Technical Disclosure Commons

Defensive Publications Series

May 2020

# Quality Improvement of Self-Piercing Riveting of High Strength Aluminum Alloys

Dechao Lin

Dewei Zhu

Julio Malpica

Sebastijan Jurendic

Zeqin Liang

*See next page for additional authors*

Inventor(s)
Dechao Lin, Dewei Zhu, Julio Malpica, Sebastijan Jurendic, Zeqin Liang, Samuel Robert Wagstaff, David Leyvraz, Julie Richard, Tudor Piroteala, Patrick Lester, and Cedric Wu

# QUALITY IMPROVEMENT OF SELF-PIERCING RIVETING OF HIGH STRENGTH ALUMINUM ALLOYS

## FIELD

The present disclosure relates to metallurgy generally and more specifically to joined metal substrates and products, and methods and tools for making and joining metal substrates and metal products.

## BACKGROUND

The strength and formability of metals can be modified by working the metal and heat treating the metal. For example, aluminum substrates may be cold worked to increase strength, but this increase in strength may come at the expense of reduced formability character. Substrates of certain alloys may be tempered to increase formability, but this increase in formability may come at the expense of reduced strength. Substrates of other alloys, however, may have their strength increased by heat treatment.

## SUMMARY

The term embodiment and like terms are intended to refer broadly to all of the subject matter of this disclosure. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope. This summary is a high-level overview of various aspects of the disclosure 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 subject matter, nor is it intended to be used in isolation to determine the scope of the subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings.

Described herein are metal products including joined metal alloy substrates, methods of joining metal alloy substrates, and devices for joining metal alloy substrates. The metal substrates in the disclosed metal products include high-strength alloys, which may be joined to another metal alloy substrate using self-piercing rivets, such as steel self-piercing rivets. Advantageously, the devices, apparatuses, and methods described herein are useful for joining

metal alloy substrates to produce a metal product, such as a metal product comprising a first metal alloy substrate joined to a second metal alloy substrate by a self-piercing rivet. As examples, robust and crack-free sheet-to-sheet joints, sheet-to-casting joints, and sheet-to-extrusion joints may be created using the methods described herein employing self-piercing rivets.

For example, a method of joining metal alloy substrates may comprise providing a first metal alloy substrate and a second metal alloy substrate; retrogressing a portion of at least one of the first metal alloy substrate or the second metal alloy substrate to increase formability or plasticity of the retrogressed portion of the at least one of the first metal alloy substrate or the second metal alloy substrate; and joining the first metal alloy substrate and the second metal alloy substrate using a self-piercing rivet, such as a self-piercing rivet that pierces the first metal alloy substrate and is retained in the second metal alloy substrate at the retrogressed portion. Joining may include driving the self-piercing rivet through the first metal alloy substrate and into the second metal alloy substrate using a punch. Joining the first metal alloy substrate and the second metal alloy substrate using the self-piercing rivet may form a button in the second metal alloy substrate such that the button that is crack-free. Optionally, the button remains crack-free after subjecting the button to natural aging and/or paint baking. For example, by joining the first and second metal alloy substrates with a self-piercing rivet while the second metal alloy substrate is heated, the resultant button can be formed in a crack-free configuration that remains crack-free, even after subsequent aging and/or heat-treating of the joined metal alloy substrates. In some embodiments, the resultant button may include minor defects, including orange peeling and/or stretch marks. In some embodiments, the resultant button may include moderate defects, such as fine and/or moderate radial cracking. Fine cracking may include cracking that has a width dimension of less than about 0.2 mm, and moderate cracking may include cracking that has a width dimension from 0.2 mm to 1 mm. Severe cracking, such as cracking having a width dimension greater than 1 mm which may include circumferential cracking, or other severe defects, such as over-flared rivet, buckled rivet, etc., can be generally avoided in the resultant button.

Retrogressing may comprise heating portions of a metal alloy substrate, for example to or above a retrogression temperature sufficient to increase formability or plasticity of the retrogressed portions of the metal alloy substrate. Optionally, retrogressing comprises maintaining the portion of the metal alloy substrate at or above the retrogression temperature for a predetermined duration of time.

In some embodiments, the method may further comprise positioning the first metal alloy substrate adjacent to the second metal alloy substrate prior to or after retrogressing the portion of the at least one of the first metal alloy substrate or the second metal alloy substrate. In some embodiments, the method may comprise retrogressing both a portion of the first metal alloy substrate to increase formability or plasticity of the portion of the first metal alloy substrate and a portion of the second metal alloy substrate to increase formability or plasticity of the portion of the second metal alloy substrate. In some embodiments, the first metal alloy substrate may be positioned adjacent to the second metal alloy substrate prior to or after retrogressing both the portion of the first metal alloy substrate and the portion of the second metal alloy substrate. In some embodiments, the method may further comprise providing a third metal alloy substrate, and joining the third metal alloy substrate to the first metal alloy substrate and the second metal alloy substrate using the self-piercing rivet, such as by piercing the third metal alloy substrate using the self-piercing rivet. In some embodiments, the method may further comprise retrogressing a portion of the third metal alloy substrate to increase formability or plasticity of the portion of the third metal alloy substrate.

Various metal alloys may be used for the first metal alloy substrate and the second metal alloy substrate. For example, a variety of high-strength alloys may be used for the second metal alloy substrate, such as a 2xxx series aluminum, a 6xxx series aluminum, a 7xxx series aluminum, or a steel alloy. Optionally, the second metal alloy is an aluminum alloy, such as a 2xxx series aluminum, a 3xxx series aluminum, a 5xxx series aluminum, a 6xxx series aluminum, or a 7xxx series aluminum. Optionally, the first metal alloy substrate comprises an aluminum alloy, a magnesium alloy, a copper alloy, a titanium alloy, a nickel alloy, or a steel alloy. In some embodiments, the first metal alloy substrate and the second metal alloy substrate have the same composition. Optionally, the first metal alloy substrate comprises a high-strength aluminum alloy, such as a 2xxx series aluminum, a 6xxx series aluminum, or a 7xxx series aluminum. Optionally, the fist metal alloy substrate or the second metal alloy substrate comprises or is substituted by a thermoplastic material, a carbon fiber material, or a carbon-fiber-reinforced polymer material.

In some embodiments, either or both the first metal alloy substrate and the second metal alloy substrate may correspond to a formed metal product subjected to a forming process prior to the retrogressing and the joining. For example, either or both the first metal alloy substrate and the second metal alloy substrate may be subjected to a stamping or drawing process prior to joining. In some embodiments, a stamping, drawing, or other forming process may modify a grain structure of the metal alloy substrate and increase a strength and reduce a formability or plasticity of the metal alloy substrate. Thus, formed metal alloy substrates may be difficult to join by self-piercing riveting.

However, by retrogressing (e.g., by heating) a portion of the metal alloy substrate that is to be pierced or that retains the shank of the self-piercing rivet, a formability or plasticity of the portion can be increased to a level where the joining process does not result in formation of cracks or other defects in the metal alloy substrate, such as in a button formed during the joining process. As examples, portions of a metal alloy substrate may be heated during retrogression to temperatures (e.g., a retrogression temperature) from 70 °C to 900 °C, such as from 70 °C to 350 °C, depending on the composition, such as about 70 °C, 75 °C, 80 °C, 85 °C, 90 °C, 95 °C, 100 °C, 105 °C, 110 °C, 115 °C, 120 °C, 125 °C, 130 °C, 135 °C, 140 °C, 145 °C, 150 °C, 155 °C, 160 °C, 165 °C, 170 °C, 175 °C, 180 °C, 185 °C, 190 °C, 195 °C, 200 °C, 205 °C, 210 °C, 215 °C, 220 °C, 225 °C, 230 °C, 235 °C, 240 °C, 245 °C, 250 °C, 255 °C, 260 °C, 265 °C, 270 °C, 275 °C, 280 °C, 285 °C, 290 °C, 295 °C, 300 °C, 305 °C, 310 °C, 315 °C, 320 °C, 325 °C, 330 °C, 335 °C, 340 °C, 345 °C, 350 °C, 355 °C, 360 °C, 365 °C, 370 °C, 375 °C, 380 °C, 385 °C, 390 °C, 395 °C, 400 °C, 405 °C, 410 °C, 415 °C, 420 °C, 425 °C, 430 °C, 435 °C, 440 °C, 445 °C, 450 °C, 455 °C, 460 °C, 465 °C, 470 °C, 475 °C, 480 °C, 485 °C, 490 °C, 495 °C, 500 °C, 505 °C, 510 °C, 515 °C, 520 °C, 525 °C, 530 °C, 535 °C, 540 °C, 545 °C, 550 °C, 555 °C, 560 °C, 565 °C, 570 °C, 575 °C, 580 °C, 585 °C, 590 °C, 595 °C, 600 °C, 605 °C, 610 °C, 615 °C, 620 °C, 625 °C, 630 °C, 635 °C, 640 °C, 645 °C, 650 °C, 655 °C, 660 °C, 665 °C, 670 °C, 675 °C, 680 °C, 685 °C, 690 °C, 695 °C, 700 °C, 705 °C, 710 °C, 715 °C, 720 °C, 725 °C, 730 °C, 735 °C, 740 °C, 745 °C, 750 °C, 755 °C, 760 °C, 765 °C, 770 °C, 775 °C, 780 °C, 785 °C, 790 °C, 795 °C, 800 °C, 805 °C, 810 °C, 815 °C, 820 °C, 825 °C, 830 °C, 835 °C, 840 °C, 845 °C, 850 °C, 855 °C, 860 °C, 865 °C, 870 °C, 875 °C, 880 °C, 885 °C, 890 °C, 895 °C, or 900 °C. Optionally, portions of a metal alloy substrate may be heated to temperatures between 70 °C and 600 °C, between 70 °C and 100 °C, between 350 °C and 600 °C, 350 °C and 500 °C, 350 °C and

400 °C, or between 150 °C and 500 °C when the second alloy substrate comprises an aluminum alloy. In some embodiments, the retrogression temperature may be from 100 °C to 350 °C, for example from 100 °C to 125 °C, from 100 °C, to 150 °C, from 100 °C to 175 °C, from 100 °C to 200 °C, from 100 °C to 225 °C, from 100 °C to 250 °C, from 100 °C to 275 °C, from 100 °C to 300 °C, from 100 °C to 325 °C, from 100 °C to 350 °C, from 125 °C, to 150 °C, from 125 °C to 175 °C, from 125 °C to 200 °C, from 125 °C to 225 °C, from 125 °C to 250 °C, from 125 °C to 275 °C, from 125 °C to 300 °C, from 125 °C to 325 °C, from 125 °C to 350 °C, from 150 °C to 175 °C, from 150 °C to 200 °C, from 150 °C to 225 °C, from 150 °C to 250 °C, from 150 °C to 275 °C, from 150 °C to 300 °C, from 150 °C to 325 °C, from 150 °C to 350 °C, from 175 °C to 200 °C, from 175 °C to 225 °C, from 175 °C to 250 °C, from 175 °C to 275 °C, from 175 °C to 300 °C, from 175 °C to 325 °C, from 175 °C to 350 °C, from 200 °C to 225 °C, from 200 °C to 250 °C, from 200 °C to 275 °C, from 200 °C to 300 °C, from 200 °C to 325 °C, from 200 °C to 350 °C, from 225 °C to 250 °C, from 225 °C to 275 °C, from 225 °C to 300 °C, from 225 °C to 325 °C, from 225 °C to 350 °C, from 250 °C to 275 °C, from 250 °C to 300 °C, from 250 °C to 325 °C, from 250 °C to 350 °C, from 275 °C to 300 °C, from 275 °C to 325 °C, from 275 °C to 350 °C, from 300 °C to 325 °C, from 300 °C to 350 °C, or from 325 °C to 350 °C.

Optionally, portions of a metal alloy substrate may be heated to temperatures between 400 °C and 800 °C when the second alloy substrate comprises coated steel. Optionally, portions of a metal alloy substrate may be heated to temperatures between 400 °C and 900 °C when the second alloy substrate comprises uncoated steel. When the substrate is or comprises a thermoplastic or a carbon-fiber-reinforced polymer, the substrate may be heated to temperatures of between 100 °C and 300 °C to modify a formability or plasticity of the substrate, for example. In embodiments, the temperature that the substrate, or a portion thereof, is heated to may be sufficient to increase formability or plasticity of the substrate, or portion thereof, at least temporarily, during the joining process. In some embodiments, heating sufficient to increase formability or plasticity of the substrate, or portion thereof, may modify a grain structure or crystal structure of the substrate, or portion thereof, such as if the temperature of the substrate, or portion thereof, exceeds a recrystallization temperature. In some embodiments, heating sufficient to increase formability or plasticity of the substrate, or portion thereof, may not modify, or may not significantly modify, a grain structure or crystal structure of the substrate, or portion thereof, such as if the temperature of the substrate, or portion thereof, does not exceed a recrystallization temperature.

Various techniques may be employed for heating portions of a metal alloy substrate. For example, heating a portion of a metal alloy substrate may include exposing the portion of the metal alloy substrate to a laser beam. Optionally, the laser beam may be focused on the second metal alloy substrate. In some embodiments, the laser beam may be focused to or include a ring profile. Various optical elements may be used to focus the laser beam, such as a lens, prism, or mirror. In some embodiments, an axicon lens is used.

As another example, heating a portion of a metal alloy substrate may include subjecting the portion to magnetic or electromagnetic induction heating. Magnetic or electromagnetic induction heating may be advantageous, for example, as heat may be generated directly within the portion of the substrate, rather than at a surface of the substrate or requiring conductive heat transfer. Induction heating may be implemented, for example, by exposing the portion of the substrate to a high-frequency rotating magnetic field, which may be generated by permanent magnets or electromagnets.

As another example, heating a portion of a metal alloy substrate may include contacting the portion of the metal alloy substrate to a die including a heating element. In this way, a die used in a self-piercing riveting process may be used to directly heat the portion of the metal alloy substrate by conductive heat transfer, such as immediately prior to and/or during the self-piercing riveting process. In an example embodiment, the die may be a multi-part structure, such as a die that includes an outer die and an inner die located within the outer die. Optionally, the inner die is translatable along an axis within the outer die, such as to allow for accommodation of a button that forms during the joining process. Optionally, the inner die includes the heating element, such as a cartridge heater, for example.

Various inner die configurations are useful with the multi-part dies described herein. For example, the inner die optionally has a relief profile, such as including one or more raised regions and/or one or more recessed regions. Use of an inner die that has a relief profile may be useful for inducing flaring of the self-piercing rivet and formation of a mechanical interlock during joining. In other cases, however, the inner die has a flat profile. Use of a flat profile may be advantageous for maximizing a contact area between the inner die and a metal alloy substrate to achieve maximum conductive heat transfer.

Since the inner die may translate during joining for accommodation of the formed button, the inner die may not be in continuous contact with the button-side metal alloy substrate prior to joining. Optionally, the die may include a resilient member providing a force on the inner die parallel to the translation axis of the inner die. Example resilient members include springs. The spring may be positioned on the opposite side of the inner die to a location where the button is formed, such as in order to direct force from the spring toward the second metal alloy substrate prior to joining. In this way, the inner die can be restored to a position where it can make contact with a metal alloy substrate prior to joining in order to heat the metal alloy substrate. To prevent the inner die from being directed to an undesirable position, such as past an extent of the outer die, a die may also include a die lock. For example, the die lock may be positioned to limit a range of translation of the inner die along the axis. As an example, a die lock may be provided as a set screw and recess in the inner die, though other configurations are possible. A set screw and recess configuration may be useful when the inner die is generally cylindrically shaped and the outer die is also generally cylindrically shaped to allow the inner die to be placed within the outer die. Additionally, such a configuration may also allow for the translation extent of the inner die to be adjusted.

To achieve optimal heating of the portion of the metal alloy substrate, one or more temperatures may be monitored. In the case of a heated die, temperatures of at least a portion of the die or of at least a portion of a metal alloy substrate can be monitored, such as by using a temperature sensor, such as a thermocouple. In some embodiments, the heated die may be heated to a temperature above a target temperature for achieving suitable formability or plasticity, for example, so as to allow for the temperature of the metal alloy substrate to achieve the target temperature quickly so that a total duration of the heating and the joining can be very short, such as 5 seconds or less, 4 seconds or less, 3 seconds or less, 2 seconds or less, or between 0.1 seconds and 1 second. As examples, heating and joining together may take about 0.1 seconds, 0.15 seconds, 0.2 seconds, 0.25 seconds, 0.3 seconds, 0.35 seconds, 0.4 seconds, 0.45 seconds, 0.5 seconds, 0.55 seconds, 0.6 seconds, 0.65 seconds, 0.7 seconds, 0.75 seconds, 0.8 seconds, 0.85 seconds, 0.9 seconds, 0.95 seconds, 1 seconds, 1.05 seconds, 1.1 seconds, 1.15 seconds, 1.2 seconds, 1.25 seconds, 1.3 seconds, 1.35 seconds, 1.4 seconds, 1.45 seconds, 1.5 seconds, 1.55 seconds, 1.6 seconds, 1.65 seconds, 1.7 seconds, 1.75 seconds, 1.8 seconds, 1.85 seconds, 1.9 seconds, 1.95 seconds, 2 seconds, 2.05 seconds, 2.1 seconds, 2.15 seconds, 2.2

seconds, 2.25 seconds, 2.3 seconds, 2.35 seconds, 2.4 seconds, 2.45 seconds, 2.5 seconds, 2.55 seconds, 2.6 seconds, 2.65 seconds, 2.7 seconds, 2.75 seconds, 2.8 seconds, 2.85 seconds, 2.9 seconds, 2.95 seconds, 3 seconds, 3.05 seconds, 3.1 seconds, 3.15 seconds, 3.2 seconds, 3.25 seconds, 3.3 seconds, 3.35 seconds, 3.4 seconds, 3.45 seconds, 3.5 seconds, 3.55 seconds, 3.6 seconds, 3.65 seconds, 3.7 seconds, 3.75 seconds, 3.8 seconds, 3.85 seconds, 3.9 seconds, 3.95 seconds, 4 seconds, 4.05 seconds, 4.1 seconds, 4.15 seconds, 4.2 seconds, 4.25 seconds, 4.3 seconds, 4.35 seconds, 4.4 seconds, 4.45 seconds, 4.5 seconds, 4.55 seconds, 4.6 seconds, 4.65 seconds, 4.7 seconds, 4.75 seconds, 4.8 seconds, 4.85 seconds, 4.9 seconds, 4.95 seconds, or 5 seconds.

In various embodiments, the inner die may be heated to between 150 °C and 1000 °C using the heating element. For example, the inner die may be heated to about 150 °C, 160 °C, 170 °C, 180 °C, 190 °C, 200 °C, 210 °C, 220 °C, 230 °C, 240 °C, 250 °C, 260 °C, 270 °C, 280 °C, 290 °C, 300 °C, 310 °C, 320 °C, 330 °C, 340 °C, 350 °C, 360 °C, 370 °C, 380 °C, 390 °C, 400 °C, 410 °C, 420 °C, 430 °C, 440 °C, 450 °C, 460 °C, 470 °C, 480 °C, 490 °C, 500 °C, 510 °C, 520 °C, 530 °C, 540 °C, 550 °C, 560 °C, 570 °C, 580 °C, 590 °C, 600 °C, 610 °C, 620 °C, 630 °C, 640 °C, 650 °C, 660 °C, 670 °C, 680 °C, 690 °C, 700 °C, 710 °C, 720 °C, 730 °C, 740 °C, 750 °C, 760 °C, 770 °C, 780 °C, 790 °C, 800 °C, 810 °C, 820 °C, 830 °C, 840 °C, 850 °C, 860 °C, 870 °C, 880 °C, 890 °C, 900 °C, 910 °C, 920 °C, 930 °C, 940 °C, 950 °C, 960 °C, 970 °C, 980 °C, 990 °C, or 1000 °C. The temperature of the inner die may be selected depending on the composition of the first metal alloy substrate or the second metal alloy substrate. For example, when the second metal alloy substrate comprises aluminum, the inner die may be heated to between 150 °C and 700 °C. As another example, when the second metal alloy substrate comprises steel (e.g., coated or uncoated steel), the inner die may be heated to between 400 °C and 1000 °C.

Devices and apparatuses for joining two metal alloy substrates using a self-piercing rivet are also disclosed herein. For example, an apparatus may comprise a blankholder; a punch located within the blankholder; a die positioned beneath the blankholder and opposite the punch; and a heat source positioned to heat at least a portion of a metal alloy substrate. Example heat sources are described above and include, without limitation, a laser source, a magnetic or electromagnetic induction source, or a conductive heat source, which may include a die heated by an internal or external heating source, such as a resistive heating element. Optionally, a temperature sensor may be included in the apparatus and positioned in contact with the die, such as for monitoring a temperature of at least a portion of the die or a temperature of at least a portion of the first metal alloy substrate or the second metal alloy substrate during or prior to joining.

As described above, the die may optionally include an inner die and an outer die surrounding the inner die, such as an inner die that is translatable along an axis within the outer die for accommodating formation of a button during joining of a first metal alloy substrate and a second metal alloy substrate using a self-piercing rivet. Optionally, the inner die includes a heating element for heating a portion of at least one of the first metal alloy or the second metal alloy substrate to or above a temperature sufficient to increase formability of the portion of at least one of the first metal alloy or the second metal alloy substrate. Optionally, the die may include a resilient member positioned to provide a force on the inner die parallel to the translation axis, such as a force that is directed toward the punch. Optionally, the die includes a die lock positioned to limit a range of translation of the inner die along the translation axis. Optionally, example inner dies include inner dies that have a relief profile to induce flaring of the self-piercing rivet and formation of a mechanical interlock during joining. Optionally, example inner dies include inner dies having a flat profile.

Other objects and advantages will be apparent from the following detailed description of non-limiting examples.

## BRIEF DESCRIPTION OF THE FIGURES

The specification makes reference to the following appended figures, in which use of like reference numerals in different figures is intended to illustrate like or analogous components.

FIG. 1A provides a schematic illustration of two metal alloy substrates prior to joining.

FIG. 1B provides a schematic illustration of two metal alloy substrates after joining.

FIG. 1C provides photographs of metal alloy substrates after joining with visible cracks.

FIG. 2A provides a schematic illustration of two metal alloy substrates prior to joining.

FIG. 2B provides a schematic illustration of two metal alloy substrates after joining.

FIG. 2C provides photographs of metal alloy substrates in a crack-free configuration after joining.

FIG. 3A provides a schematic illustration of heating a portion of a metal alloy substrate using a laser.

FIG. 3B provides a schematic illustration of heating a portion of a metal alloy substrate using electromagnetic induction heating.

FIG. 4A and FIG. 4B provide schematic illustrations of joining metal alloy substrates using a self-piercing rivet.

FIG. 5A and FIG. 5B provide schematic illustrations of heating a metal alloy substrate with a heated die and joining metal alloy substrates using a self-piercing rivet.

FIG. 6 provides a photograph of metal alloy substrates joined by self-piercing riveting, comparing substrates with and without retrogression prior to joining.

FIG. 7A provides a photograph of a retrogressed metal alloy substrate joined to another metal alloy substrate by self-piercing riveting.

FIG. 7B provides a photograph of a metal alloy substrate without retrogression and joined to another metal alloy substrate by self-piercing riveting.

FIG. 8A provides a photograph of metal alloy substrate without retrogression and joined to another metal alloy substrate by self-piercing riveting.

FIG. 8B, FIG. 8C, FIG. 8D, FIG. 8E, and FIG. 8F provide photographs of retrogressed metal alloy substrates each joined to another metal alloy substrate by self-piercing riveting.

## DETAILED DESCRIPTION

Described herein are metal products, such as a metal product including metal alloy substrates joined by self-piercing rivets. Example metal products include those comprising at least one high-strength metal alloy substrate, such as a 2xxx series aluminum alloy substrate, a 6xxx series aluminum alloy substrate, or a 7xxx series aluminum alloy substrate. Methods of joining metal alloy substrates using self-piercing rivets are also disclosed, as are devices for joining metal alloy substrates using self-piercing rivets.

It can be challenging to join high-strength metal alloy substrates without impacting the strength of at least one of the substrates or in a way that results in a joint that is as strong as the substrates. Conventional joining techniques, such as welding, can be used to successfully join high-strength metal substrates, but the resultant weld or portions of the substrate adjacent to the weld may exhibit reduced strength as compared to the remainder of the substrate. Such a condition may arise, at least in part, because of tempering/annealing effects within the metal that occur when the metal is heated during the welding process. As the metal is heated during welding, the grain and crystal structure of the metal in or around the weld may relax and/or be formed, reformed, crystallized, or recrystallized in a way that results in low intrinsic strength. For some metal alloys, strength can be imparted by cold working, but cold working may be impractical for many joined metal products.

Other joining techniques, such as the use of adhesives, may not form a strong, permanent bond between metal alloy substrates. Mechanical joining methods, such as riveting, may be useful, but without careful attention to the joining process, strength of the joint may be insufficient. For example, self-piercing riveting is a useful technique for joining metal alloy substrates. Self-piercing rivets have been used successfully in a number of applications to join, for example, metal alloy substrates of different compositions, for which welding may not be practical, such as for different metal alloy substrates with large melting temperature differences. As illustrated in FIG. 1A and FIG. 1B, self-piercing riveting involves driving a self-piercing rivet 105 through and into at least two different metal alloy substrates 110 and 115. Upon joining, the self-piercing rivet 105 is retained within the substrates 110 and 115, with the lower substrate 115 forming a button 120 on the bottom side, with the rivet head located at the top substrate 110. For some high-strength alloys, the button 120 may include or form cracks 125 at one or more locations along the button. For some metal alloys, the button 120 may form initially in a crack-free configuration but may develop cracks 125 as the substrate 115 naturally ages or is exposed to elevated temperatures, such as during a paint baking process. As an example, FIG. 1C provides photographs of self-piercing rivet buttons of a high-strength 7xxx series aluminum substrate in W temper. The photographs show cracks 125 that formed after naturally aging the substrate for 1 day at room temperature.

The present disclosure, however, provides crack-free joints and methods and devices for joining metal alloy substrates in a crack-free configuration. Example metal alloy substrates include aluminum products, such as aluminum sheets, aluminum shate, aluminum plate, aluminum cast products, aluminum extrusion products, etc. Advantageously, self-piercing rivets may be used for sheet-to-sheet joints, sheet-to-casting joints, and sheet-to-extrusion joints. As illustrated in FIG. 2A, prior to joining of metal alloy substrates 210 and 215 by self-piercing rivet 205, metal alloy substrate 215 is heated at portion 225 to increase a formability property of portion 225. Optionally, metal alloy substrate 210 may also be heated at portion 230 that overlaps with portion 225 of metal alloy substrate 215 to increase a formability property of portion 230 of metal alloy substrate 210. Portion 230 is subsequently punched through by self-piercing rivet 205 during joining.

As shown in FIG. 2B, self-piercing rivet 205 pierces through metal alloy substrate 210 and into metal alloy substrate 215 to create a mechanical interlock and button 220 in the heated portion 225. FIG. 2C provides photographs of self-piercing rivet buttons of a high-strength 7xxx series aluminum substrate with a crack-free state.

By controlling the formability of a metal alloy substrate prior to and/or during joining by a self-piercing rivet, self-piercing rivet buttons that are of high quality can be created. The quality of a self-piercing rivet button, also referred to herein as a button, can be assessed visually or by touch, because cracks formed in the button are visible to the naked eye or can be felt by hand as fractures, raised/recessed fragments, or otherwise non-continuous surface profiles. In some embodiments, cracks may be viewed under magnification.

In some examples, cracks may form due to internal stresses within the metal alloy substrate, where the stresses can be relieved by material separation and formation of a discontinuity in the metal alloy substrate surface. For example, internal stresses may arise due to insertion of a self-piercing rivet and the resultant forming of the metal alloy substrates around the self-piercing rivet, including formation of the button. Although a button can form in a crack-free configuration, natural or accelerated aging processes may modify, for example, a crystal or grain structure of a metal alloy substrate to result in a condition where internal stresses are beyond a fracture strength and a crack can form.

Cracks may be characterized, in some examples, in terms of a size of a surface discontinuity, such as a gap in material that is large enough to be seen visibly or felt by touch. Cracks may include microcracks, in which a gap may have a dimension of from about 1 μm to about 100 μm. Larger cracks may have a gap dimension of from about 100 μm to about 1 mm or larger.

Crack formation is undesirable, as strength of a cracked material can be severely degraded due to excessive strain that can arise when regions of a material that would otherwise be continuous are connected by a reduced dimension continuous section such that forces have smaller transmission areas and are thus magnified across the reduced dimension continuous section. As strain is increased, for example, under a load, cracks may increase in size. Cracks also undesirably impact visual surface quality.

In some examples, a button or a metal alloy substrate is substantially free of cracks having a width of greater than about 2 µm and/or length of greater than about 10 µm. As used herein, the term substantially free, as related to the number of cracks having a certain dimension (e.g., a width and/or a length) means that the percentage of cracks having the certain dimension (or larger) is less than 0.1%, less than 0.01%, less than 0.001%, or less than 0.0001% based on the total number of cracks. In some cases, a button (and optionally a region of a metal alloy substrate surrounding a button, such as within 1 button diameter) is crack-free or substantially free of cracks having a measurement in any dimension of greater than 0.25 µm, 0.5 µm, 0.75 µm, 1 µm, 1.25 µm, 1.5 µm, 1.75 µm, 2 µm, 3 µm, 4 µm, 5 µm, 6 µm, 7 µm, 8 µm, 9 µm, or 10 µm, or between 0.25 µm and 1 mm.

*Definitions and Descriptions:*

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

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).

Reference may be 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. 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. A W condition or temper refers to an aluminum alloy after solution heat treatment.

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

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

Metal alloy products described herein may also be referred to as "metal substrates." Example metal substrates may include metal sheets, metal plates, metal shates, cast metal products, extruded metal products, and other metal objects, which can be joined, for example, by a self-piercing riveting process. Metal substrates may be formed into other products, such as by one or more blanking, stamping, drawing, roll forming, joining, or other mechanical process.

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

As used herein, "and/or" means that one, all, or any combination of items in a list separated by "and/or" are included in the list; for example "A, B, and/or C" is equivalent to "'A', or 'B', or 'C', or 'A and B', or 'A and C', or 'B and C', or 'A, B, and C'."

Unavoidable impurities, including materials or elements, may be present in a metal or metal alloy, such as aluminum or an aluminum alloy, in minor amounts due to inherent properties of the metal or leaching from contact with processing equipment. Some impurities typically found in aluminum include iron and silicon.

Formability refers to a character of a metal or other substrate to undergo plastic deformation without undergoing cracking or other damage or destruction to the substrate. Formability properties may include ductility, plasticity, flow behavior, etc. Formability and formability properties may be temperature dependent, in some embodiments, such as where increasing a temperature of a metal substrate results in increased formability. Depending on the configuration (temperature, material, etc.), formability may be modified temporarily by increasing a temperature. In some cases, formability may be modified permanently by increasing a temperature.

*Methods of Producing the Metal and Metal Alloy Products*

The metals, metal alloys and metal alloy products described herein (e.g., metal substrates) can be cast using any suitable casting method known to those of ordinary skill in the art. As a few non-limiting examples, the casting process can include a Direct Chill (DC) casting process or a Continuous Casting (CC) process. The continuous casting system can include a pair of moving opposed casting surfaces (e.g., moving opposed belts, rolls, or blocks), a casting cavity between the pair of moving opposed casting surfaces, and a molten metal injector. The molten metal injector can have an end opening from which molten metal can exit the molten metal injector and be injected into the casting cavity.

A cast ingot or other cast product can be processed by any suitable means. Optionally, the processing steps can be used to prepare sheets. Such processing steps include, but are not limited to, homogenization, hot rolling, cold rolling, solution heat treatment, and an optional pre-aging step, as known to those of ordinary skill in the art.

*Methods of Using the Disclosed Metals and Metal Alloy Products*

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

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

*Methods of Treating and Using Metals and Metal Alloys*

Described herein are methods of treating and using metals and metal alloys, including aluminum, aluminum alloys, magnesium, magnesium alloys, magnesium composites, and steel, among others, and the resultant treated metals and metal alloys. In some examples, the metals for use in the methods described herein include aluminum alloys, for example, 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys. In some examples, the materials for use in the methods described herein include non-ferrous materials, including aluminum, aluminum alloys, magnesium, magnesium-based materials, magnesium alloys, magnesium composites, titanium, titanium-based materials, titanium alloys, copper, copper-based materials, nickel, nickel-based materials, composites, sheets or layers used in composites, or any other suitable metal, non-metal or combination of materials. Monolithic as well as non-monolithic, such as roll-bonded materials, cladded alloys, clad layers, composite materials, such as but not limited to carbon fiber-containing materials, or various other materials are also useful with the methods described herein. In some examples, aluminum alloys containing iron are useful with the methods described herein.

By way of non-limiting examples, exemplary AA1xxx series alloys for use in the methods 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.

Non-limiting exemplary AA2xxx series alloys for use in the methods 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.

Non-limiting exemplary AA3xxx series alloys for use in the methods 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.

Non-limiting exemplary AA4xxx series alloys for use in the methods 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.

Non-limiting exemplary AA5xxx series alloys for use in the methods 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.

Non-limiting exemplary AA6xxx series alloys for use in the methods 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, AA6963, AA6064, AA6064A, AA6065, AA6066, AA6068, AA6069, AA6070, AA6081, AA6181, AA6181A, AA6082, AA6082A, AA6182, AA6091, or AA6092.

Non-limiting exemplary AA7xxx series alloys for use in the methods 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, AA7204, 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.

Non-limiting exemplary AA8xxx series aluminum alloys for use in the methods 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.

In certain metals and metal alloys, strength and formability may be inversely related to one another and an increase in one property may accompany a decrease in the other. It is common in the metal industry, including, for example in the sheet, shate, or plate metal industry, cast or extruded metal industry, etc., to provide a product with uniform or substantially uniform properties. Such a configuration can allow for reliability of use of the sheet, shate, plate, cast product, extruded product, etc., such as in a stamping, drawing, or other forming process. Some metals or metal alloys may be desirable for their strength characteristics, while other metals or metal alloys may be desirable for their formability characteristics. It will be appreciated that heating and/or working metals may modify these properties.

In some cases, it can be difficult or impractical to join metal products in a way that does not permanently alter the formability and/or strength properties. However, it may be desirable to join metal products in a way that provides a strong permanent bond between the metal products, such as a bond that is robust and exhibits high strength, such as comparable to the strength of the individual metal products being joined. In the case of joining a high-strength metal alloy product (*e.g.*, products comprising a 2xxx series aluminum, a 6xxx series aluminum, or a 7xxx series aluminum) to another metal alloy product, which may be a high-strength metal alloy product or another metal alloy product (e.g., products comprising a 1xxx series aluminum, a 2xxx series aluminum, a 3xxx series aluminum, a 4xxx series aluminum, a 5xxx series aluminum, a 6xxx series aluminum, a 7xxx series aluminum, an 8xxx series aluminum, steel, magnesium, brass, etc.), the high-strength metal alloy product may undergo cracking during and/or after joining if not handled appropriately during and/or prior to the joining process.

Forming processes that take place prior to joining can also impact the ability of a metal alloy substrate to be suitably joined to another substrate. For example, forming processes can alter the strength of the substrate. For example, in some embodiments, subjecting a metal substrate to a forming process results in an increase in strength and reduction of ductility, for example. As such, formed metal substrates can exhibit higher strengths than unformed metal substrates, exacerbating the previously mentioned problems that can be associated with joining.

In some embodiments, the formability of high-strength metal alloys may be increased, at least temporarily, by heating. In some cases, formability may be permanently altered by heating, such as when the temperature of the metal alloy is driven close to or above the recrystallization temperature of the metal. In other cases, formability may be temporarily altered by heating, such as when the metal alloy is heated to a temperature below the recrystallization temperature of the metal. These aspects may be exploited to form joined metal products comprising high-strength metal alloy substrates using self-piercing rivets. For example, a portion of a high-strength metal alloy substrate may be heated to a temperature to, at least temporarily, increase the formability. While the portion of the metal alloy substrate has an increased formability, such as while in a heated condition, a self-piercing rivet may be used to join the metal alloy substrate to another substrate at the portion with increased formability.

A variety of techniques may be used to heat the portion of the substrate. For example, FIG. 3A illustrates a technique in which a laser source 305 is used to illuminate a portion 310 of a metal alloy substrate 315. Laser source 305 may be focused on the portion 310 of the metal alloy substrate 315. Optionally, laser source 305 may have a ring profile, such as may be created using an axicon lens, for example. In some cases, the laser source may be used to heat the metal alloy substrate 315 immediately prior to and/or during joining by the self-piercing rivet. Such a configuration may be useful when the formability of the portion 310 of metal alloy substrate 315 is only temporarily modified for the joining process, for example. For example, laser source 305 may optionally be included in an apparatus for joining metal alloy substrates using self-piercing rivets.

In some embodiments, however, laser source 305 can be used in a rolling or finishing process, where metal alloy substrate 315 is subjected to laser light from laser source 305 to heat and modify the formability properties of various portions 310. Optionally, laser source 305 can be a component of a computer numerical control (CNC) system, where laser source 305 is moved to heat various portions 310 of substrate 315 to increase formability, such as during a blanking or other laser machining process, such as laser trimming. In addition to heating portions 310 of substrate 315 to modify formability for improved joining by self-piercing rivets, other regions or portions of substrate 315 can also have their formability modified by laser source 305, such as an edge region to improve formability for a hemming process.

In some embodiments, laser source 305 may be incorporated as an element of an apparatus for a stamping or forming process, such as a stamping die or press, where regions of the substrate 315 can be subjected to heating by laser source 305 before, during, or after the forming process. In some cases, laser heating may be used during a die quenching process to reduce a quench rate of a region of substrate 315. Depending on the alloy and the heating process prior to quenching, heating during die quenching in this way may result in the region having increased formability properties as compared to non-heated regions. These laser treated regions with increased formability may correspond, for example, to positions to be joined to another substrate 325 by a self-piercing rivet.

In some embodiments, portions 330 of substrate 325 at which self-piercing rivets may punch through to join substrate 325 to substrate 315 may also be subjected to heating before, during, or after the forming process. In some cases, the same laser source 305 for heating portions 310 of substrate 315, a second laser source, or other heating mechanism, may be used for heating portions 330 of substrate 325. For example, laser source 305 may be configured such that the heat generated by laser source 305 may be sufficient to heat multiple stacked substrates, e.g., substrates 315, 325, simultaneously. As another example, substrates 310, 330 may be subjected to heating by a common laser source, e.g., laser source 305, individually before being positioned adjacent to one another. Although FIG. 3A illustrates that laser source 305 is positioned on the side of substrates 310, 330 opposite to the side through which a self-piercing rivet may be punched, laser source 305 may be positioned on the same side through which a self-piercing rivet may be punched to heat one or multiple substrates, e.g., substrates 310, 330, one by one individually or all together simultaneously.

As another example, a magnetic or electromagnetic induction process may be used to heat a metal alloy substrate to achieve improved formability for joining using a self-piercing rivet, as illustrated in FIG. 3B. In FIG. 3B, portion 310 of metal alloy substrate 315 and/or portion 330 of metal alloy substrate 320 may be subjected to heating using coil 320, where a high frequency electric current passed through coil 320 may generate a rotating magnetic field that induces eddy currents within portion 310, leading to heat generation within portion 310 and/or portion 330. The use of coil 320 is merely exemplary and other configurations may be used. For example, coil 320 may be replaced by rotating permanent magnets, for example. Other coil configurations may also be used. A position of coil 320 relative to substrate 315 and/or substrate

325 may be useful for adjusting the rate of heat generation within portion 310 of substrate 315 and/or the rate of heat generating within portion 330 of substrate 325. A frequency of the rotating magnetic field may also be useful for adjusting the rate of heat generation within portion 310 of substrate 315 and/or the rate of heat generating within portion 330 of substrate 325.

FIGs. 4A and 4B depict schematic overviews of joining metal alloy substrates 410 and 415 using a self-piercing rivet 405. In FIG. 4A, self-piercing rivet has not yet been inserted into metal alloy substrates 410 and 415, but is positioned adjacent to metal alloy substrate 410 and within blankholder 420. Metal alloy substrate 415 include heated portion 425 having improved formability properties. In some embodiments, metal alloy substrate 410 also includes heated portion 450 having improved formability properties. Punch 430 is also positioned within blankholder 420 for joining metal alloy substrates 410 and 415 using self-piercing rivet 405.

Die 435 is positioned adjacent to metal alloy substrate 415 and includes recess 440 with a relief profile for flaring self-piercing rivet 405 during joining. FIG. 4B shows self-piercing rivet 405 pressed into metal alloy substrates 410 and 415 by punch 430. At least part of portion 425 is formed into a button 445 within recessed region 435 of die, where the shank of self-piercing rivet 405 is flared and forms a mechanical interlock to join metal alloy substrates 410 and 415. Although self-piercing rivet 405 is illustrated as flush with the top surface of metal alloy substrate 410, it will be appreciated that various alternative configurations are contemplated, including where the top of self-piercing rivet 405 is recessed or sunk below the top surface of metal alloy substrate 410 or where the top of self-piercing rivet 405 is raised or extends above the top surface of metal alloy substrate 410.

FIGs. 5A and 5B depict schematic overviews of heating and joining metal alloy substrates 510 and 515 using a self-piercing rivet 505. In FIG. 5A, self-piercing rivet 505 has not yet been inserted into metal alloy substrates 510 and 515, but is positioned adjacent to metal alloy substrate 510 and within blankholder 520. Punch 530 is also positioned within blankholder 520 for joining metal alloy substrates 510 and 515 using self-piercing rivet 505. Metal alloy substrate 515 includes heated portion 525, heated by contact with die 535, positioned adjacent to metal alloy substrate 515. In some embodiments, metal alloy substrate 510 may also include heated portion 585. In some cases, portion 585 of metal alloy substrate 510 may be heated simultaneously with portion 525 of metal alloy substrate 515 by die 535. In some cases, portion

585 of metal alloy substrate 510 may be heated by any other mechanisms described herein prior to being positioned adjacent to metal alloy substrate 515.

Die 535 may optionally include recessed region 540 to accommodate forming of metal alloy substrate 515 during joining. Die 535 includes multiple components, including outer die 545 and inner die 550. Inner die 550 is located within outer die 545 and is translatable along axis 555. Inner die 550 includes heating element 560 for modifying a temperature of inner die 550 and other components in contact with inner die 550, such as metal alloy substrate portion 525 and/or metal alloy substrate portion 585, by conductive heat transfer, for example. Heating element 560 may be a resistive heating element, including a build-in cartridge heater, for example. Optionally, a temperature sensor, such as a thermocouple or thermistor, may be included in inner die, such as at a surface between inner die 550 and metal alloy substrate 515 and/or at a surface between metal alloy substrate 515 and metal alloy substrate 510, for example, use in monitoring and controlling a temperature of inner die 550, metal alloy substrate 515, and/or metal alloy substrate 510 and to achieve various temperatures of inner die 550 as well as various temperatures of heated portion 525 and/or portion 585.

Die 535 also includes a resilient member, exemplified as a spring 565 in FIGs. 5A and 5B. Spring 565 provides a force to inner die 550, such as parallel to axis 555, to direct it towards punch 530 and/or metal alloy substrate 515, for example, in order to maintain contact between metal alloy substrate 515 and inner die 550, such as to allow for efficient conductive heat transfer.

Since inner die 550 is translatable along axis 555, a die lock may be included in die 535 to limit the extent of travel of inner die 550, such as to prevent spring 565 from pushing inner die 550 beyond a desirable position. Die lock is exemplified in FIGs. 5A and 5B as a set screw 570 and recess 575. As illustrated, an end of set screw 570 is adjustable within recess 575 to allow the maximum travel position of inner die 550 to be adjusted.

FIG. 5B shows self-piercing rivet 505 pressed into metal alloy substrates 510 and 515 by punch 530, where at least part of portion 525 is formed into a button 580, with inner die 550 travelling downward by compression of spring 555 in order to accommodate button 580. Outer die is illustrated in FIG. 5A as including a recessed region 540 for accommodating formation of button 580 in metal alloy substrate 515. Recessed region 540 is an optional feature and may not be included in all embodiments. Inner die 550 is illustrated as having a flat profile in FIGs. 5A and 5B. In some embodiments, inner die 550 has a raised or recessed profile to aid or cause flaring of self-piercing rivet. Shank of self-piercing rivet 505 is flared and forms a mechanical interlock to join metal alloy substrates 510 and 515. Bottom end of die 535 may serve as a hard stop for inner die 550, limiting maximum travel away from metal alloy substrate 515.

## EXAMPLE 1

Samples of a 7xxx aluminum alloy sheet having a T6 temper were heat treated by retrogression (i.e., retrogressed) to increase the formability and/or plasticity, e.g., elongation and bendability of the sample substrates to test the performance in joining by self-piercing riveting.

Retrogression can be accomplished by local heating a portion of a product (or portions of multiple products) in a high strength/low formability condition (e.g., solution heat treated temper conditions, including T6 temper, T7 temper, etc.) to a certain temperature during a short period of time. The portion(s) of the product(s) subjected to retrogression may advantageously be the location where a self-piercing rivet is applied.

The temperature to which the portion(s) of the product(s) may be heated to achieve improvements in formability and/or plasticity may be referred to as the retrogression temperature. The retrogression temperature may range between 70 °C and 600 °C, between 70 °C and 100 °C, between 350 °C and 600 °C, 350 °C and 500 °C, 350 °C and 400 °C, or between 150 °C and 500 °C. In some embodiments, the retrogression temperature may range from about 100 °C to about 350 °C.

For example, the product or a portion thereof may be locally heated to a temperature of from 70 °C to 100 °C, from 75 °C to 100 °C, from 80 °C to 100 °C, from 85 °C to 100 °C, from 90 °C to 100 °C, from 95 °C to 100 °C, from 70 °C to 95 °C, from 75 °C to 95 °C, from 80 °C to 95 °C, from 85 °C to 95 °C, from 90 °C to 95 °C, from 70 °C to 90 °C, from 75 °C to 90 °C, from 80 °C to 90 °C, from 85 °C to 90 °C, from 70 °C to 85 °C, from 75 °C to 85 °C, from 80 °C to 85 °C, from 70 °C to 80 °C, from 75 °C to 80 °C, or from 70 °C to 75 °C.

For example, the product or a portion thereof may be locally heated to a temperature of from 100 °C to 350 °C, from 110 °C to 350 °C, from 120 °C to 350 °C, from 130 °C to 350 °C, from 140 °C to 350 °C, from 150 °C to 350 °C, from 160 °C to 350 °C, from 170 °C to 350 °C, from 180 °C to 350 °C, from 190 °C to 350 °C, from 200 °C to 350 °C, from 210 °C to 350 °C, from 220 °C to 350 °C, from 230 °C to 350 °C, from 240 °C to 350 °C, from 250 °C to 350 °C, from 260 °C to 350 °C, from 270 °C to 350 °C, from 280 °C to 350 °C, from 290 °C to 350 °C, from 300 °C to 350 °C, from 310 °C to 350 °C, from 320 °C to 350 °C, from 330 °C to 350 °C, from 340 °C to 350 °C, from 100 °C to 340 °C, from 110 °C to 340 °C, from 120 °C to 340 °C, from 130 °C to 340 °C, from 140 °C to 340 °C, from 150 °C to 340 °C, from 160 °C to 340 °C, from 170 °C to 340 °C, from 180 °C to 340 °C, from 190 °C to 340 °C, from 200 °C to 340 °C, from 210 °C to 340 °C, from 220 °C to 340 °C, from 230 °C to 340 °C, from 240 °C to 340 °C, from 250 °C to 340 °C, from 260 °C to 340 °C, from 270 °C to 340 °C, from 280 °C to 340 °C, from 290 °C to 340 °C, from 300 °C to 340 °C, from 310 °C to 340 °C, from 320 °C to 340 °C, from 330 °C to 340 °C, from 100 °C to 330 °C, from 110 °C to 330 °C, from 120 °C to 330 °C, from 130 °C to 330 °C, from 140 °C to 330 °C, from 150 °C to 330 °C, from 160 °C to 330 °C, from 170 °C to 330 °C, from 180 °C to 330 °C, from 190 °C to 330 °C, from 200 °C to 330 °C, from 210 °C to 330 °C, from 220 °C to 330 °C, from 230 °C to 330 °C, from 240 °C to 330 °C, from 250 °C to 330 °C, from 260 °C to 330 °C, from 270 °C to 330 °C, from 280 °C to 330 °C, from 290 °C to 330 °C, from 300 °C to 330 °C, from 310 °C to 330 °C, from 320 °C to 330 °C, from 100 °C to 320 °C, from 110 °C to 320 °C, from 120 °C to 320 °C, from 130 °C to 320 °C, from 140 °C to 320 °C, from 150 °C to 320 °C, from 160 °C to 320 °C, from 170 °C to 320 °C, from 180 °C to 320 °C, from 190 °C to 320 °C, from 200 °C to 320 °C, from 210 °C to 320 °C, from 220 °C to 320 °C, from 230 °C to 320 °C, from 240 °C to 320 °C, from 250 °C to 320 °C, from 260 °C to 320 °C, from 270 °C to 320 °C, from 280 °C to 320 °C, from 290 °C to 320 °C, from 300 °C to 320 °C, from 310 °C to 320 °C, from 100 °C to 310 °C, from 110 °C to 310 °C, from 120 °C to 310 °C, from 130 °C to 310 °C, from 140 °C to 310 °C, from 150 °C to 310 °C, from 160 °C to 310 °C, from 170 °C to 310 °C, from 180 °C to 310 °C, from 190 °C to 310 °C, from 200 °C to 310 °C, from 210 °C to 310 °C, from 220 °C to 310 °C, from 230 °C to 310 °C, from 240 °C to 310 °C, from 250 °C to 310 °C, from 260 °C to 310 °C, from 270 °C to 310 °C, from 280 °C to 310 °C, from 290 °C to 310 °C, from 300 °C to 310 °C, from 100 °C to 300 °C, from 110 °C to 300 °C, from 120 °C to 300 °C, from 130 °C to 300 °C, from 140 °C to 300 °C, from 150 °C to 300 °C, from 160 °C to 300 °C, from 170 °C to 300 °C, from 180 °C to 300 °C, from 190 °C to 300 °C, from 200 °C to 300 °C, from 210 °C to 300 °C, from 220 °C to 300 °C, from 230 °C to 300 °C, from 240 °C to 300 °C, from 250 °C to 300 °C, from 260 °C to 300 °C, from 270 °C to 300 °C, from 280 °C to 300 °C, from 290 °C to 300 °C, from 100 °C to 290 °C, from 110 °C to 290 °C, from 120 °C to 290 °C, from 130 °C to 290 °C, from 140 °C to 290 °C, from 150 °C to 290 °C, from 160 °C to 290 °C, from 170 °C to 290 °C, from 180 °C to 290 °C, from 190 °C to 290 °C, from 200 °C to 290 °C, from 210 °C to 290 °C, from 220 °C to 290 °C, from 230 °C to 290 °C, from 240 °C to 290 °C, from 250 °C to 290 °C, from 260 °C to 290 °C, from 270 °C to 290 °C, from 280 °C to 290 °C, from 100 °C to 280 °C, from 110 °C to 280 °C, from 120 °C to 280 °C, from 130 °C to 280 °C, from 140 °C to 280 °C, from 150 °C to 280 °C, from 160 °C to 280 °C, from 170 °C to 280 °C, from 180 °C to 280 °C, from 190 °C to 280 °C, from 200 °C to 280 °C, from 210 °C to 280 °C, from 220 °C to 280 °C, from 230 °C to 280 °C, from 240 °C to 280 °C, from 250 °C to 280 °C, from 260 °C to 280 °C, from 270 °C to 280 °C, from 100 °C to 270 °C, from 110 °C to 270 °C, from 120 °C to 270 °C, from 130 °C to 270 °C, from 140 °C to 270 °C, from 150 °C to 270 °C, from 160 °C to 270 °C, from 170 °C to 270 °C, from 180 °C to 270 °C, from 190 °C to 270 °C, from 200 °C to 270 °C, from 210 °C to 270 °C, from 220 °C to 270 °C, from 230 °C to 270 °C, from 240 °C to 270 °C, from 250 °C to 270 °C, from 260 °C to 270 °C, from 100 °C to 260 °C, from 110 °C to 260 °C, from 120 °C to 260 °C, from 130 °C to 260 °C, from 140 °C to 260 °C, from 150 °C to 260 °C, from 160 °C to 260 °C, from 170 °C to 260 °C, from 180 °C to 260 °C, from 190 °C to 260 °C, from 200 °C to 260 °C, from 210 °C to 260 °C, from 220 °C to 260 °C, from 230 °C to 260 °C, from 240 °C to 260 °C, from 250 °C to 260 °C, from 100 °C to 250 °C, from 110 °C to 250 °C, from 120 °C to 250 °C, from 130 °C to 250 °C, from 140 °C to 250 °C, from 150 °C to 250 °C, from 160 °C to 250 °C, from 170 °C to 250 °C, from 180 °C to 250 °C, from 190 °C to 250 °C, from 200 °C to 250 °C, from 210 °C to 250 °C, from 220 °C to 250 °C, from 230 °C to 250 °C, from 240 °C to 250 °C, from 100 °C to 240 °C, from 110 °C to 240 °C, from 120 °C to 240 °C, from 130 °C to 240 °C, from 140 °C to 240 °C, from 150 °C to 240 °C, from 160 °C to 240 °C, from 170 °C to 240 °C, from 180 °C to 240 °C, from 190 °C to 240 °C, from 200 °C to 240 °C, from 210 °C to 240 °C, from 220 °C to 240 °C, from 230 °C to 240 °C, from 100 °C to 230 °C, from 110 °C to 230 °C, from 120 °C to 230 °C, from 130 °C to 230 °C, from 140 °C to 230 °C, from 150 °C to 230 °C, from 160 °C to 230 °C, from 170 °C to 230 °C, from 180 °C to 230 °C, from 190 °C to 230 °C, from 200 °C to 230 °C, from 210 °C to 230 °C, from 220 °C to 230 °C, from 100 °C to 220 °C, from 110 °C to 220 °C, from 120 °C to 220 °C, from 130 °C to 220 °C, from 140 °C to 220 °C, from 150 °C to 220 °C, from 160 °C to 220 °C, from 170 °C to 220 °C, from 180 °C to 220 °C, from 190 °C to 220 °C, from 200 °C to 220 °C, from 210 °C to 220 °C, from 100 °C to 210 °C, from 110 °C to 210 °C, from 120 °C to 210 °C, from 130 °C to 210 °C, from 140 °C to 210 °C, from 150 °C to 210 °C, from 160 °C to 210 °C, from 170 °C to 210 °C, from 180 °C to 210 °C, from 190 °C to 210 °C, from 200 °C to 210 °C, from 100 °C to 200 °C, from 110 °C to 200 °C, from 120 °C to 200 °C, from 130 °C to 200 °C, from 140 °C to 200 °C, from 150 °C to 200 °C, from 160 °C to 200 °C, from 170 °C to 200 °C, from 180 °C to 200 °C, from 190 °C to 200 °C, from 100 °C to 190 °C, from 110 °C to 190 °C, from 120 °C to 190 °C, from 130 °C to 190 °C, from 140 °C to 190 °C, from 150 °C to 190 °C, from 160 °C to 190 °C, from 170 °C to 190 °C, from 180 °C to 190 °C, from 100 °C to 180 °C, from 110 °C to 180 °C, from 120 °C to 180 °C, from 130 °C to 180 °C, from 140 °C to 180 °C, from 150 °C to 180 °C, from 160 °C to 180 °C, from 170 °C to 180 °C, from 100 °C to 170 °C, from 110 °C to 170 °C, from 120 °C to 170 °C, from 130 °C to 170 °C, from 140 °C to 170 °C, from 150 °C to 170 °C, from 160 °C to 170 °C, from 100 °C to 160 °C, from 110 °C to 160 °C, from 120 °C to 160 °C, from 130 °C to 160 °C, from 140 °C to 160 °C, from 150 °C to 160 °C, from 100 °C to 150 °C, from 110 °C to 150 °C, from 120 °C to 150 °C, from 130 °C to 150 °C, from 140 °C to 150 °C, from 100 °C to 140 °C, from 110 °C to 140 °C, from 120 °C to 140 °C, from 130 °C to 140 °C, from 100 °C to 130 °C, from 110 °C to 130 °C, from 120 °C to 130 °C, from 100 °C to 120 °C, from 110 to 120 °C, or from 100 °C to 110 °C.

For example, the product or a portion thereof may be locally heated to a temperature of from 350 °C to 600 °C, from 375 °C to 600 °C, from 400 °C to 600 °C, from 425 °C to 600 °C, from 450 °C to 600 °C, from 475 °C to 600 °C, from 500 °C to 600 °C, from 525 °C to 600 °C, from 550 °C to 600 °C, from 575 °C to 600 °C, from 350 °C to 575 °C, from 375 °C to 575 °C, from 400 °C to 575 °C, from 425 °C to 575 °C, from 450 °C to 575 °C, from 475 °C to 575 °C, from 500 °C to 575 °C, from 525 °C to 575 °C, from 550 °C to 575 °C, from 350 °C to 550 °C, from 375 °C to 550 °C, from 400 °C to 550 °C, from 425 °C to 550 °C, from 450 °C to 550 °C, from 475 °C to 550 °C, from 500 °C to 550 °C, from 525 °C to 550 °C, from 350 °C to 525 °C, from 375 °C to 525 °C, from 400 °C to 525 °C, from 425 °C to 525 °C, from 450 °C to 525 °C, from 475 °C to 525 °C, from 500 °C to 525 °C, from 350 °C to 500 °C, from 375 °C to 500 °C, from 400 °C to 500 °C, from 425 °C to 500 °C, from 450 °C to 500 °C, from 475 °C to 500 °C, from 350 °C to 475 °C, from 375 °C to 475 °C, from 400 °C to 475 °C, from 425 °C to 475 °C, from 450 °C to 475 °C, from 350 °C to 450 °C, from 375 °C to 450 °C, from 400 °C to 450 °C, from 425 °C to 450 °C, from 350 °C to 425 °C, from 375 °C to 425 °C, from 400 °C to 425 °C, from 350 °C to 400 °C, from 375 °C to 400 °C, or from 350 °C to 375 °C.

The appropriate retrogression temperature or the appropriate range thereof may also vary depending on the alloy. For example, for a 2xxx series aluminum alloy, the retrogression temperature may be from 200 °C to 300 °C or any and all subranges subsumed therein, including any of the subranges discussed above. For a 3xxx series aluminum alloy, the retrogression temperature may be from 70 °C to 600 °C or any and all subranges subsumed therein, including any of the subranges discussed above. For a 5xxx series aluminum alloy, the retrogression temperature may be from 70 °C to 600 °C or any and all subranges subsumed therein, including any of the subranges discussed above. For a 6xxx series aluminum alloy, the retrogression temperature may be from 200 °C to 300 °C or any and all subranges subsumed therein, including any of the subranges discussed above. For a 7xxx series aluminum alloy, the retrogression temperature may be from 180 °C to 250 °C or any and all subranges subsumed therein, including any of the subranges discussed above.

The appropriate retrogression temperature or the appropriate range thereof may also vary depending on the temper or condition of the alloy. For example, an alloy may be in a heat treated temper condition, including but not limited to, solution heat treated temper conditions, such as T6 temper, T7 temper, etc. For an alloy that may be in a solution heat treated temper condition, the retrogression temperature may be from 70 °C to 600 °C or any and all subranges subsumed therein, including any of the subranges discussed above. For an alloy that may be in a T6 temper condition, the retrogression temperature may be from 180 °C to 300 °C or any and all subranges subsumed therein, including any of the subranges discussion above. For an alloy that may be in a T7 temper condition, the retrogression temperature may be from 200 °C to 300 °C or any and all subranges subsumed therein, including any of the subranges discussion above.

The duration for which the local heating is performed may be referred to as the retrogression duration. The retrogression duration may include a first duration or a heat-up duration, followed by a second duration or a soak duration. By the end of the first or heat-up duration, the heated portion of the product reaches the intended retrogression temperature. The second or soak duration refers to the duration the portion of the product is maintained at or above the retrogression temperature. The second or soak duration may be shorter than the first or heat-up duration.

Depending on the product to be heated and/or the heating mechanism utilized, the first or heat-up duration may range from about 1 second to about 15 minutes. For example, the first or heat-up duration may be from 1 second to 15 minutes, from 2 seconds to 15 minutes, from 3 seconds to 15 minutes, from 4 seconds to 15 minutes, from 5 seconds to 15 minutes, from 10 seconds to 15 minutes, from 15 seconds to 15 minutes, from 30 seconds to 15 minutes, from 1 minute to 15 minutes, from 2 minutes to 15 minutes, from 3 minutes to 15 minutes, from 4 minutes to 15 minutes, from 5 minutes to 15 minutes, from 6 minutes to 15 minutes, from 7 minutes to 15 minutes, from 8 minutes to 15 minutes, from 9 minutes to 15 minutes, from 10 minutes to 15 minutes, from 11 minutes to 15 minutes, from 12 minutes to 15 minutes, from 13 minutes to 15 minutes, from 14 minutes to 15 minutes, from 1 second to 14 minutes, from 2 seconds to 14 minutes, from 3 seconds to 14 minutes, from 4 seconds to 14 minutes, from 5 seconds to 14 minutes, from 10 seconds to 14 minutes, from 15 seconds to 14 minutes, from 30 seconds to 14 minutes, from 1 minute to 14 minutes, from 2 minutes to 14 minutes, from 3 minutes to 14 minutes, from 4 minutes to 14 minutes, from 5 minutes to 14 minutes, from 6 minutes to 14 minutes, from 7 minutes to 14 minutes, from 8 minutes to 14 minutes, from 9 minutes to 14 minutes, from 10 minutes to 14 minutes, from 11 minutes to 14 minutes, from 12 minutes to 14 minutes, from 13 minutes to 14 minutes, from 1 second to 13 minutes, from 2 seconds to 13 minutes, from 3 seconds to 13 minutes, from 4 seconds to 13 minutes, from 5 seconds to 13 minutes, from 10 seconds to 13 minutes, from 15 seconds to 13 minutes, from 30 seconds to 13 minutes, from 1 minute to 13 minutes, from 2 minutes to 13 minutes, from 3 minutes to 13 minutes, from 4 minutes to 13 minutes, from 5 minutes to 13 minutes, from 6 minutes to 13 minutes, from 7 minutes to 13 minutes, from 8 minutes to 13 minutes, from 9 minutes to 13 minutes, from 10 minutes to 13 minutes, from 11 minutes to 13 minutes, from 12 minutes to 13 minutes, from 1 second to 12 minutes, from 2 seconds to 12 minutes, from 3 seconds to 12 minutes, from 4 seconds to 12 minutes, from 5 seconds to 12 minutes, from 10 seconds to 12 minutes, from 15 seconds to 12 minutes, from 30 seconds to 12 minutes, from 1 minute to 12 minutes, from 2 minutes to 12 minutes, from 3 minutes to 12 minutes, from 4 minutes to 12 minutes, from 5 minutes to 12 minutes, from 6 minutes to 12 minutes, from 7 minutes to 12 minutes, from 8 minutes to 12 minutes, from 9 minutes to 12 minutes, from 10 minutes to 12 minutes, from 11 minutes to 12 minutes, from 1 second to 11 minutes, from 2 seconds to 11 minutes, from 3 seconds to 11 minutes, from 4 seconds to 11 minutes, from 5 seconds to 11 minutes, from 10 seconds to 11 minutes, from 15 seconds to 11 minutes, from 30 seconds to 11 minutes, from 1 minute to 11 minutes, from 2 minutes to 11 minutes, from 3 minutes to 11 minutes, from 4 minutes to 11 minutes, from 5 minutes to 11 minutes, from 6 minutes to 11 minutes, from 7 minutes to 11 minutes, from 8 minutes to 11 minutes, from 9 minutes to 11 minutes, from 10 minutes to 11 minutes, from 1 second to 10 minutes, from 2 seconds to 10 minutes, from 3 seconds to 10 minutes, from 4 seconds to 10 minutes, from 5 seconds to 10 minutes, from 10 seconds to 10 minutes, from 15 seconds to 10 minutes, from 30 seconds to 10 minutes, from 1 minute to 10 minutes, from 2 minutes to 10 minutes, from 3 minutes to 10 minutes, from 4 minutes to 10 minutes, from 5 minutes to 10 minutes, from 6 minutes to 10 minutes, from 7 minutes to 10 minutes, from 8 minutes to 10 minutes, from 9 minutes to 10 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 9 minutes, from 30 seconds to 9 minutes, from 1 minute to 9 minutes, from 2 minutes to 9 minutes, from 3 minutes to 9 minutes, from 4 minutes to 9 minutes, from 5 minutes to 9 minutes, from 6 minutes to 9 minutes, from 7 minutes to 9 minutes, from 8 minutes to 9 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 8 minutes, from 30 seconds to 8 minutes, from 1 minute to 8 minutes, from 2 minutes to 8 minutes, from 3 minutes to 8 minutes, from 4 minutes to 8 minutes, from 5 minutes to 8 minutes, from 6 minutes to 8 minutes, from 7 minutes to 8 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 7 minutes, from 30 seconds to 7 minutes, from 1 minute to 7 minutes, from 2 minutes to 7 minutes, from 3 minutes to 7 minutes, from 4 minutes to 7 minutes, from 5 minutes to 7 minutes, from 6 minutes to 7 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 6 minutes, from 30 seconds to 6 minutes, from 1 minute to 6 minutes, from 2 minutes to 6 minutes, from 3 minutes to 6 minutes, from 4 minutes to 6 minutes, from 5 minutes to 6 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 5 minutes, from 30 seconds to 5 minutes, from 1 minute to 5 minutes, from 2 minutes to 5 minutes, from 3 minutes to 5 minutes, from 4 minutes to 5 minutes, from 1 second to 4 minutes, from 2 seconds to 4 minutes, from 3 seconds to 4 minutes, from 4 seconds to 4 minutes, from 5 seconds to 4 minutes, from 10 seconds to 4 minutes, from 15 seconds to 4 minutes, from 30 seconds to 4 minutes, from 1 minute to 4 minutes, from 2 minutes to 4 minutes, from 3 minutes to 4 minutes, from 1 second to 3 minutes, from 2 seconds to 3 minutes, from 3 seconds to 3 minutes, from 4 seconds to 3 minutes, from 5 seconds to 3 minutes, from 10 seconds to 3 minutes, from 15 seconds to 3 minutes, from 30 seconds to 3 minutes, from 1 minute to 3 minutes, from 2 minutes to 3 minutes, from 1 second to 2 minutes, from 2 seconds to 2 minutes, from 3 seconds to 2 minutes, from 4 seconds to 2 minutes, from 5 seconds to 2 minutes, from 10 seconds to 2 minutes, from 15 seconds to 2 minutes, from 30 seconds to 2 minutes, from 1 minute to 2 minutes, from 1 second to 1 minute, from 2 seconds to 1 minute, from 3 seconds to 1 minute, from 4 seconds to 1 minute, from 5 seconds to 1 minute, from 10 seconds to 1 minute, from 15 seconds to 1 minute, from 30 seconds to 1 minute, from 1 second to 30 seconds, from 2 seconds to 30 seconds, from 3 seconds to 30 seconds, from 4 seconds to 30 seconds, from 5 seconds to 30 seconds, from 10 seconds to 30 seconds, from 15 seconds to 30 seconds, from 1 second to 15 seconds, from 2 seconds to 15 seconds, from 3 seconds to 15 seconds, from 4 seconds to 15 seconds, from 5 seconds to 15 seconds, from 10 seconds to 15 seconds, from 1 second to 10 seconds, from 2 seconds to 10 seconds, from 3 seconds to 10 seconds, from 4 seconds to 10 seconds, from 5 seconds to 10 seconds, from 1 second to 5 seconds, from 2 seconds to 5 seconds, from 3 seconds to 5 seconds, from 4 seconds to 5 seconds, from 1 second to 4 seconds, from 2 seconds to 4 seconds, from 3 seconds to 4 seconds, from 1 second to 3 seconds, from 2 seconds to 3 seconds, from 1 second to 2 seconds, or less than 1 second.

The second or soak duration may range from 1 second to 5 minutes or 1 minute to 5 minutes. For example, the product may held at or above the retrogression temperature, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 6 minutes, from 30 seconds to 6 minutes, from 1 minute to 6 minutes, from 2 minutes to 6 minutes, from 3 minutes to 6 minutes, from 4 minutes to 6 minutes, from 5 minutes to 6 minutes, from 1 second to 5 minutes, from 2 seconds to 5 minutes, from 3 seconds to 5 minutes, from 4 seconds to 5 minutes, from 5 seconds to 5 minutes, from 10 seconds to 5 minutes, from 15 seconds to 5 minutes, from 30 seconds to 5 minutes, from 1 minute to 5 minutes, from 2 minutes to 5 minutes, from 3 minutes to 5 minutes, from 4 minutes to 5 minutes, from 1 second to 4 minutes, from 2 seconds to 4 minutes, from 3 seconds to 4 minutes, from 4 seconds to 4 minutes, from 5 seconds to 4 minutes, from 10 seconds to 4 minutes, from 15 seconds to 4 minutes, from 30 seconds to 4 minutes, from 1 minute to 4 minutes, from 2 minutes to 4 minutes, from 3 minutes to 4 minutes, from 1 second to 3 minutes, from 2 seconds to 3 minutes, from 3 seconds to 3 minutes, from 4 seconds to 3 minutes, from 5 seconds to 3 minutes, from 10 seconds to 3 minutes, from 15 seconds to 3 minutes, from 30 seconds to 3 minutes, from 1 minute to 3 minutes, from 2 minutes to 3 minutes, from 1 second to 2 minutes, from 2 seconds to 2 minutes, from 3 seconds to 2 minutes, from 4 seconds to 2 minutes, from 5 seconds to 2 minutes, from 10 seconds to 2 minutes, from 15 seconds to 2 minutes, from 30 seconds to 2 minutes, from 1 minute to 2 minutes, from 1 second to 1 minute, from 2 seconds to 1 minute, from 3 seconds to 1 minute, from 4 seconds to 1 minute, from 5 seconds to 1 minute, from 10 seconds to 1 minute, from 15 seconds to 1 minute, from 30 seconds to 1 minute, from 1 second to 30 seconds, from 2 seconds to 30 seconds, from 3 seconds to 30 seconds, from 4 seconds to 30 seconds, from 5 seconds to 30 seconds, from 10 seconds to 30 seconds, from 15 seconds to 30 seconds, from 1 second to 15 seconds, from 2 seconds to 15 seconds, from 3 seconds to 15 seconds, from 4 seconds to 15 seconds, from 5 seconds to 15 seconds, from 10 seconds to 15 seconds, from 1 second to 10 seconds, from 2 seconds to 10 seconds, from 3 seconds to 10 seconds, from 4 seconds to 10 seconds, from 5 seconds to 10 seconds, from 1 second to 5 seconds, from 2 seconds to 5 seconds, from 3 seconds to 5 seconds, from 4 seconds to 5 seconds, from 1 second to 4 seconds, from 2 seconds to 4 seconds, from 3 seconds to 4 seconds, from 1 second to 3 seconds, from 2 seconds to 3 seconds, from 1 second to 2 seconds, or less than 1 second.

In some embodiments, self-piercing riveting may be performed before the portion(s) of the product(s) are cooled to room or ambient temperature. In some embodiments, the product(s) may be allowed to cool to room or ambient temperature once retrogression is completed, and self-piercing riveting is performed at room or ambient temperature. Retrogression may improve formability and/or plasticity, e.g., bendability and/or elongation, which facilitates achieving a crack-free or substantially crack-free self-piercing rivet button. It has been observed that the retrogressed or improved bending and forming properties can be maintained for days prior to hardening, the period of which may be referred to as the retrogressed timeframe or retrogressed window. Depending on the products retrogressed and the parameters of the retrogression performed, the retrogressed timeframe or retrogressed window may last from 5 minutes to 40 days, from 15 minutes to 40 days, from 30 minutes to 40 days, from 45 minutes to 40 days, from 1 hour to 40 days, or from 2 hour to 40 days. For example, the retrogressed timeframe or retrogressed window may last from 1 hour to 40 days, from 2 hours to 40 days, from 5 hours to 40 days, from 10 hours to 40 days, from 15 hours to 40 days, from 1 day to 40 days, from 5 days to 40 days, from 10 days to 40 days, from 15 days to 40 days, from 20 days to 40 days, from 25 days to 40 days, from 30 days to 40 days, from 35 days to 40 days, 1 hour to 35 days, from 2 hours to 35 days, from 5 hours to 35 days, from 10 hours to 35 days, from 15 hours to 35 days, from 1 day to 35 days, from 5 days to 35 days, from 10 days to 35 days, from 15 days to 35 days, from 20 days to 35 days, from 25 days to 35 days, from 30 days to 35 days, 1 hour to 30 days, from 2 hours to 30 days, from 5 hours to 30 days, from 10 hours to 30 days, from 15 hours to 30 days, from 1 day to 30 days, from 5 days to 30 days, from 10 days to 30 days, from 15 days to 30 days, from 20 days to 30 days, from 25 days to 30 days, from 1 hour to 25 days, from 2 hours to 25 days, from 5 hours to 25 days, from 10 hours to 25 days, from 15 hours to 25 days, from 1 day to 25 days, from 5 days to 25 days, from 10 days to 25 days, from 15 days to 25 days, from 20 days to 25 days, from 1 hour to 20 days, from 2 hours to 20 days, from 5 hours to 20 days, from 10 hours to 20 days, from 15 hours to 20 days, from 1 day to 20 days, from 5 days to 20 days, from 10 days to 20 days, from 15 days to 20 days, from 1 hour to 15 days, from 2 hours to 15 days, from 5 hours to 15 days, from 10 hours to 15 days, from 15 hours to 15 days, from 1 day to 15 days, from 5 days to 15 days, from 10 days to 15 days, from 1 hour to 10 days, from 2 hours to 10 days, from 5 hours to 10 days, from 10 hours to 10 days, from 15 hours to 10 days, from 1 day to 10 days, from 5 days to 10 days, from 1 hour to 5 days, from 2 hours to 5 days, from 5 hours to 5 days, from 10 hours to 5 days, from 15 hours to 5 days, from 1 day to 5 days, from 1 hour to 1 day, from 2 hours to 1 day, from 5 hours to 1 day, from 10 hours to 1 day, from 15 hours to 1 day, from 1 hour to 15 hours, from 2 hours to 15 hours, from 5 hours to 15 hours, from 10 hours to 15 hours, from 1 hour to 10 hours, from 2 hours to 110 hours, from 5 hours to 10 hours, from 2 hours to 5 hours, from 1 hour to 5 hours, or from 1 hour to 2 hours. Within the retrogressed timeframe or retrogressed window, self-piercing riveting can be achieved with minimal to no cracking.

In some embodiments, the product, such as a substrate, within which the button will be formed may be retrogressed. In some embodiments, the product, such as another substrate, that will be pierced through by the rivet may be retrogressed. In some embodiments, both the substrate to be pierced and the substrate forming the button may be retrogressed. In some embodiments, the substrates may be stacked together or otherwise positioned next to each other prior to being retrogressed. The stacked substrates may then be retrogressed and joined by self-piercing riveting. In some embodiments, one or more of the substrates may be retrogressed before being positioned adjacent to one or more other substrates for joining by self-piercing riveting. The retrogression may be performed well before the self-piercing riveting as long as the self-piercing riveting is performed within the retrogressed window. Although two substrates are discussed as exemplary embodiments, three or more substrates may be stacked together and be joined using self-piercing riveting. One or more of the substrates may be retrogressed prior to or after the substrates are stacked together for joining by self-piercing riveting.

Referring back to samples shown in FIGS. 6 to 8, sample 7xxx aluminum alloy substrates in T6 temper were heat treated by retrogression or retrogressed. Self-piercing riveting was performed once samples were allowed to reach room temperature. The results were rated or evaluated based on the presence or absence of various types of defects. The defects may include defects formed on the button. The defects may be characterized or described in terms of the defects' shape and/or form, such as orange peeling, stretch marks, cracking, material breakthrough, etc. The defects may also be characterized or described in terms of the orientation and/or location of the defects, such as radial cracking, circumferential cracking, cracking along or on a neck or sidewall of the button, etc. The defects may also be characterized or described in terms of the size or dimension of the defects. For example, cracking that has a width dimension of less than about 0.2 mm may be referred to as fine cracking, cracking that has a width dimension from 0.2 mm to 1 mm may be referred to as moderate cracking, and cracking that has a width dimension greater than 1 mm may be referred to as severe cracking, etc. Fine and/or moderate cracking may optionally include radial cracking. Severe cracking may optionally include circumferential cracking. However, in some embodiments, radial cracking may have a width dimension greater than 1 mm, and/or circumferential cracking may have a width dimension less than 1 mm, meaning that some radial cracking may be considered severe cracking and some circumferential cracking may be considered fine or moderate cracking. In addition to defects that may be formed on the button, defects related to the rivet may also be considered, including but not limited to, over-flared rivet, buckled rivet, etc. Other defects, such as defects created by slug material in the die, may also be considered when evaluating the self-piercing riveting results.

Depending on the alloy to be heated and/or the heating mechanism utilized, in some embodiments, no orange peeling, cracking and/or stretch marks may appear in the alloy substrates, and the button formed may be considered defect-free. In some embodiments, no cracking may form, but other minor or slight defects may occur, such as orange peeling and/or stretch marks, then the button formed may be referred to as having minor defects. In some embodiments, fine and/or moderate radial cracking may occur, then the button may be referred to as having moderate defects. Depending on the application, minor or moderate defects may be acceptable. In some embodiments, the button formed may contain severe defects, including severe radial and/or circumferential cracking, crack growth along neck of button (i.e., “flaking”), breakthrough, buckled rivet, distorted, etc.

Table 1 below shows the retrogression condition for samples shown in FIGS. 8A-8F (sample ID corresponding to figure number). Die diameter and die depth describe the die used for performing the self-piercing riveting.

| **Sample** | **Retrogression Condition** | **Die Diameter & Die Depth** | **Crack Rating** |
|---|---|---|---|
| 8A | No retrogression | n/a | Severe |
| 8B | Sand bed, 240 °C (heat up ~45s + 5s soak) | 9 mm, 1.75 mm | Moderate |
| 8C | Sand bed, 240 °C (heat up ~45s + 5s soak) | 9 mm, 2 mm | Moderate |
| 8D | Sand bed, 240 °C (heat up ~45s + 5s soak) | 9 mm, 2 mm | Moderate |
| 8E | Sand bed, 240 °C (heat up ~45s + 5s soak) | 9 mm, 2 mm | Moderate |
| 8F | Sand bed, 240 °C (heat up ~45s + 5s soak) | 9 mm, 2 mm | Moderate |

**Table 1.**

As the photographs show, the retrogressed samples had improved cracking rating, e.g., from a self-piercing riveting cracking rating of severe cracking to moderate cracking. In other words, retrogression reduces cracks that may be formed or develop overtime due to self-piercing riveting. By adjusting the retrogression temperature, retrogression duration, the heating mechanism, etc., self-piercing rivet buttons free of cracks may be achieved.

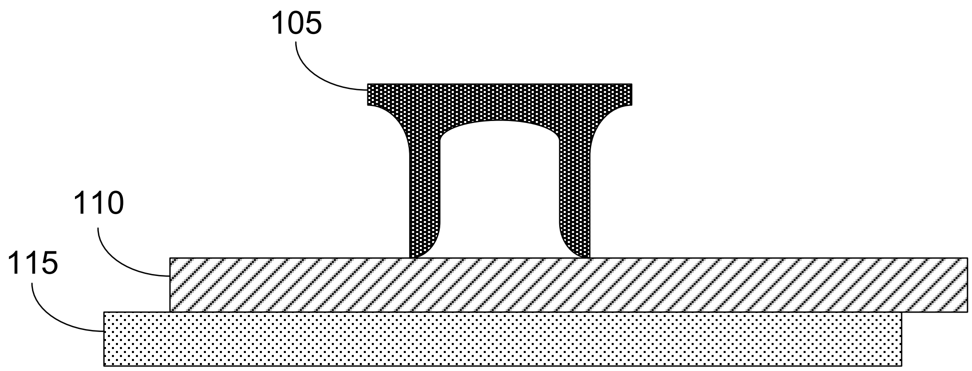



FIG. 1A

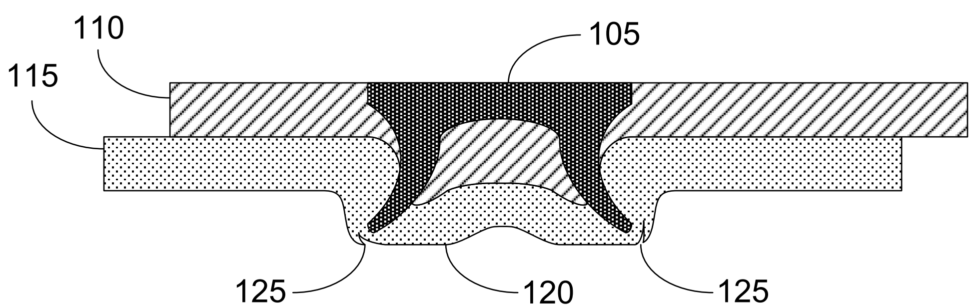



FIG. 1B

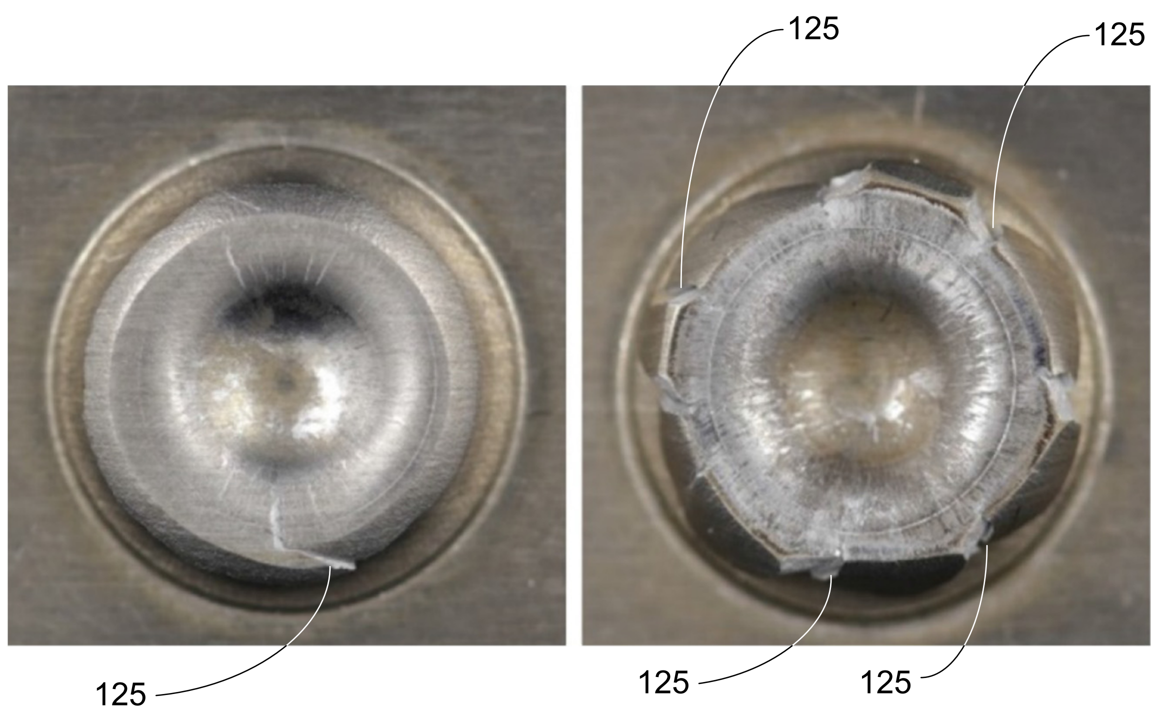



FIG. 1C

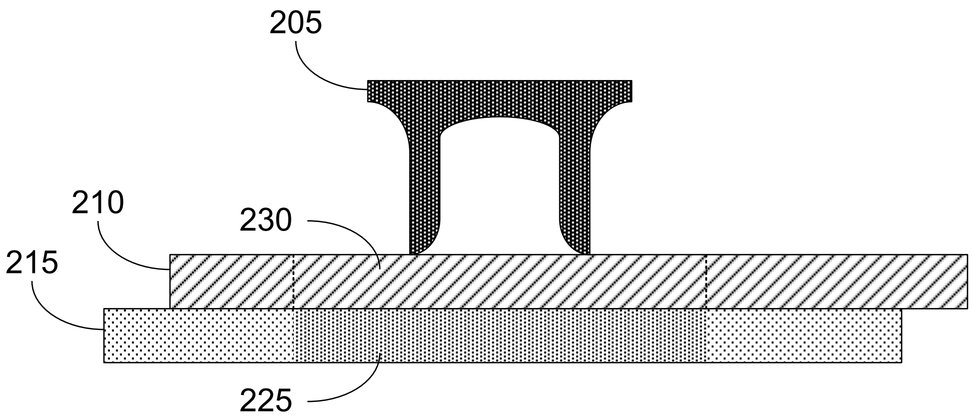



FIG. 2A

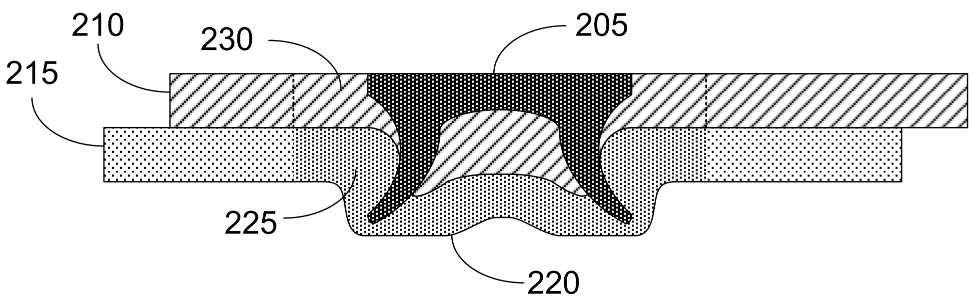



FIG. 2B

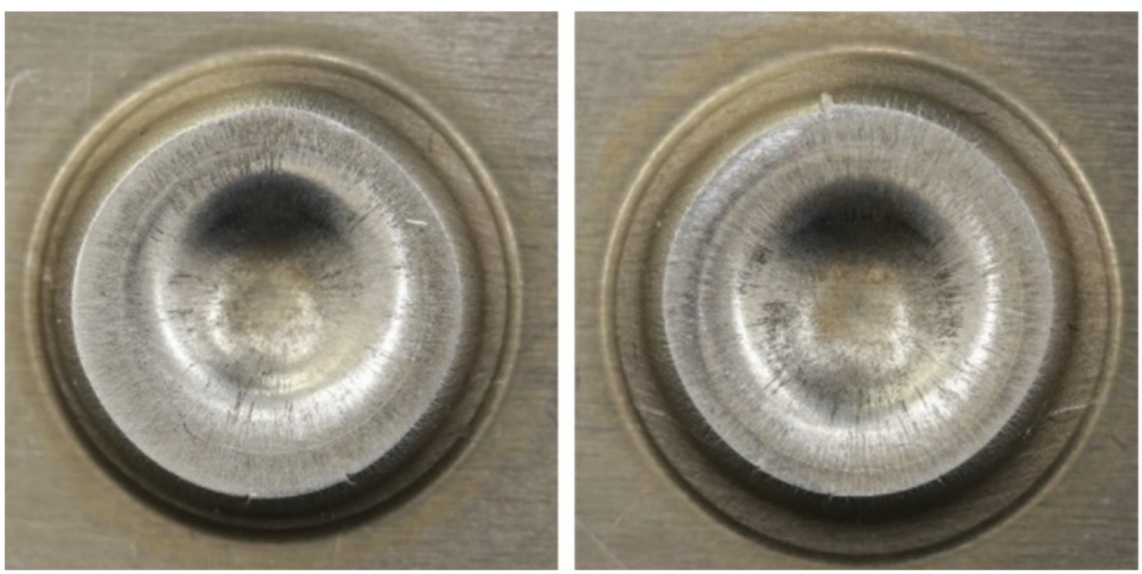


FIG. 2C

3/9

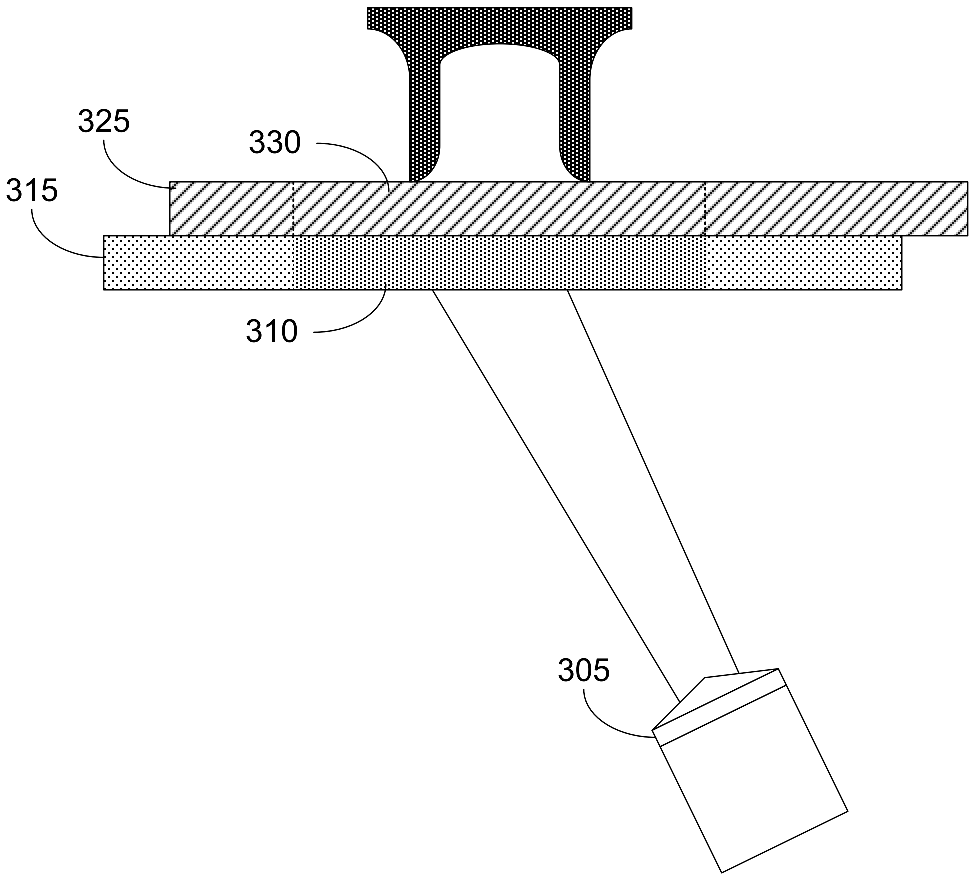



FIG. 3A

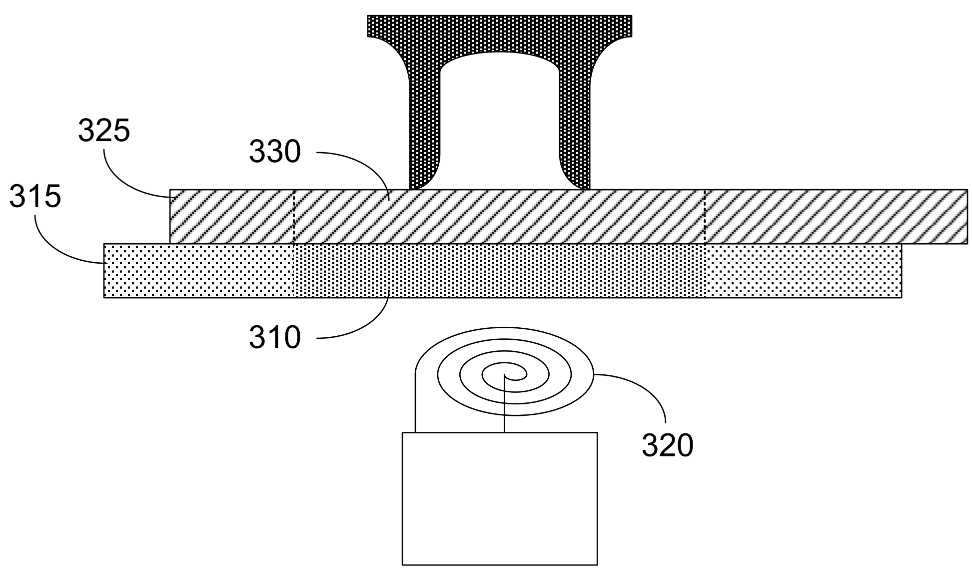



FIG. 3B

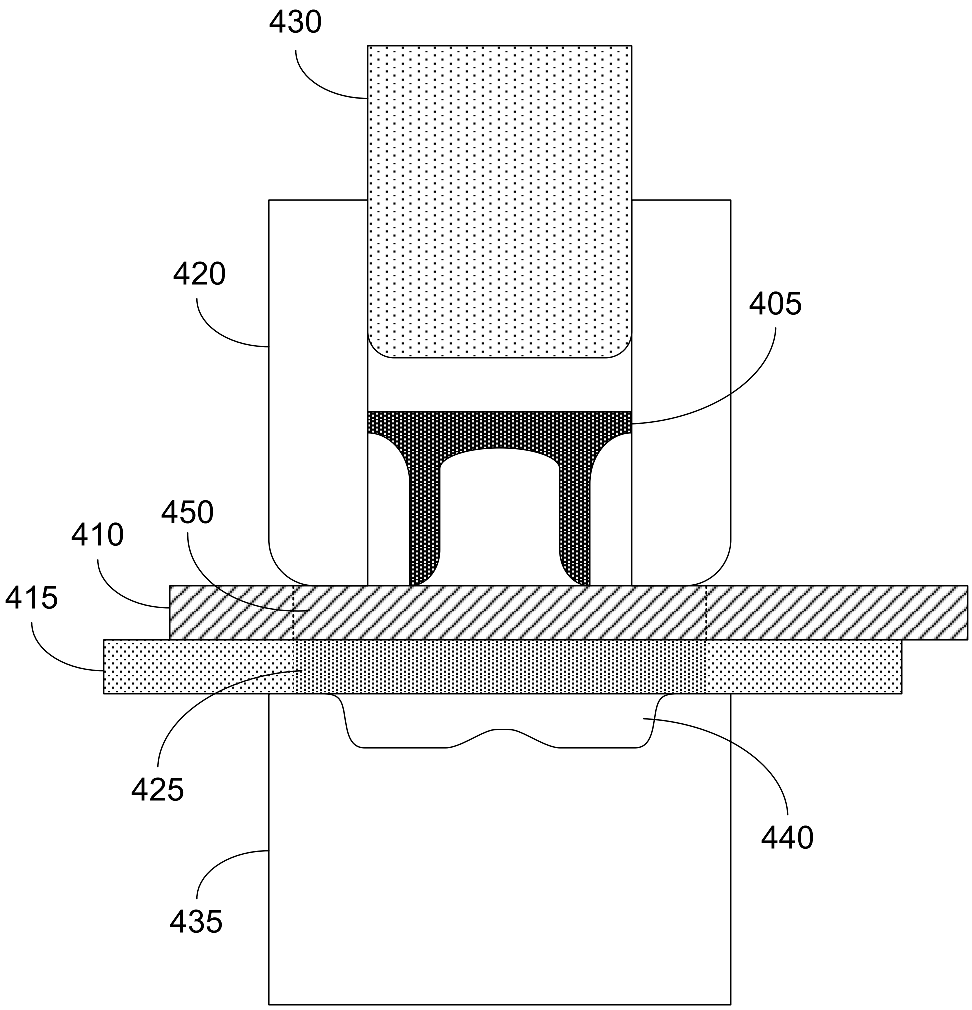



FIG. 4A

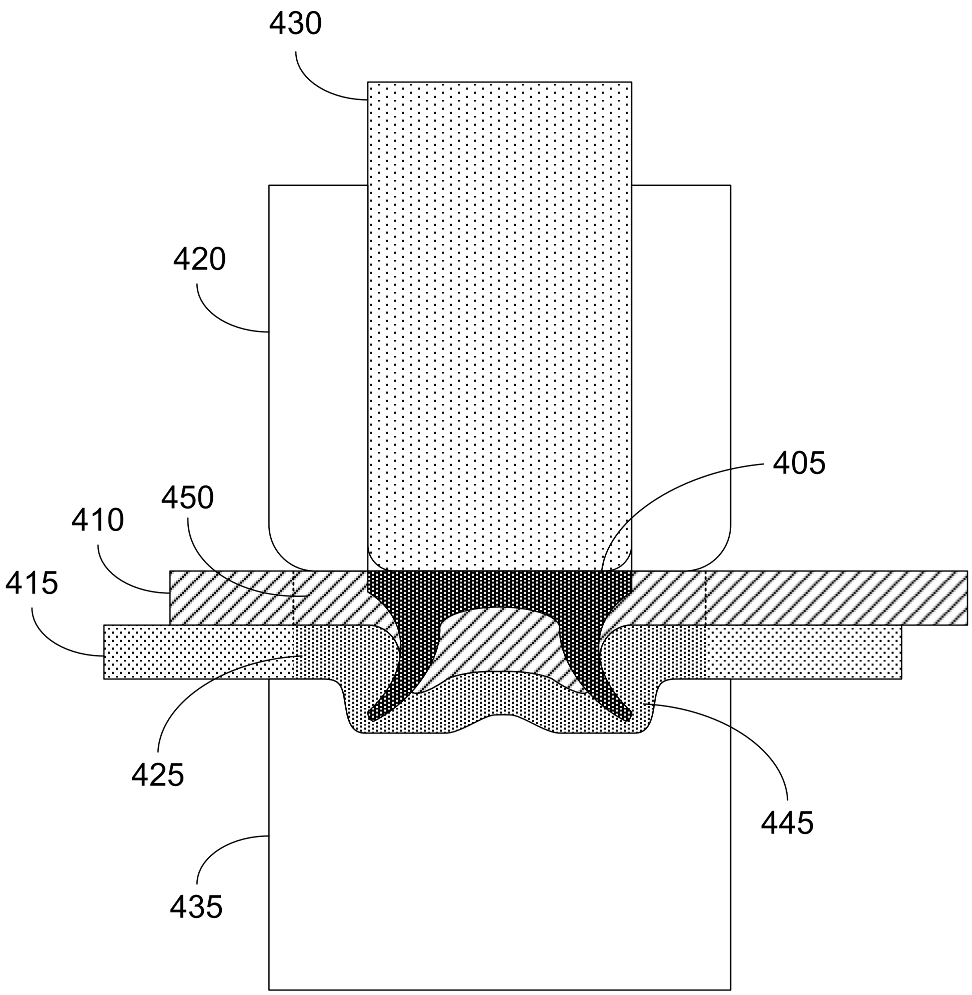



FIG. 4B

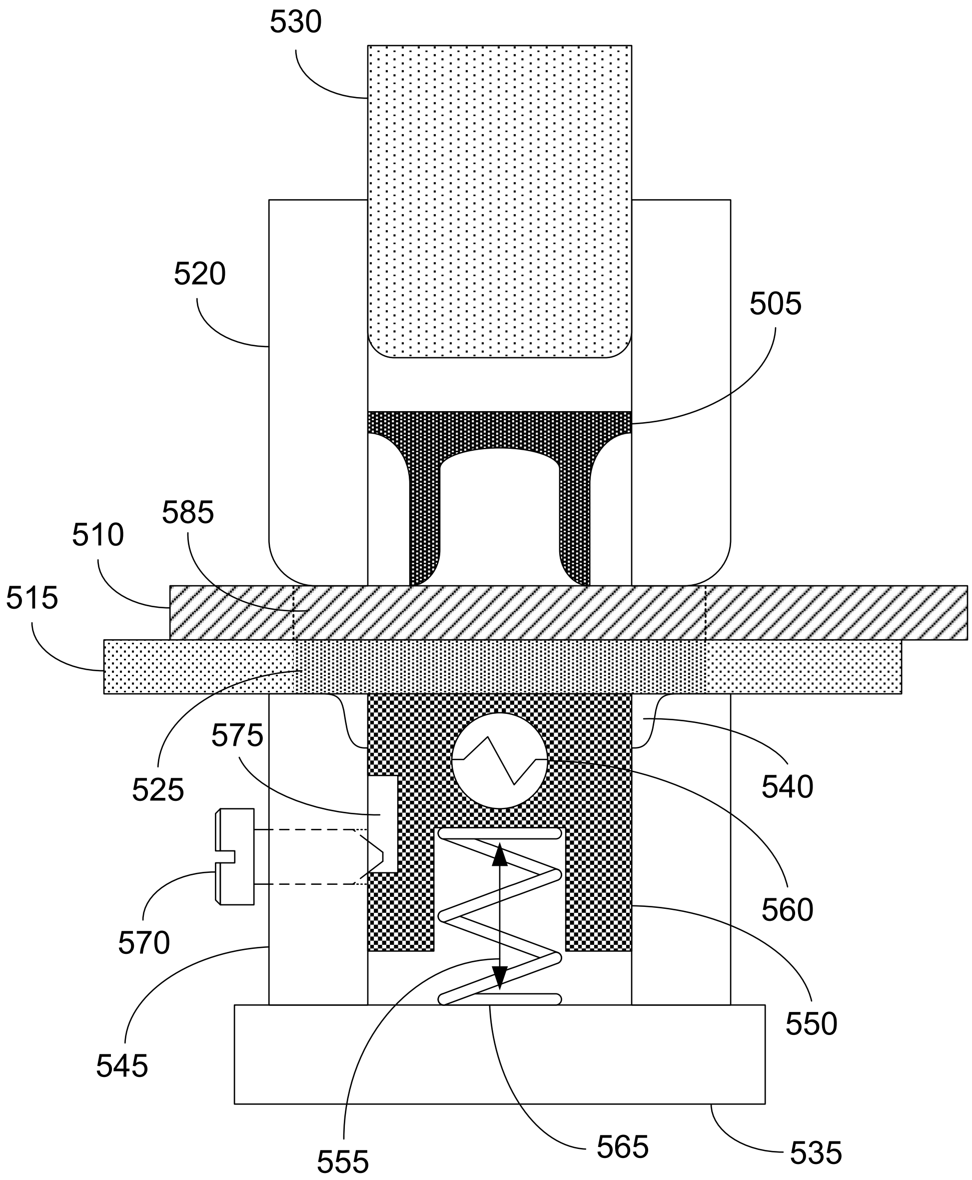



FIG. 5A

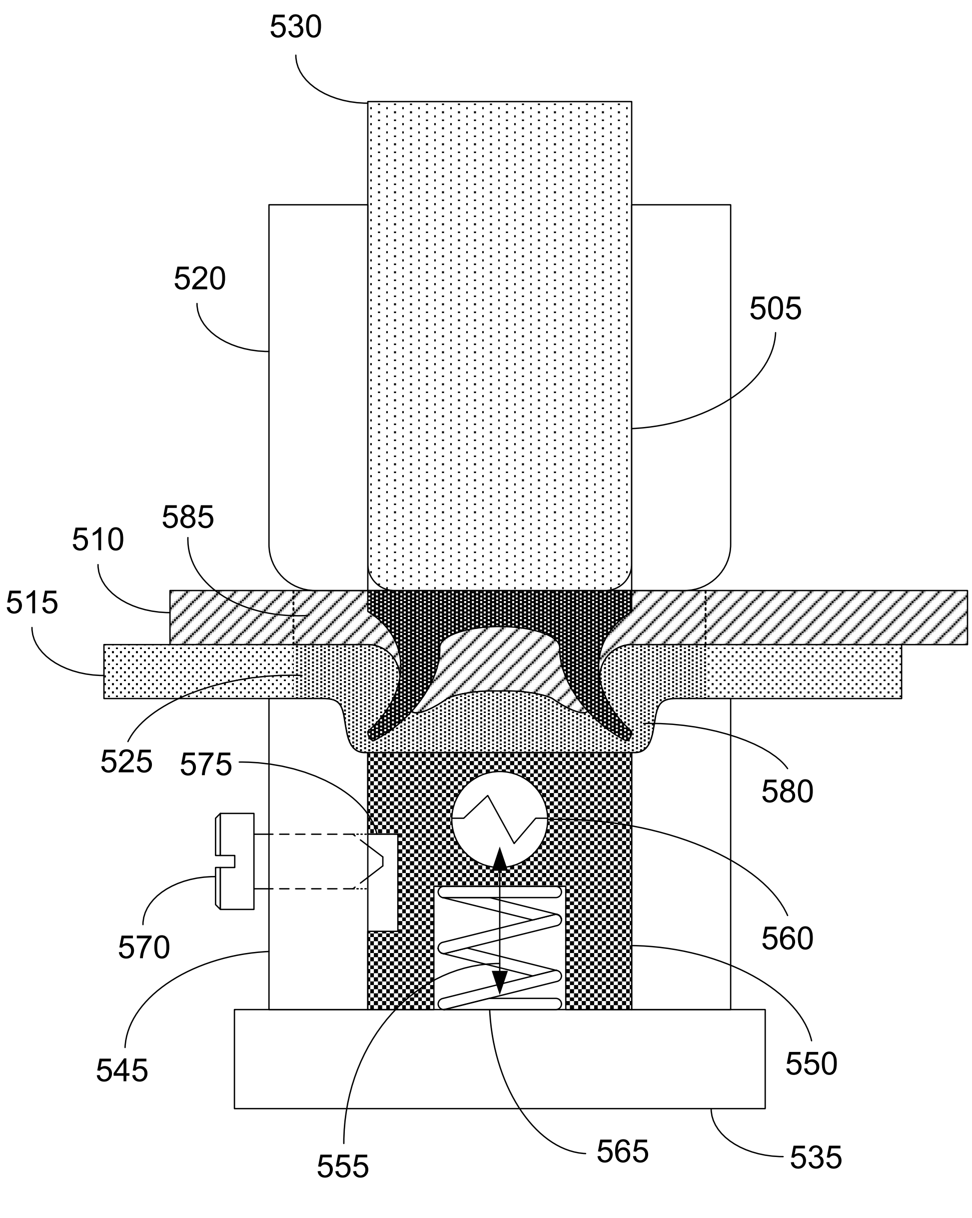
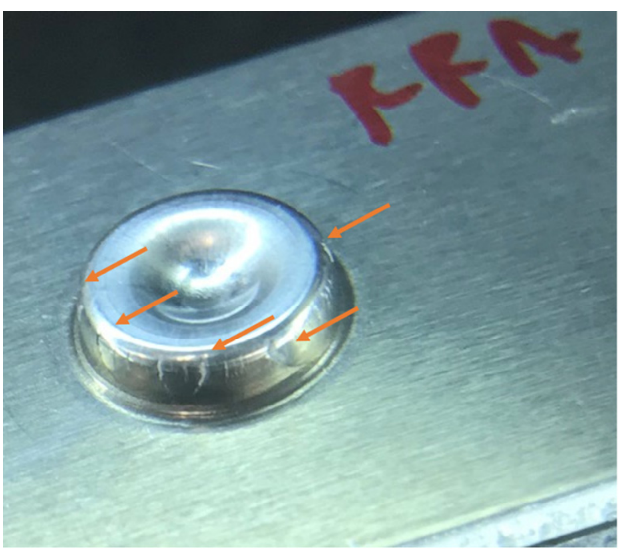


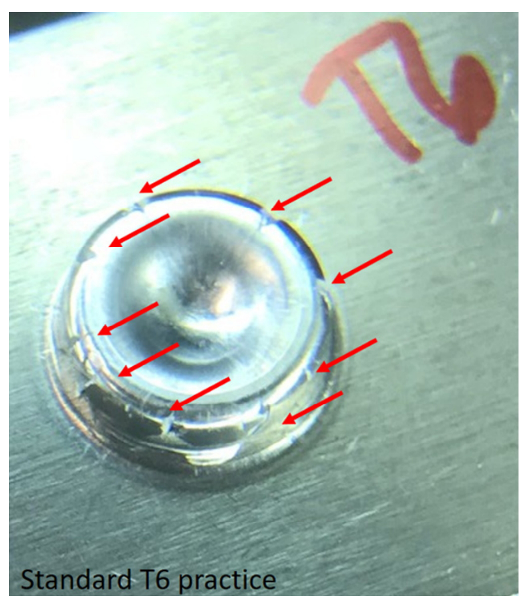

FIG. 5B


FIG. 6




*STD T6 → RRA @ Sand bed -240C (heat up ~ 45Secs + 5Secs Soak)*

FIG. 7A




Standard T6 practice

FIG. 7B

T6

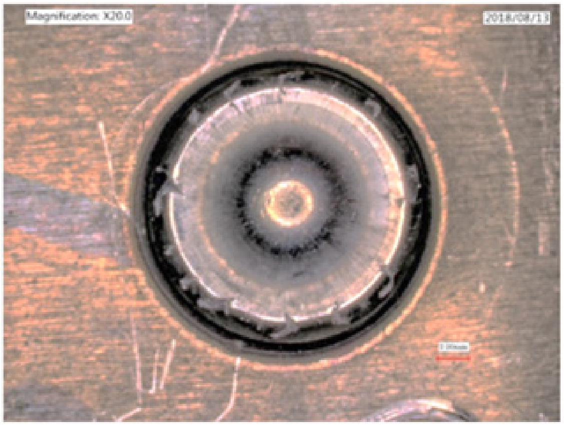


FIG. 8A

T6 → RRA → SPR

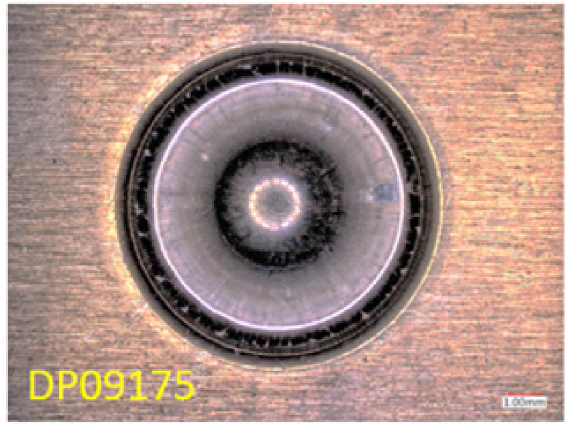



FIG. 8B

T6 → RRA → SPR


FIG. 8C

T6 → RRA → SPR


FIG. 8D

T6 → RRA → SPR


FIG. 8E

T6 → RRA → SPR


FIG. 8F