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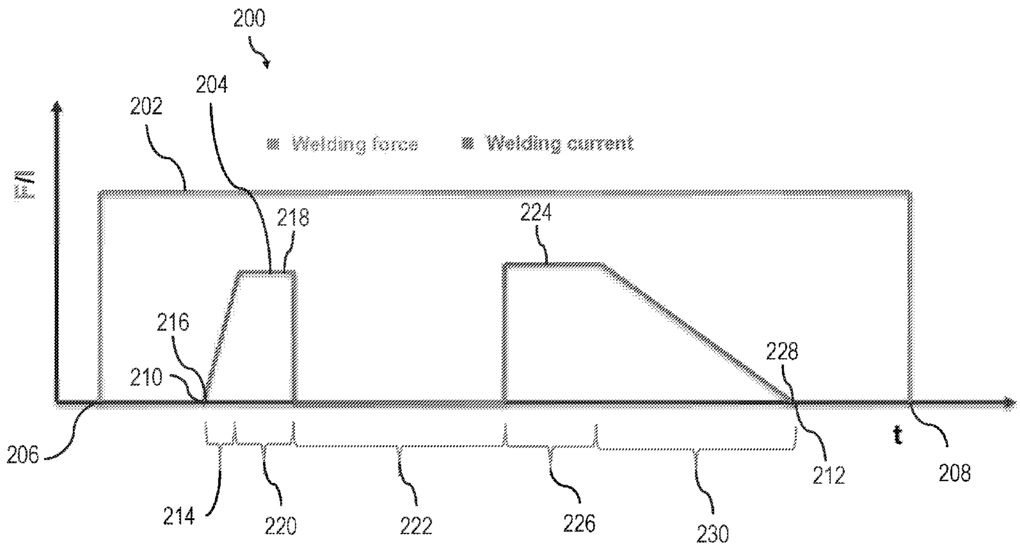

FIG. 2

(57) Abstract: A method of joining metal substrates includes applying a compressive force to at least two overlapping metal substrates, applying an electric current at a first level, and ramping the electric current from the first level to a second level greater than the first level over a first time period. The method also includes, after the first time period, applying the electric current at the second level for a second time period, and, after the second time period, discontinuing the electric current for a third time period. The method further includes, after the third time period, applying the electric current at a third level for a fourth time period, and ramping the electric current from the third level to a fourth level less than the third level over a fifth time period after the fourth time period.

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[Continued on next page]

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SYSTEMS AND METHODS FOR IMPROVING ALUMINUM RESISTANCE SPOT WELDING

REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/266,418, filed on January 5, 2022 and entitled SYSTEMS AND METHODS FOR IMPROVING ALUMINUM RESISTANCE SPOT WELDING, the content of which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] This application relates to resistance spot welding, and, more particularly, to control systems and methods for improving aluminum resistance spot welding.

BACKGROUND

[0003] Metal manufacturing can involve welding metal substrates or metal alloy substrates together to form various parts or components of a final product. Various techniques or processes, including, for example, resistance spot welding, can be used to weld the metal substrates. Resistance spot welding can involve positioning metal substrates between electrodes and using the electrodes to apply a compressive force and an electric current to the metal substrates. Heat produced from a resistance of the metal substrates to the electric current, along with the compressive force of the electrodes, can be used to join the metal substrates at the interface, forming local cohesive zones known as weld nuggets. However, certain metals, including, but not limited to, 7xxx aluminum alloys, may be difficult to weld with traditional welding techniques. For example, with traditional resistance spot welding, a 7xxx aluminum alloy may suffer from inside cracks and/or other joining issues, and customers may refuse to use such metals due to the joining issues and/or weld quality.

SUMMARY

[0004] The terms "invention," "the invention," "this invention" and "the present invention" used in this patent are intended to refer broadly to all of the subject matter of this patent and the patent claims below. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope of the patent claims below. Embodiments of the invention covered by this patent are defined by the claims below, not this summary. This summary is a high-level overview of various embodiments of the invention and introduces some of the concepts that are further described in the Detailed Description section below. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this patent, any or all drawings, and each claim.

[0005] According to certain embodiments, a method for joining metal substrates includes applying a compressive force to at least two overlapping metal substrates. In some embodiments, at least one metal substrate of the at least two metal substrates includes aluminum or an aluminum alloy. The method includes applying an electric current at a first level and ramping the electric current from the first level to a second level greater than the first level over a first time period. In various embodiments, the method includes applying the electric current at the second level for a second time period after the first time period, discontinuing the electric current for a third time period after the second time period, and applying the electric current at a third level for a fourth time period after the third time period. The method may further include ramping the electric current from the third level to a fourth level less than the third level over a fifth time period after the fourth time period. An improved weld may be formed by the method, particularly, but not limited to, a weld of a 7xxx series aluminum alloy.

[0006] According to various embodiments, a method for joining metal substrates includes applying a compressive force to at least two overlapping metal substrates. In certain embodiments, at least one metal substrate of the at least two metal substrates comprises aluminum or an aluminum alloy. The method includes applying a first electric current for a first duration, and applying the first electric current may include ramping up the first electric current from a first level of the first electric current to a second level of the first electric current. The method also includes discontinuing the first electric current for a second duration after the first duration. The method further includes applying a second electric current for a third duration, and applying the second electric current may include ramping down the second electric current from a first level of the second electric current to a second level of the second electric current. An improved weld may be formed by the method, particularly, but not limited to, a weld of a 7xxx series aluminum alloy.

[0007] Various implementations described in the present disclosure can include additional systems, methods, features, and advantages, which cannot necessarily be expressly disclosed herein but will be apparent to one of ordinary skill in the art upon examination of the following detailed description and accompanying drawings. It is intended that all such systems, methods, features, and advantages be included within the present disclosure and protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The features and components of the following figures are illustrated to emphasize the general principles of the present disclosure. Corresponding features and components throughout the figures can be designated by matching reference characters for the sake of consistency and clarity.

[0009] FIG. 1 illustrates a resistance spot system according to embodiments.

[0010] FIG. 2 is a graph depicting a camel curve schedule according to embodiments.

[0011] FIG. 3 is another graph depicting a camel curve schedule according to embodiments.

[0012] FIG. 4 is a flow chart depicting an exemplary process of joining two or more metal substrates according to embodiments.

[0013] FIGS. 5A-B illustrate a weld formed via traditional resistance spot welding and a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

[0014] FIGS. 6A-B illustrate a weld formed via traditional resistance spot welding and a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

[0015] FIGS. 7A-B illustrate a weld formed via traditional resistance spot welding and a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

[0016] FIGS. 8A-B illustrate a weld formed via traditional resistance spot welding and a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

[0017] FIG. 9 illustrates a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

[0018] FIG. 10 illustrates a weld formed via resistance spot welding with the camel curve schedule according to embodiments.

DETAILED DESCRIPTION

[0019] Described herein are methods and systems for joining two or more metal substrates together by resistance spot welding. In certain embodiments, one or more of the metal substrates are aluminum or an aluminum alloy. During a welding technique, a compressive force and an electric current can be applied to the metal substrates. Applying the compressive force and the electrical current may include controlling an amount of current pursuant to a camel curve while applying an amount of the compressive force to the metal substrates. Controlling the amount of current pursuant to the camel curve may allow for the weld to initially form, cool, and then re-weld to cure any defects (e.g., inside cracks) that may have formed during the initial welding. In some embodiments, the weld may be gradually cooled after re-welding while applying the compressive force, which may prevent and/or remove the defect from the weld. In some examples, metal sheets comprising a metal alloy having a large freezing range and low solidus temperatures (e.g., aluminum or aluminum alloys in the 7xxx series) may be especially susceptible to the formation of defects in a welded metal sheet and may benefit from the resistance spot welding schedule described herein.

[0020] FIG. 1 illustrates a system 100 for resistance spot welding at least a first metal substrate 102 with at least a second metal substrate 104. In certain embodiments, the system 100 may be utilized to join a plurality of metal substrates. In some examples, one or more of the metal substrates may be aluminum or an aluminum alloy. In certain cases, aluminum or aluminum alloys in the 1xxx series, 2xxx series, 3xxx series, 4xxx series, 5xxx series, 6xxx series, 7xxx series, 8xxx series and/or any other aluminum or aluminum alloy materials may be utilized as one or more of the metal substrates.

[0021] By way of non-limiting examples, exemplary 1xxx alloys for use in the methods and products described herein can include AA1100, AA1100A, AA1200, AA1200A, AA1300, AA1110, AA1120, AA1230, AA1230A, AA1235, AA1435, AA1145, AA1345, AA1445, AA1150, AA1350, AA1350A, AA1450, AA1370, AA1275, AA1185, AA1285, AA1385, AA1188, AA1190, AA1290, AA1193, AA1198, or AA1199.

[0022] Non-limiting exemplary 2xxx series alloys for use in the methods and products described herein can include AA2001, A2002, AA2004, AA2005, AA2006, AA2007, AA2007A, AA2007B, AA2008, AA2009, AA2010, AA2011, AA2011A, AA2111,

AA2111A, AA2111B, AA2012, AA2013, AA2014, AA2014A, AA2214, AA2015, AA2016, AA2017, AA2017A, AA2117, AA2018, AA2218, AA2618, AA2618A, AA2219, AA2319, AA2419, AA2519, AA2021, AA2022, AA2023, AA2024, AA2024A, AA2124, AA2224, AA2224A, AA2324, AA2424, AA2524, AA2624, AA2724, AA2824, AA2025, AA2026, AA2027, AA2028, AA2028A, AA2028B, AA2028C, AA2029, AA2030, AA2031, AA2032, AA2034, AA2036, AA2037, AA2038, AA2039, AA2139, AA2040, AA2041, AA2044, AA2045, AA2050, AA2055, AA2056, AA2060, AA2065, AA2070, AA2076, AA2090, AA2091, AA2094, AA2095, AA2195, AA2295, AA2196, AA2296, AA2097, AA2197, AA2297, AA2397, AA2098, AA2198, AA2099, or AA2199.

[0023] Non-limiting exemplary 3xxx series alloys for use in the methods and products described herein can include AA3002, AA3102, AA3003, AA3103, AA3103A, AA3103B, AA3203, AA3403, AA3004, AA3004A, AA3104, AA3204, AA3304, AA3005, AA3005A, AA3105, AA3105A, AA3105B, AA3007, AA3107, AA3207, AA3207A, AA3307, AA3009, AA3010, AA3110, AA3011, AA3012, AA3012A, AA3013, AA3014, AA3015, AA3016, AA3017, AA3019, AA3020, AA3021, AA3025, AA3026, AA3030, AA3130, or AA3065.

[0024] Non-limiting exemplary 4xxx series alloys for use in the methods and products described herein can include AA4004, AA4104, AA4006, AA4007, AA4008, AA4009, AA4010, AA4013, AA4014, AA4015, AA4015A, AA4115, AA4016, AA4017, AA4018, AA4019, AA4020, AA4021, AA4026, AA4032, AA4043, AA4043A, AA4143, AA4343, AA4643, AA4943, AA4044, AA4045, AA4145, AA4145A, AA4046, AA4047, AA4047A, or AA4147.

[0025] Non-limiting exemplary 5xxx series alloys for use in the methods and products described herein can include AA5182, AA5183, AA5005, AA5005A, AA5205, AA5305, AA5505, AA5605, AA5006, AA5106, AA5010, AA5110, AA5110A, AA5210, AA5310, AA5016, AA5017, AA5018, AA5018A, AA5019, AA5019A, AA5119, AA5119A, AA5021, AA5022, AA5023, AA5024, AA5026, AA5027, AA5028, AA5040, AA5140, AA5041, AA5042, AA5043, AA5049, AA5149, AA5249, AA5349, AA5449, AA5449A, AA5050, AA5050A, AA5050C, AA5150, AA5051, AA5051A, AA5151, AA5251, AA5251A, AA5351, AA5451, AA5052, AA5252, AA5352, AA5154, AA5154A, AA5154B, AA5154C, AA5254, AA5354, AA5454, AA5554, AA5654, AA5654A, AA5754, AA5854, AA5954, AA5056, AA5356, AA5356A, AA5456, AA5456A, AA5456B, AA5556, AA5556A, AA5556B, AA5556C, AA5257, AA5457, AA5557, AA5657, AA5058, AA5059, AA5070,

AA5180, AA5180A, AA5082, AA5182, AA5083, AA5183, AA5183A, AA5283, AA5283A, AA5283B, AA5383, AA5483, AA5086, AA5186, AA5087, AA5187, or AA5088.

[0026] Non-limiting exemplary 6xxx series alloys for use in the methods and products described herein can include AA6101, AA6101A, AA6101B, AA6201, AA6201A, AA6401, AA6501, AA6002, AA6003, AA6103, AA6005, AA6005A, AA6005B, AA6005C, AA6105, AA6205, AA6305, AA6006, AA6106, AA6206, AA6306, AA6008, AA6009, AA6010, AA6110, AA6110A, AA6011, AA6111, AA6012, AA6012A, AA6013, AA6113, AA6014, AA6015, AA6016, AA6016A, AA6116, AA6018, AA6019, AA6020, AA6021, AA6022, AA6023, AA6024, AA6025, AA6026, AA6027, AA6028, AA6031, AA6032, AA6033, AA6040, AA6041, AA6042, AA6043, AA6151, AA6351, AA6351A, AA6451, AA6951, AA6053, AA6055, AA6056, AA6156, AA6060, AA6160, AA6260, AA6360, AA6460, AA6460B, AA6560, AA6660, AA6061, AA6061A, AA6261, AA6361, AA6162, AA6262, AA6262A, AA6063, AA6063A, AA6463, AA6463A, AA6763, A6963, AA6064, AA6064A, AA6065, AA6066, AA6068, AA6069, AA6070, AA6081, AA6181, AA6181A, AA6082, AA6082A, AA6182, AA6091, or AA6092.

[0027] Non-limiting exemplary 7xxx series alloys for use in the methods and products described herein can include AA7011, AA7019, AA7020, AA7021, AA7039, AA7072, AA7075, AA7085, AA7108, AA7108A, AA7015, AA7017, AA7018, AA7019A, AA7024, AA7025, AA7028, AA7030, AA7031, AA7033, AA7035, AA7035A, AA7046, AA7046A, AA7003, AA7004, AA7005, AA7009, AA7010, AA7011, AA7012, AA7014, AA7016, AA7116, AA7122, AA7023, AA7026, AA7029, AA7129, AA7229, AA7032, AA7033, AA7034, AA7036, AA7136, AA7037, AA7040, AA7140, AA7041, AA7049, AA7049A, AA7149,7204, AA7249, AA7349, AA7449, AA7050, AA7050A, AA7150, AA7250, AA7055, AA7155, AA7255, AA7056, AA7060, AA7064, AA7065, AA7068, AA7168, AA7175, AA7475, AA7076, AA7178, AA7278, AA7278A, AA7081, AA7181, AA7185, AA7090, AA7093, AA7095, or AA7099.

[0028] Non-limiting exemplary 8xxx series alloys for use in the methods and products described herein can include AA8005, AA8006, AA8007, AA8008, AA8010, AA8011, AA8011A, AA8111, AA8211, AA8112, AA8014, AA8015, AA8016, AA8017, AA8018, AA8019, AA8021, AA8021A, AA8021B, AA8022, AA8023, AA8024, AA8025, AA8026, AA8030, AA8130, AA8040, AA8050, AA8150, AA8076, AA8076A, AA8176, AA8077, AA8177, AA8079, AA8090, AA8091, or AA8093.

[0029] As one non-limiting example, one or more of the metal substrates may be a 7xxx series aluminum alloy. In some non-limiting examples, one of the metal substrates (e.g., the first metal substrate 102) may be a 7xxx series aluminum alloy and the other metal substrate (e.g., the second metal substrate 104) may be a 7xxx series aluminum alloy, a 6xxx series aluminum alloy, and/or a 5xxx series aluminum alloy. The composition of one metal substrate (e.g., the first metal substrate 102) need not be the same as the composition of another metal substrate (e.g., the second metal substrate 104). Each of the metal substrates 102, 104 may have various sizes or thicknesses as desired, and the size or thickness of one metal substrate need not be the same as another metal substrate. In some non-limiting examples, the thickness of one or more metal substrates may be from greater than 0 mm to 5 mm, although other thicknesses may be utilized. As illustrated in FIG. 1, the metal substrates 102, 104 may be arranged relative to each other such that the metal substrates 102, 104 overlap and have outermost opposite sides 110, 112.

[0030] The resistance spot welding system 100 includes electrodes 106A-B. While two electrodes 106A-B are illustrated, any number of electrodes may be utilized with the system 100 as desired. The electrodes 106A-B may be any suitable type of electrodes for supplying a desired conductivity during welding, and may include, but are not limited to, copper electrodes, steel electrodes, or tungsten electrodes.

[0031] In certain embodiments, the electrodes 106A-B are communicatively coupled with a weld controller 114 for controlling one or more welding parameters, including, but not limited to, the welding duration and the welding current, during resistance spot welding. In one non-limiting example, the weld controller 114 may be a middle frequency direct current controller, although in other embodiments, the weld controller 114 may be various other suitable devices or mechanisms as desired. In various aspects, the weld controller 114 may control one or more welding parameters based on a characteristic of the metal substrates 102, 104 to be joined and/or other characteristics of the resistance spot welding system 100. For example, the weld controller 114 may control the welding duration and/or the welding current based at least in part on a composition of the metal substrates 102, 104, a thickness or size of the metal substrates 102, 104, a size of the electrodes 106A-B, and/or other characteristics as desired. In certain embodiments, the weld controller 114 controls the resistance spot welding system 100 pursuant to a camel curve schedule 200, as discussed in detail below.

[0032] As discussed in detail below, the welding current provided for the welding duration and pursuant to the camel curve schedule 200 produces a weld 108 having a minimum weld size to join the metal substrates 102, 104, or a weld nugget that meets size and mechanical requirements for the joint. Minimum weld size is defined as $4\sqrt{t}$, where t is the thickness of the governing metal thickness. In a stack of two metal substrates, the governing metal thickness is generally the thinnest substrate.

[0033] FIG. 2 illustrates a camel curve schedule 200 according to various embodiments. As illustrated in FIG. 2, the camel curve schedule 200 generally includes both a compressive force 202 and an electric current 204 that is applied to the metal substrates 102, 104 to form a weld such as the weld 108. In certain embodiments, the camel curve schedule 200 may minimize or prevent the formation of defects in the weld such as inside cracking. The camel curve schedule 200 will be discussed in conjunction with the system 100 but may be used in any existing welding apparatus, and may not require additional parts, equipment, and/or machinery other than that associated with resistance spot welding processes.

[0034] As depicted in FIG. 2, the compressive force 202 and the electric current 204 are applied to the two or more metal substrates 102, 104 via the electrodes 106A-B. In various embodiments, and as previously discussed, the metal substrates 102, 104 may be metal alloys, and optionally at least one of the metal substrates 102, 104 may be a 7xxx series aluminum alloy. In certain embodiments, the compressive force 202 is applied prior to the application of the electric current 204 and maintained during the application of the electric current 204. In some embodiments, a constant compressive force 202 is applied for the duration of the application of the electric current 204. In various embodiments, the constant compressive force 202 may reduce potential welding fluctuation. Various compressive forces 202 may be applied as desired. As one non-limiting example, the compressive force may be from greater than 0 kN to 10 kN, such as from 4 kN to 8 kN, such as from 5 kN to 7 kN, such as about 6 kN and/or such as about 6.5 kN. In other embodiments, the compressive force 202 may be other compressive forces as desired. In FIG. 2, the compressive force 202 is illustrated at about 600 decanewtons (daN), or 6 kN. The compressive force 202 may be applied for a force duration having a force start time 206 and a force end time 208. The period between the force start time 206 and the force end time 208 may be any span or duration of time as desired.

[0035] The electric current 204 may correspond to various amounts of electric current, energy, or heat and may be applied in various levels a discussed in detail below. In certain examples, the levels of electric current 204 may be between 0 kA and 65 kA, such as from greater than 0 kA to 55 kA. The electric current 204 may controlled and selectively applied for a current duration having a current start time 210 and a current end time 212. In certain embodiments, the current duration is less than the force duration. In various aspects, the current start time 210 is a predetermined duration or period of time after the force start time 206. In such examples, delaying the current start time 210 to be after the force start time 206 may ensure that the metal substrates are positioned as desired between the electrodes 106A-B. As one non-limiting example, the force duration may be about 3000 ms, and the current duration may be about 1100 ms.

[0036] As mentioned, within the current duration, the electric current 204 may be applied to various levels and for certain time periods. In some embodiments, during a first time period 214, the electric current 204 is ramped up from a first level 216 to a second level 218 that is greater than the first level 216. In some embodiments, the first level 216 may be 0 kA (e.g., the current is ramped from 0 kA to the welding current used during a second time period 220), although it need not be in other embodiments. In the embodiment illustrated, the first level 216 is 0 kA and the second level 218 is 36 kA, although in other embodiments the first level 216 and/or the second level 218 may be various current levels as desired. In certain aspects, applying the electric current 204 that is ramped up from the first level 216 to the second level of the first time period 214 may avoid or minimize potential explosion, among other benefits.

[0037] After the first time period 214 and during the second time period 220, the electric current 204 is applied at the second level 218. In certain embodiments, applying the electric current 204 at the second level 218 for the second time period 220 may allow for the creation of a weld nugget. However, for certain metal substrates such as 7xxx series aluminum alloys, the weld nugget formed may have defects such as inside cracking, which would make the joint otherwise unsuitable for use. In certain embodiments, the second time period 220 optionally may be less than the first time period 214, although it need not be in other examples.

[0038] After the second time period 220, the electric current 204 is discontinued (e.g., returns to 0 kA) for a third time period 222. Discontinuing the electric current 204 for the third time period 222 may allow for the weld nugget formed after the second time period 220 to at least partially cool. In some embodiments and as illustrated in FIG. 2, the third time period 222 optionally may be greater than the first time period 214 and may be greater than the second time period 220. However, in other embodiments, the third time period 222 may be various other time periods as desired, including time periods that are less than or equal to the first time period 214 and/or the second time period 220.

[0039] As depicted in FIG. 2, after the third time period 222, the electric current 204 may be applied at a third level 224 for a fourth time period 226. In certain embodiments, applying the electric current 204 at the third level 224 and for the fourth time period 226 may cure the weld nugget formed after the second time period 220 by at least partially re-melting the weld and such that cracks or other defects are refilled. In some embodiments and as illustrated in FIG. 2, the third level 224 optionally may be about the same as the second level 218. However, in other embodiments, the third level 224 may be less than or greater than the second level 218 as desired. Similarly, the fourth time period 226 may be the same as, greater than, or less than the second time period 220 as desired. In the embodiment illustrated, the fourth time period 226 is greater than the second time period 220. While the fourth time period 226 is illustrated as less than the third time period 222 and greater than the first time period 214, in other embodiments, the fourth time period 226 may have various durations compared to the first time period 214 and/or the third time period 222 as desired.

[0040] In certain embodiments, after the fourth time period 226, the electric current 204 may be ramped down from the third level 224 to a fourth level 228 that is less than the third level 224 during a fifth time period 230. In some embodiments, the fourth level 228 may be 0 kA (e.g., the electric current is ramped down from the third level 224 to 0 kA), although it need not be in other embodiments. Ramping down the electric current 204 over the fifth time period 230 may reduce the tendency of cracks or other defects to form in the cured weld nugget. In some embodiments, the rate at which the electric current 204 is ramped down during the fifth time period is less than the rate at which the electric current 204 is ramped up during the first time period 214, although it need not be in other embodiments. In some embodiments and as illustrated in FIG. 2, the fourth level 228 may be the same as the first level 216 (e.g., 0 kA in FIG. 2). However, in other embodiments the fourth level 228 may be less than or greater than the first level 216 as desired.

[0041] The camel curve schedule 200 in FIG. 2 is provided for illustrative purposes only, and the specific values of the levels of the electric current 204, the level of the compressive force 202, and/or the time periods of the electric current 204 should not be considered limiting. As a non-limiting example, FIG. 3 illustrates another example of a camel curve schedule 300 according to embodiments of the disclosure. The camel curve schedule 300 is similar to the camel curve schedule 200 and includes the compressive force 202 and the electric current 204. However, compared to the camel curve schedule 200, the compressive force 202 is applied at about 650 daN (or 6.5 kN) and the force duration is about 1800 ms.

Additionally, compared to the camel curve schedule 200, the current start time 210 is about 500 ms after the force start time 206 and the current duration is about 1000 ms. Compared to the camel curve schedule 200, the first level 216 and the fourth level 228 of the electric current 204 of the camel curve schedule 300 are each 18 kA, and the second level 218 and the third level 224 of the electric current 204 of the camel curve schedule 300 are each 40 kA. In addition, compared to the camel curve schedule 200, in the camel curve schedule 300, the first time period 214 is about the same as the second time period 220 and the fourth time period 226 is about the same as the fifth time period 230. In this example, the third time period 222 is the time period with the greatest duration between the current start time 210 and the current end time 212.

[0042] FIG. 4 illustrates a method of joining at least two metal substrates 102, 104 using a camel curve schedule according to various embodiments. While reference will be made to the camel curve schedule 200 illustrated in FIG. 2 and the system 100 illustrated in FIG. 1, the method may be performed with other camel curve schedules consistent with the disclosure as desired and/or other systems as desired.

[0043] In a block 402, the method includes applying the compressive force 202 to the metal substrates 102, 104 using the electrodes 106A-B. In certain embodiments, applying the compressive force brings the metal substrates 102, 104 into contact with one another and/or may position the metal substrates 102, 104 relative to each other. In one non-limiting example, block 402 includes applying the compressive force 202 at 6 kN. The method may include performing the steps illustrated in blocks 404, 406, and 408 while applying the clamping force.

[0044] In the block 404, the method includes applying the electric current 204 for a first duration. As used herein, the “first duration” refers to the first time period 214 and the second time period 220. In various embodiments, block 404 includes applying the electric current 204 at the first level 216 and ramping the electric current 204 from the first level 216 to the second level 218 over the first time period 214. Block 404 also includes applying the electric current 204 at the second level 218 for the second time period 220. As one non-limiting example, block 404 includes applying the electric current 204 at the first level 216 of 0 kA and ramping it up to the second level 218 of 36 kA for the first time period 214, and applying the electric current 204 at the second level 218 for the second time period 220.

[0045] In the block 406, the method includes discontinuing the electric current 204 for the third time period 222.

[0046] In a block 408, the method includes applying the electric current 204 for a second duration. As used herein, the "second duration" refers to the fourth time period 226 and the fifth time period 230. In various embodiments, block 408 includes applying the electric current 204 at the third level 224 for the fourth time period 226. Block 408 also includes ramping the electric current 204 from the third level 224 to the fourth level 228 over the fifth time period 230. As one non-limiting example, block 408 includes applying the electric current 204 at the third level 224 of 36 kA for the fourth time period 226 and ramping it down to the fourth level 228 of 0 kA for the fifth time period 230.

[0047] FIGS. 5A-B, 6A-B, 7A-B, and 8A-B illustrate non-limiting examples of traditional RSW joints formed using a conventional welding schedule recommended for aluminum alloys as set forth in ISO 18595:2021 and VDA 238-401 (hereinafter "conventional schedule") compared to RSW joints formed using the camel curve schedule 200. In these examples, other than the welding schedules, the metal substrates and other parameters were maintained for both joints. In general, and as discussed in detail below, the RSW joints formed using the camel curve schedule 200 had an improved quality and did not suffer from cracking as was found in the traditional RSW joints.

[0048] FIGS. 5A-B illustrate a first non-limiting example of a traditional RSW joint 501 (FIG. 5A) using the conventional schedule and a RSW joint 503 (FIG. 5B) using the camel curve schedule. In this example, both joints 501, 503 were formed using the same stack of metal substrates where the upper metal substrate 505 was a 7075 aluminum alloy with a thickness of 1.8 mm and the lower metal substrate 507 was a 7075 aluminum alloy with a thickness of 1.8 mm. In this example, the conventional schedule was performed with a maximum current of 32 kA, a welding duration of 200 ms, and a compressive force of 6.5 kN, and the camel schedule was performed with a maximum current of 30 kA, a first duration (i.e., first time period 214 and second time period 220) of 200 ms, a second duration (i.e., third time period 222) of 400 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 380 ms. and a compressive force of 6.5 kN. As illustrated by comparing FIG. 5A with FIG. 5B, the traditional RSW joint 501 suffered from inside cracking 509 whereas the RSW joint 503 did not, and thus the RSW joint 503 was the improved and better joint.

[0049] FIGS. 6A-B illustrate a second non-limiting example of a traditional RSW joint 601 (FIG. 6A) using the conventional schedule and a RSW joint 603 (FIG. 6B) using the camel curve schedule. In this example, both joints 601, 603 were formed using the same stack of metal substrates where the upper metal substrate 605 was a 6451 aluminum alloy with a thickness of 1.8 mm and the lower metal substrate 607 was a 7075 aluminum alloy with a thickness of 2.0 mm. In this example, the conventional schedule was performed with a maximum current of 35 kA, a welding duration of 200 ms, and a compressive force of 6.5 kN, and the camel schedule was performed with a maximum current of 35 kA, a first duration (i.e., first time period 214 and second time period 220) of 160 ms, a second duration (i.e., third time period 222) of 410 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 450 ms, and a compressive force of 6.5 kN. As illustrated by comparing FIG. 6A with FIG. 6B, the traditional RSW joint 601 included inside cracking 609 whereas the RSW joint 603 did not, and thus the RSW joint 603 was the improved and better joint.

[0050] FIGS. 7A-B illustrate a third non-limiting example of a traditional RSW joint 701 (FIG. 7A) using the conventional schedule and a RSW joint 703 (FIG. 7B) using the camel curve schedule. In this example, both joints 701, 703 were formed using the same stack of metal substrates where the upper metal substrate 705 was a 7075 aluminum alloy with a thickness of 1.8 mm and the lower metal substrate 707 was a 5182 aluminum alloy with a thickness of 1.0 mm. In this example, the conventional schedule was performed with a maximum current of 30 kA, a welding duration of 200 ms, and a compressive force of 6.5 kN, and the camel schedule was performed with a maximum current of 30 kA, a first duration (i.e., first time period 214 and second time period 220) of 150 ms, a second duration (i.e., third time period 222) of 350 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 450 ms, and a compressive force of 6.5 kN. As illustrated by comparing FIG. 7A with FIG. 7B, the traditional RSW joint 701 included inside cracking 709 whereas the RSW joint 703 did not, and thus the RSW joint 703 was the improved and better joint.

[0051] As the last non-limiting example, FIGS. 8A-B illustrate a traditional RSW joint 801 (FIG. 8A) using the conventional schedule and a RSW joint 803 (FIG. 8B) using the camel curve schedule. In this example, both joints 801, 803 were formed using the same stack of metal substrates where the upper metal substrate 805 was a 6451 aluminum alloy with a thickness of 2.5 mm and the lower metal substrate 807 was a 7075 aluminum alloy with a thickness of 2.8 mm. In this example, the conventional schedule was performed with a maximum current of 38 kA, a welding duration of 150 ms, and a compressive force of 6.5 kN, and the camel schedule was performed with a maximum current of 38 kA, a first duration (i.e., first time period 214 and second time period 220) of 200 ms, a second duration (i.e., third time period 222) of 540 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 380 ms, and a compressive force of 6.5 kN. As illustrated, the traditional RSW joint 801 included cracking 809 but the RSW joint 803 did not. As such, the RSW joint 803 was the improved and better joint.

[0052] FIG. 9 illustrates another non-limiting example of a RSW joint 903 using the camel curve schedule. In this example, the upper metal substrate 905 was cast aluminum with a thickness of 3.0 mm, and the lower metal substrate 907 was a 7075 aluminum alloy with a thickness of 1.8 mm. In this example, the camel schedule was performed with a maximum current of 34 kA, a first duration (i.e., first time period 214 and second time period 220) of 150 ms, a second duration (i.e., third time period 222) of 400 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 300 ms, and a compressive force of 6.0 kN. As illustrated in FIG. 9, the RSW joint 903 did not include inside cracking and was thus an improved joint.

[0053] FIG. 10 illustrates another non-limiting example of a RSW joint 1003 using the camel curve schedule. In this example, the upper metal substrate 1005 was a 6056 aluminum alloy with a thickness of 2.0 mm, and the lower metal substrate 1007 was a 6056 aluminum alloy with a thickness of 2.0 mm. In this example, the camel schedule was performed with a maximum current of 34 kA, a first duration (i.e., first time period 214 and second time period 220) of 150 ms, a second duration (i.e., third time period 222) of 300 ms, a third duration (i.e., fourth time period 226 and fifth time period 230) of 230 ms, and a compressive force of 5.0 kN. As illustrated in FIG. 10, the RSW joint 1003 did not include inside cracking and was thus an improved joint.

[0054] A collection of exemplary embodiments are provided below, including at least some explicitly enumerated as "Illustrations" providing additional description of a variety of example embodiments in accordance with the concepts described herein. These illustrations are not meant to be mutually exclusive, exhaustive, or restrictive; and the disclosure not limited to these example illustrations but rather encompasses all possible modifications and variations within the scope of the issued claims and their equivalents.

[0055] Illustration 1. A method for joining metal substrates, the method comprising: applying a compressive force to at least two overlapping metal substrates, wherein at least one metal substrate of the at least two metal substrates comprises aluminum or an aluminum alloy; applying an electric current at a first level and ramping the electric current from the first level to a second level greater than the first level over a first time period; applying the electric current at the second level for a second time period after the first time period; discontinuing the electric current for a third time period after the second time period; applying the electric current at a third level for a fourth time period after the third time period; and ramping the electric current from the third level to a fourth level less than the third level over a fifth time period after the fourth time period.

[0056] Illustration 2. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein applying the electric current at the first level comprises applying the electric current at the first level a predetermined duration after applying the compressive force.

[0057] Illustration 3. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein applying the compressive force comprises applying a constant compressive force.

[0058] Illustration 4. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the first level is 0 kA.

[0059] Illustration 5. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the first time period is greater than the second time period, and wherein the third time period is greater than the first time period.

[0060] Illustration 6. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the fifth time period is greater than the fourth time period, and wherein the third time period is greater than the fourth time period.

[0061] Illustration 7. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the fifth time period is greater than the fourth time period, and wherein the third time period is greater than the fourth time period.

[0062] Illustration 8. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the third time period is from 300-400 ms, inclusive.

[0063] Illustration 9. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the at least one metal substrate comprises a 7xxx series aluminum alloy.

[0064] Illustration 10. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein each of the at least two metal substrates comprises a 7xxx series aluminum alloy.

[0065] Illustration 11. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein a rate of ramping the electric current from the third level to a fourth level is less than a rate of ramping the electric current from the first level to the second level.

[0066] Illustration 12. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the second level is greater than the first level and the fourth level, and wherein the third level is greater than the first level and the fourth level.

[0067] Illustration 13. A weld formed by the method of any of the preceding or subsequent illustrations or combination of illustrations.

[0068] Illustration 14. A method for joining metal substrates, the method comprising: applying a compressive force to at least two overlapping metal substrates, wherein at least one metal substrate of the at least two metal substrates comprises aluminum or an aluminum alloy; applying a first electric current for a first duration, wherein applying the first electric current comprises ramping up the first electric current from a first level of the first electric current to a second level of the first electric current; discontinuing the first electric current for a second duration after the first duration; and applying a second electric current for a third duration, wherein applying the second electric current comprises ramping down the second electric current from a first level of the second electric current to a second level of the second electric current.

[0069] Illustration 15. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the third duration is greater than the first duration.

[0070] Illustration 16. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the second duration is greater than the first duration.

[0071] Illustration 17. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the second level of the first current is greater than the first level of the first current and greater than the second level of the second current, and wherein the first level of the second current is greater than the first level of the first current and greater than the second level of the second current.

[0072] Illustration 18. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the at least one metal substrate comprises a 7xxx series aluminum alloy.

[0073] Illustration 19. The method of any of the preceding or subsequent illustrations or combination of illustrations, wherein the first level is 0 kA .

[0074] Illustration 20. A weld formed in the at least two overlapping metal substrates and by the method of any of the preceding or subsequent illustrations or combination of illustrations.

[0075] The subject matter of embodiments of the present invention is described here with specificity to meet statutory requirements, but this description is not necessarily intended to limit the scope of the claims. The claimed subject matter may be embodied in other ways, may include different elements or steps, and may be used in conjunction with other existing or future technologies. This description should not be interpreted as implying any particular order or arrangement among or between various steps or elements except when the order of individual steps or arrangement of elements is explicitly described. Directional references such as "up," "down," "top," "bottom," "left," "right," "front," and "back," among others, are intended to refer to the orientation as illustrated and described in the figure (or figures) to which the components and directions are referencing. As used herein, the meaning of "a," "an," or "the" includes singular and plural references unless the context clearly dictates otherwise. 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.

[0076] Aspects and features of the present disclosure can be used with any suitable metal substrate, however may be especially useful for bonding aluminum and/or aluminum alloys. In this description, reference is made to alloys identified by aluminum industry 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.

[0077] The above-described aspects are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the present disclosure. Many variations and modifications can be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the present disclosure. All such modifications and variations are intended to be included herein within the scope of the present disclosure, and all possible claims to individual aspects or combinations of elements or steps are intended to be supported by the present disclosure. Moreover, although specific terms are employed herein, as well as in the claims that follow, they are used only in a generic and descriptive sense, and not for the purposes of limiting the described invention, nor the claims that follow.

CLAIMS

That which is claimed:

1. A method for joining metal substrates, the method comprising:

applying a compressive force to at least two overlapping metal substrates, wherein at least one metal substrate of the at least two metal substrates comprises aluminum or an aluminum alloy;

over a first time period, applying an electric current at a first level and ramping the electric current from the first level to a second level greater than the first level ;

after the first time period, applying the electric current at the second level for a second time period;

after the second time period, discontinuing the electric current for a third time period;

after the third time period, applying the electric current at a third level for a fourth time period; and

after the fourth time period, ramping the electric current from the third level to a fourth level less than the third level over a fifth time period.

2. The method of claim 1, wherein applying the electric current at the first level comprises applying the electric current at the first level for a predetermined duration after applying the compressive force.

3. The method of claim 1, wherein applying the compressive force comprises applying a constant compressive force.

4. The method of claim 1, wherein the first level is 0 kA .

5. The method of claim 1, wherein the first time period is greater than the second time period, and wherein the third time period is greater than the first time period.

6. The method of claim 5, wherein the fifth time period is greater than the fourth time period, and wherein the third time period is greater than the fourth time period.

7. The method of claim 1, wherein the fifth time period is greater than the fourth time period, and wherein the third time period is greater than the fourth time period.

8. The method of claim 1, wherein the third time period is from 300-400 ms, inclusive.

9. The method of claim 1, wherein the at least one metal substrate comprises a 7xxx series aluminum alloy.

10. The method of claim 1, wherein each of the at least two metal substrates comprises a 7xxx series aluminum alloy.

11. The method of claim 1, wherein a rate of ramping the electric current from the third level to a fourth level is less than a rate of ramping the electric current from the first level to the second level.

12. The method of claim 1, wherein the second level is greater than the first level and the fourth level, and wherein the third level is greater than the first level and the fourth level.

13. A weld formed by the method of claim 1.

14. A method for joining metal substrates, the method comprising:

applying a compressive force to at least two overlapping metal substrates, wherein at least one metal substrate of the at least two metal substrates comprises aluminum or an aluminum alloy;

applying a first electric current for a first duration, wherein applying the first electric current comprises ramping up the first electric current from a first level of the first electric current to a second level of the first electric current;

after the first duration, discontinuing the first electric current for a second duration ; and

applying a second electric current for a third duration, wherein applying the second electric current comprises ramping down the second electric current from a first level of the second electric current to a second level of the second electric current.

15. The method of claim 14, wherein the third duration is greater than the first duration.

16. The method of claim 15, wherein the second duration is greater than the first duration.

17. The method of claim 14, wherein the second level of the first current is greater than the first level of the first current and greater than the second level of the second current, and wherein the first level of the second current is greater than the first level of the first current and greater than the second level of the second current.

18. The method of claim 14, wherein the at least one metal substrate comprises a 7xxx series aluminum alloy.

19. The method of claim 14, wherein the first level is 0 kA .

20. A weld formed in at least two overlapping metal substrates by the method of claim 14.

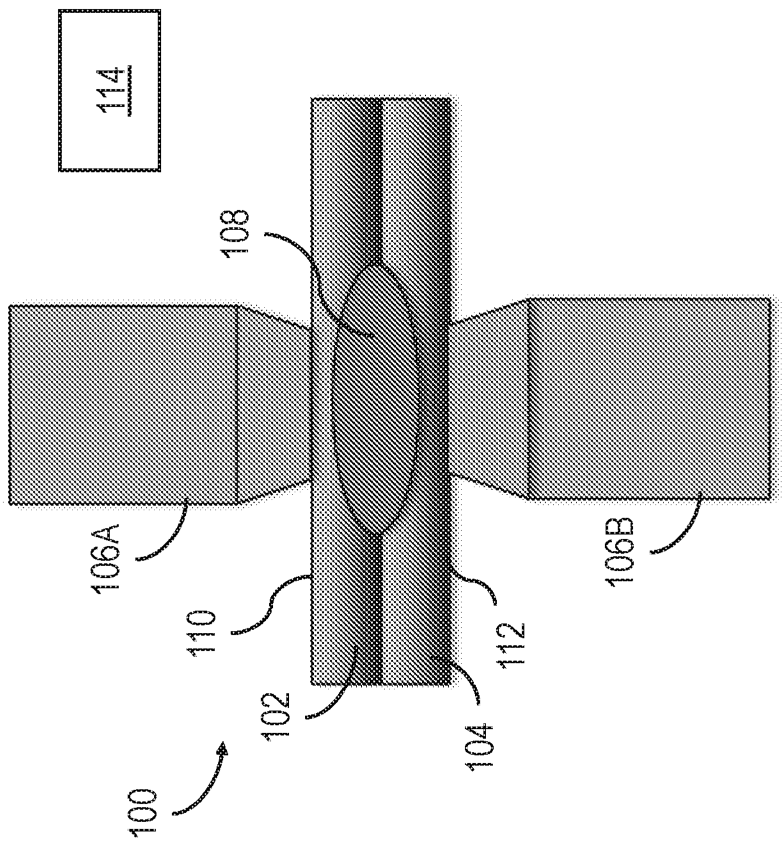

FIG. 1

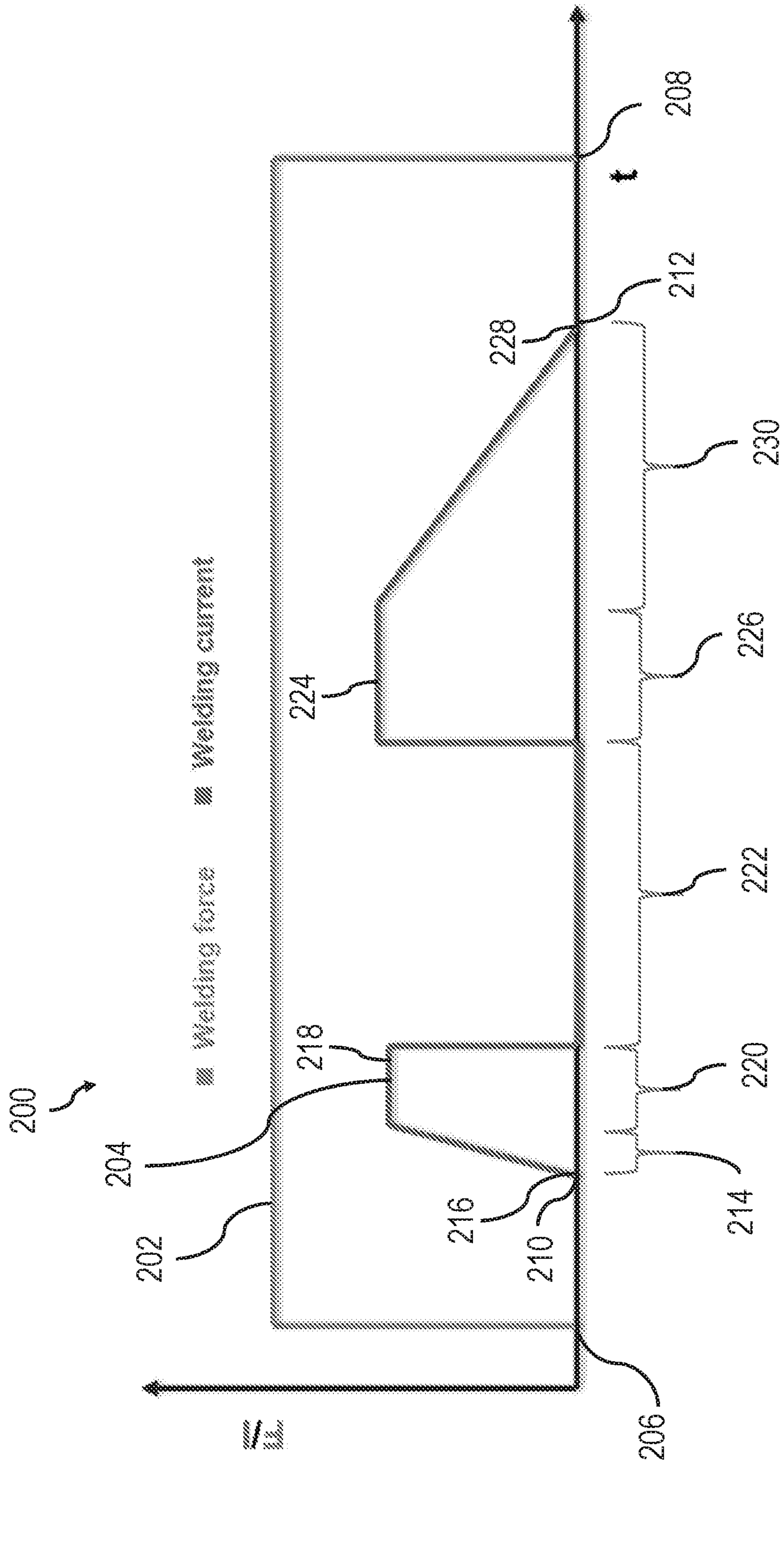
200
Welding force
Welding current
F/I
t
202
204
206
208
210
212
214
216
218
220
222
224
226
228
230

FIG. 2

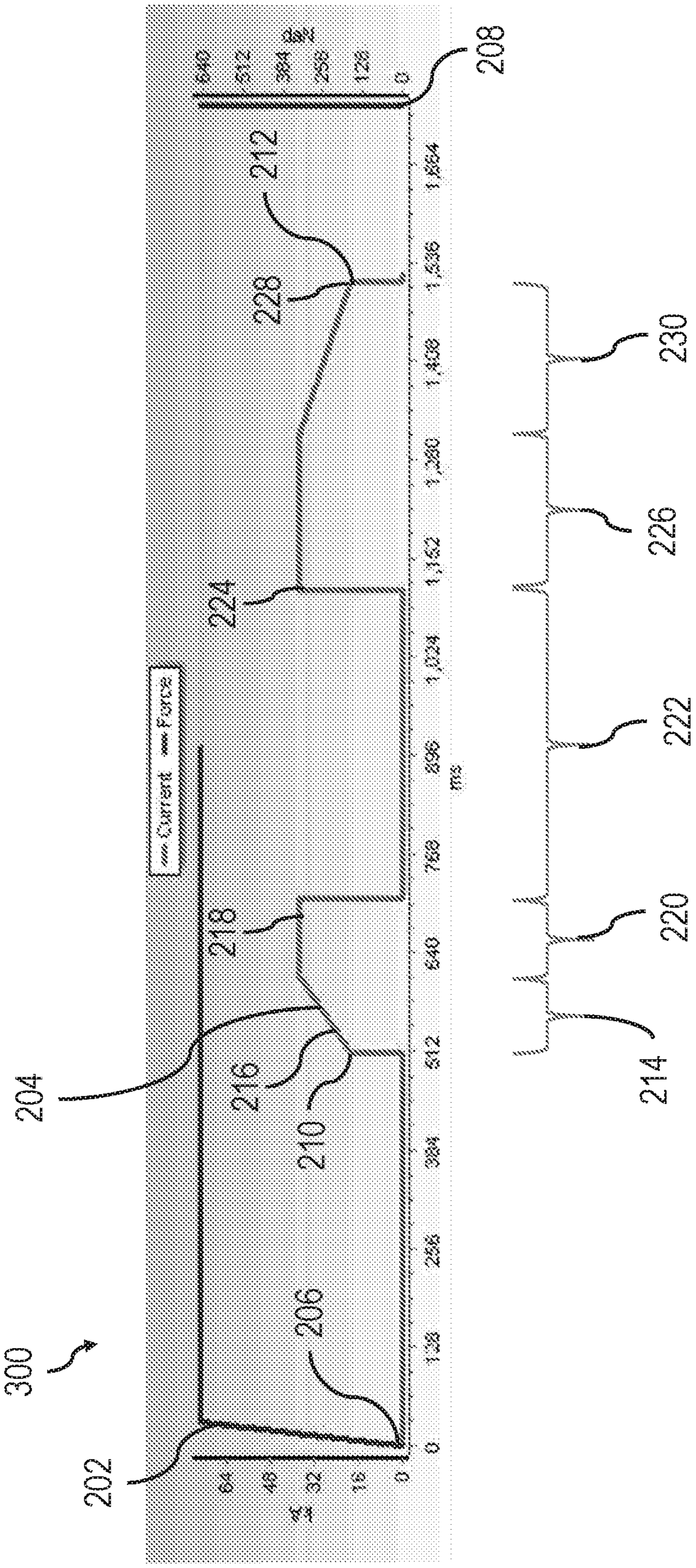
300
202
204
206
208
210
212
214
216
218
220
222
224
226
228
230
Current
Force
ms

FIG. 3

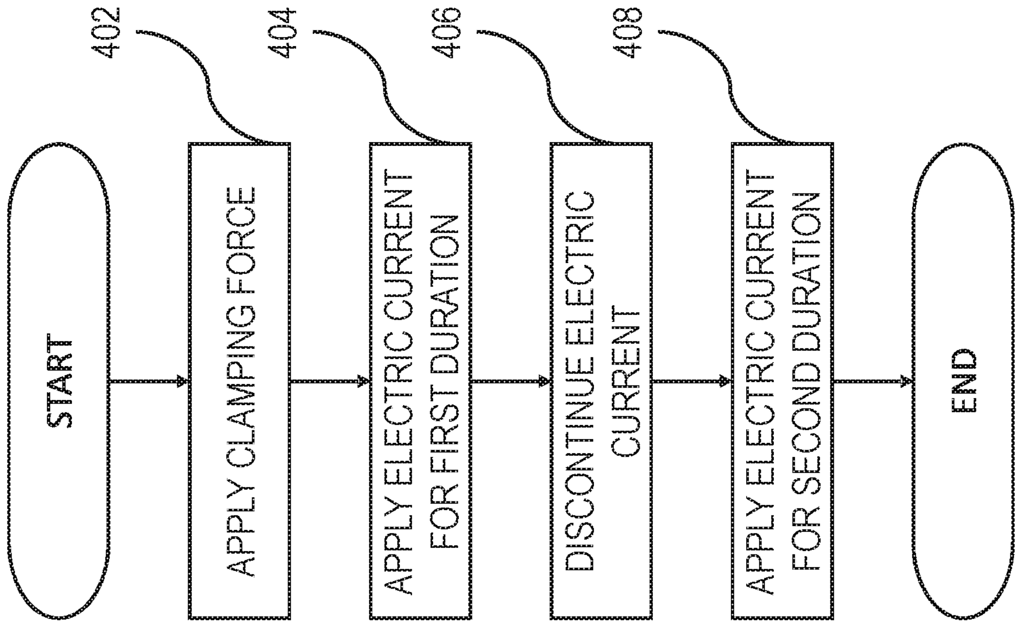
START
APPLY CLAMPING FORCE
402
APPLY ELECTRIC CURRENT FOR FIRST DURATION
404
DISCONTINUE ELECTRIC CURRENT
406
APPLY ELECTRIC CURRENT FOR SECOND DURATION
408
END

FIG. 4

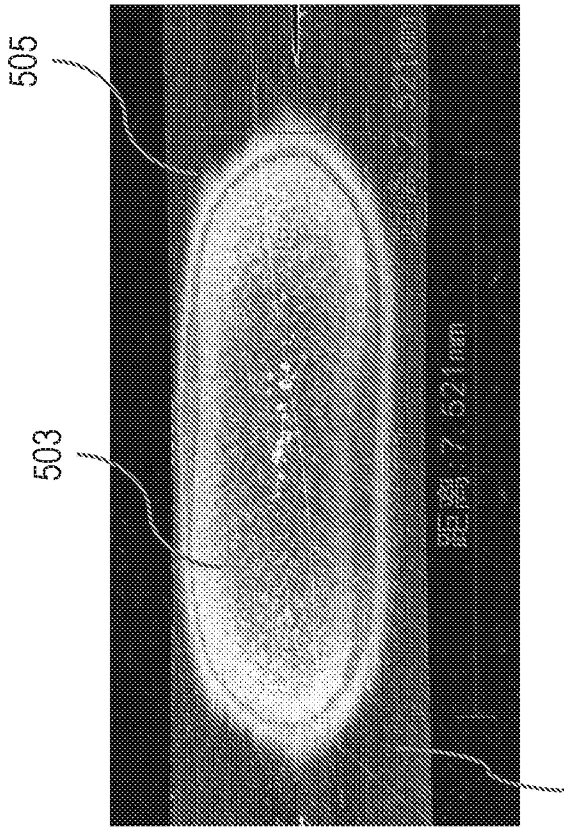

FIG. 5B

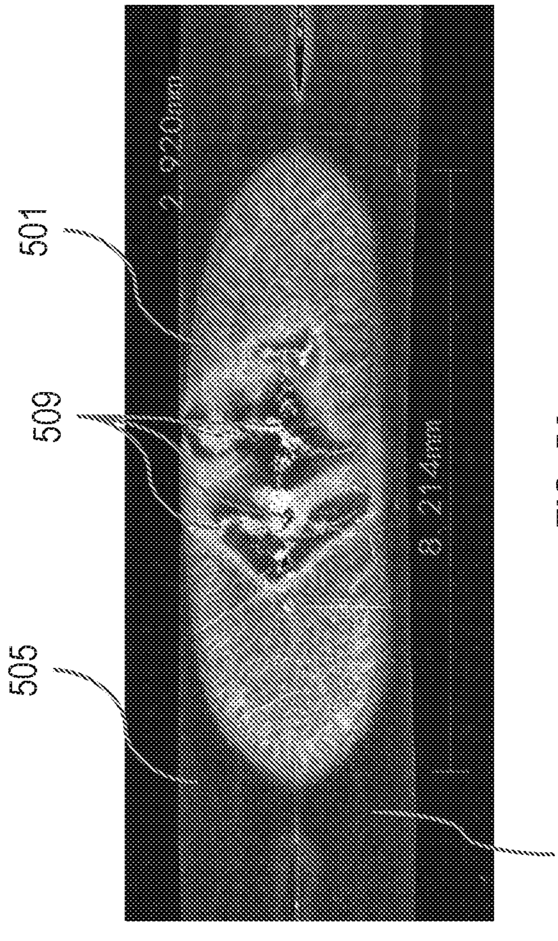

FIG. 5A

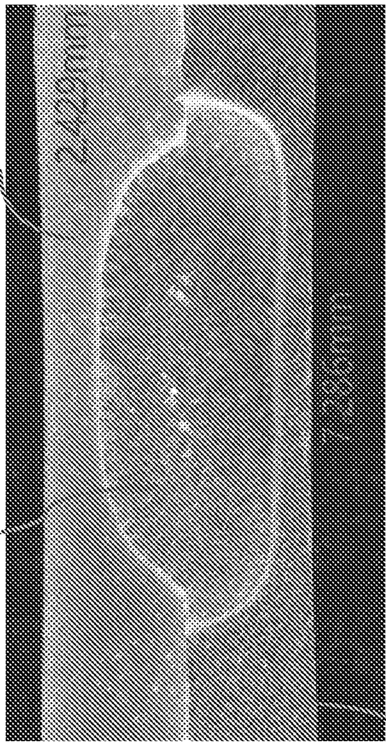

FIG. 6B

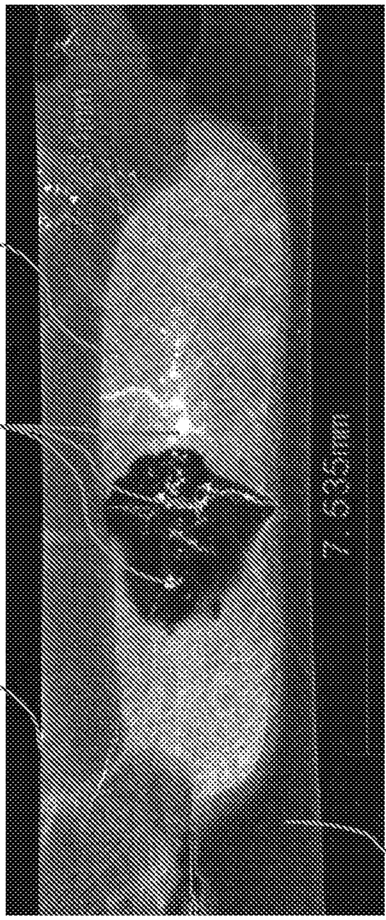

FIG. 6A

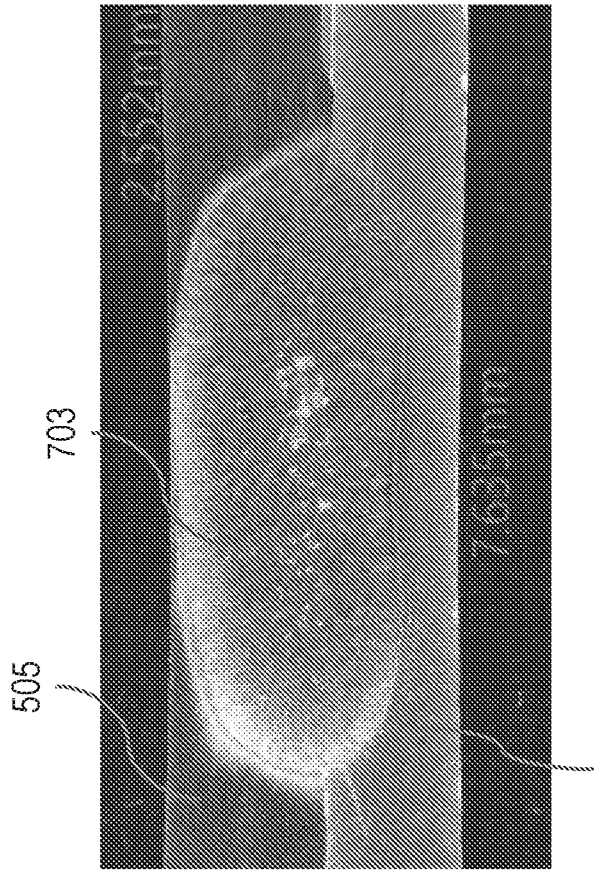

FIG. 7B

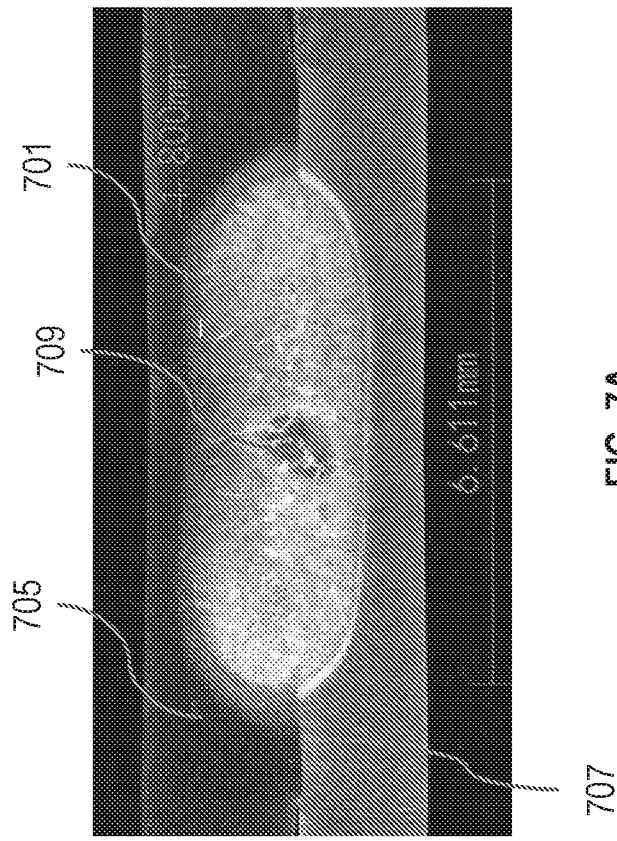

FIG. 7A

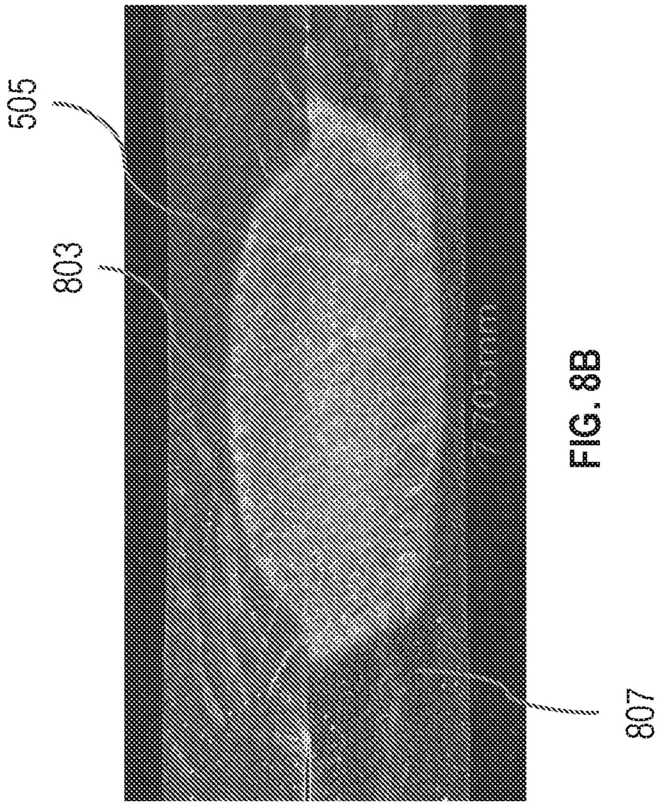

FIG. 8B

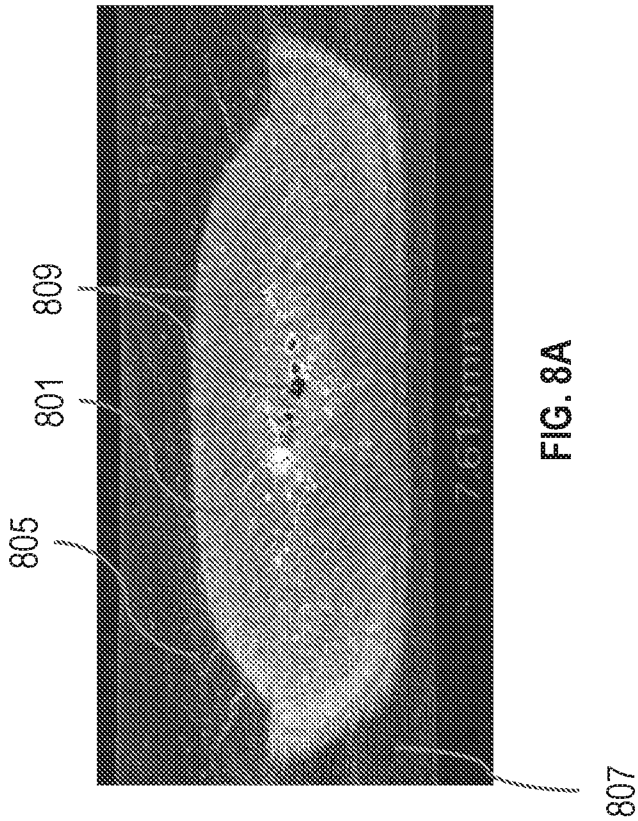

FIG. 8A

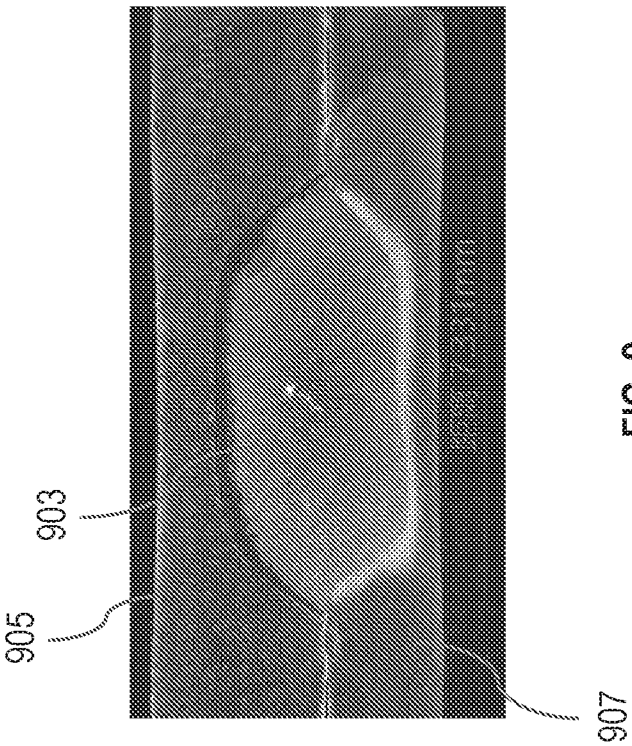

FIG. 9

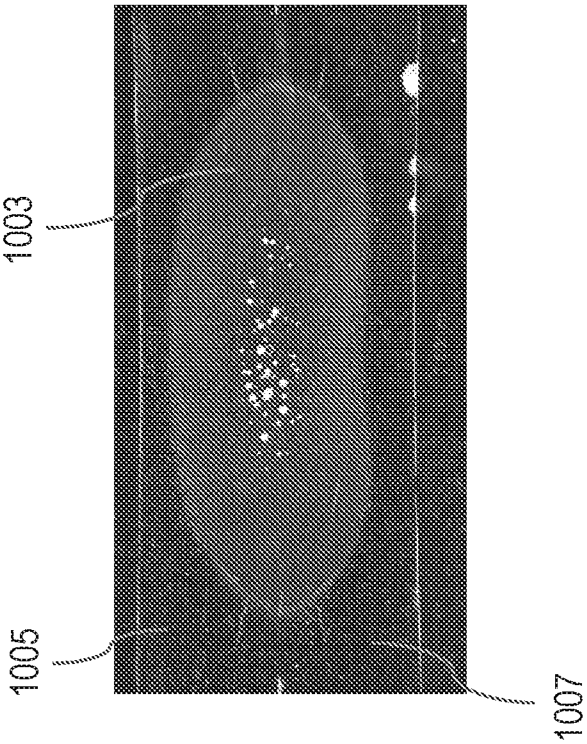

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/CN2022/125035

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23K11/11 B23K11/18 B23K11/30 B23K103/10
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016/144451 A1 (FUJIMOTO HIROKI [JP] ET AL) 26 May 2016 (2016-05-26)	1-7, 11-17, 19,20
A	figure 3 paragraphs [0016], [0020], [0044], [0047], [0058] claims 1-9 -----	8-10,18
X	JP 2006 224150 A (KOBE STEEL LTD; NISSHIN STEEL CO LTD) 31 August 2006 (2006-08-31) claims 1-4; figure 2c paragraphs [0005], [0015], [0027] -----	1-20

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2023	26/01/2023

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Pircher, Ernst

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BIN NIU ET AL: "Dynamic electrode force control of resistance spot welding robot", ROBOTICS AND BIOMIMETICS (ROBIO), 2009 IEEE INTERNATIONAL CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 19 December 2009 (2009-12-19), pages 2421-2426, XP031642018, ISBN: 978-1-4244-4774-9 figure 3c page 2422, left-hand column, last paragraph - right-hand column, paragraph first -----	1-20
A	US 2021/039189 A1 (GOTO TAKASHI [JP] ET AL) 11 February 2021 (2021-02-11) paragraphs [0035] - [0036], [0053], [0068]; claims 1-3; figure 5 -----	1-20
A	CN 112 570 867 A (SHANGHAI INST OPTICS & FINE MECH CAS) 30 March 2021 (2021-03-30) claims 1-10; figure 2 -----	1-20
A	WO 2019/203363 A1 (KOBE STEEL LTD [JP]; NADEX CO LTD [JP]) 24 October 2019 (2019-10-24) paragraph [0034]; claims 1-10; figures 2, 8 -----	1-20

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/CN2022/125035

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		JP 6094676 B2	15-03-2017
		JP WO2015005134 A1	02-03-2017
		KR 20160021858 A	26-02-2016
		MX 367552 B	27-08-2019
		MY 174502 A	23-04-2020
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