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Electrically Treated Metal Products and Methods of Making the Same

Shreyas Devanathan
Novelis Inc.

Patrick Lester
Novelis Inc.

Rajasekhar Talla
Novelis Inc.

Rashmi Mohanty
Novelis Inc.

Julio Malpica
Novelis Inc.

ELECTRICALLY TREATED METAL PRODUCTS AND METHODS OF MAKING THE SAME

By: Shreyas Devanathan, Patrick Lester, Rajasekhar Talla, Rashmi Mohanty, and Julio Malpica

FIELD

The present disclosure is directed to metal products and the atomic characteristics of the same. The disclosure further relates to methods of artificially aging aluminum alloy products. The disclosure additionally relates to methods of joining aluminum alloy products.

BACKGROUND

Metal products (e.g., aluminum alloy products) are often bonded or joined to other metals or alloys, including other aluminum alloys, during fabrication of aluminum alloy-based products and other metal-based products. Requirements of the products include, for example, resistance to fracture about the joining site, good bond durability, and high resistance to harsh environmental conditions.

SUMMARY

Covered embodiments of the invention are defined by the claims, not this summary. This summary is a high-level overview of various aspects 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, any or all drawings, and each claim.

Described herein is a method of treating metal products, comprising: passing an electric current through a portion of a first metal product to electrically age the portion of the first metal product, wherein the portion of the first metal product is heated to a temperature sufficient to soften the portion of the first metal product without melting the portion of the first metal product, wherein

the portion of the first metal product is a location on the first metal product where the first metal product can be subsequently joined to at least a second metal product. In some cases, the method further comprises cooling the location on the first metal product where the first metal product can be subsequently joined to at least a second metal product; and after the cooling, joining the first metal product to the second metal product. In certain aspects, the location on the first metal product where the first metal product can be joined to at least the second metal product is a joining point.

In some non-limiting examples, the method further comprises passing the electric current through the second metal product at a joining point of the second metal product. (e.g., pulsing the electric current through the portion of the first metal product). In certain aspects, passing the electric current through the portion of the first metal product comprises locally heating the portion of the first metal product to provide a locally heat-treated portion of the first metal and/or decreasing an activation energy of atoms within at least the first metal product to control a kinetic activity of atoms within at least the first metal product. In some cases, controlling the kinetic activity of atoms within at least the first metal product comprises one or more of controlling grain growth, controlling precipitate growth, controlling an aging response, and controlling a solutionizing response. In some further examples, controlling the aging response further comprises increasing a rate of aging kinetics of at least the first metal product. For example, increasing the rate of the aging kinetics of at least the first metal product further comprises reducing heat treatment time to achieve a desired heat treated state, wherein the desired heat treated state comprises a T5 temper, a T6 temper, a T7 temper, a T8x temper, a T9 temper, or a T10 temper (e.g., increasing the rate of the aging kinetics of at least the first metal product further comprises increasing a strength of at least the first metal product).

In some cases, passing the electric current through the portion of the first metal product comprises passing a direct current through the portion of the first metal product or passing an alternating current through the portion of the first metal product. In certain aspects, passing the electric current through the portion of the first metal product comprises tuning a waveform of the electric current (e.g., tuning the waveform of the electric current comprises creating a square wave, a sawtooth wave, a sine wave, a triangle wave, or any combination thereof). In other cases, tuning the waveform of the electric current comprises controlling an amplitude and a pulse width of the waveform. Additionally, for example, passing the electric current through the portion of the first metal product comprises passing up to about 20 kiloamperes of electric current through the portion of the first metal product for up to about 60 seconds. In some examples, cooling the portion of the first metal product is performed at a rate of up to about 600 °C per second.

In some cases, joining the first metal product to the second metal product comprises inserting a piercing fastener into a joining point, wherein inserting a piercing fastener into the joining point comprises inserting a self-piercing rivet, a self-piercing screw, a self-drilling screw, a self-piercing grommet, or any suitable self-piercing fastener. For example, inserting a piercing fastener into the joining point does not fracture the first metal product and does not fracture the second metal product.

Also described herein is a system for pierce-joining metal products without fracturing the metal products according to the method of any preceding or subsequent illustration, comprising: a piercing-fastener driving system; a current source; a first counter-electrode, wherein the first counter-electrode is electrically connected to the current source; a second counter-electrode, wherein the second counter-electrode is electrically connected to the current source; and a clamping system, wherein the clamping system is configured to electrically contact the first counter-electrode to a surface of a first metal product and contact the second counter-electrode to a surface of at least a second metal product, wherein the first metal product and at least the second metal product are positioned to contact each other at a joining point, wherein the surface of the first metal product and the surface of the second metal product are opposite each other across the joining point, and wherein the first counter-electrode and the second counter-electrode are configured to pass a current supplied by the current source through at least the joining point of the first metal product to heat the joining point of the first metal product to soften the joining point without melting the joining point to electrically age the first metal product before joining the first metal product to the second metal product with the piercing-fastener driving system. In certain aspects, the system comprises a cooling system configured to cool the joining point after the current is passed through the joining point, and a control system configured to activate the current source and maintain current flow until a temperature of the joining point achieves a temperature of from 250 °C to 350 °C, and to deactivate the current source when the temperature of the joining point achieves a temperature of from 250 °C to 350 °C. In some examples, the system further comprises a temperature probe, wherein the temperature probe is configured to monitor a temperature of the joining point and to communicate the temperature of the joining point to the control system. In some cases, the system further comprises a control system configured to activate the cooling system after deactivating the current source, to maintain the cooling system until the temperature of the joining point is room temperature, to deactivate the cooling system when the temperature of the joining point is room temperature, and to activate the piercing-fastener driving system after deactivating the cooling system.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a micrograph of a self-piercing rivet button joining two metal products together according to a comparative method described herein.

Figure 2 is a micrograph of a self-piercing rivet button joining two metal products together according to the methods described herein.

Figure 3 is a micrograph of a self-piercing rivet button joining two metal products together according to the methods described herein.

Figure 4 is a micrograph of a self-piercing rivet button joining two metal products together according to the methods described herein and depicting the effect of the electro-pulse treatment on an impact region.

Figure 5 is a graph showing the electrical conductivity of aluminum alloy coupons after various electrical aging processes described herein.

Figure 6 is a graph showing the hardness of aluminum alloy coupons after various electrical aging processes described herein.

Figure 7 shows scanning transmission electron microscope (STEM) images showing the microstructure of aluminum alloy coupons prepared according to the methods described herein.

DETAILED DESCRIPTION

Provided herein are methods of treating metal products such that the metal products can be, for example, joined without fracturing during a joining process, including (i) passing an electric current through a portion of a first metal product corresponding to a location where the first metal product can be joined to at least a second metal product, (ii) placing the first metal product adjacent to a second metal product, such that the first metal product and the second metal product are configured to be joined, and (iii) joining the first metal product to the second metal product. Accordingly, the location on the first metal product where the first metal product can be joined to at least a second metal product is a joining point. Passing the electric current through the joining point heats the first metal at the joining point such that the metal is softened without melting the metal (e.g., heats the first metal to a temperature below its melting point). Optionally, the methods include cooling the joining point after passing the electric current through the joining point. In some examples, passing the electric current through the joining point includes pulsing the electric current through the joining point, locally heating the joining point, and/or locally heat treating the joining point. In some examples, passing the electric current through the joining point includes decreasing an activation energy of atoms within the metal product(s), wherein decreasing the activation energy of atoms within the metal product(s) comprises controlling kinetic activity of atoms within the metal product(s). Accordingly, controlling the kinetic activity of atoms within the metal product(s) results in controlling grain growth, controlling precipitate growth, controlling an aging response, and controlling a solutionizing response.

Controlling the kinetic activity of atoms within the metal product(s) can facilitate fastening with a piercing fastener, including a self-piercing rivet, a self-piercing screw, a self-drilling screw, a self-piercing grommet, or any suitable self-piercing fastener. Further, as described herein, inserting a piercing fastener into the electrically aged joining point does not fracture the metal product(s) and provides improved formability and a more durable, corrosion resistant, and more aesthetically pleasing pierce-fastened joint.

In certain aspects, the methods described herein, e.g., electrically aging at least a portion of a 7xxx series aluminum alloy artificially aged to a T6 temper, can provide a 7xxx series aluminum alloy in T6 temper that is amenable to forming and/or joining processes that a 7xxx series aluminum alloy in T6 temper is otherwise not amendable to, including, for example, hemming, bending, forming, stamping, drawing, shaping, roll forming, or the like.

Definitions and Descriptions:

As used herein, the terms “invention,” “the invention,” “this invention,” and “the present invention” are intended to refer broadly to all of the subject matter of this patent application and the 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.

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

In this description, reference is made to alloys identified by AA numbers and other related designations, such as “7xxx” and “series.” 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.

Reference is made in this application to alloy temper or condition. For an understanding of the alloy temper descriptions most commonly used, see “American National Standards (ANSI) H35 on Alloy and Temper Designation Systems.” An F condition or temper refers to an aluminum alloy as fabricated. A W condition or temper refers to an aluminum alloy solution heat treated at a temperature greater than a solvus temperature of the aluminum alloy and then quenched. An O condition or temper refers to an aluminum alloy after annealing. An Hxx condition or temper, also referred to herein as an H temper, refers to a non-heat treatable aluminum alloy after cold rolling with or without thermal treatment (e.g., annealing). Suitable H tempers include HX1, HX2, HX3 HX4, HX5, HX6, HX7, HX8, or HX9 tempers. A T1 condition or temper refers to an aluminum alloy cooled from hot working and naturally aged (e.g., at room temperature). A T2 condition or temper refers to an aluminum alloy cooled from hot working, cold worked and naturally aged. A T3 condition or temper refers to an aluminum alloy solution heat treated, cold worked, and naturally aged. A T4 condition or temper refers to an aluminum alloy solution heat treated and naturally aged. A T5 condition or temper refers to an aluminum alloy cooled from hot working and artificially aged (at elevated temperatures). A T6 condition or temper refers to an aluminum alloy solution heat treated and artificially aged. A T7 condition or temper refers to an aluminum alloy solution heat treated and artificially overaged. A T8x condition or temper refers to an aluminum alloy solution heat treated, cold worked, and artificially aged. A T9 condition or temper refers to an aluminum alloy solution heat treated, artificially aged, and cold worked.

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.

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.

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).

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.

All ranges disclosed herein are to be understood to encompass any and endpoints and 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.

As used herein, terms such as "cast metal product," "cast product," "cast aluminum alloy product," and the like are interchangeable and refer to a product produced by direct chill casting (including direct chill co-casting) or semi-continuous casting, continuous casting (including, for example, by use of a twin belt caster, a twin roll caster, a twin block caster, or any other continuous caster), electromagnetic casting, hot top casting, or any other casting method.

Methods of Making Electrically Treated Metal Products and Metal Product Joints

In some non-limiting examples, the methods described herein include joining a first metal product to a second metal product. In certain aspects, the first metal product and/or the second metal product is an aluminum alloy, though one or both need not be. In some cases, the aluminum alloy is provided in an F temper (e.g., an "as-fabricated" temper condition as described above). In further examples, the aluminum alloy is provided after solutionizing and optionally the aluminum alloy is provided after solutionizing and quenching after the solutionizing step (e.g., an aluminum alloy, such as an artificially aged 7xxx series aluminum alloy, in a T6 temper). In certain examples, the aluminum alloy is an aluminum alloy product (e.g., a rolled product including a plate, shate, or sheet as described above, and/or a formed product provided by forming an aluminum alloy plate, shate, or sheet).

As described herein, the methods include electrically treating (e.g., electrically aging) at least a portion of one or more of the metal products (e.g., the first metal product and/or the second metal product) before joining the two products. In one configuration, placing a first metal product adjacent to a second metal product, such that the first and second metal products are configured to be joined, provides a joining point. As used herein, a “joining point” is an overlap or an abutment of at least a portion of a first metal product and at least a portion of a second metal product at which, for example a piercing fastener, as described herein, is driven through the first metal product and at least the second metal product to mechanically join the metal products. In some examples, the first metal product and the second metal product can be joined by clinching, flow drill screwing, crimping, any mechanical joining process including a forming step, or any combination thereof. In certain aspects, the portion of the first metal product and the portion of the second metal product are in electrical contact with each other at the joining point.

Electrically aging at least a portion of the first metal product(s) is performed by passing a current through at least the portion of the first metal product. In certain examples, the current is supplied in any suitable waveform, including a square wave, a sine wave, a sawtooth wave, a triangular wave, or any combination thereof. In some cases, the current is supplied as a constant current. In some examples, the current is supplied as a pulsed current. In certain cases, the current is supplied as a direct current (DC). In certain examples, the current is supplied as an alternating current (AC). Not to be bound by theory, supplying the current as a pulsed current can alter the precipitation and/or dissolution rates of intermetallic and/or interstitial precipitates. Additionally, supplying the current as a pulsed current can affect the size and distribution of intermetallic and/or interstitial precipitates by providing increased energy in a short time.

Further, the increased energy can lower the overall activation energy needed for intermetallic and/or precipitate formation and can affect the interdiffusion behavior of the elements present. An increased precipitation rate provides increased aging kinetics and thus can provide a higher strength after strengthening heat treatment when compared to non-electrically aged metal products subjected to the same strengthening heat treatment. Additionally, electrically aging the metal products can reduce heat treatment time typically employed to strengthen heat-treatable metals. Further, increasing the dissolution rate can reduce heat treatment and/or solutionizing time typically employed to thermally process heat-treatable metals.

Additionally, applying an electric field can affect the stability of the equilibrium vacancy concentration in a solutionized aluminum alloy, or in a solutionized and quenched aluminum alloy. In certain examples, applying the electric field to a solutionized or solutionized and quenched aluminum alloy can alter the natural aging kinetics of aluminum alloys. For example, applying the electric field to an aluminum alloy can decrease the natural aging kinetics to suppress the natural aging (e.g., natural age hardening) such that the aluminum alloy will not age harden over time. In certain cases, applying the electric field can increase the natural aging kinetics such that natural aging is accelerated and can reach an age hardened temper in a reduced period of time when compared to an aluminum alloy not subjected to the electric field. Thus, in some cases, applying the electric field to a solutionized or solutionized and quenched aluminum alloy provides controllable aging kinetics.

In some cases, applying an electric field can improve plasticity, grain refinement, and phase transformations in a solutionized aluminum alloy. Applying the electric field is an instantaneous input of energy into the aluminum alloy. Thus, applying the electric field can facilitate cold forming by dissolving precipitate clusters and Guinier-Preston (GP) zones (e.g., Guinier-Preston zones of the first kind (GP-I) and of the second kind (GP-II), as known to those of ordinary skill in the art) formed during natural aging, bringing the aluminum alloy to a metallurgical state similar to a W temper. GP-I zones include precipitates that are approximately 1-2 atoms thick and up to 25 atoms in diameter, whereas GP-II zones include precipitates that are approximately 8-10 atoms thick and from 30 to 100 atoms in diameter. In certain aspects, applying the electric field can reduce total aging time (e.g., natural aging and/or artificial aging) by forming GP II zones from rapidly pre-aging the aluminum alloy. Additionally, in some cases, applying the electric field can enhance strength and/or formability by producing nanometer-scale grains in the aluminum alloy.

In certain aspects, applying the electric field to a solutionized and/or solutionized and quenched aluminum alloy, and passing an electric current through the aluminum alloy (e.g., at the joining point of at least a first metal product, or two or more metal products, including aluminum alloys) affects downstream processes by affecting atomic migration within the aluminum alloy or other metal. For example, artificial aging, natural aging, solutionizing, precipitation hardening, and/or overaging can be affected by electrically aging the aluminum alloy and/or other metals. In certain aspects, the time required for artificial aging, natural aging, solutionizing, precipitation hardening, and/or overaging can be reduced when compared to aluminum alloys and/or other metals that are not electrically aged. Additionally, electrically aging the metal products as described herein can provide a strengthened and/or hardened metal product that is amendable to processing methods normally unavailable to strengthened and/or hardened metal products.

For example, a 7xxx series aluminum alloy in T4 or T6 temper can be amenable to cold forming after electrical treatment by reducing the size and quantity of precipitates, and/or dissolving precipitates formed during aging. In a further example, and described in more detail below, a 7xxx series aluminum alloy in T6 temper can be amenable to piercing-fastener joining by locally altering the microstructure of the metal products. As such, localized electrical aging can locally refine the grain structure of the metal products and reduce the fracture toughness at the locally electrically aged area, thus allowing the metal products to be pierced without fracturing. Accordingly, a locally refined grain structure can further provide improved resistance to corrosion, and tunable strength and/or formability properties.

In certain aspects, passing an electric current through the joining point is performed by controlling a pulse width of the waveform. In certain cases, the pulse width of the waveform can range from about 1 microsecond (μs) to about 1 s (e.g., from about 5 μs to about 990 ms, from about 10 μs to about 980 ms, from about 15 μs to about 970 ms, from about 20 μs to about 960 ms, from about 25 μs to about 950 ms, from about 30 μs to about 940 ms, from about 35 μs to about 930 ms, from about 40 μs to about 920 ms, from about 45 μs to about 910 ms, from about 50 μs to about 900 ms, from about 55 μs to about 890 ms, from about 60 μs to about 880 ms, from about 65 μs to about 870 ms, from about 70 μs to about 860 ms, from about 75 μs to about 850 ms, from about 80 μs to about 840 ms, from about 85 μs to about 830 ms, from about 90 μs to about 820 ms, from about 95 μs to about 810 ms, from about 100 μs to about 800 ms, from about 110 μs to about 790 ms, from about 120 μs to about 780 ms, from about 130 μs to about 770 ms, from about 140 μs to about 760 ms, from about 150 μs to about 750 ms, from about 160 μs to about 740 ms, from about 170 μs to about 730 ms, from about 180 μs to about 720 ms, from about 190 μs to about 710 ms, from about 200 μs to about 700 ms, from about 210 μs to about 690 ms, from about 220 μs to about 680 ms, from about 230 μs to about 670 ms, from about 240 μs to about 660 ms, from about 250 μs to about 650 ms, from about 260 μs to about 640 ms, from about 270 μs to about 630 ms, from about 280 μs to about 620 ms, from about 290 μs to about 610 ms, from about 300 μs to about 600 ms, from about 310 μs to about 590 ms, from about 320 μs to about 580 ms, from about 330 μs to about 570 ms, from about 340 μs to about 560 ms, from about 350 μs to about 550 ms, from about 360 μs to about 540 ms, from about 370 μs to about 530 ms, from about 380 μs to about 520 ms, from about 390 μs to about 510 ms, from about 400 μs to about 500 ms, from about 410 μs to about 490 ms, from about 420 μs to about 480 ms, from about 430 μs to about 470 ms, or from about 440 μs to about 460 ms). For example, the pulse width can be about 1 μs, about 5 μs, about 10 μs, about 15 μs, about 20 μs, about 25 μs, about 30 μs, about 35 μs, about 40 μs, about 45 μs, about 50 μs, about 55 μs, about 60 μs, about 65 μs, about 70 μs, about 75 μs, about 80 μs, about 85 μs, about 90 μs, about 95 μs, about 100 μs, about 105 μs, about 110 μs, about 115 μs, about 120 μs, about 125 μs, about 130 μs, about 135 μs, about 140 μs, about 145 μs, about 150 μs, about 155 μs, about 160 μs, about 165 μs, about 170 μs, about 175 μs, about 180 μs, about 185 μs, about 190 μs, about 195 μs, about 200 μs, about 205 μs, about 210 μs, about 215 μs, about 220 μs, about 225 μs, about 230 μs, about 235 μs, about 240 μs, about 245 μs, about 250 μs, about 255 μs, about 260 μs, about 265 μs, about 270 μs, about 275 μs, about 280 μs, about 285 μs, about 290 μs, about 295 μs, about 300 μs, about 305 μs, about 310 μs, about 315 μs, about 320 μs, about 325 μs, about 330 μs, about 335 μs, about 340 μs, about 345 μs, about 350 μs, about 355 μs, about 360 μs, about 365 μs, about 370 μs, about 375 μs, about 380 μs, about 385 μs, about 390 μs, about 395 μs, about 400 μs, about 405 μs, about 410 μs, about 415 μs, about 420 μs, about 425 μs, about 430 μs, about 435 μs, about 440 μs, about 445 μs, about 450 μs, about 455 μs, about 460 μs, about 465 μs, about 470 μs, about 475 μs, about 480 μs, about 485 μs, about 490 μs, about 495 μs, about 500 μs, about 505 μs, about 510 μs, about 515 μs, about 520 μs, about 525 μs, about 530 μs, about 535 μs, about 540 μs, about 545 μs, about 550 μs, about 555 μs, about 560 μs, about 565 μs, about 570 μs, about 575 μs, about 580 μs, about 585 μs, about 590 μs, about 595 μs, about 600 μs, about 605 μs, about 610 μs, about 615 μs, about 620 μs, about 625 μs, about 630 μs, about 635 μs, about 640 μs, about 645 μs, about 650 μs, about 655 μs, about 660 μs, about 665 μs, about 670 μs, about 675 μs, about 680 μs, about 685 μs, about 690 μs, about 695 μs, about 700 μs, about 705 μs, about 710 μs, about 715 μs, about 720 μs, about 725 μs, about 730 μs, about 735 μs, about 740 μs, about 745 μs, about 750 μs, about 755 μs, about 760 μs, about 765 μs, about 770 μs, about 775 μs, about 780 μs, about 785 μs, about 790 μs, about 795 μs, about 800 μs, about 805 μs, about 810 μs, about 815 μs, about 820 μs, about 825 μs, about 830 μs, about 835 μs, about 840 μs, about 845 μs, about 850 μs, about 855 μs, about 860 μs, about 865 μs, about 870 μs, about 875 μs, about

880 µs, about 885 µs, about 890 µs, about 895 µs, about 900 µs, about 905 µs, about 910 µs, about 915 µs, about 920 µs, about 925 µs, about 930 µs, about 935 µs, about 940 µs, about 945 µs, about 950 µs, about 955 µs, about 960 µs, about 965 µs, about 970 µs, about 975 µs, about 980 µs, about 985 µs, about 990 µs, about 995 µs, about 1 ms, about 5 ms, about 10 ms, about 15 ms, about 20 ms, about 25 ms, about 30 ms, about 35 ms, about 40 ms, about 45 ms, about 50 ms, about 55 ms, about 60 ms, about 65 ms, about 70 ms, about 75 ms, about 80 ms, about 85 ms, about 90 ms, about 95 ms, about 100 ms, about 105 ms, about 110 ms, about 115 ms, about 120 ms, about 125 ms, about 130 ms, about 135 ms, about 140 ms, about 145 ms, about 150 ms, about 155 ms, about 160 ms, about 165 ms, about 170 ms, about 175 ms, about 180 ms, about 185 ms, about 190 ms, about 195 ms, about 200 ms, about 205 ms, about 210 ms, about 215 ms, about 220 ms, about 225 ms, about 230 ms, about 235 ms, about 240 ms, about 245 ms, about 250 ms, about 255 ms, about 260 ms, about 265 ms, about 270 ms, about 275 ms, about 280 ms, about 285 ms, about 290 ms, about 295 ms, about 300 ms, about 305 ms, about 310 ms, about 315 ms, about 320 ms, about 325 ms, about 330 ms, about 335 ms, about 340 ms, about 345 ms, about 350 ms, about 355 ms, about 360 ms, about 365 ms, about 370 ms, about 375 ms, about 380 ms, about 385 ms, about 390 ms, about 395 ms, about 400 ms, about 405 ms, about 410 ms, about 415 ms, about 420 ms, about 425 ms, about 430 ms, about 435 ms, about 440 ms, about 445 ms, about 450 ms, about 455 ms, about 460 ms, about 465 ms, about 470 ms, about 475 ms, about 480 ms, about 485 ms, about 490 ms, about 495 ms, about 500 ms, about 505 ms, about 510 ms, about 515 ms, about 520 ms, about 525 ms, about 530 ms, about 535 ms, about 540 ms, about 545 ms, about 550 ms, about 555 ms, about 560 ms, about 565 ms, about 570 ms, about 575 ms, about 580 ms, about 585 ms, about 590 ms, about 595 ms, about 600 ms, about 605 ms, about 610 ms, about 615 ms, about 620 ms, about 625 ms, about 630 ms, about 635 ms, about 640 ms, about 645 ms, about 650 ms, about 655 ms, about 660 ms, about 665 ms, about 670 ms, about 675 ms, about 680 ms, about 685 ms, about 690 ms, about 695 ms, about 700 ms, about 705 ms, about 710 ms, about 715 ms, about 720 ms, about 725 ms, about 730 ms, about 735 ms, about 740 ms, about 745 ms, about 750 ms, about 755 ms, about 760 ms, about 765 ms, about 770 ms, about 775 ms, about 780 ms, about 785 ms, about 790 ms, about 795 ms, about 800 ms, about 805 ms, about 810 ms, about 815 ms, about 820 ms, about 825 ms, about 830 ms, about 835 ms, about 840 ms, about 845 ms, about 850 ms, about 855 ms, about 860 ms, about 865 ms, about 870 ms, about 875 ms, about 880 ms, about 885 ms, about 890 ms, about 895 ms, about 900 ms, about 905 ms, about 910 ms, about 915 ms, about 920 ms, about 925

ms, about 930 ms, about 935 ms, about 940 ms, about 945 ms, about 950 ms, about 955 ms, about 960 ms, about 965 ms, about 970 ms, about 975 ms, about 980 ms, about 985 ms, about 990 ms, about 995 ms, or about 1 s.

In certain examples, a pulse frequency of the electric current through the joining point is controlled. The pulse frequency can range from about 1 Hertz (Hz) to about 120 kiloHertz (kHz) (e.g., from about 5 Hz to about 110 kHz, from about 10 Hz to about 100 kHz, from about 20 Hz to about 90 kHz, from about 30 Hz to about 80 kHz, from about 40 Hz to about 70 kHz, from about 50 Hz to about 60 kHz, from about 60 Hz to about 50 kHz, from about 70 Hz to about 40 kHz, from about 80 Hz to about 30 kHz, from about 90 Hz to about 20 kHz, from about 100 Hz to about 10 kHz, from about 110 Hz to about 1 kHz, from about 120 Hz to about 900 Hz, from about 130 Hz to about 850 Hz, from about 140 Hz to about 800 Hz, from about 150 Hz to about 750 Hz, from about 160 Hz to about 700 Hz, from about 170 Hz to about 650 Hz, from about 180 Hz to about 600 Hz, from about 190 Hz to about 550 Hz, from about 200 Hz to about 500 Hz, from about 225 Hz to about 475 Hz, from about 250 Hz to about 450 Hz, from about 275 Hz to about 425 Hz, from about 300 Hz to about 400 Hz, or from about 325 Hz to about 375 Hz). For example, the frequency of the pulse can be about 1 Hz, about 10 Hz, about 20 Hz, about 30 Hz, about 40 Hz, about 50 Hz, about 60 Hz, about 70 Hz, about 80 Hz, about 90 Hz, about 100 Hz, about 110 Hz, about 120 Hz, about 130 Hz, about 140 Hz, about 150 Hz, about 160 Hz, about 170 Hz, about 180 Hz, about 190 Hz, about 200 Hz, about 210 Hz, about 220 Hz, about 230 Hz, about 240 Hz, about 250 Hz, about 260 Hz, about 270 Hz, about 280 Hz, about 290 Hz, about 300 Hz, about 310 Hz, about 320 Hz, about 330 Hz, about 340 Hz, about 350 Hz, about 360 Hz, about 370 Hz, about 380 Hz, about 390 Hz, about 400 Hz, about 410 Hz, about 420 Hz, about 430 Hz, about 440 Hz, about 450 Hz, about 460 Hz, about 470 Hz, about 480 Hz, about 490 Hz, about 500 Hz, about 510 Hz, about 520 Hz, about 530 Hz, about 540 Hz, about 550 Hz, about 560 Hz, about 570 Hz, about 580 Hz, about 590 Hz, about 600 Hz, about 610 Hz, about 620 Hz, about 630 Hz, about 640 Hz, about 650 Hz, about 660 Hz, about 670 Hz, about 680 Hz, about 690 Hz, about 700 Hz, about 710 Hz, about 720 Hz, about 730 Hz, about 740 Hz, about 750 Hz, about 760 Hz, about 770 Hz, about 780 Hz, about 790 Hz, about 800 Hz, about 810 Hz, about 820 Hz, about 830 Hz, about 840 Hz, about 850 Hz, about 860 Hz, about 870 Hz, about 880 Hz, about 890 Hz, about 900 Hz, about 910 Hz, about 920 Hz, about 930 Hz, about 940 Hz, about 950 Hz, about 960 Hz, about 970 Hz, about 980 Hz, about 990 Hz, about 1 kHz, about 10 kHz, about 20 kHz, about 30 kHz, about 40 kHz, about

50 kHz, about 60 kHz, about 70 kHz, about 80 kHz, about 90 kHz, about 100 kHz, about 110 kHz, or about 120 kHz.

In certain examples, passing the electric current through at least the joining point of the first metal product (e.g., through the joining point of the first metal product, a joining point of the first metal product and the second metal product, a joining point of a first metal product, a second metal product, and a third metal product, or any possible configuration of metal products to be joined at a joining point) comprises passing a magnitude of up to about ± 20 kiloamperes (kA) through the joining point for up to about 60 seconds. For example, the electric current passing through the joining point can be from about ± 1 amp (A) to about ± 20 kA, from about ± 2 A to about ± 19 kA, from about ± 3 A to about ± 18 kA, from about ± 4 A to about ± 17 kA, from about ± 5 A to about ± 16 kA, from about ± 6 A to about ± 15 kA, from about ± 7 A to about ± 14 kA, from about ± 8 A to about ± 13 kA, from about ± 9 A to about ± 12 kA, from about ± 10 A to about ± 11 kA, from about ± 15 A to about ± 10 kA, from about ± 20 A to about ± 5 kA, from about ± 25 A to about ± 1 kA, from about ± 30 A to about ± 900 A, from about ± 35 A to about ± 850 A, from about ± 40 A to about ± 800 A, from about ± 45 A to about ± 750 A, from about ± 50 A to about ± 700 A, from about ± 55 A to about ± 650 A, from about ± 60 A to about ± 600 A, from about ± 65 A to about ± 550 A, from about ± 70 A to about ± 500 A, from about ± 75 A to about ± 450 A, from about ± 80 A to about ± 400 A, from about ± 85 A to about ± 350 A, from about ± 90 A to about ± 300 A, from about ± 100 A to about ± 250 A, or from about ± 150 A to about ± 200 A. For example, the electric current passing through the joining point can be about ± 1 A, about ± 10 A, about ± 20 A, about ± 30 A, about ± 40 A, about ± 50 A, about ± 60 A, about ± 70 A, about ± 80 A, about ± 90 A, about ± 100 A, about ± 110 A, about ± 120 A, about ± 130 A, about ± 140 A, about ± 150 A, about ± 160 A, about ± 170 A, about ± 180 A, about ± 190 A, about ± 200 A, about ± 210 A, about ± 220 A, about ± 230 A, about ± 240 A, about ± 250 A, about ± 260 A, about ± 270 A, about ± 280 A, about ± 290 A, about ± 300 A, about ± 310 A, about ± 320 A, about ± 330 A, about ± 340 A, about ± 350 A, about ± 360 A, about ± 370 A, about ± 380 A, about ± 390 A, about ± 400 A, about ± 410 A, about ± 420 A, about ± 430 A, about ± 440 A, about ± 450 A, about ± 460 A, about ± 470 A, about ± 480 A, about ± 490 A, about ± 500 A, about ± 510 A, about ± 520 A, about ± 530 A, about ± 540 A, about ± 550 A, about ± 560 A, about ± 570 A, about ± 580 A, about ± 590 A, about ± 600 A, about ± 610 A, about ± 620 A, about ± 630 A, about ± 640 A, about ± 650 A, about ± 660 A, about ± 670 A, about ± 680 A, about ± 690 A, about ± 700 A, about ± 710 A, about ± 720 A, about ± 730 A, about ± 740 A, about ± 750 A, about ± 760 A, about ± 770 A, about ± 780 A, about ± 790 A, about ± 800 A, about ± 810 A, about ± 820 A, about ± 830 A, about ± 840 A, about ± 850 A, about ± 860 A, about ± 870 A, about ± 880 A, about ± 890 A, about ± 900 A, about ± 910 A, about ± 920 A, about ± 930 A, about ± 940 A, about ± 950 A, about ± 960 A, about ± 970 A, about ± 980 A, about ± 990 A, about ± 1 kA, about ± 2 kA, about ± 3 kA, about ± 4 kA, about ± 5 kA, about ± 6 kA, about ± 7 kA, about ± 8 kA, about ± 9 kA, about ± 10 kA, about ± 11 kA, about ± 12 kA, about ± 13 kA, about ± 14 kA, about ± 15 kA, about ± 16 kA, about ± 17 kA, about ± 18 kA, about ± 19 kA, or about ± 20 kA.

Additionally, the electric current can be passed through the joining point for up to about 60 seconds (s) (e.g., from about 1 s to about 55 s, from about 2 s to about 50 s, from about 3 s to about 45 s, from about 4 s to about 40 s, from about 5 s to about 35 s, from about 10 s to about 30 s, or from about 15 s to about 25 s). For example, the electric current can be passed through the joining point for about 0 s (e.g., for a time equivalent to a single pulse width described above), about 1 s, about 2 s, about 3 s, about 4 s, about 5 s, about 6 s, about 7 s, about 8 s, about 9 s, about 10 s, about 11 s, about 12 s, about 13 s, about 14 s, about 15 s, about 16 s, about 17 s, about 18 s, about 19 s, about 20 s, about 21 s, about 22 s, about 23 s, about 24 s, about 25 s, about 26 s, about 27 s, about 28 s, about 29 s, about 30 s, about 31 s, about 32 s, about 33 s, about 34 s, about 35 s, about 36 s, about 37 s, about 38 s, about 39 s, about 40 s, about 41 s, about 42 s, about 43 s, about 44 s, about 45 s, about 46 s, about 47 s, about 48 s, about 49 s, about 50 s, about 51 s, about 52 s, about 53 s, about 54 s, about 55 s, about 56 s, about 57 s, about 58 s, about 59 s, or about 60 s.

In some non-limiting examples, the electrical aging step is a local heating step. For example, electrically aging the aluminum alloy and/or other metals at the joining point can include locally heating the aluminum alloy and/or other metals at the joining point to a temperature below the melting temperature of the metals. For example, electrically aging the aluminum alloy and/or other metals at the joining point can include locally heating the aluminum alloy and/or other metals at the joining point to a temperature of up to about 350 °C (e.g., from about 230 °C to about 350 °C, from about 240 °C to about 340 °C, from about 250 °C to about 330 °C, from about 260 °C to about 320 °C, from about 270 °C to about 310 °C, or from about 280 °C to about 300 °C). For example, the joining point can be locally heated to a temperature of about 230 °C, about 231 °C, about 232 °C, about 233 °C, about 234 °C, about 235 °C, about 236 °C, about 237 °C, about 238 °C, about 239 °C, about 240 °C, about 241 °C, about 242 °C, about 243 °C, about 244 °C, about

245 °C, about 246 °C, about 247 °C, about 248 °C, about 249 °C, about 250 °C, about 251 °C, about 252 °C, about 253 °C, about 254 °C, about 255 °C, about 256 °C, about 257 °C, about 258 °C, about 259 °C, about 260 °C, about 261 °C, about 262 °C, about 263 °C, about 264 °C, about 265 °C, about 266 °C, about 267 °C, about 268 °C, about 269 °C, about 270 °C, about 271 °C, about 272 °C, about 273 °C, about 274 °C, about 275 °C, about 276 °C, about 277 °C, about 278 °C, about 279 °C, about 280 °C, about 281 °C, about 282 °C, about 283 °C, about 284 °C, about 285 °C, about 286 °C, about 287 °C, about 288 °C, about 289 °C, about 290 °C, about 291 °C, about 292 °C, about 293 °C, about 294 °C, about 295 °C, about 296 °C, about 297 °C, about 298 °C, about 299 °C, about 300 °C, about 301 °C, about 302 °C, about 303 °C, about 304 °C, about 305 °C, about 306 °C, about 307 °C, about 308 °C, about 309 °C, about 310 °C, about 311 °C, about 312 °C, about 313 °C, about 314 °C, about 315 °C, about 316 °C, about 317 °C, about 318 °C, about 319 °C, about 320 °C, about 321 °C, about 322 °C, about 323 °C, about 324 °C, about 325 °C, about 326 °C, about 327 °C, about 328 °C, about 329 °C, about 330 °C, about 331 °C, about 332 °C, about 333 °C, about 334 °C, about 335 °C, about 336 °C, about 337 °C, about 338 °C, about 339 °C, about 340 °C, about 341 °C, about 342 °C, about 343 °C, about 344 °C, about 345 °C, about 346 °C, about 347 °C, about 348 °C, about 349 °C, or about 350 °C.

In some examples, the electrically aged joining point is cooled after electrically aging. The joining point can be cooled to a temperature of about room temperature (e.g., from about 15 °C to about 30 °C, from about 17 °C to about 28 °C, from about 19 °C to about 26 °C, from about 21 °C to about 24 °C, or from about 22 °C to about 23 °C). For example, the joining point can be cooled to a temperature of 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. In some examples, cooling the electrically aged joining point is performed at a rate of up to about 200 °C/second (°C/s) (e.g., from about 10 °C/s to about 180 °C/s, from about 20 °C/s to about 160 °C/s, from about 30 °C/s to about 140 °C/s, from about 40 °C/s to about 120 °C/s, from about 50 °C/s to about 100 °C/s, or from about 60 °C/s to about 80 °C/s). For example, cooling can be performed at a rate of about 10 °C/s, about 15 °C/s, about 20 °C/s, about 25 °C/s, about 30 °C/s, about 35 °C/s, about 40 °C/s, about 45 °C/s, about 50 °C/s, about 55 °C/s, about 60 °C/s, about 65 °C/s, about 70 °C/s, about 75 °C/s, about 80 °C/s, about 85 °C/s, about 90 °C/s, about 95 °C/s, about 100 °C/s, about 105 °C/s, about 110 °C/s, about 115 °C/s, about 120 °C/s, about 125 °C/s, about 130 °C/s, about 135 °C/s, about 140 °C/s, about 145 °C/s, about 150 °C/s, about 155 °C/s, about 160 °C/s, about 165 °C/s, about 170 °C/s, about 175 °C/s, about 180 °C/s, about 185 °C/s, about 190 °C/s, about 195 °C/s, about 200 °C/s, about 205 °C/s, about 210 °C/s, about 215 °C/s, about 220 °C/s, about 225 °C/s, about 230 °C/s, about 235 °C/s, about 240 °C/s, about 245 °C/s, about 250 °C/s, about 255 °C/s, about 260 °C/s, about 265 °C/s, about 270 °C/s, about 275 °C/s, about 280 °C/s, about 285 °C/s, about 290 °C/s, about 295 °C/s, about 300 °C/s, about 305 °C/s, about 310 °C/s, about 315 °C/s, about 320 °C/s, about 325 °C/s, about 330 °C/s, about 335 °C/s, about 340 °C/s, about 345 °C/s, about 350 °C/s, about 355 °C/s, about 360 °C/s, about 365 °C/s, about 370 °C/s, about 375 °C/s, about 380 °C/s, about 385 °C/s, about 390 °C/s, about 395 °C/s, about 400 °C/s, about 405 °C/s, about 410 °C/s, about 415 °C/s, about 420 °C/s, about 425 °C/s, about 430 °C/s, about 435 °C/s, about 440 °C/s, about 445 °C/s, about 450 °C/s, about 455 °C/s, about 460 °C/s, about 465 °C/s, about 470 °C/s, about 475 °C/s, about 480 °C/s, about 485 °C/s, about 490 °C/s, about 495 °C/s, about 500 °C/s, about 505 °C/s, about 510 °C/s, about 515 °C/s, about 520 °C/s, about 525 °C/s, about 530 °C/s, about 535 °C/s, about 540 °C/s, about 545 °C/s, about 550 °C/s, about 555 °C/s, about 560 °C/s, about 565 °C/s, about 570 °C/s, about 575 °C/s, about 580 °C/s, about 585 °C/s, about 590 °C/s, about 595 °C/s, or about 600 °C/s.

In certain examples, after electrically aging and cooling the joining point, the first metal product and the second metal product (e.g., at least one aluminum alloy) are subjected to a joining process. In some cases, the joining process includes inserting a piercing fastener into the joining point. In some examples, the joining process is performed by hemming, butt joining, or any other suitable joining process.

<u>Alloy Compositions</u>

In some non-limiting examples, the first and/or second metal product includes an aluminum alloy. The aluminum alloy can include a 1xxx series aluminum alloy, a 2xxx series aluminum alloy, a 3xxx series aluminum alloy, a 4xxx series aluminum alloy, a 5xxx series aluminum alloy, a 6xxx series aluminum alloy, a 7xxx series aluminum alloy, or an 8xxx series aluminum alloy.

Optionally, the aluminum alloy as described herein can be a 1xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 2xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 3xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 4xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 5xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 6xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

Optionally, the aluminum alloy as described herein can be a 7xxx series aluminum alloy according to one of the following aluminum alloy designations: 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, 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.

Optionally, the aluminum alloy as described herein can be an 8xxx series aluminum alloy according to one of the following aluminum alloy designations: 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.

In some examples, the aluminum alloy is a monolithic alloy. In some examples, the aluminum alloy is a clad aluminum alloy, having a core layer and one or two cladding layers. In some cases, the core layer may be different from one or both of the cladding layers.

While aluminum alloy products are described throughout the text, the methods and products apply to any metal. In some examples, the metal product is aluminum, an aluminum alloy, magnesium, a magnesium-based material, titanium, a titanium-based material, copper, a copper-based material, steel, a steel-based material, bronze, a bronze-based material, brass, a brass-based material, a composite, a sheet used in composites, or any other suitable metal or combination of materials. The product may include monolithic materials, as well as non-monolithic materials such as roll-bonded materials, clad materials, composite materials, or various other materials. In some examples, the metal product is a metal coil, a metal strip, a metal plate, a metal sheet, a metal billet, a metal ingot, or the like.

<u>Systems for Making Electrically Treated Metal Products and Metal Product Joints</u>

In some examples, systems for performing the methods described above can include a piercing-fastener driving system; a current source; a first counter-electrode electrically connected to the current source; a second counter-electrode electrically connected to the current source; a clamping system configured to electrically contact the first counter-electrode to a first surface of the first metal product and contact the second counter-electrode to at least a surface opposite the first surface of the first metal product such that current can flow through the metal. In certain cases, the first metal product can be contacted to a second metal product at a point where the first metal product can be joined to the second metal product (e.g., a joining point). Accordingly, the first counter-electrode can be contacted to the surface of the first metal product and the second counter-electrode can be contacted to a surface of the second metal product, such that the current can propagate from the first counter-electrode through the first metal product, through the second metal product and into the second counter-electrode. As such, any number of metal products can be electrically aged by the systems described herein.

Optionally, the systems further include a cooling system configured to cool the joining point during and/or after passing current through the joining point. In some cases, the system further comprises a temperature probe, wherein the temperature probe is configured to monitor a temperature of the joining point and to communicate the temperature of the joining point to the control system. In some examples, the systems further include a control system configured to apply the current as described above. In some cases, the control system can be integrated into the current source. In some examples, the control system includes a temperature probe configured to monitor the temperature of at least the first metal product. In certain aspects, the control system is configured to activate the current source and maintain current flow until the temperature of the joining point achieves a temperature of up to 350 °C (e.g., from about 250 °C to about 350 °C), and to deactivate the current source when the temperature of the joining point achieves a temperature of up to 350 °C (e.g., from about 250 °C to about 350 °C). Thus, the control system can apply the current until the temperature of at least the first metal product reaches a predetermined temperature (e.g., from about 250 °C to about 350 °C as described above) and the control system can discontinue the current. In certain aspects, the cooling control system can be employed as a heat localization system, configured to cool an area about the joining point such that the heat generated when passing current through at least the first metal product is confined to the joining point, thus providing the localized heating and localized aging.

Additionally, the control system can be configured to pulse the current as described above. In some examples, the control system can be configured to supply the current in any suitable waveform (e.g., a square wave, a sawtooth wave, a sine wave, a triangle wave, or any combination thereof). In some non-limiting examples, the control system is configured to activate the cooling system after deactivating the current source, to maintain the cooling system until the temperature of the joining point is room temperature, to deactivate the cooling system when the temperature of the joining point is room temperature, and to activate the piercing-fastener driving system after deactivating the cooling system.

Further, the systems described herein include a piercing-fastener driving system. The piercing-fastener driving system can be configured to drive a piercing-fastener (e.g., a rivet, a self-piercing rivet, a screw, a self-piercing screw, a tack, a nail, any suitable piercing-fastener, or any combination thereof) through the joining point after the electrically aging joining point. Accordingly, the electrically aging allows the metal products to be joined by pierce-fastening, clinching, flow drill screwing, crimping, any mechanical joining process including a forming step, or any combination thereof, without fracturing about the joining point.

Methods of Use

The disclosed aluminum alloy products provided in the tempers described herein may be incorporated into existing processes and lines for production of aluminum alloy products, such as hot formed aluminum products (for example, hot formed automotive structural members), thereby improving the processes and the resulting products in a streamlined and economical manner. The systems and methods for performing the forming processes and producing the products described herein are included within the scope of the disclosure.

The described aluminum alloy products and processes can be advantageously employed in the transportation industry, including, but not limited to, automotive manufacturing, truck manufacturing, manufacturing of ships and boats, manufacturing of trains, airplanes and spacecraft manufacturing. Some non-limiting examples of the automotive parts include floor panels, rear walls, rockers, motor hoods, fenders, roofs, door panels, B-pillars, body sides, rockers, or crash members. The term “automotive” and the related terms as used herein are not limited to automobiles and include various vehicle classes, such as, automobiles, cars, buses, motorcycles, marine vehicles, off highway vehicles, light trucks, trucks, or lorries. However, aluminum alloy products are not limited to automotive parts; other types of aluminum products manufactured according to the processes described in this application are envisioned. For example, the described processes can be advantageously employed in manufacturing of various parts of mechanical and other devices or machinery, including weapons, tools, bodies of electronic devices, and other parts and devices.

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

The aluminum alloy products and processes described herein can be used in any other desired application.

Illustrations of Suitable Alloys, Products, and Methods

The following illustrations will serve to further illustrate the present invention without, however, constituting any limitation thereof. On the contrary, it is to be clearly understood that resort may be had to various embodiments, modifications, and equivalents thereof which, after reading the description herein, may suggest themselves to those skilled in the art without departing from the spirit of the invention.

Illustration 1 is a method of treating metal products, comprising: passing an electric current through a portion of a first metal product to electrically age the portion of the first metal product, wherein the portion of the first metal product is heated to a temperature sufficient to soften the portion of the first metal product without melting the portion of the first metal product, wherein the portion of the first metal product is a location on the first metal product where the first metal product can be subsequently joined to at least a second metal product.

Illustration 2 is the method of any preceding or subsequent illustration, further comprising: cooling the location on the first metal product where the first metal product can be subsequently joined to at least a second metal product; and after the cooling, joining the first metal product to the second metal product.

Illustration 3 is the method of any preceding or subsequent illustration, wherein the location on the first metal product where the first metal product can be joined to at least the second metal product is a joining point.

Illustration 4 is the method of any preceding or subsequent illustration, further comprising passing the electric current through the second metal product at a joining point of the second metal product.

Illustration 5 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises pulsing the electric current through the portion of the first metal product.

Illustration 6 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises locally heating the portion of the first metal product to provide a locally heat-treated portion of the first metal product.

Illustration 7 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises decreasing an activation energy of atoms within at least the first metal product.

Illustration 8 is the method of any preceding or subsequent illustration, wherein decreasing the activation energy of atoms within at least the first metal product comprises controlling a kinetic activity of atoms within at least the first metal product.

Illustration 9 is the method of any preceding or subsequent illustration, wherein controlling the kinetic activity of atoms within at least the first metal product comprises one or more of controlling grain growth, controlling precipitate growth, controlling an aging response, and controlling a solutionizing response.

Illustration 10 is the method of any preceding or subsequent illustration, wherein controlling the aging response further comprises increasing a rate of aging kinetics of at least the first metal product.

Illustration 11 is the method of any preceding or subsequent illustration, wherein increasing the rate of the aging kinetics of at least the first metal product further comprises reducing heat treatment time to achieve a desired heat treated state, wherein the desired heat treated state comprises a T5 temper, a T6 temper, a T7 temper, a T8x temper, a T9 temper, or a T10 temper.

Illustration 12 is the method of any preceding or subsequent illustration, wherein increasing the rate of the aging kinetics of at least the first metal product further comprises increasing a strength of at least the first metal product.

Illustration 13 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises passing a direct current through the portion of the first metal product or passing an alternating current through the portion of the first metal product.

Illustration 14 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises tuning a waveform of the electric current.

Illustration 15 is the method of any preceding or subsequent illustration, wherein tuning the waveform of the electric current comprises creating a square wave, a sawtooth wave, a sine wave, a triangle wave, or any combination thereof.

Illustration 16 is the method of any preceding or subsequent illustration, wherein tuning the waveform of the electric current comprises controlling an amplitude and a pulse width of the waveform.

Illustration 17 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises passing up to about 20 kiloamperes of electric current through the portion of the first metal product.

Illustration 18 is the method of any preceding or subsequent illustration, wherein passing the electric current through the portion of the first metal product comprises passing the electric current through the portion of the first metal product for up to about 60 seconds.

Illustration 19 is the method of any preceding or subsequent illustration, wherein cooling the portion of the first metal product is performed at a rate of up to about 600 °C per second.

Illustration 20 is the method of any preceding or subsequent illustration, wherein joining the first metal product to the second metal product comprises inserting a piercing fastener into a joining point, wherein inserting a piercing fastener into the joining point comprises inserting a self-piercing rivet, a self-piercing screw, a self-drilling screw, a self-piercing grommet, or any suitable self-piercing fastener.

Illustration 21 is the method of any preceding or subsequent illustration, wherein inserting a piercing fastener into the joining point does not fracture the first metal product and does not fracture the second metal product.

Illustration 22 is a system for pierce-joining metal products without fracturing the metal products according to the method of any preceding or subsequent illustration, comprising: a piercing-fastener driving system; a current source; a first counter-electrode, wherein the first counter-electrode is electrically connected to the current source; a second counter-electrode, wherein the second counter-electrode is electrically connected to the current source; and a clamping system, wherein the clamping system is configured to electrically contact the first counter-electrode to a surface of a first metal product and contact the second counter-electrode to a surface of at least a second metal product, wherein the first metal product and at least the second metal product are positioned to contact each other at a joining point, wherein the surface of the first metal product and the surface of the second metal product are opposite each other across the joining point, and wherein the first counter-electrode and the second counter-electrode are configured to pass a current supplied by the current source through at least the joining point of the first metal product to heat the joining point of the first metal product to soften the joining point without melting the joining point to electrically age the first metal product before joining the first metal product to the second metal product with the piercing-fastener driving system.

Illustration 23 is the system of any preceding or subsequent illustration, further comprising a cooling system configured to cool the joining point after the current is passed through the joining point.

Illustration 24 is the system of any preceding or subsequent illustration, further comprising a control system configured to activate the current source and maintain current flow until a temperature of the joining point achieves a temperature of from 250 °C to 350 °C, and to deactivate the current source when the temperature of the joining point achieves a temperature of from 250 °C to 350 °C.

Illustration 25 is the system of any preceding or subsequent illustration, further comprising a temperature probe, wherein the temperature probe is configured to monitor a temperature of the joining point and to communicate the temperature of the joining point to the control system.

Illustration 26 is the system of any preceding illustration, further comprising a control system configured to activate the cooling system after deactivating the current source, to maintain the cooling system until the temperature of the joining point is room temperature, to deactivate the cooling system when the temperature of the joining point is room temperature, and to activate the piercing-fastener driving system after deactivating the cooling system.

EXAMPLES

Example 1 – Effects of Electrically Assisted Aging on Self-piercing Riveting

Aluminum alloy products were prepared and processed according to the methods described herein. For example, a 7xxx series aluminum alloy (e.g., AA7075) was provided as a coil having a sheet gauge thickness (e.g., less than about 4 mm). Test coupons were removed from the coil and provided in F temper. The F temper coupons were heat treated to provide the coupons in a T6 temper by heating the coupons to a temperature of 480 °C and maintaining the temperature for a period of 5 minutes. The coupons were then quenched with water and artificially aged at a temperature of 125 °C for 24 hours.

The aluminum alloy coupons were then electrically aged as described herein. Two counter-electrodes electrically connected to a direct current (DC) power supply were positioned in electrical contact on opposite sides of the coupons such that, when energized, the DC current flowed from a first counter electrode, through the thickness of the coupon, and into a second counter electrode. In one example, the DC current was applied at magnitude of + 3.5 kA with a pulse width of 300 ms for a duration of 60 seconds. In a second example, the DC current was applied at magnitude of +11 kA with a pulse width of 300 ms for a duration of 60 seconds. The coupons were electrically aged at several points to provide comparative data. After electrical aging, self-piercing rivets were driven through the coupons at three positions: (i) a position where the coupons were not electrically aged, (ii) a position within where the coupons were electrically aged, and (iii) a position partially within where the coupons were electrically aged.

Figure 1 shows the effect of driving a self-piercing rivet through a portion of the coupons that was not electrically aged. Visible cracks 110 surrounded the self-piercing rivet button 120. Figure 2 shows the effect of driving a self-piercing rivet through a portion of the coupons that was electrically aged using a DC current having a magnitude of + 3.5 kA. Visible cracks 110 surrounded the self-piercing rivet button 120. Figure 3 shows the effect of driving a self-piercing rivet through a portion of the coupon that was electrically aged using a DC current having a magnitude of + 11 kA. No visible cracks surrounded the self-piercing rivet button 120. Finally, Figure 4 shows the effect of electrically aging the coupons where a self-piercing rivet was partially driven through the electrically aged area 410 (referred to as "EPT Region" in the example of Figure 4). As shown in Figure 4, visible cracks 110 surrounded the self-piercing rivet button 120 in the portion of the coupon that was not electrically aged, and no visible cracks were present in the electrically aged area 410. Thus, electrically aging a metal product can improve the quality of a self-piercing riveting process, providing riveted areas devoid of metal cracking. Additionally, electrically aging a metal product can locally alter the microstructure of a metal product without affecting the properties of the bulk material.

Electrical conductivity and hardness of additional aluminum coupons were measured after various electrical aging times. In one example, the DC current was applied at magnitude of + 11 kA with a pulse width of 300 ms for a duration of 15 seconds. In a second example, the DC current was applied at magnitude of + 11 kA with a pulse width of 300 ms for a duration of 60 seconds. Electrical conductivity and hardness of the aluminum alloy coupons were measured at several points linearly about the electrically aged area 410 (see Figure 4), including 6 inches (”) from the electrically aged area 410, 5” from the electrically aged area 410, 4” from the electrically aged area 410, 3” from the electrically aged area 410, 2” from the electrically aged area 410, 1” from the electrically aged area 410, 0.5” from the electrically aged area 410, at the electrically aged area 410, 0.5” from the electrically aged area 410 on a side opposite the first 0.5” point, 1” from the electrically aged area 410 on a side opposite the first 1” point, and 2” from the electrically aged area 410 on a side opposite the first 2” point. Results of the electrical conductivity and hardness tests are shown in Figures 5 and 6, respectively.

In the example of Figure 5, the electrical conductivity (measured in %IACS) is about 6 %IACS greater at the electrically aged area 410 (referred to as “EPT” in the example of Figure 5), and in the area up to about 1” from the electrically aged area 410 for the aluminum alloy coupon electrically aged for 15 seconds. Similarly, the electrical conductivity is about 9 %IACS greater at the electrically aged area 410 (referred to as “EPT” in the example of Figure 5), and in the area up to about 2” from the electrically aged area 410 for the aluminum alloy coupon electrically aged for 60 seconds. Thus, the electrical aging time can affect a size of the region subjected to the electrical aging. In the example of Figure 6, the hardness (measured under the Rockwell hardness scale B (HRB) using a 1.588 mm steel sphere indenter) is lower at the electrically aged area 410 (referred to as “EPT” in the example of Figure 6) and in the area up to about 2” from the electrically aged area 410 for both aluminum alloy coupons (electrically aged for 15 seconds and 60 seconds). The aluminum alloy coupon electrically aged for 15 seconds showed a 40 HRB reduction, and the aluminum alloy coupon electrically aged for 60 seconds showed a 60 HRB reduction in hardness at the electrically aged area 410. Thus, the electrical aging time can significantly affect a magnitude of the change in hardness.

The microstructure of the aluminum alloy coupon subjected to the +11 kA DC current with a pulse width of 300 ms and a duration of 60 seconds was analyzed by STEM. Figure 7 shows the STEM micrographs taken at magnifications of 150 KX (top row of Figure 7) and 200 KX (bottom row of Figure 7). Further, micrographs were taken at the electrically aged area 410 (see Figure 4, and the left column of Figure 7), 0.5” away from the electrically aged area (center column of Figure

7), and in an area not subjected to electrical aging (right column of Figure 7). The electrically aged area 410 shows coarsened and/or dissolved precipitates 710 (indicated as dark areas). The area 0.5" away from the electrically aged area 410 (referred to as "Close to Electric Pulse" in Figure 7) shows precipitates 710 dissolving and coarsening (e.g., increasing in size). The area not subjected to electrical aging (referred to as "No Electric Pulse" in Figure 7) shows precipitate 710 formation without any precipitate 710 dissolving or coarsening. Thus, the electrical aging described herein can alter precipitate formation and eliminate cracking at joining points of metal products.

All patents, publications, and abstracts cited above are incorporated herein by reference in their entireties. Various embodiments of the invention have been described in fulfillment of the various objectives of the invention. It should be recognized that these embodiments are merely illustrative of the principles of the present invention. Numerous modifications and adaptions thereof will be readily apparent to those skilled in the art without departing from the spirit and scope of the present invention as defined in the following claims.

ABSTRACT

Provided herein are methods of joining metal products without fracturing the metal products, including electrically treating (for example, electrically aging) the metal products and pierce-fastening the metal products or hemming the metal products. In some examples, electrically aging the metal products includes locally heating a joining point of the metal products and decreasing an activation energy of atoms within the metal products, thus controlling the kinetic activity of atoms within the metal products.

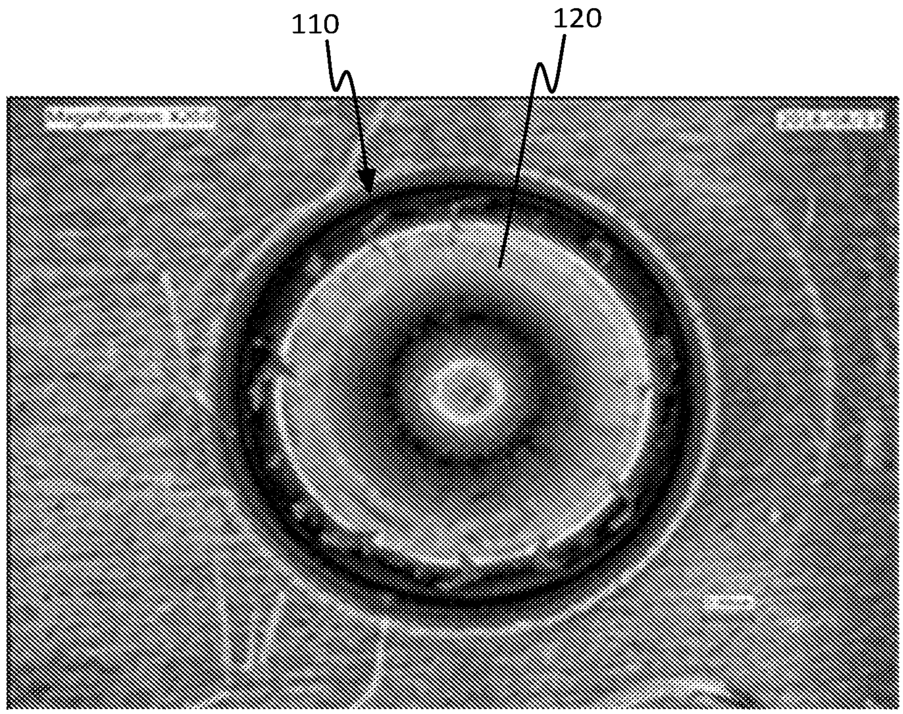

Figure 1

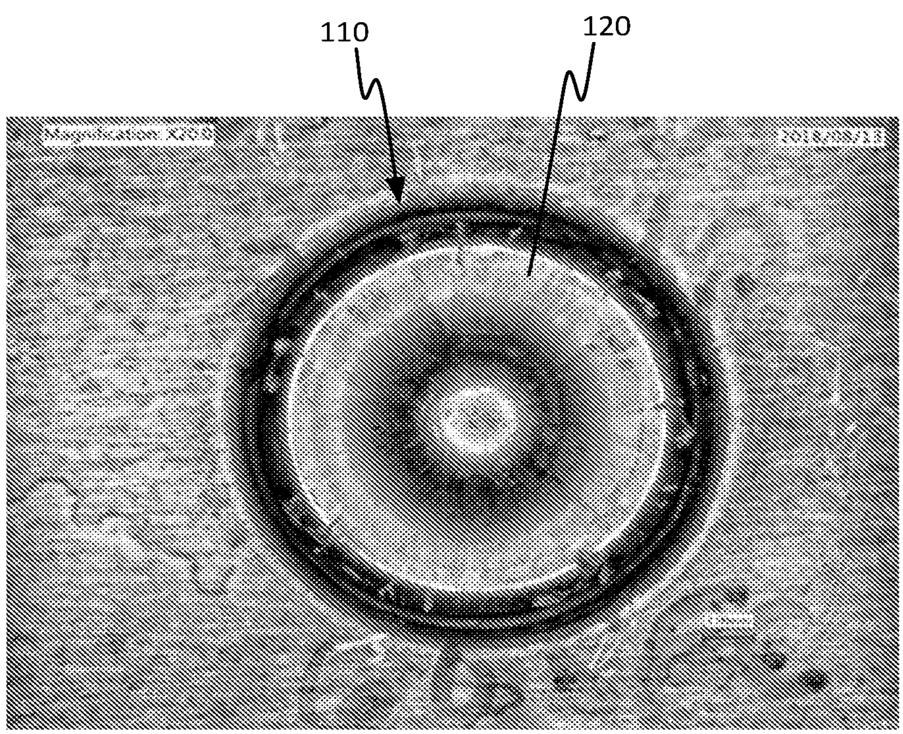

Figure 2

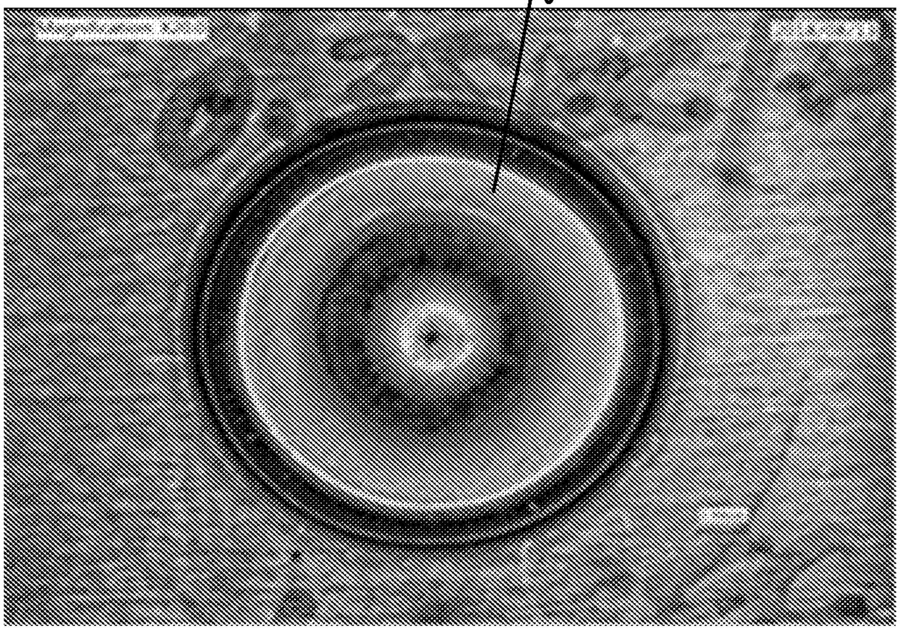

FIGURE 3

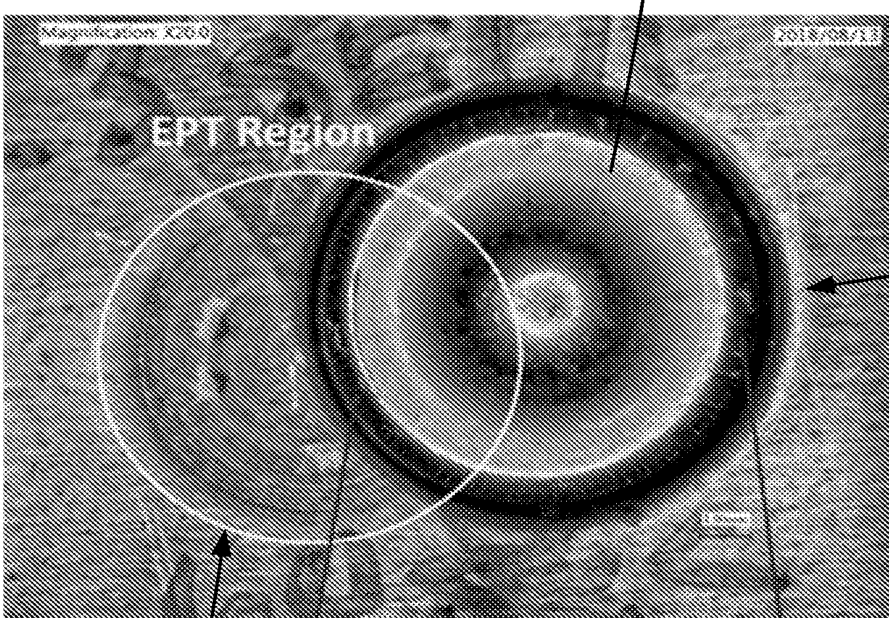

FIGURE 4

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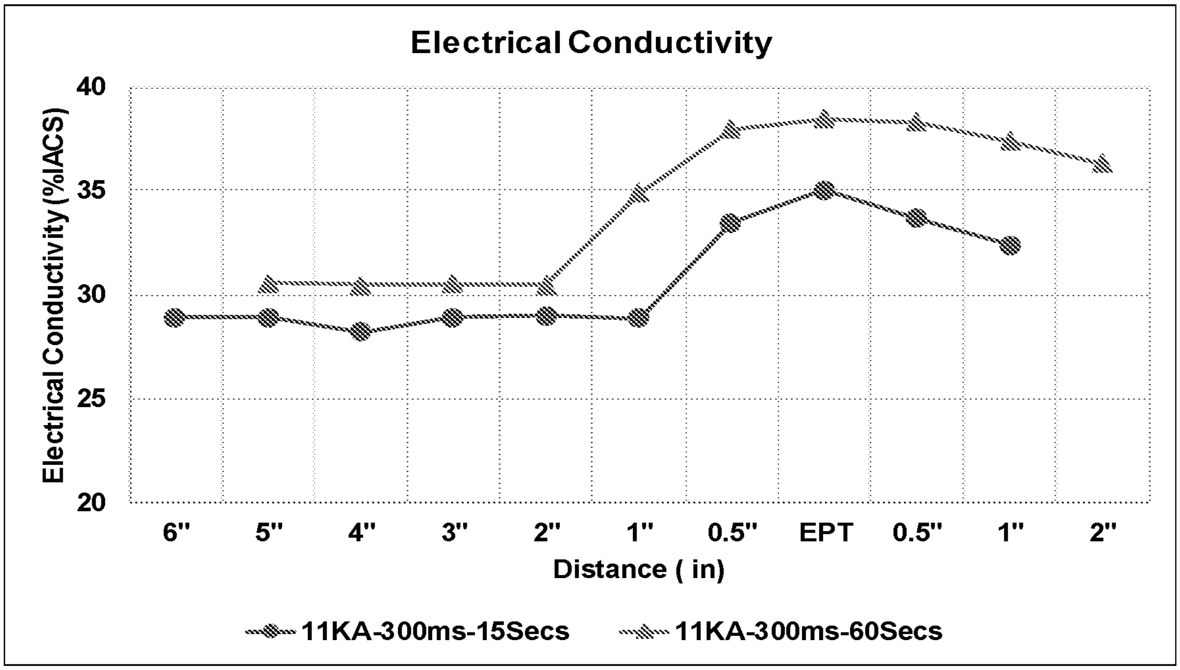

FIGURE 5

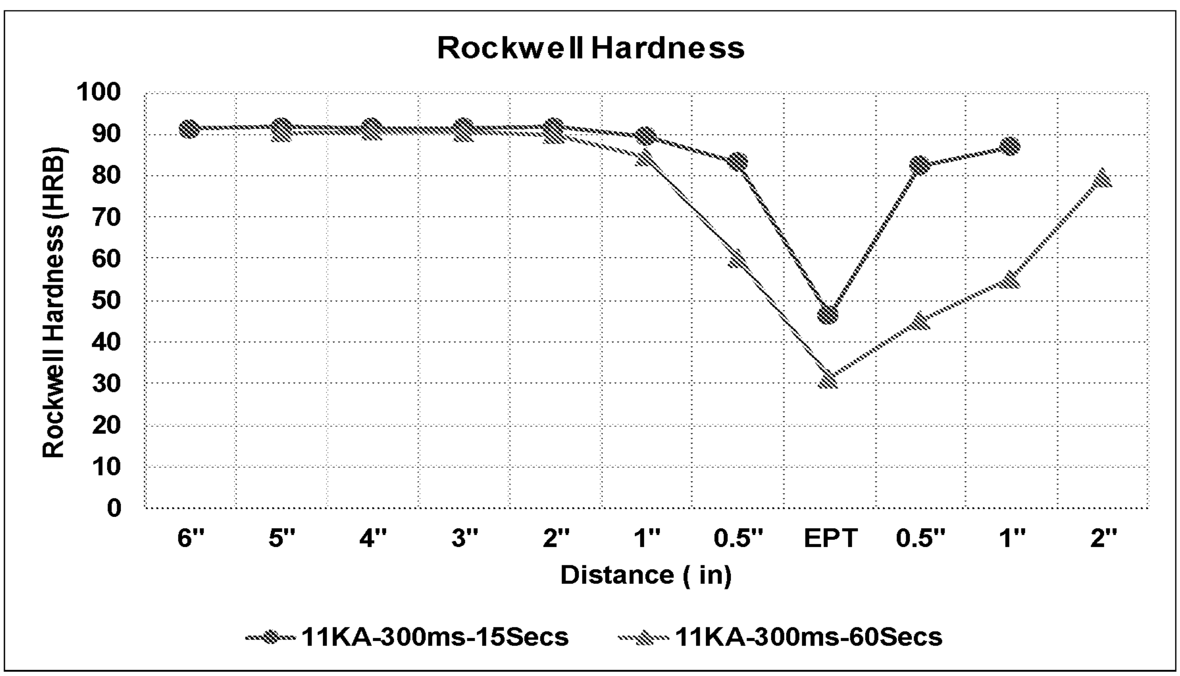

FIGURE 6

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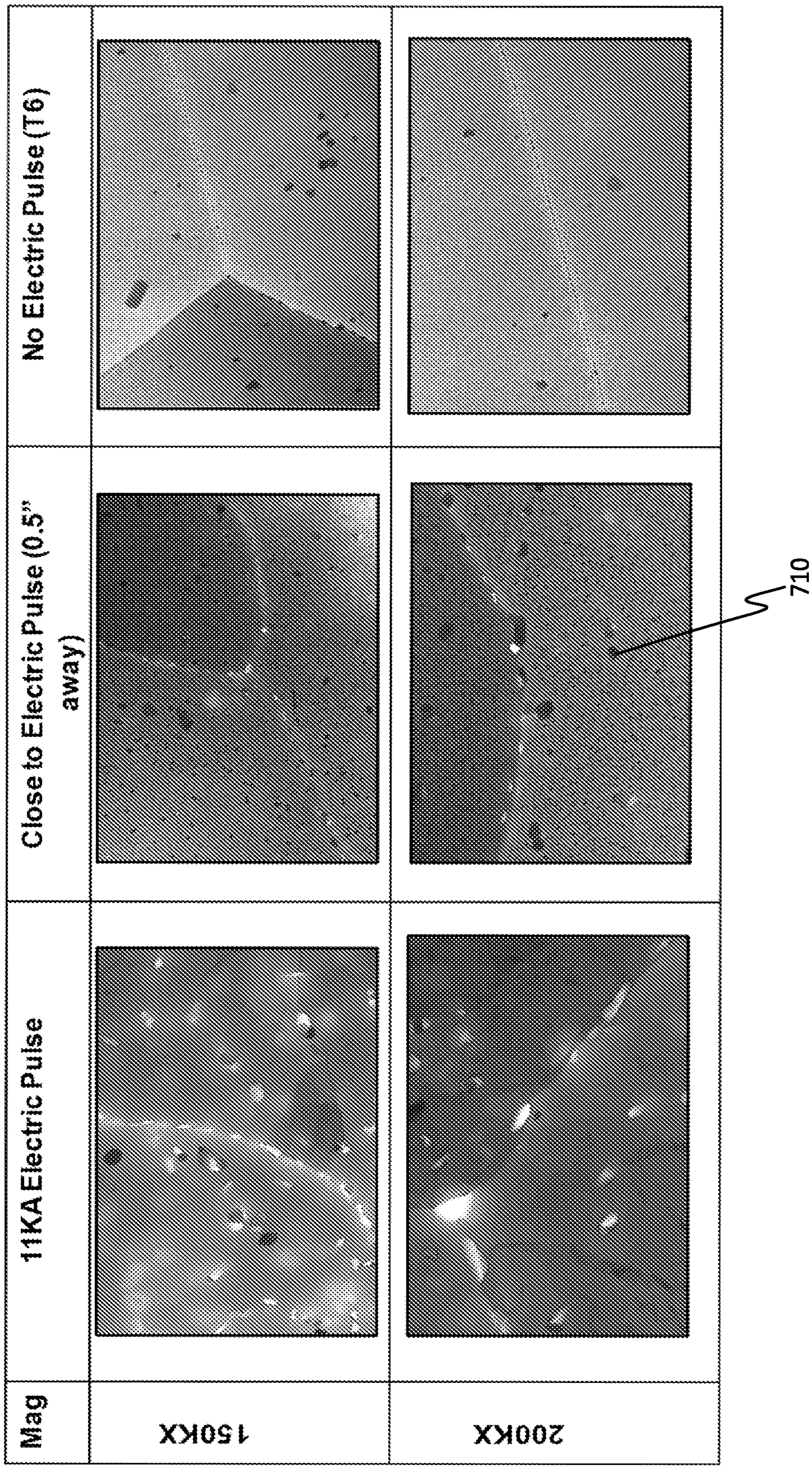
Mag
150KX
200KX
11KA Electric Pulse
Close to Electric Pulse (0.5" away)
No Electric Pulse (T6)
710

FIGURE 7