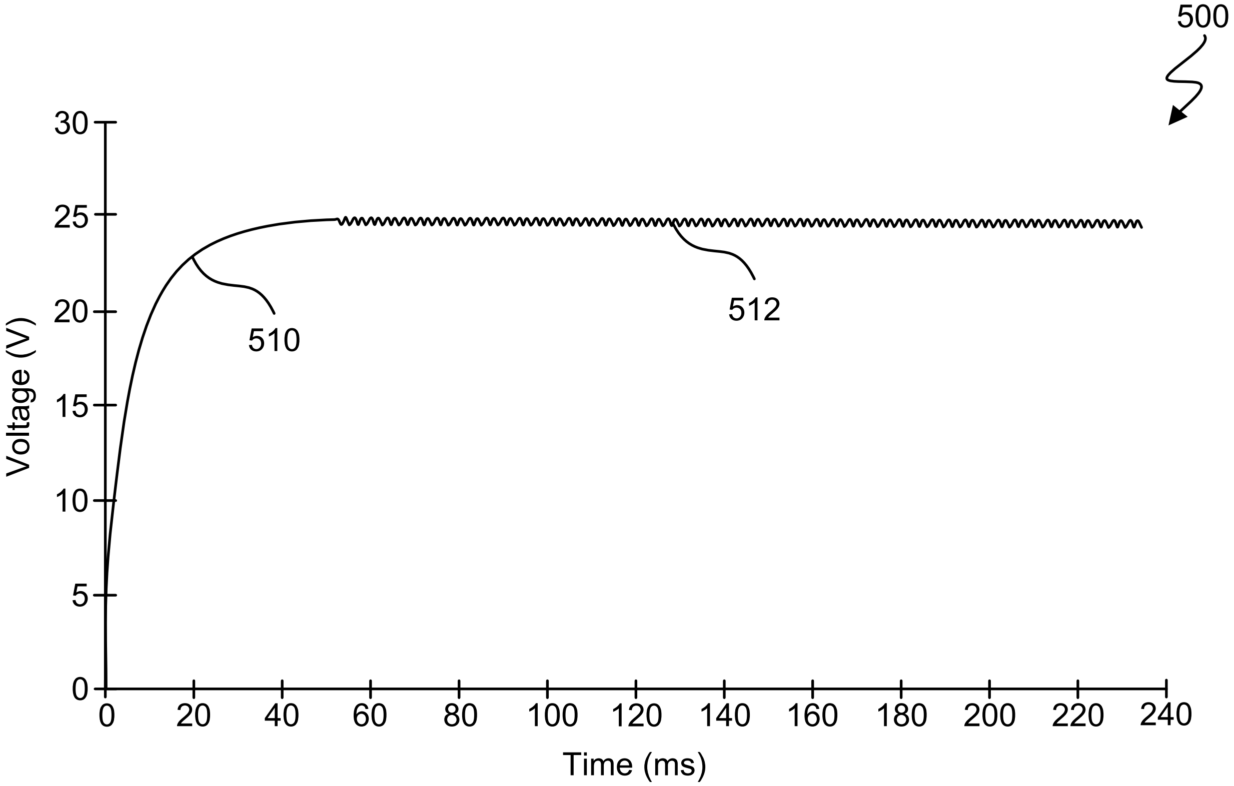
500
510
512
Voltage (V)
0
5
10
15
20
25
30
Time (ms)
0
20
40
60
80
100
120
140
160
180
200
220
240

FIG. 5

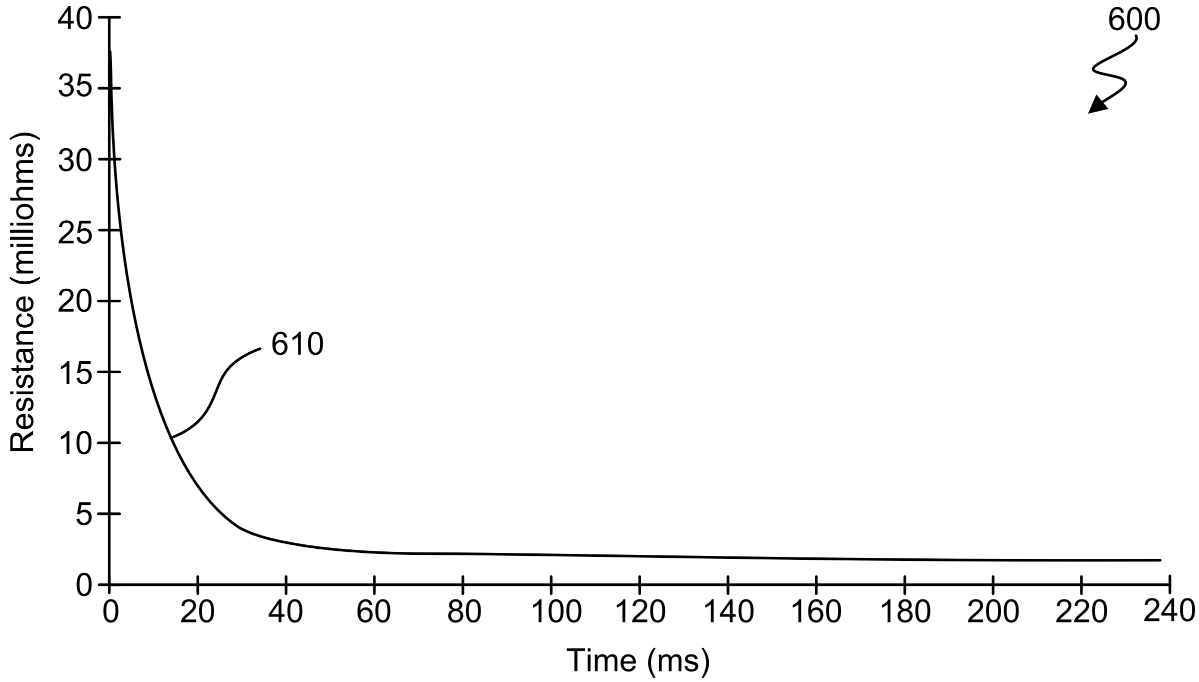
600
610
Resistance (milliohms)
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
200
220
240
Time (ms)

FIG. 6

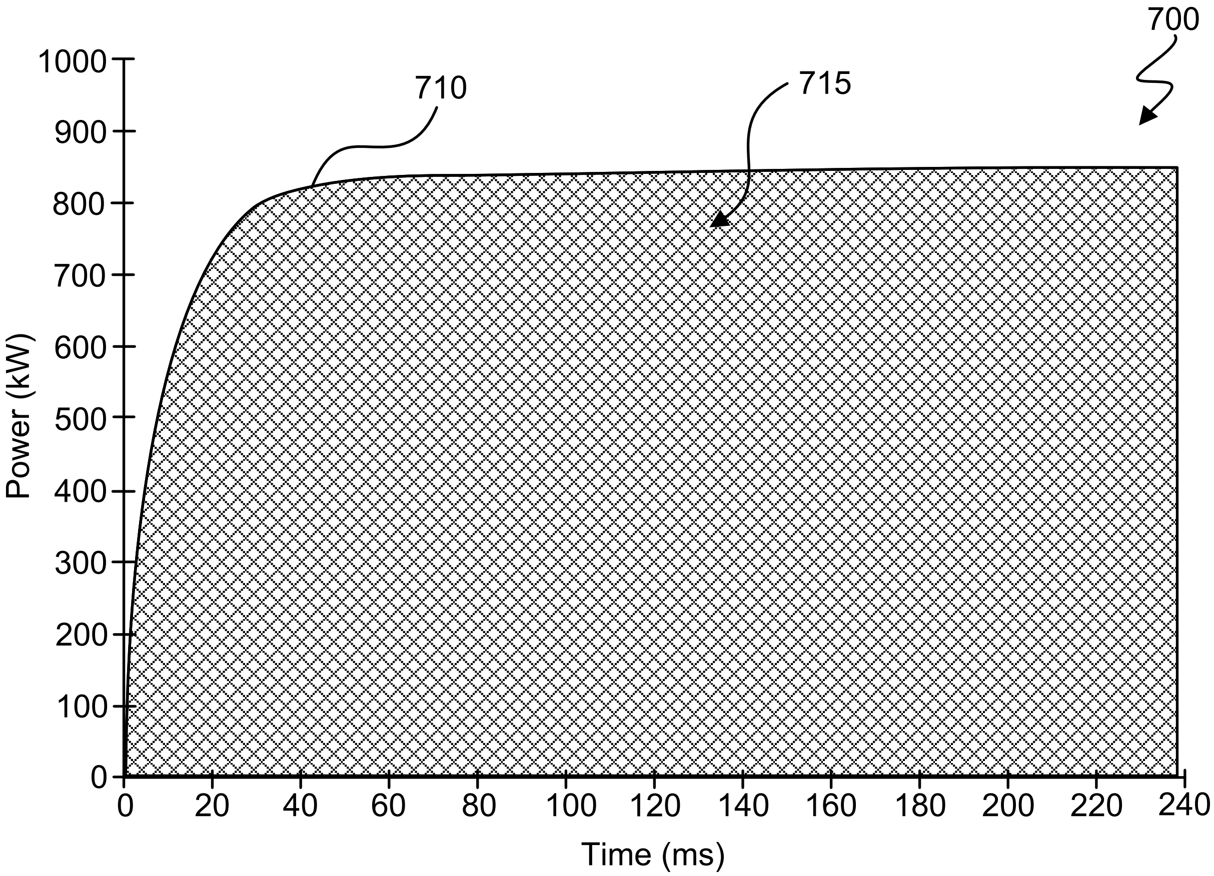
700
710
715
Power (kW)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
180
200
220
240
Time (ms)

FIG. 7

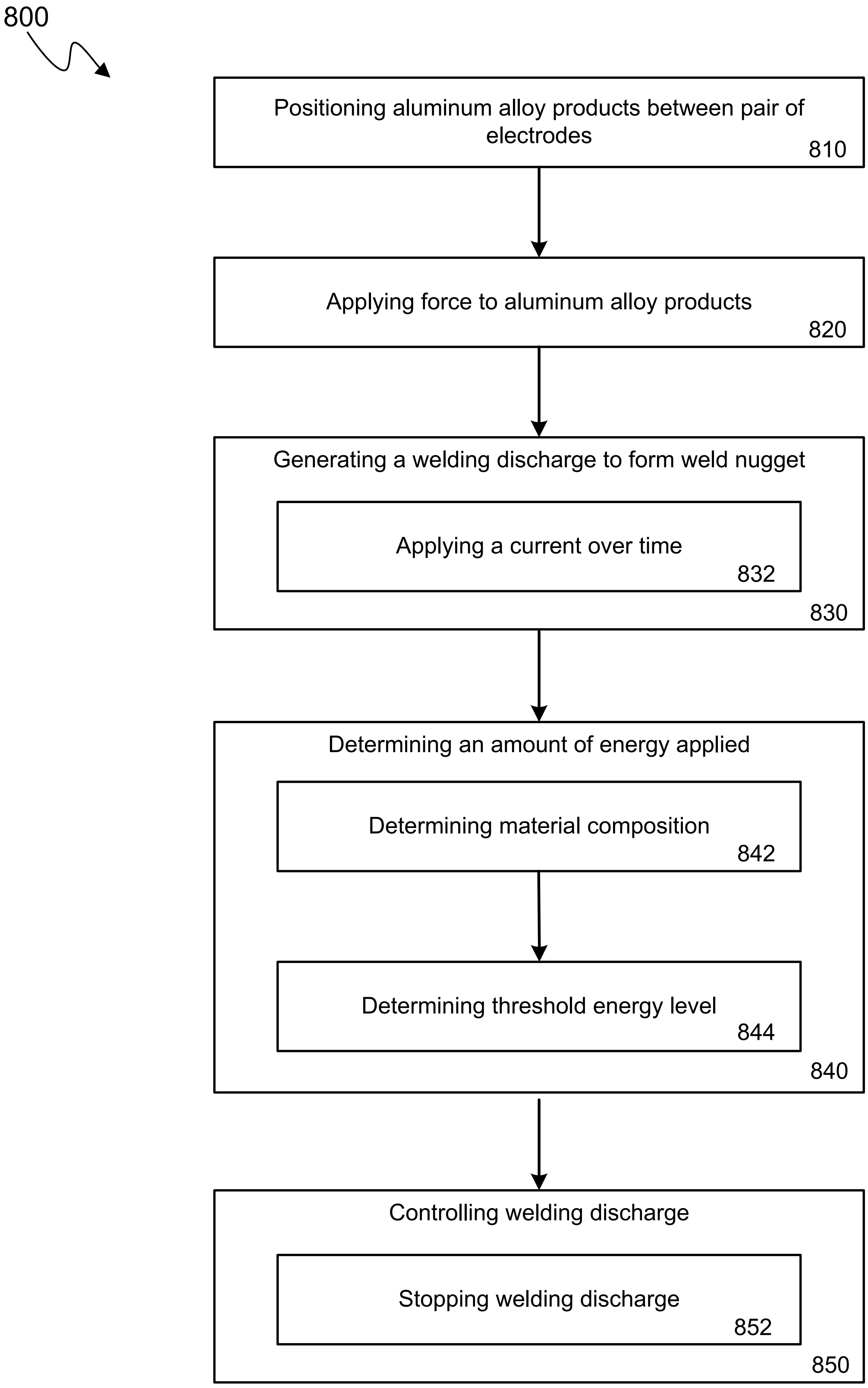
800
Positioning aluminum alloy products between pair of electrodes
810
Applying force to aluminum alloy products
820
Generating a welding discharge to form weld nugget
Applying a current over time
832
830
Determining an amount of energy applied
Determining material composition
842
Determining threshold energy level
844
840
Controlling welding discharge
Stopping welding discharge
852
850

FIG. 8

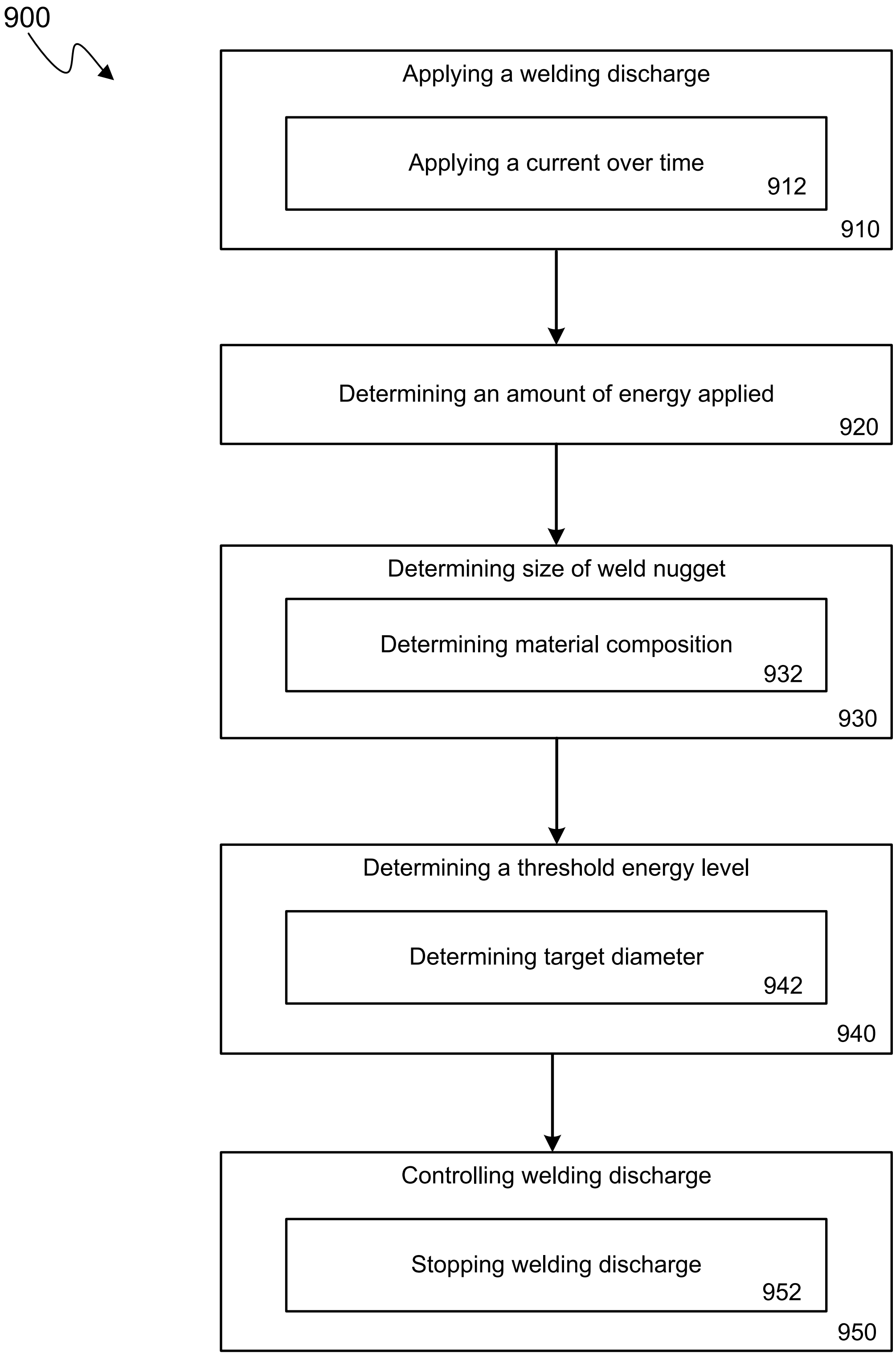
900
Applying a welding discharge
Applying a current over time
912
910
Determining an amount of energy applied
920
Determining size of weld nugget
Determining material composition
932
930
Determining a threshold energy level
Determining target diameter
942
940
Controlling welding discharge
Stopping welding discharge
952
950

FIG. 9

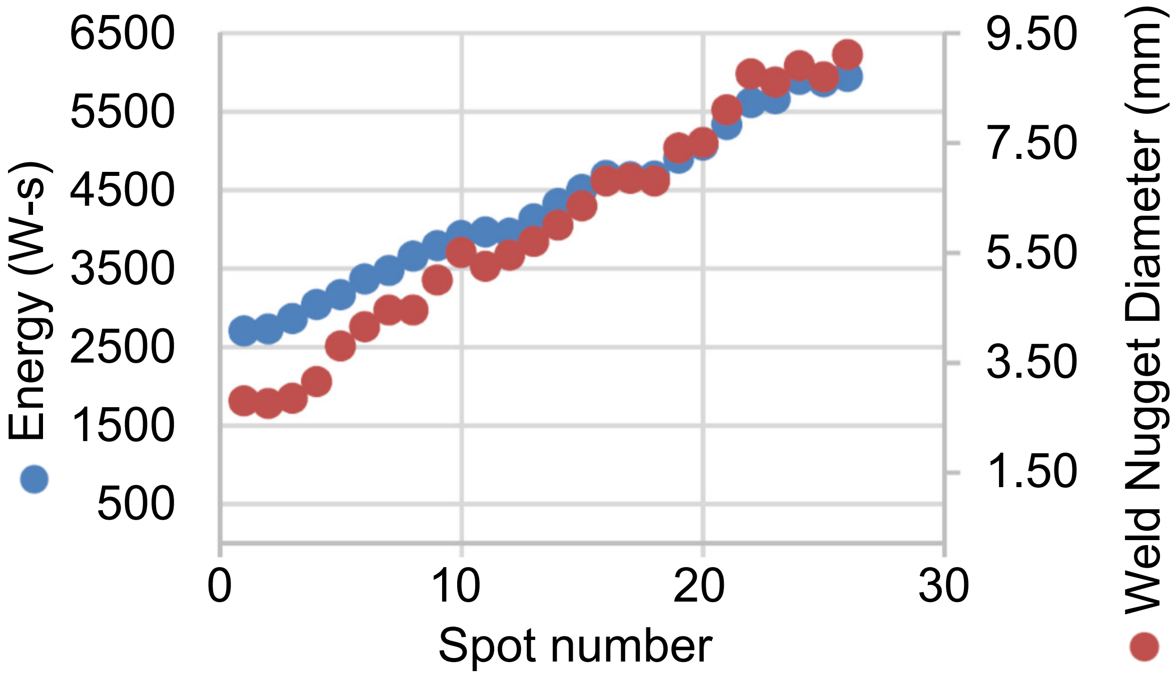
6500
5500
4500
3500
2500
1500
500
● Energy (W-s)
9.50
7.50
5.50
3.50
1.50
● Weld Nugget Diameter (mm)
0
10
20
30
Spot number

FIG. 10

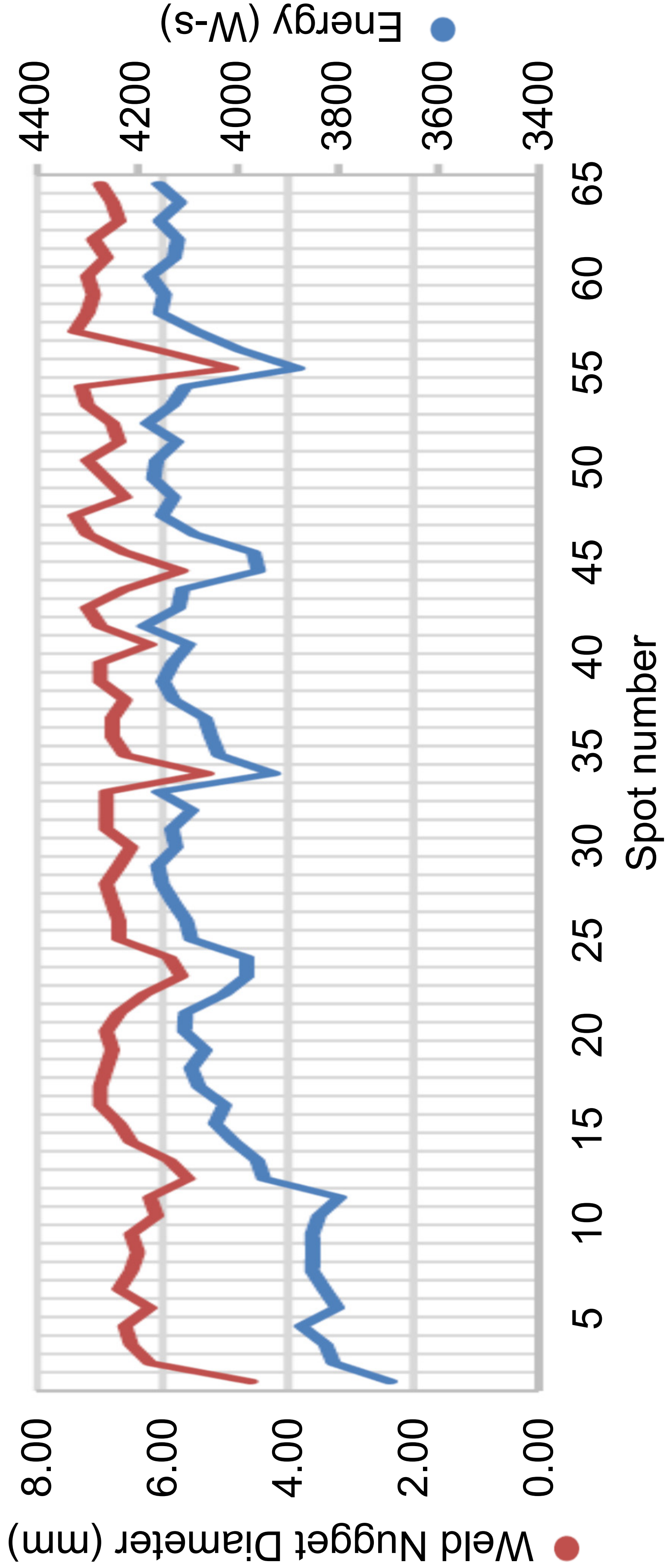
● Energy (W-s)
4400
4200
4000
3800
3600
3400
5
10
15
20
25
30
35
40
45
50
55
60
65
Spot number
8.00
6.00
4.00
2.00
0.00
● Weld Nugget Diameter (mm)

FIG. 11

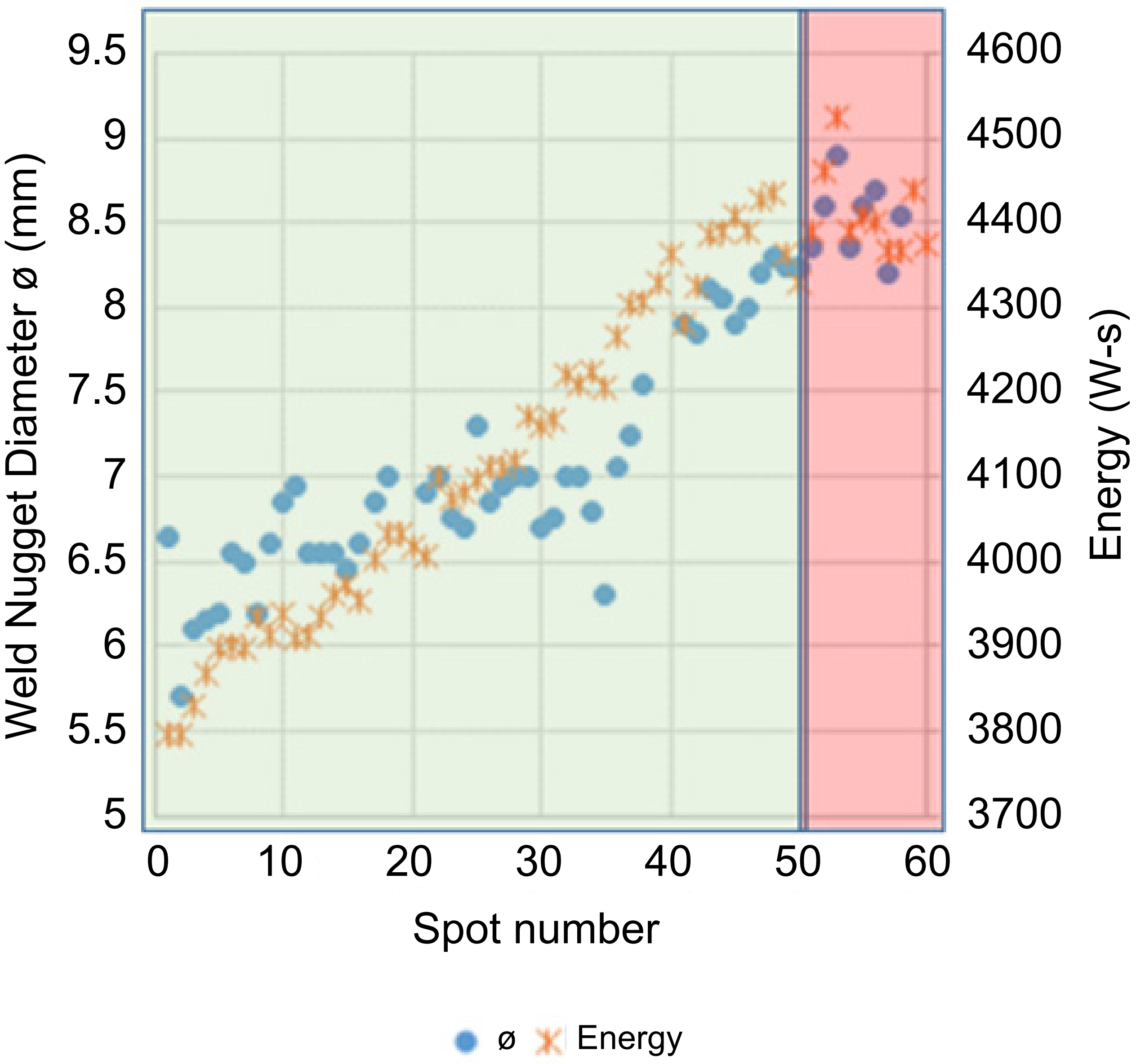
Weld Nugget Diameter ø (mm)
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
Energy (W-s)
0
10
20
30
40
50
60
Spot number
ø
Energy

FIG. 12

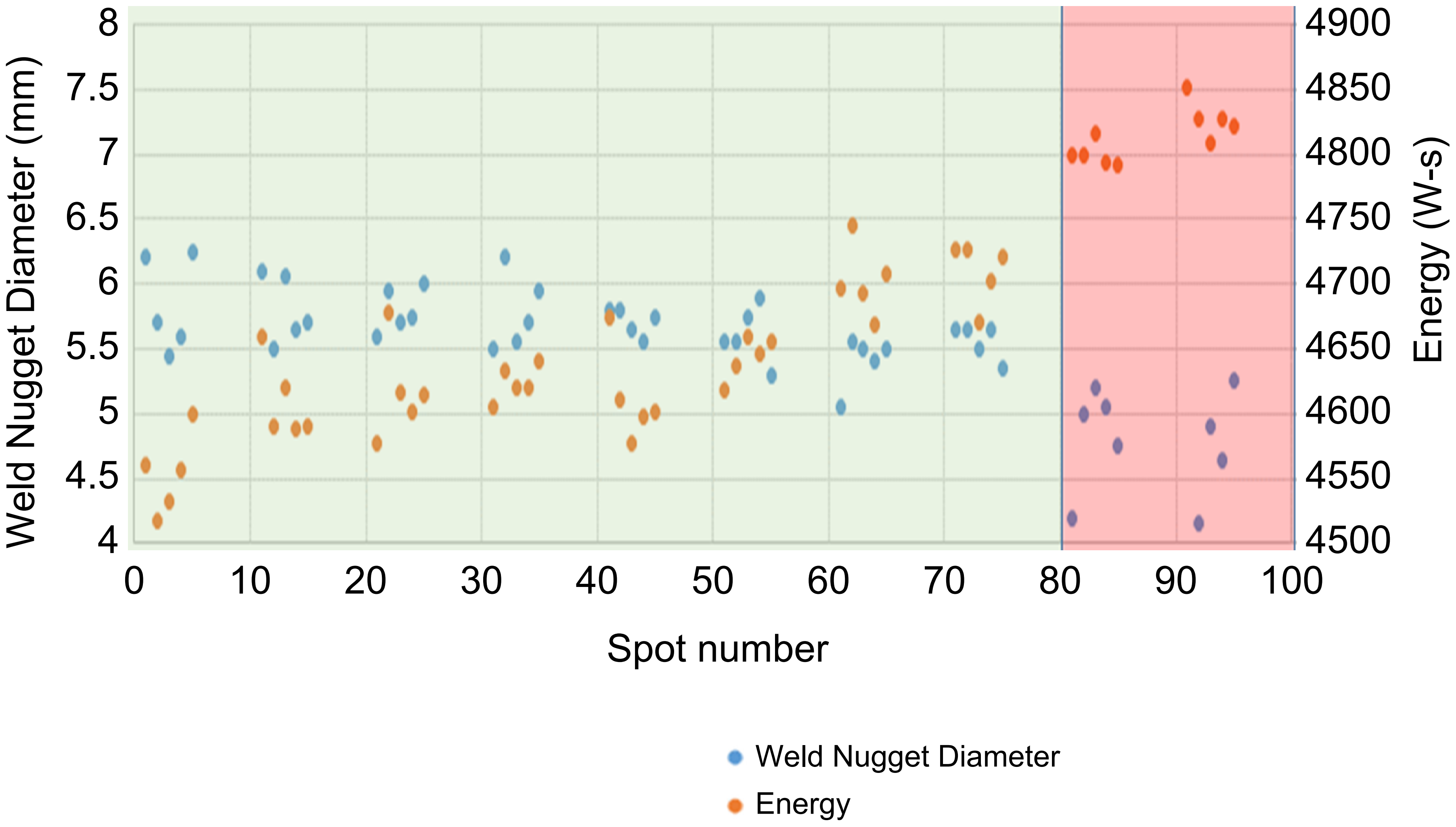
Weld Nugget Diameter (mm)
8
7.5
7
6.5
6
5.5
5
4.5
4
0
10
20
30
40
50
60
70
80
90
100
Spot number
Energy (W-s)
4900
4850
4800
4750
4700
4650
4600
4550
4500
● Weld Nugget Diameter
● Energy

FIG. 13