A hybrid resistance heating/ultrasonic welding method is used to join substrates. The resistance heating sufficiently softens or melts the substrates at an interface, and an ultrasonic wave is used to solid state bond the substrates at the interface. The hybrid method can be used for both spot welding as well as continuous welding.
HYBRID RESISTANCE/ULTRASONIC WELDING SYSTEM AND METHOD

FIELD OF THE INVENTION

[0001] The present disclosure relates to a hybrid resistance/ultrasonic welding system and method.

BACKGROUND OF THE INVENTION

[0002] The statements in this section merely provide background information related to the present disclosure and may not constitute prior art.

[0003] As automotive technology has advanced, weight reduction requirements have increased. In pursuit of these lower weight requirements, investigation into materials for use in automotive components that are lighter in weight and higher in strength has also increased. Materials such as aluminum, magnesium, and advanced high strength steels, therefore, are beginning to become more common in automotive applications. The use of these materials, however, has caused problems in that these materials are generally difficult to join together by welding.

[0004] For example, a material known as twinning induced plasticity (TWIP) steel shows dramatic improvement in both strength and ductility. TWIP steel, however, contains carbon and manganese in a content that results in a carbon equivalent (CE) value that ranges from 3.33 to 4.7. The CE value is commonly used to evaluate the weldability of steel. When this value exceeds 0.5, the material is considered difficult to weld. Because the CE value of TWIP steel is 6.7 to 9.4 times larger than more commonly used steel sheets that are presently used in automotive applications, the weldability of TWIP is difficult. Accordingly, there is a need for an improved welding technology that makes it possible to join the lightweight and increased strength materials that are now considered for use in automotive applications.

SUMMARY OF THE INVENTION

[0005] To satisfy the above need, the present teachings provide a spot welding method that includes providing a pair of substrates, and applying an electric current to the substrates to soften the substrates at an interface between the substrates. After the substrates are softened, an ultrasonic wave is applied to the substrates to solid-state bond the substrates at the interface.

[0006] The present teachings also provide a continuous welding method that includes feeding a pair of substrates through a first set of rollers. The first set of rollers are adapted to apply an electric current through the substrates at an interface between the substrates. The pair of substrates are also fed through a second set of rollers. The second set of rollers are adapted to apply an ultrasonic wave through the substrates at the interface. The substrates are subsequently joined at the interface by applying the electric current and the ultrasonic wave to the substrates.

[0007] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The drawings disclosed herein are for illustration purposes only and they are not intended to limit the scope of the present disclosure in any way.

[0009] FIGS. 1A and 1B are schematic cross-sectional representations of a spot welding method according to the present teachings;

[0010] FIGS. 2A and 2B are schematic cross-sectional representations of a seam welding method according to the present teachings;

[0011] FIGS. 3A and 3B are schematic cross-sectional representations of another spot welding method according to the present teachings; and

[0012] FIGS. 4A and 4B are a schematic cross-section representations of an electrode/sonotrode used in accordance with the present teachings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0013] The following description is merely exemplary in nature and is not intended to limit the present disclosure, application, or uses.

[0014] Referring to FIG. 1, a first embodiment of the present teachings will now be described. In FIG. 1, a pair of substrates 10 and 12 are being welded together according to the method of the present teachings. The substrates 10 and 12 are formed of advanced high strength steels (AHSS), and particularly twinning induced plasticity steel (TWIP). Although the present teachings are advantageous in welding AHSS such as TWIP steel, it should be understood that other materials that may be welding in this manner include substrates formed from steel, stainless steel, titanium (Ti), cobalt (Co), silver (Ag), copper (Cu), brass, bronze, Fe-Austenite, nickel (Ni), platinum (Pt), platinum iridium (Pt-Ir), chromium (Cr), iridium (Ir), Fe-Martensite, molybdenum (Mo), niobium (Nb), tantalum (Ta), and other difficult-to-weld alloys such as Inconel, Monel, and nickel-based (Ni) superalloys. Substrates formed of dissimilar materials (i.e., one substrate formed of a first material and another substrate formed of a second and different material) may also be joined together using the present teachings.

[0015] Additionally, metal substrates that include a coating such as zinc (Zn) or an oxide may also be used. In the present embodiment shown in FIG. 1, the substrates 10 and 12 are coated with Zn. The coating 11 and 13 formed on the substrates 10 and 12, respectively, prevents rust and other materials from reducing the useful life of the substrates 10 and 12. To join the substrates 10 and 12 together, a pair of electrodes 14 and 16 pass an electric current 18 through the substrates 10 and 12.

[0016] The electrodes 14 and 16 press the substrates 10 and 12 with enough force to sufficiently ensure that no gap is between the substrates 10 and 12 at an interface 19 where the substrates 10 and 12 are to be joined together. By having no gap at the interface 19 between the substrates 10 and 12, there is sufficient contact between the substrates 10 and 12 to ensure electrical conductivity between the substrates 10 and 12. To press the substrates 10 and 12 together with the
electrodes 14 and 16, the electrodes 14 and 16 may be coupled to a device (not shown) such as a pneumatic or hydraulic device that is sufficient to ensure face-to-face contact between the substrates 10 and 12 at the interface 19. In this regard, the device should be capable of pressing the electrodes 14 and 16 against the substrates 10 and 12 with a sufficient force to bring the substrates 10 and 12 into close contact. Preferably, the substrates 10 and 12 are pressed with the electrodes 14 and 16 with a force in the range between about 600-1200 lbs per square inch. Preferable devices include an air cylinder and a servo motor. With respect to a servo motor, this device is more preferable in that it is able to quickly apply and remove the force needed to press substrates 10 and 12 together. In this manner, the force can be stationary or changed throughout the welding process.

The magnitude of the electric current 18 is controlled to prevent, or at least substantially minimize, melting of the substrates 10 and 12 from occurring. In this regard, the electric current 18 heats the substrates 10 and 12, as well as the Zn coating 11 and 13 at the intended joining area or interface 19. It should be understood that controlling the magnitude of the electric current 18 is an important aspect of the present teachings because the Zn coating 11 and 13 has a melting point less than a melting point of the substrates 10 and 12. By controlling the magnitude of the electric current 18 passing through the substrates 10 and 12, as well as the Zn coating 11 and 13, the substrates 10 and 12 can be sufficiently heated to soften the substrates 10 and 12 without melting them. Notwithstanding, the magnitude of the electric current 18 is enough to reach the melting point of the Zn coating 11 and 13. The coating 11 and 13, therefore, is reduced to a molten form that is expelled or "squeezed" out from between the substrates 10 and 12.

The coating 11 and 13 is expelled from the interface 19 between the substrate 10 and 12 at small gaps between the substrates 10 and 12 located in areas outside of and adjacent where the force is applied by the electrodes 14 and 16. Further, although not shown in the drawings, it should be understood that the coating 11 and 13 is sufficiently heated at the electrode/substrate interface such that the coating 11 and 13 is also expelled there. Moreover, it should be understood that the heating of the substrates 10 and 12 at the substrate/electrode interface causes thermal expansion at the substrate/electrode interface. Regardless, the force applied by the electrodes 14 and 16 is sufficient to enable face-to-face contact between the substrates 10 and 12 at the interface 19, but at the area outside and adjacent the interface 19, the substrates 10 and 12 may bend upwards to allow a gap to form. This gap may also be caused by thermal expansion of the substrates 10 and 12 during application of the electric current 18 of the substrates 10 and 12.

The preferred magnitude of the electric current 18 is preferably in the range of 2 kA to 30 kA, and more preferably in the range of 2 kA to 14 kA. Although the ranges described above are preferred, one skilled in the art will readily acknowledge and appreciate that the electric current 18 should not be limited to the above ranges and can be set at any magnitude sufficient to soften any type of substrate known in the art. That is, although the present teachings are being described relative to joining substrates generally used in an automotive application, the present teachings should not be limited thereto. For example, the present teachings may be adaptable to preparing electronic devices where the substrates are formed of a material such as silicon (Si) or some other type of semiconductor material. In this regard, the current 18 needed to sufficiently soften the substrates 10 and 12 will be much less than the above-defined ranges.

By expelling the Zn coating 11 and 13 from the interface 19 between the substrates 10 and 12, intimate metal to metal contact between the substrates 10 and 12 is achieved. What’s more, localized heating of the substrates 10 and 12 induces localized thermal expansion of the substrates 10 and 12, which in turn creates the gap and reduces the contact area between the substrates 10 and 12 at the interface 19, which is beneficial for concentrating the ultrasonic energy that is subsequently applied to the interface 19 in the desired bonding area between the substrates 10 and 12.

More specifically, as the electric current 18 is being passed through the substrates 10 and 12, as stated above, the electric current 18 heats and softens the substrates 10 and 12. When the substrates 10 and 12 are sufficiently softened (plastically deformed), an ultrasonic wave 22 is passed through the substrates 10 and 12 by a sonotrode 24 which causes the substrates 10 and 12 to locally vibrate relative to each other at a microscopic level at the interface 19 which generates friction between the substrates 10 and 12 at the interface. The friction results in a solid state bonding between the substrates 10 and 12 to occur at the interface 19. The ultrasonic wave 22 may be applied through the substrates 10 and 12 simultaneously with the electric current 18, or after the electric current 18 has been applied. More particularly, it should be understood that the electric current 18 is used to sufficiently soften the substrates 10 and 12. As such, long as the ultrasonic wave 22 is applied to the substrates 10 and 12 when the substrates are sufficiently softened by the electric current 18, an improved weld between the substrates 10 and 12 can be formed.

Although it is preferable to apply the ultrasonic wave 22 to the substrates 10 and 12 after the substrates 10 and 12 are sufficiently softened, certain applications require that the ultrasonic wave 22 be applied to the substrates 10 and 12 before the electric current 18 is applied. When joining substrates 10 and 12 that include an insulating layer (such as an oxide film) over a surface thereof, it is desirable to apply the ultrasonic wave 22 to the substrates 10 and 12 first. In this manner, the vibration between the substrates 10 and 12 caused by the ultrasonic wave 22 rubs the substrates 10 and 12 such that the oxide coating is removed from the interface 19.

After the oxide coating has been removed from the interface 19, the substrates 10 and 12 have a more intimate face to face contact at the interface 19. Subsequently, the electrodes 14 and 16 may apply the current 18 to the substrates 10 and 12 to sufficiently soften them. During application of the electric current 18, the ultrasonic wave 22 may continue to be applied, or cease to be applied until the substrates 10 and 12 are sufficiently softened. Once the substrates 10 and 12 are sufficiently softened, the ultrasonic wave 22 may be re-applied to the substrates 10 and 12 to join them together.

The frequency of the ultrasonic wave 22 is preferably in the range of 20 kHz to 35 kHz, and is generated by a sonotrode 24. The sonotrode 24 may be any sonotrode commercially available. Alternatively, the electrodes 14 and 16 may be configured to additionally act as sonotrode 24 by coupling an ultrasonic generator (not shown), such as a
piezoelectric-based device, to the electrodes 14 and 16. In another embodiment, a pair of sonotrodes may be used on opposite sides of the substrates 10 and 12, respectively.

By using a pair of sonotrodes, vibrations may be introduced to substrates 10 and 12 that are opposite in phase. In this regard, vibrations that are perpendicular and/or parallel to the substrates may be introduced simultaneously to produce normal and shear frictional forces at the interface 19. The normal and shear forces at the interface 19 are advantageous in providing a more robust connection between the substrates 10 and 12 during the solid-state bonding process. Although perpendicular and parallel forces are described, it should be understood that forces with any arbitrary direction or orientation with respect to the substrates 10 and 12 may be introduced. For example, rotational or angular vibrational forces may be introduced.

It should be understood that combining the use of resistance welding and ultrasonic welding utilizes the benefits of each process. More specifically, the use of resistance welding softens the substrates 10 and 12 to a point where plastic deformation of the substrates 10 and 12 occurs. The plastic deformation of the substrates 10 and 12 allows the substrates 10 and 12 to come into intimate contact at the interface 19 on a molecular level due to a rise in energy of the molecules of the substrates 10 and 12. That is, when the substrates 10 and 12 are sufficiently softened to plastically deform, the molecules of the substrates 10 and 12 begin to commingle at the interface 19 between the substrates. In addition to plastic deformation, the heat generated by the electric current 18 also results in thermal expansion of the substrates 10 and 12 at the interface which enhances the commingling of the molecules.

It should also be understood that depending on the properties of the materials to be joined, the ultrasonic wave 22 applied to the substrates 10 and 12 may not have a sufficient energy to bring the substrates 10 and 12 into a satisfactory bonding condition within the required time frame necessary for physical manufacturing processing. By plastically deforming the substrates 10 and 12 prior to application of the ultrasonic wave 22, the molecules of the substrates 10 and 12 are sufficiently excited such that the energy of the ultrasonic wave 22 is sufficient to solid state bond the substrates 10 and 12. What’s more, the vibrational forces applied by the ultrasonic wave 22 assist in further commingling the molecules of the substrates 10 and 12 at the interface 19. In this manner, the substrates 10 and 12 are joined with a more robust bond between them.

The above-described disclosure is advantageous in a spot welding method. The present teachings, however, should not be limited thereto. That is, the hybrid resistance heating/ultrasonic welding method is also applicable to welding substrates 10 and 12 along a seam in a so-called seam welding method. Referring to FIG. 2A, the electrodes 14 and 16 are in the form of rollers. By using rollers 14 and 16 configured to apply the electric current 18 between the substrates 10 and 12, the substrates 10 and 12 can be pulled or pushed through the rollers 14 and 16 and still be sufficiently heated to soften or melt the substrates 10 and 12. The rollers 14 and 16 can also be configured to act as the sonotrode 24 that applies the ultrasonic wave 22 to the substrates 10 and 12 to solid state bond the substrates 10 and 12 or control solidification of the molten nugget 26. In this manner, the electric current 18 and the ultrasonic wave 22 can be applied simultaneously to the substrates 10 and 12.

Alternatively, another set of rollers 15 and 17 configured to act as the sonotrode 24 can be used in conjunction with the rollers 14 and 16 that act as electrodes to apply the electric current 18. Referring to FIG. 2B, the rollers 15 and 17 may be disposed downstream (i.e., after) of the rollers 14 and 16 in a welding direction. Accordingly, the electric current 18 may be applied by the rollers 14 and 16 and, subsequently, the ultrasonic wave 22 may be applied after the substrates 10 and 12 are sufficiently softened. It should be understood, however, that the rollers 15 and 17 can be upstream (i.e., before) from the rollers 14 and 16 such that the ultrasonic wave 22 can be applied to the substrates 10 and 12 prior to the electric current 18 being applied. As stated above, such a method is advantageous when joining substrates 10 and 12 that may be covered with an oxide coating. Although the pairs of rollers are shown disposed a distance from one another in the figures, it should be understood that the rollers may be disposed closer together. Further, it should be understood that although the substrates 10 and 12 are shown in a seam welding application, the present teachings are also applicable to substrates in a lap seam welding configuration, a mash seam welding configuration, and a butt seam welding configuration. Still further, the substrates 10 and 12 do not necessarily have to be the same thickness. That is, the substrates 10 and 12 can each have a different thickness without departing from the spirit and scope of the present invention.

Now referring to FIG. 3A, a second embodiment of the present teachings will be described. As shown in FIG. 3A, the same configuration as shown in FIG. 1A is depicted. Notwithstanding, in the second embodiment a higher magnitude electric current 18 is passed through the substrates 10 and 12. Because the electric current 18 is higher, the substrates 10 and 12 are sufficiently heated to induce melting of the substrates 10 and 12, which forms a molten nugget 26.

Once the nugget 26 is formed, the ultrasonic wave 22 is used to control solidification of the nugget 26. According to conventional welding methods, the solidified nugget 28 may have defects caused by a higher alloying element content or a higher CE value which may result in element segregation, solidification cracks, or porosities. These defects are undesirable in that when the molten nugget 26 solidifies, the strength of the weld between the substrates 10 and 12 will not be as strong as that required for automotive applications. Notwithstanding, according to the method of the present teachings, by applying the ultrasonic wave 22 to the molten nugget 26 (see FIG. 3B), a stirring effect is introduced inside the molten nugget 26 that can break solidification dendrites that may occur during solidification of the nugget 28. Because of the stirring effect caused by application of the ultrasonic wave 22 during the solidification process, a uniform element distribution within the molten nugget 26 occurs, which results in a solidified nugget 28 with a uniform microstructure and a defect-free weld.

It should be understood that the ultrasonic wave 22 is used to control the solidification process of the molten nugget 26. Due to the high alloy element content generally found in advanced high strength steels, the advanced high strength steel solidifies in a very large temperature range. During this interval, super cooling can occur, which may cause significant dendritic growth and redistribution of the alloy elements within the solidified nugget 28. By applying an ultrasonic wave 22 to the molten nugget 26, a stirring effect is occurring within the nugget 26 which eliminates, or
at least substantially minimizes, the super cooling and non-uniform element distribution which results in the dendrites being formed. By eliminating the non-uniform element distribution, and by that the constitutional super cooling, the present teachings prevents severe detrimental residual stress in the weld between the substrates 10 and 12. Further, a shorter welding time and more robust weld between these difficult-to-weld substrates 10 and 12 is enabled.

[0033] In the above-described hybrid resistance heating/ultrasonic welding process, the electrodes 14 and 16 are used to compress the substrates 10 and 12 at an interface 19. To further enhance the compression of the substrates 10 and 12, it should be understood that the electrodes 14 and 16 can be provided with a plurality of teeth or a grooved surface that assist in gripping the substrates 10 and 12. Referring to FIGS. 4A and 4B, it can be seen that the electrode 14 includes a plurality of teeth 30. Each of the teeth 30 include inclined surfaces 32. When the electrode 14 is also adapted to act as a sonotrode 24, the profile of the teeth 30 can be used to influence a direction and orientation of the vibratory actuation force between the substrates 10 and 12 during application of the ultrasonic wave 22. That is, as stated above, a pair of sonotrodes may be used to apply ultrasonic waves 22 with differing frequencies to the substrates 10 and 12. In this manner, normal and shear forces that act perpendicular and parallel to the substrates 10 and 12 can be formed during the ultrasonic welding process. The use of these normal and shear forces further enhances the solid state bonding between the substrates 10 and 12.

[0034] The description of the invention is merely exemplary in nature and, thus, variations that do not depart from the gist of the invention are intended to be within the scope of the invention. Such variations are not to be regarded as a departure from the spirit and scope of the invention.

What is claimed is:
1. A method comprising:
   providing a pair of substrates with a contact interface therebetween;
   applying an electric current to said substrates to soften said substrates at the interface; and
   applying an ultrasonic wave to said substrates to solid-state bond said substrates at the interface.
2. The method of claim 1, wherein said ultrasonic wave is applied simultaneously with said electric current.
3. The method of claim 1, wherein said ultrasonic wave is applied before said electric current.
4. The method of claim 1, wherein each substrate of said pair of substrates is selected from the group consisting of steel, stainless steel, twinning induced plasticity steel, aluminum, magnesium, tungsten, titanium, cobalt, and nickel-based alloys.
5. The method of claim 1, wherein a first substrate of said pair of substrates is formed of a first material and a second substrate of said pair of substrates is formed of a second different material.
6. The method according to claim 1, wherein at least one substrate of said pair of substrates includes a coating.
7. The method according to claim 6, wherein during application of said electric current, said coating is expelled from said interface between said substrates.
8. The method according to claim 1, wherein application of said electric current melts said substrates at said interface to form a molten nugget.
9. The method according to claim 8, wherein said ultrasonic wave is applied to said substrates to prevent formation of defects in said molten nugget as said molten nugget cools into a solidified nugget.
10. The method according to claim 1, wherein said electric current is applied to said substrates by at least one electrode.
11. The method according to claim 10, wherein said electrode is adapted to form a roller.
12. The method according to claim 1, wherein said ultrasonic wave is applied by a sonotrode.
13. The method according to claim 12, wherein said sonotrode is adapted to form a roller.
14. The method according to claim 1, wherein said ultrasonic wave is applied to said substrates at a plurality of frequencies.
15. The method according to claim 1, wherein said electric current is applied to said substrates by an electrode, said electrode including a plurality of teeth.
16. A method comprising:
   feeding a pair of substrates through a first set of rollers,
   said first set of rollers adapted to apply an electric current through said substrates at an interface between said substrates;
   feeding said pair of substrates through a second set of rollers, said second set of rollers adapted to apply an ultrasonic wave through said substrates at said interface; and
   joining said pair of substrates at said interface by applying said electric current and said ultrasonic wave to said substrates.
17. The method according to claim 16, wherein said second set of rollers is disposed downstream in a weld direction from said first set of rollers.
18. The method according to claim 16, wherein said second set of rollers is disposed upstream in a weld direction from said first set of rollers.
19. The method according to claim 16, wherein application of said electric current either softens or melts said substrates at said interface.
20. The method according to claim 16, wherein said application of said ultrasonic wave solid state bonds said substrates at said interface.

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