



US 20060024145A1

(19) **United States**

(12) **Patent Application Publication**

Wang et al.

(10) **Pub. No.: US 2006/0024145 A1**

(43) **Pub. Date: Feb. 2, 2006**

(54) **FRICTION STIR RIVET AND METHOD OF JOINING THEREWITH**

Publication Classification

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(51) **Int. Cl.**
F16B 13/04 (2006.01)
(52) **U.S. Cl.** **411/34**

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(57) **ABSTRACT**

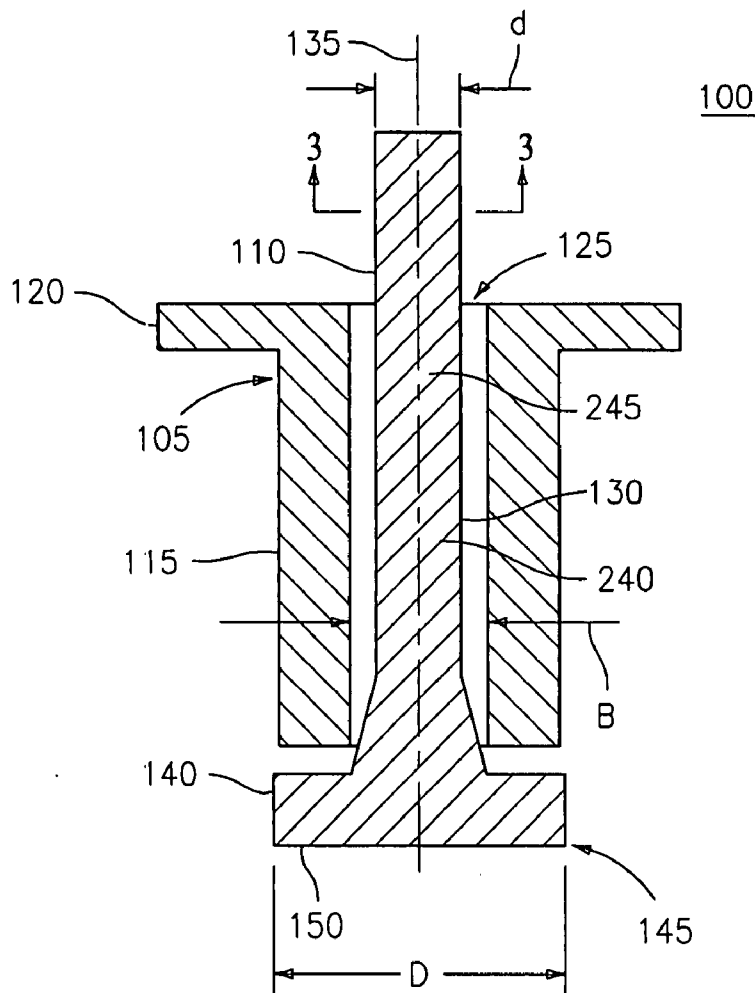
A friction stir rivet having a body, a mandrel, and a mechanical interface therebetween, is disclosed. The body has an elongated cylindrical shank, a cap at a first end, and an axial hole therethrough. The mandrel has an elongated shaft defining an axis and a head at one end thereof, the head having an effective outside diameter greater than the effective outside diameter of the shaft, the shaft being disposed within the axial hole of the body, the mandrel head being disposed at an opposite end of the body to that of the cap, and the end of the mandrel head having a flat surface oriented substantially perpendicular to the axis of the shaft. The mechanical interface between the body and the mandrel is such that the body rotates in response to rotation of the mandrel.

(21) Appl. No.: **10/997,473**

(22) Filed: **Nov. 24, 2004**

Related U.S. Application Data

(60) Provisional application No. 60/592,048, filed on Jul. 29, 2004.



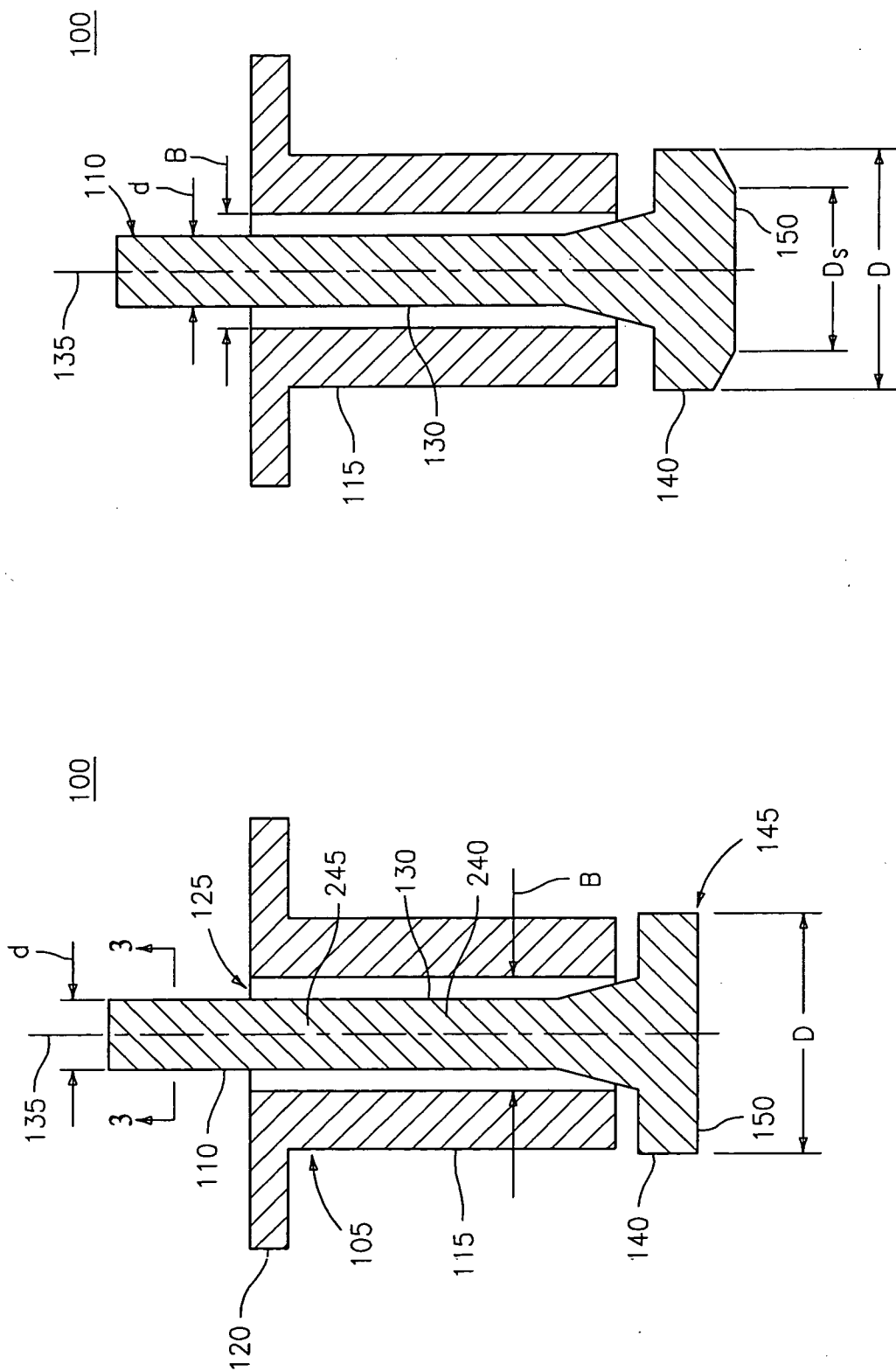


FIG. 1

FIG. 2

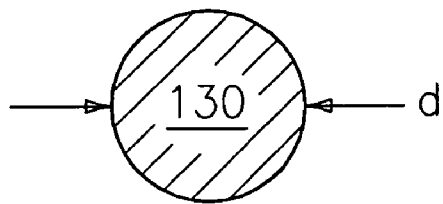


FIG. 3

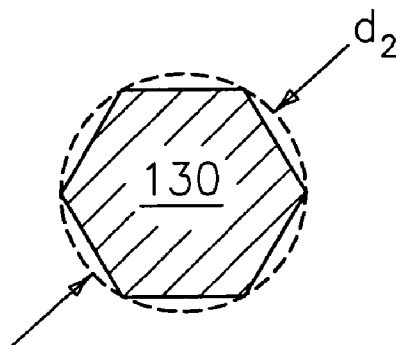


FIG. 4

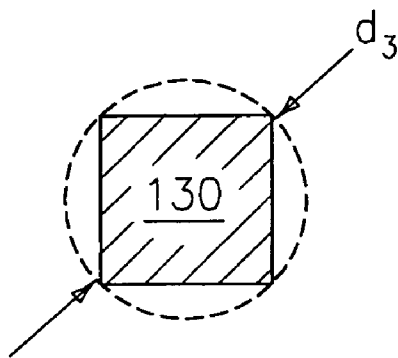


FIG. 5

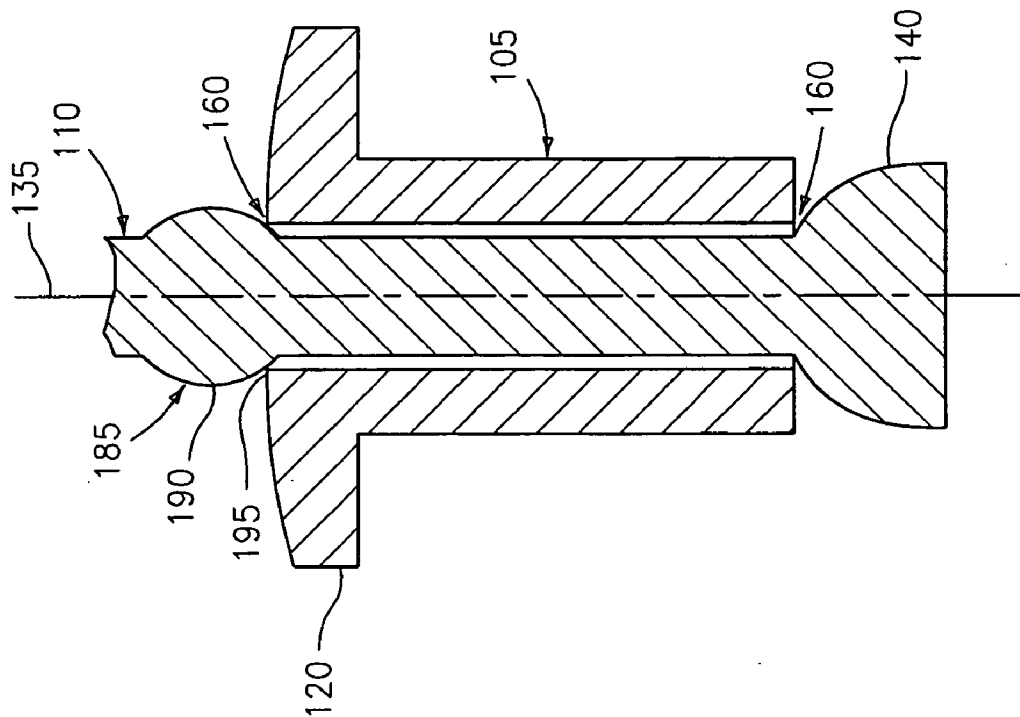


FIG. 6

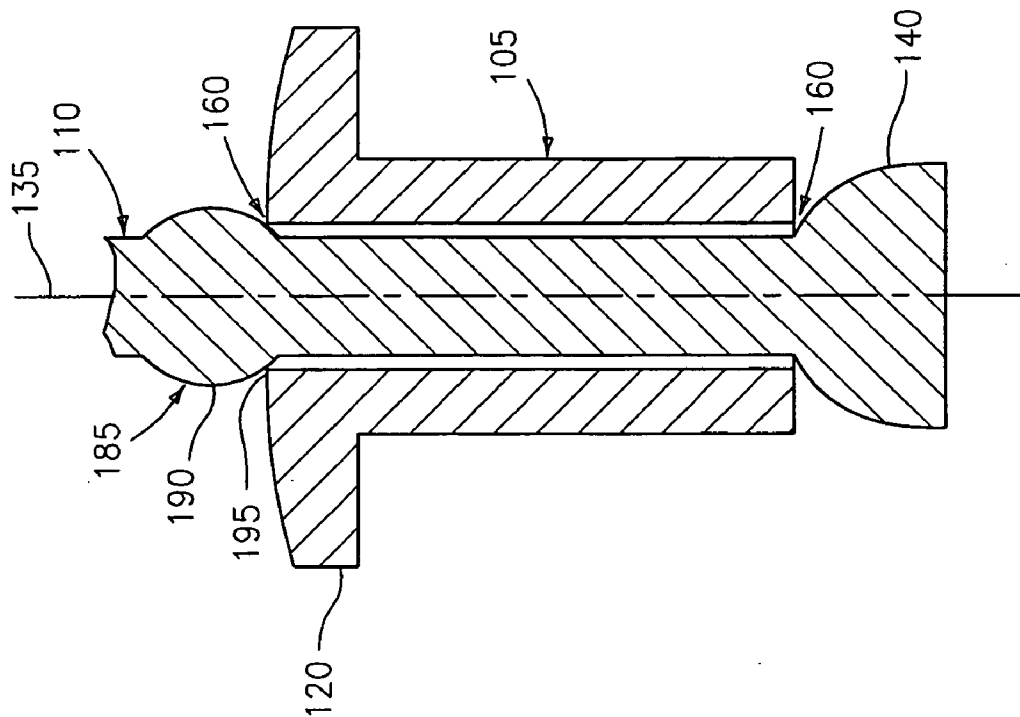


FIG. 7

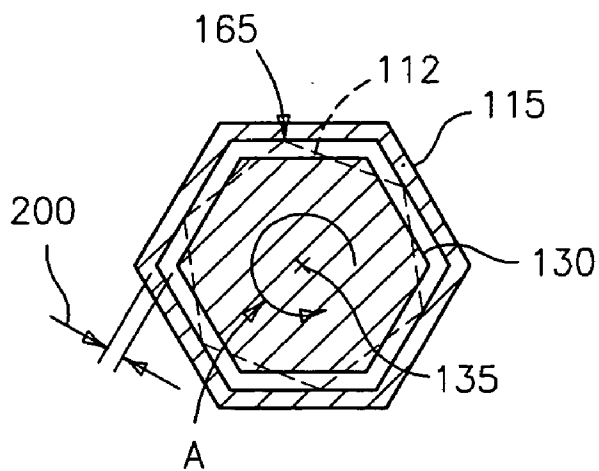


FIG. 8

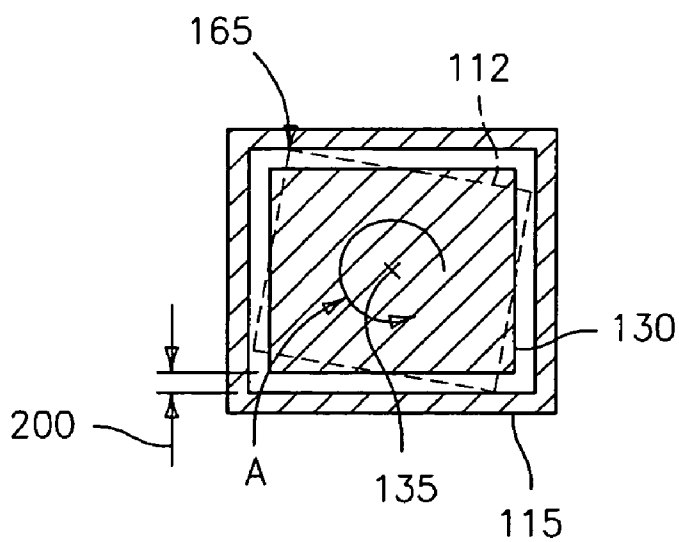


FIG. 9

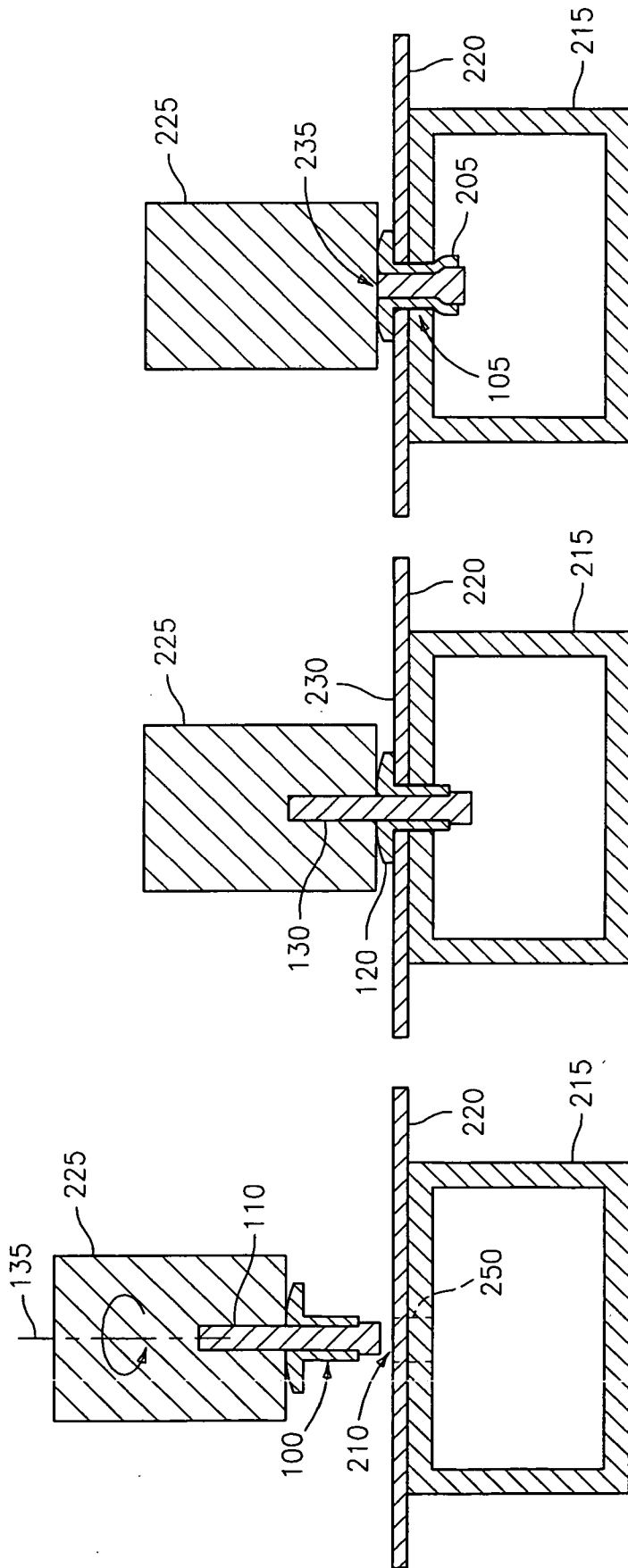


FIG. 10

FIG. 11

FIG. 12

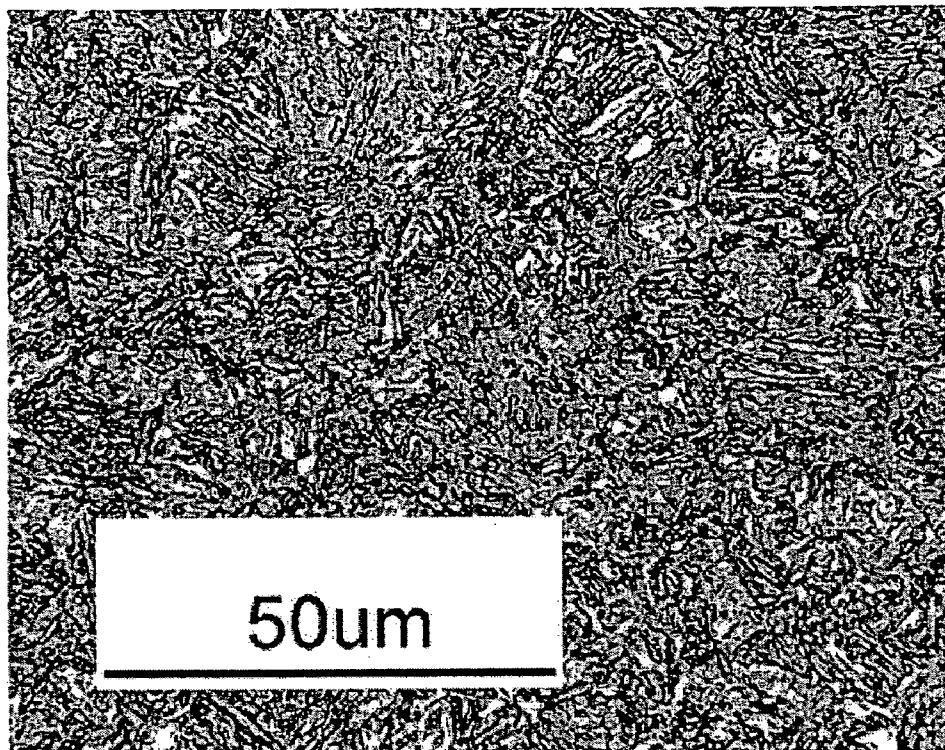


FIG. 13

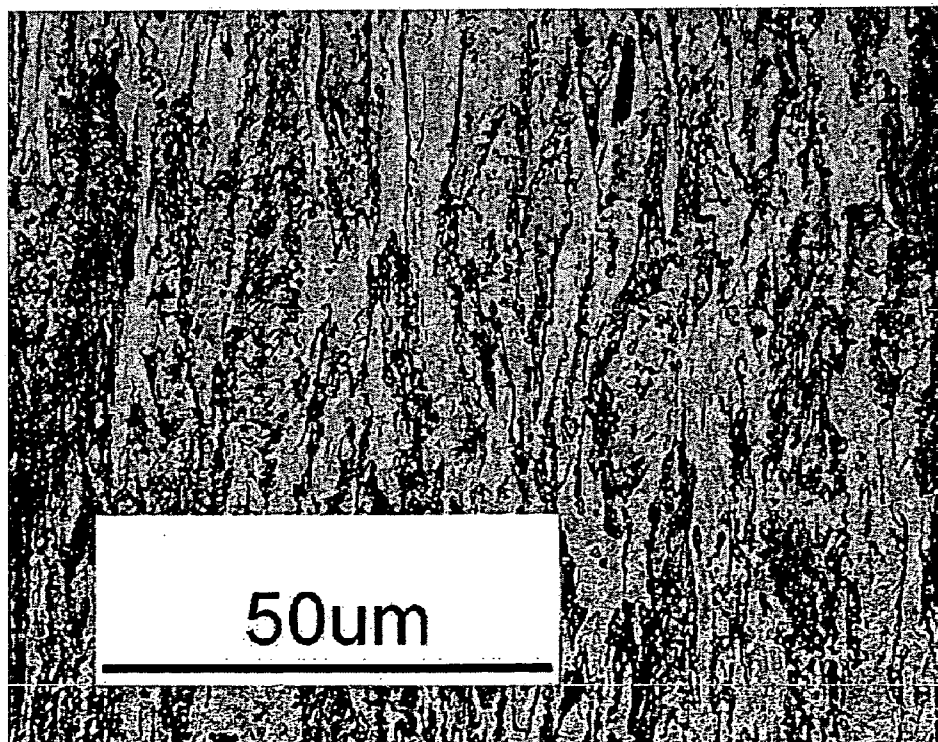


FIG. 14

FRICTION STIR RIVET AND METHOD OF JOINING THEREWITH

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Docket No. GP-305227 (GM2-0141), filed Jul. 29, 2004, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] The present disclosure relates generally to friction stir riveting and a method of joining therewith, and particularly to a friction stir rivet and method that has a reduced tendency to undesirably displace softened friction stirred material sideways into the joint between the workpieces being joined.

[0003] Friction stir welding (FSW) is a method used to join metal workpieces that generally uses a cylindrical shouldered tool with a profiled pin that is rotated at the joint line between two workpieces while being traversed along the joint line. The rotary motion of the tool generates frictional heat that serves to soften and plasticize the workpieces. As the pin moves laterally, the softened material, contributed by both workpieces, intermingles in the wake of the traversing pin and cools and hardens due to the absence of further frictional stirring, creating a bond between the two workpieces.

[0004] Recent advances in friction stir processes have extended the FSW technique to friction stir riveting (FSR), where a stir rivet is rotated and advanced into an arrangement of workpieces to be joined such that the material of the workpieces plasticizes around the rivet during the friction stirring, and then hardens around the rivet when the body of the rivet stops rotating and the workpieces and rivet are allowed to cool.

[0005] While present devices and methods may be suitable for their intended purposes, it is desirable to further advance the technology of friction stir riveting in a manner that offers opportunities for joining dissimilar materials.

BRIEF DESCRIPTION OF THE INVENTION

[0006] Embodiments of the invention include a friction stir rivet having a body, a mandrel, and a mechanical interface therebetween. The body has an elongated cylindrical shank, a cap at a first end, and an axial hole there-through. The mandrel has an elongated shaft defining an axis and a head at one end thereof, the head having an effective outside diameter greater than the effective outside diameter of the shaft, the shaft being disposed within the axial hole of the body, the mandrel head being disposed at an opposite end of the body to that of the cap, and the end of the mandrel head having a flat surface oriented substantially perpendicular to the axis of the shaft. The mechanical interface between the body and the mandrel is such that the body rotates in response to rotation of the mandrel.

[0007] Other embodiments of the invention include a method of joining upper and lower workpieces fluidly bondable at a point of engagement using the aforementioned friction stir rivet. The rivet is positioned at the point of engagement of the workpieces, and the mandrel is rotated

about its rotational axis. The rivet is driven toward and into the workpieces such that resultant frictional heating between the rivet and the workpieces causes the materials of the workpieces to soften at a process temperature thereby providing a friction stirred displaceable path for the rivet to traverse. The rivet is driven along the displaceable path until the cap is seated against the workpieces. Further rotation of the mandrel is stopped, allowing the workpieces and mandrel to cool below the process temperature, thereby permitting the softened workpieces to harden. The mandrel is axially loaded with sufficient force to drive the mandrel head into the end of the body thereby upsetting and expanding the body end to create an interference between the body and the underside of the lowermost workpiece and to cause the mandrel shaft to sever at a point internal to the body and proximate the cap. As a result, the workpieces are held together by the fluidly bonded materials of the workpieces, the differential thermal contraction of the workpieces and the rivet, and the mechanical loading between the mandrel and the body, at the point of engagement.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Referring to the exemplary drawings wherein like elements are numbered alike in the accompanying Figures:

[0009] **FIGS. 1 and 2** depict in cross section longitudinal view exemplary rivets in accordance with embodiments of the invention;

[0010] **FIGS. 3-5** depict in cross section axial view exemplary shafts of a mandrel of a rivet for use in embodiments of the invention;

[0011] **FIGS. 6 and 7** depict in cross section longitudinal view alternative exemplary rivets in accordance with embodiments of the invention;

[0012] **FIGS. 8 and 9** depict in cross section axial view alternative exemplary rivet geometries having a non-circular cross section in accordance with embodiments of the invention;

[0013] **FIGS. 10-12** depict a riveting method in accordance with embodiments of the invention;

[0014] **FIG. 13** depicts a martensite microstructure for use in accordance with embodiments of the invention; and

[0015] **FIG. 14** depicts a cold drawn microstructure for use in accordance with embodiments of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0016] Embodiments of the invention disclose a friction stir rivet having an outer body and an inner mandrel with a mechanical interface therebetween such that the outer body rotates in response to the mandrel being rotated. The mandrel has a flat head that engages the workpieces to be joined, thereby providing a friction stir surface that has a reduced tendency to undesirably displace the softened friction stirred material sideways in the joint between the workpieces. Other embodiments disclose a method of joining two or more workpieces using the friction stir rivet disclosed herein, and doing so in the absence of a preexisting hole in the workpieces to be joined.

[0017] **FIG. 1** depicts a cross section view of an exemplary embodiment of a friction stir rivet **100** having a body

105 and a mandrel **110**. Body **105** has an elongated cylindrical shank **115**, a cap **120** at one end, and an axial hole **125** extending from one end to the other. Mandrel **110** has an elongated shaft **130** defining an axis **135**, and a head **140** at one end. Head **140** has an effective outside diameter D that is greater than the effective outside diameter d of shaft **130**.

[0018] As used herein, the term effective diameter refers to that diameter that the respective cross section would transcribe if it were rotated about its axis of rotation, such as axis **135** in the case of shaft **130**. For example, and referring now to FIGS. 3-5 which depict exemplary cross section cuts through shaft **130**, a shaft **130** having a circular cross section would have an effective diameter defined by its own diameter d (see FIG. 3), a shaft **130** having a hexagonal cross section would have an effective diameter defined by d_2 (see dashed line, FIG. 4), and a shaft **130** having a square cross section would have an effective diameter defined by d_3 (see dashed line, FIG. 5). While only shaft **130** is depicted in FIGS. 3-5, it will be appreciated that the same configuration may be applied to both the mandrel head **140** and the body shank **115**. That is, a circular mandrel shaft **130** may be used with a circular body shank **115**, a hexagonal mandrel shaft with a hexagonal body shank, and a square mandrel shaft with a square body shank, for example. In an embodiment where both shaft **130** and shank **115** are non-circular, the outer and inner surfaces, respectively, may provide a mechanical interface therebetween, thereby resulting in the rotation of shank **115** and body **105** in response to mandrel **110** being rotated. Also, while only three cross section geometries are depicted in FIGS. 3-5, it will be appreciated that rivet **100** is not so limited and that any cross section geometry may be applied to rivet **100** in accordance with embodiments of the invention.

[0019] As depicted in FIG. 1, shaft **130** is disposed within axial hole **125**, and head **140** is disposed at the opposite end of body **105** to that of cap **120**. In an embodiment, the end **145** of mandrel head **140** has a flat surface **150** that is oriented substantially perpendicular to axis **135** of shaft **130**, and preferably flat surface **150** is oriented substantially perpendicular to axis **135** within plus-or-minus two degrees of axis **135**. While it is desirable to have flat surface **150** extend over about 100% of the effective diameter D of the end **145** mandrel head **140**, it may also be possible to have and use flat surface **150** that extends over something less than 100% of effective diameter D . In an alternative embodiment, and referring now to FIG. 2, flat surface **150** may have an effective outside diameter D_s that is less than the effective outside diameter D of mandrel head **140**. For example, flat surface **150** may have an effective outside diameter D_s that is equal to or greater than about 80% of the effective outside diameter D of mandrel head **140**. Notwithstanding the foregoing, it has been observed that the closer effective diameter D_s is to effective diameter D , the less the tendency will be to displace the softened friction stirred material sideways into the joint between the workpieces.

[0020] A mechanical interface **155**, **160**, **165**, best seen by now referring to FIGS. 6-9, between body **105** and mandrel **110** of FIGS. 6 and 7, and between shaft **130** and shank **115** of FIGS. 8 and 9, enables body **105** and shank **115** to rotate in response to the rotation of mandrel **110** and shaft **130**. FIGS. 6 and 7 depict section cuts containing axis **135**

similar to that of FIGS. 1 and 2, and FIGS. 8 and 9 depict section cuts perpendicular to axis **135** similar to that of FIGS. 4 and 5.

[0021] Referring first to FIG. 6, body **105** includes a deformed region **170** such that inner surface **175** of shank **115** is compressed against outer surface **180** of shaft **130**, thereby forming mechanical interface **155**. The compressive force at interface **155** is made sufficient to cause body **105** to rotate in response to mandrel **110** being rotated. In an embodiment, deformed region **170** is created by a crimping operation.

[0022] Referring now to FIG. 7, mandrel **110** includes a deformed, upset or flared region **185** such that outer surface **190** of deformed region **185** is compressed against inner edge **195** of cap **120** during a friction stir riveting operation. In an alternative embodiment, deformed region **185** and head **140** form a tight fit between top and bottom of body **105**, thereby tightly gripping and constraining body **105** during a friction stir riveting operation. In either embodiment of FIG. 7, mechanical interfaces **160** may result. The degree of interference at interfaces **160** is made sufficient to cause body **105** to rotate in response to mandrel **110** being rotated during a friction stir riveting operation.

[0023] Referring now to FIGS. 8 and 9, shaft **130** of mandrel **110**, and shank **115** of body **105**, each have matching non-circular cross sections perpendicular to axis **135** that define an annulus **200** therebetween, such that the outer surface of shaft **130** engages the inner surface of shank **115** in response to rotation (arrow A) of mandrel **110** about axis **135**, thereby forming mechanical interface **165**, best seen by referring to the phantom lines **112** of each figure, which represent a rotated mandrel **110**.

[0024] In an alternative embodiment, the material and outside diameter d of shaft **130** and the material and inside diameter B of shank **115** are selected and sized such that diameter d is less than diameter B at room temperature, such as 20 degree Celsius (deg-C.) for example, and is equal to or greater than diameter B at a process temperature, such as greater than 20 deg-C. and less than or equal to the melt temperature of the workpieces for example. In an embodiment where the workpieces are aluminum, the process temperature is less than or equal to about 660 deg-C., for example, and in an embodiment where the workpieces are thermoplastic, the process temperature is less than the melt temperature of the respective thermoplastic. In this manner, a thermal expansion compression fit between shaft **130** and shank **115** at the appropriate process temperature will produce the desired mechanical interface between shaft **130** and shank **115** such that shank **115** and body **105** will rotate in response to the rotation of mandrel **110** and shaft **130**.

[0025] In an embodiment, mandrel **110** and body **105** are selected to be copper, titanium, iron, or any alloy having at least one of the foregoing materials. If mandrel **110** is steel, it is preferable to use medium or high carbon steel. As used herein, medium carbon steel refers to a steel having equal to or greater than about 0.29 weight % carbon and equal to or less than about 0.53 weight % carbon, and high carbon steel refers to a steel having equal to or greater than about 0.55 weight % carbon and equal to or less than about 0.95 weight % carbon.

[0026] The materials used for mandrel **110** and body **105** are selected such that head **140** of mandrel **110** is strong

enough to deform the end 205 of body 105 in response to head 140 being axially pulled into hole 125 of body 105 subsequent to the friction stirring process, best seen by now referring to FIGS. 10-12, which depict an exemplary method of friction stir riveting in accordance with embodiments of the invention.

[0027] In FIG. 10, workpiece 215 is supported in an appropriate fashion, workpiece 220 is positioned on top of workpiece 215, friction stir rivet 100 is positioned at the point of engagement 210 of the workpieces 215, 220, and mandrel 110 is rotated about its rotational axis 135 via a rotary drive tool 225. In FIG. 11, tool 225 has driven rivet 100 downward towards and into workpieces 220 and 215 in a rotary fashion such that resultant frictional heating between rivet 100 and workpieces 220, 215 causes the materials of workpieces 220, 215 to soften, thereby providing a friction stirred displaceable path (depicted generally as numeral 250) for rivet 100 to traverse. Rivet 100 is driven along the displaceable path until cap 120 is seated against the top surface 230 of workpiece 220. While it may be possible to rotate and drive rivet 100 at sufficient speed and rate to cause melting of workpieces 220, 215, it has been observed that rotating and driving rivet 100 to cause softening of workpieces 220, 215 is sufficient for producing a suitable joint. In an embodiment, tool 225 rotates mandrel 110 at a speed of about 12,000 revolutions per minute (rpm), and drives rivet 100 downward at a rate of equal to or greater than about 6 millimeters per minute (mm/min) and equal to or less than about 150 mm/min. However, it is contemplated that rotational speeds of equal to or less than about 12,000 rpm may be suitable for the purposes disclosed herein. An exemplary drive rate of about 12 mm/min was applied using 2024-T3 aluminum workpieces 220, 215. As a result of the rotation speed in combination with the drive rate, the friction heating initiated between the end 140 of mandrel 110 and the surface 230 of workpiece 220, a friction stir process temperature is established that results in the softening of workpieces 220 and 215, and preferably but not necessarily results in softening without melting. As discussed previously, the process temperature is that temperature between room temperature and the melt temperature of workpieces 220, 215 at which workpieces 220, 215 are soft enough to provide a displaceable friction stir path for rivet 100 to traverse. In an embodiment, the process temperature is substantially less than the melt temperature of rivet 100.

[0028] In an embodiment, and with reference still to FIG. 11, tool 225 drives rivet 100 toward workpieces 220, 215 until the underside of cap 120 is in loaded contact with the top side surface 230 of workpiece 220, resulting in friction stirring and partial penetration of cap 120 into surface 230, holds the 12,000 rpm rotation of mandrel 110 for a defined period of time, such as two seconds for example, and then stops further rotation to allow workpieces 220, 215 and mandrel 110 to cool below the process temperature. During the cooling, the softened workpieces 220, 215 harden.

[0029] In an alternative embodiment, tool 225 holds the 12,000 rpm rotation of mandrel 110 for a defined period of time subsequent to the underside of cap 120 being seated against the top side surface 230 of workpiece 220, and then stops further rotation to allow workpieces 220, 215 and mandrel 110 to cool below the process temperature.

[0030] Subsequent to hardening, and with reference now to FIG. 12, tool 225 applies an axial tensile load (pulling

operation) to mandrel 110 with sufficient force to drive mandrel head 140 into end 205 of body 105, deform end 205 in an upsetting like operation, and cause mandrel shaft 130 to sever at a location 235 internal to body 105 and proximate cap 120. As a result, workpieces 220, 215 are held together by the fluidly bonded materials of the workpieces 220, 215, the differential thermal contraction of the workpieces 220, 215 and the rivet 100, and the mechanical loading between mandrel 110 and body 105 and between body 105 and workpieces 220, 215, at the point of engagement 210.

[0031] To assist in the severing of shaft 130 during the pulling operation, an embodiment of shaft 130 includes a first region of relatively high tensile strength 240 and a second region of relatively low tensile strength 245, depicted in FIG. 1 but also applicable to other embodiments of shaft 130 depicted in FIGS. 2, 6, 7, and 10-12. In an embodiment, the first and second regions 240, 245 of relatively high and low tensile strength are achieved by differing the cross section area of shaft 130 in the two regions. Second region 245 is proximate cap 120, thereby resulting in a substantial amount of shaft 130 remaining within body 105 after being severed, which adds to the strength of the resultant riveted joint. It has been observed in an embodiment that by causing a portion of mandrel 110 to be retained within body 105, the joint strength is improved by about a factor of two compared to the same joint absent the portion of mandrel 110.

[0032] In an embodiment, and as previously discussed, end 145 of mandrel 110 is flat to within plus-or-minus two degrees of perpendicular relative to axis 135, where flat surface 150 has an effective diameter at about 100% of the effective diameter of head 140. The use of flat surface 150 provides an effective way of initiating and generating frictional heating as the rotating flat surface 150 of mandrel 110 is driven into workpieces 220, 215, and the use of a 100% flat surface 150 provides an effective way of reducing the tendency for the displaced material along the displaceable path to penetrate the region between workpieces 220, 215 at the faying surfaces as rivet 100 is driven into and through workpieces 220, 215.

[0033] Due to the elevated temperatures (process temperature) associated with friction stir riveting, it is desirable to use a material for the mandrel 110 that can withstand the elevated temperatures without substantially losing tensile strength qualities during the duration of the riveting process. Metallurgical hardening processes, such as transformation hardening or workhardening, generally develop microstructures which, due to diffusional processes, degrade upon exposure to elevated temperatures. The mandrel 110, is designed to upset the body 105 of the rivet 100 before severing. To maintain this capability after friction stir riveting, the mandrel should be strengthened using a process that will substantially maintain mandrel strength under the temperature-time history experienced by the mandrel during the friction stir riveting process. Ideally this would entail that the mandrel tensile strength be unaffected by the time-temperature history of the riveting process, but less stringent requirements may be imposed provided that the operational requirement of upsetting before severing is satisfied. Since the degree of softening is influenced by the initial choice of strengthening mechanism, the maximum temperature experienced, and the time during which the mandrel 110 is exposed to the process temperature, the softening behavior

of the mandrel **110** under the time-temperature history to which it is exposed should be taken into consideration. Thus, for example, a mandrel **110** with a tempered martensite structure, such as is shown in **FIG. 13**, would generally be preferred over a cold drawn mandrel, such as is shown in **FIG. 14**, since the tempered martensite mandrel has already been subjected to a short-term elevated temperature excursion during the tempering process, while the cold drawn structure has not. Thus, the cold drawn structure would be expected to soften more than the tempered martensite structure under identical riveting process conditions. As used herein, the term short-term temperature excursion refers to a temperature at or below the process temperature for a period of time equal to or less than about two minutes. As depicted, **FIGS. 13 and 14** are magnified views of the respective material microstructure, with a scale of 50 μm (micro-meters) also shown.

[0034] In an embodiment, a suitable material for mandrel **110** is a medium carbon steel, such as having 0.40 weight % carbon for example, that is quenched to form martensite, and is then tempered at a temperature of not less than about 450 deg.-C. for not less than about 30 minutes, and is preferably tempered at a temperature of not less than about 500 deg.-C. for not less than about 30 minutes.

[0035] In another embodiment, a suitable material for mandrel **110** is a material that undergoes a change in tensile strength in response to the friction stir process, which may involve an elevated temperature at the process temperature for the period of hold time, that is equal to or less than about 5% change, and preferably is equal to or less than about 1% change.

[0036] In a further embodiment, a suitable material for mandrel **110** is a material that can withstand a process temperature of equal to or greater than about 50% and equal to or less than about 100% of the highest melt temperature of metallic workpieces **220, 215**, at a process time of equal to or less than about two minutes, such that the end **205** of body **105** is upset prior to second region **245** being severed during the pulling process.

[0037] In yet another embodiment, a suitable material for mandrel **110** is a material that can withstand a process temperature of equal to or greater than the highest glass transition temperature and equal to or less than the highest melt temperature of polymeric workpieces **220, 215**, at a process time of equal to or less than about two minutes, such that the end **205** of body **105** is upset prior to second region **245** being severed during the pulling process.

[0038] In yet a further embodiment having dissimilar materials for workpieces **220, 215**, such as a polymeric upper workpiece **220** and a metallic lower workpiece **215** for example, a suitable material for mandrel **110** is a material that can withstand the higher of the aforementioned process temperatures for polymeric **220** and metallic **215** workpieces, respectively.

[0039] While some manufacturing processes may be desirous of short friction stir hold cycles, such as the aforementioned two seconds for example, other manufacturing processes may prefer longer hold cycles, such as one minute or two minutes for example. With a two second or longer hold cycle, it is contemplated that the use of a martensite or bainite microstructure for mandrel **110** will result in a

stronger rivet **100** as compared to a rivet **100** having a mandrel **110** with a cold drawn microstructure.

[0040] However, it will be appreciated that overall production process cycles may be sensitive to the drive rate of the friction stir riveting process, with a faster drive rate being preferred, and that a faster drive rate may result in lower temperatures for less time, and consequently less annealing of the mandrel, thereby enabling mandrel materials, such as cold drawn microstructures for example, to endure the desired time-temperature process parameters of the friction stir riveting process. Accordingly, and under certain conditions, a cold drawn microstructure for the material of mandrel **110** may be suitable for the purposes disclosed herein.

[0041] From the foregoing, it will be appreciated that a suitable material for mandrel **110** is not limited to martensite, bainite, or any other specific microstructure, but is rather determined by the resultant material characteristics of the mandrel **110** subsequent to exposure to the process parameters of time and temperature.

[0042] In accordance with embodiments of the invention, 3 mm thick workpieces **220** and **215** made of 5052 aluminum have been successfully joined. However, it is contemplated that embodiments of the invention also offer opportunities for joining dissimilar materials including but not limited to composites to aluminum, polymers to aluminum, and aluminum to magnesium. For composite to aluminum or polymer to aluminum joints, it is contemplated that the aluminum be mounted below the composite or polymer so that the expanding rivet during the pulling operation may engage the aluminum as it is expanded by head **140** of mandrel **110**, while the composite or polymer is held by the larger rivet cap **120** of body **105**, and thus subjected to a lower, less localized stress.

[0043] As disclosed, some embodiments of the invention may include some of the following advantages: the ability to join workpieces together in the absence of a preexisting hole, thereby minimizing clearance, tolerance, fit-up and alignment issues, particularly for multi-member stack-ups; improved flow control of the displaced material that reduces its tendency to penetrate the joint area between the workpieces, thereby reducing the likelihood of the displaced material forcing the workpieces apart as it cools and hardens, leaving a large gap therebetween; and, the opportunity for friction stir riveting dissimilar materials.

[0044] While the invention has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to a particular embodiment disclosed as the best or only mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims. Moreover, the use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another. Furthermore, the use of the terms a, an, etc. do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item.

What is claimed is:

1. A friction stir rivet, comprising:

a body having an elongated cylindrical shank, a cap at a first end, and an axial hole therethrough;

a mandrel having an elongated shaft defining an axis and a head at one end thereof, the head having an effective outside diameter greater than the effective outside diameter of the shaft, the shaft being disposed within the axial hole of the body, the mandrel head being disposed at an opposite end of the body to that of the cap, and the end of the mandrel head having a flat surface oriented substantially perpendicular to the axis of the shaft; and

a mechanical interface between the body and the mandrel such that the body rotates in response to rotation of the mandrel.

2. The rivet of claim 1, wherein:

the flat surface oriented substantially perpendicular to the axis of the shaft is perpendicular to within plus-or-minus two degrees thereof.

3. The rivet of claim 1, wherein:

the flat surface has an effective outside diameter that is equal to or greater than about 80% of the effective outside diameter of the mandrel head.

4. The rivet of claim 3, wherein:

the flat surface extends over about 100% of the effective diameter of the end of the mandrel head.

5. The rivet of claim 1, wherein:

the shaft has a first region having a first tensile strength and a second region having a second tensile strength, the second tensile strength being less than the first tensile strength, and the second region being disposed proximate the cap.

6. The rivet of claim 1, wherein:

the mandrel comprises a material having a microstructure that substantially maintains its strength during a short-term temperature excursion, such that subsequent to a short-term temperature excursion, and in response to the mandrel head being pulled into the body, the mandrel has sufficient strength to upset the body prior to the mandrel severing.

7. The rivet of claim 1, wherein:

the mandrel comprises a material having a martensite microstructure.

8. The rivet of claim 1, wherein:

the mandrel comprises a material having a bainite microstructure.

9. The rivet of claim 1, wherein:

the mandrel comprises a material having a cold drawn microstructure.

10. The rivet of claim 1, wherein:

the body comprises a deformed region thereby defining the mechanical interface.

11. The rivet of claim 1, wherein:

the mandrel comprises a deformed region thereby defining the mechanical interface.

12. The rivet of claim 1, wherein:

the mandrel and the body have non-circular cross sections perpendicular to the axis of rotation defining a non-circular annulus such that the outer surface of the mandrel engages the inner surface of the body in response to rotation of the mandrel thereby defining the mechanical interface.

13. The rivet of claim 1, wherein:

the shaft has an effective outside diameter equal to or greater than the effective inside diameter of the shank at a process temperature greater than room temperature thereby defining the mechanical interface.

14. The rivet of claim 1, wherein:

the mandrel and body comprise copper, titanium, iron, or any alloy comprising at least one of the foregoing.

15. The rivet of claim 1, wherein:

the mandrel comprises medium carbon steel or high carbon steel.

16. The rivet of claim 1, wherein:

the mandrel comprises a medium carbon steel having equal to or greater than about 0.29 weight % carbon and equal to or less than about 0.53 weight % carbon that is quenched to form a martensite microstructure and is then tempered at a temperature of equal to or greater than about 450 deg-C. for equal to or greater than about 30 minutes.

17. The rivet of claim 16, wherein:

the mandrel is tempered at a temperature of equal to or greater than about 500 deg-C. for equal to or greater than about 30 minutes.

18. The rivet of claim 1, wherein:

the mandrel comprises a material that undergoes a change in tensile strength in response to the friction stir process that is equal to or less than about 5% change.

19. The rivet of claim 18, wherein:

the mandrel comprises a material that undergoes a change in tensile strength in response to the friction stir process that is equal to or less than about 1% change.

20. A method of joining upper and lower workpieces fluidly bondable at a point of engagement, comprising:

positioning a friction stir rivet at the point of engagement of the workpieces, the rivet comprising: a body having an elongated cylindrical shank, a cap at a first end, and an axial hole therethrough; a mandrel having an elongated shaft defining an axis and a head at one end thereof, the head having an effective outside diameter greater than the effective outside diameter of the shaft, the shaft being disposed within the axial hole of the body, the mandrel head being disposed at an opposite end of the body to that of the cap, and the end of the mandrel head having a flat surface oriented substantially perpendicular to the axis of the shaft; and, a mechanical interface between the body and the mandrel such that the body rotates in response to rotation of the mandrel;

rotating the mandrel about its rotational axis, driving the rivet toward and into the workpieces such that resultant frictional heating between the rivet and the workpieces causes the materials of the workpieces to soften at a process temperature thereby providing a friction stirred displaceable path for the rivet to traverse, and driving the rivet along the displaceable path until the cap is seated against the workpieces;

stopping further rotation of the mandrel and allowing the workpieces and mandrel to cool below the process temperature, thereby permitting the softened workpieces to harden; and

axially loading the mandrel with sufficient force to drive the mandrel head into the end of the body thereby upsetting and expanding the body end to create an interference between the body and the underside of the lowermost workpiece and to cause the mandrel shaft to sever at a point internal to the body and proximate the cap, thereby resulting in the workpieces being held together by the fluidly bonded materials of the workpieces, the differential thermal contraction of the workpieces and the rivet, and the mechanical loading between the mandrel and the body, at the point of engagement.

21. The method of claim 20, wherein the rotating comprises:

rotating the mandrel at equal to or less than about 12,000 revolutions per minute.

22. The method of claim 20, wherein the driving comprises:

driving the rivet at a rate equal to or greater than about 6 millimeters per minute and equal to or less than about 150 millimeters per minute.

23. The method of claim 20, further comprising:

holding the mandrel rotation at about 12,000 revolutions per minute for about 2 seconds subsequent to the cap being seated against the workpieces.

24. The method of claim 20, wherein the resultant frictional heating is initiated by the friction stir interaction between the flat surface of the mandrel and the workpieces.

25. The method of claim 20, wherein the flat surface extends over equal to or greater than about 80% of the effective diameter of the end of the mandrel head, thereby displacing the material along the displaceable path in such a manner as to reduce the tendency for the displaced material to penetrate the region between the workpieces as the rivet is driven into the workpieces.

26. The method of claim 25, wherein the flat surface extends over about 100% of the effective diameter of the end of the mandrel head.

27. The method of claim 20, wherein the driving the rivet into the workpieces comprises:

driving the rivet absent a preexisting hole in the workpieces.

28. The method of claim 20, wherein the causing the materials of the workpieces to soften at a process temperature comprises:

causing the materials to soften at a process temperature that is substantially lower than the melting temperature of the rivet.

29. The method of claim 20, further comprising:

driving the rivet along the displaceable path until the underside of the cap is in loaded contact with one of the workpieces; and

friction stirring and partially penetrating the cap into the one of the workpieces.

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