



US007234626B2

(12) **United States Patent**  
**Trapp et al.**

(10) **Patent No.:** **US 7,234,626 B2**  
(45) **Date of Patent:** **Jun. 26, 2007**

(54) **METHOD OF FRICTION STIR WELDING AND RETRACTABLE SHOULDERLESS VARIABLE PENETRATION FRICTION STIR WELDING TOOL FOR SAME**

(75) Inventors: **Timothy J. Trapp**, Columbus, OH (US); **James J. Fisher, Jr.**, Columbus, OH (US); **Jeffrey J. Bernath**, Columbus, OH (US)

(73) Assignee: **Edison Welding Institute, Inc.**, Columbus, OH (US)

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 336 days.

(21) Appl. No.: **10/970,907**

(22) Filed: **Oct. 22, 2004**

(65) **Prior Publication Data**  
US 2006/0086775 A1 Apr. 27, 2006

(51) **Int. Cl.**  
**B23K 31/02** (2006.01)

(52) **U.S. Cl.** ..... **228/112.1**

(58) **Field of Classification Search** ..... 228/112.1, 228/2.1

See application file for complete search history.

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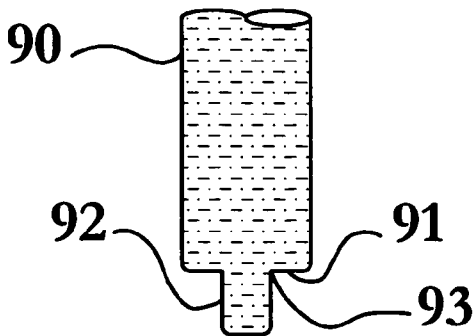
*Primary Examiner*—Jonathan Johnson

(74) *Attorney, Agent, or Firm*—Gallagher & Dawsey Co., LPA; David J. Dawsey; Michael J. Gallagher

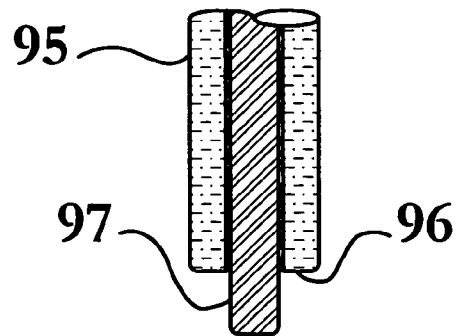
(57) **ABSTRACT**

A method of friction stir welding and a non-consumable retractable shoulderless variable penetration friction stir welding tool. The tool includes a substantially cylindrical body portion, a head portion, and a tip section, each integral to the tool. The body portion has a longitudinal axis about which it is rotatable, a diameter, a sidewall substantially parallel to the longitudinal axis, a proximal end, and a distal end. The head portion is located at the distal end of the body portion. The head portion has a base with a diameter substantially equal to the diameter of the body portion thereby forming a smooth transition between the body portion and the head portion, thus, the tool has no shoulder. The head portion includes a face that converges to the tip section. The tool is retractable, reduces overheating, improves weld quality by reducing internal voids and lack of fusion, and facilitates variable penetration welds.

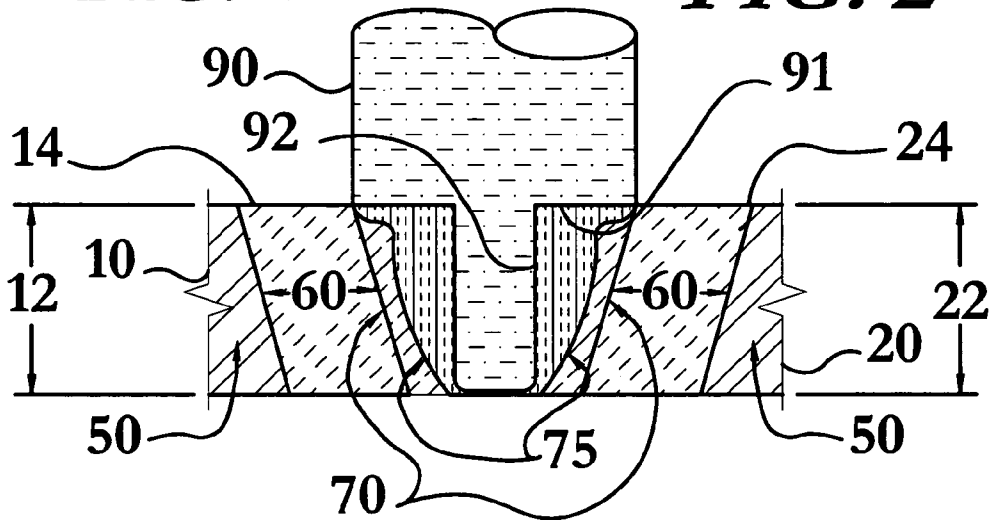
**24 Claims, 12 Drawing Sheets**



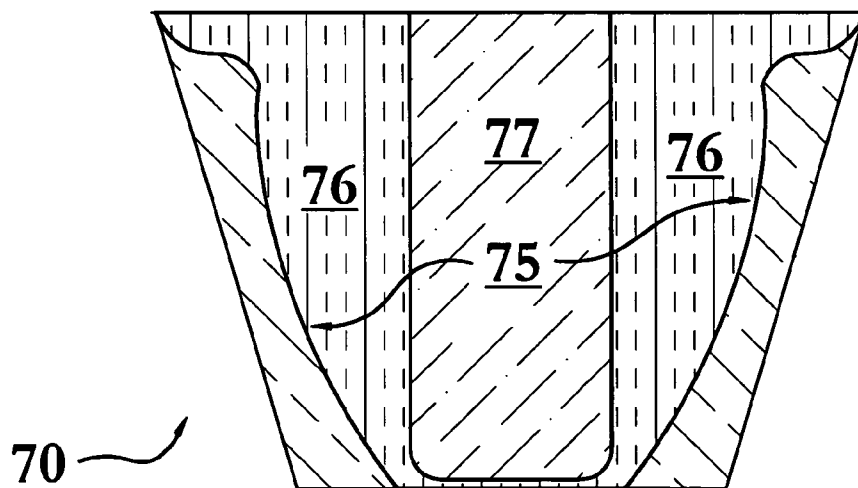
(Prior Art)  
**FIG. 1**



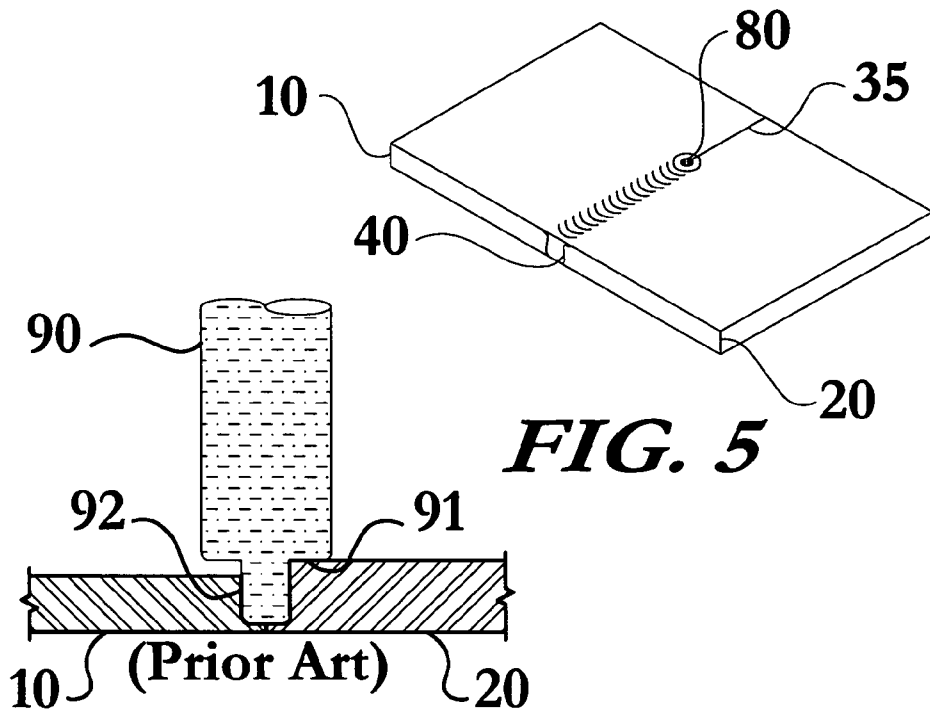
(Prior Art)  
**FIG. 2**



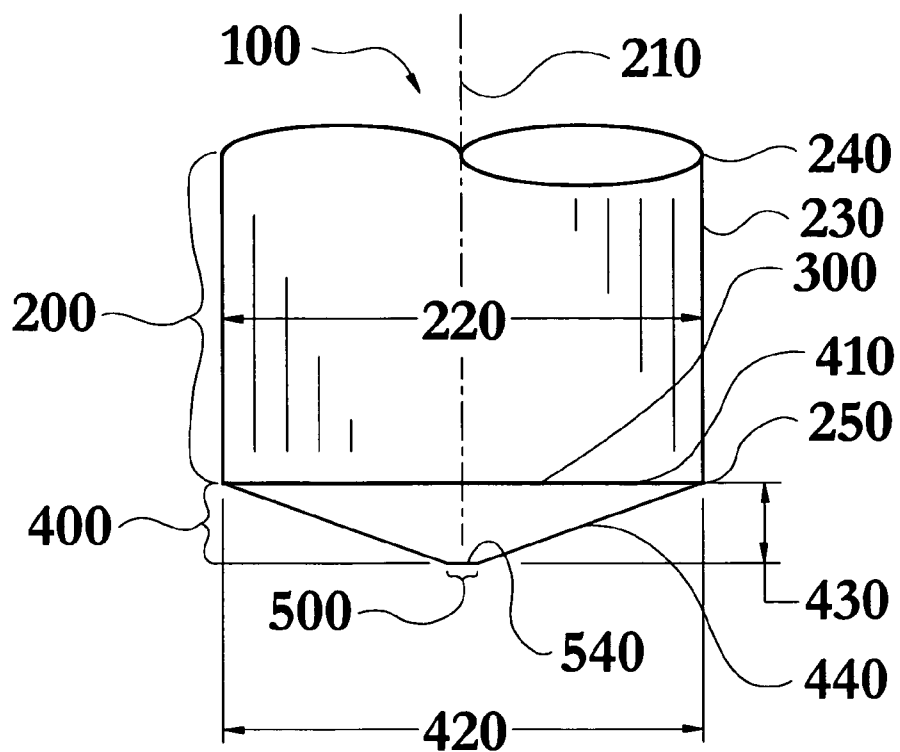
**FIG. 3**



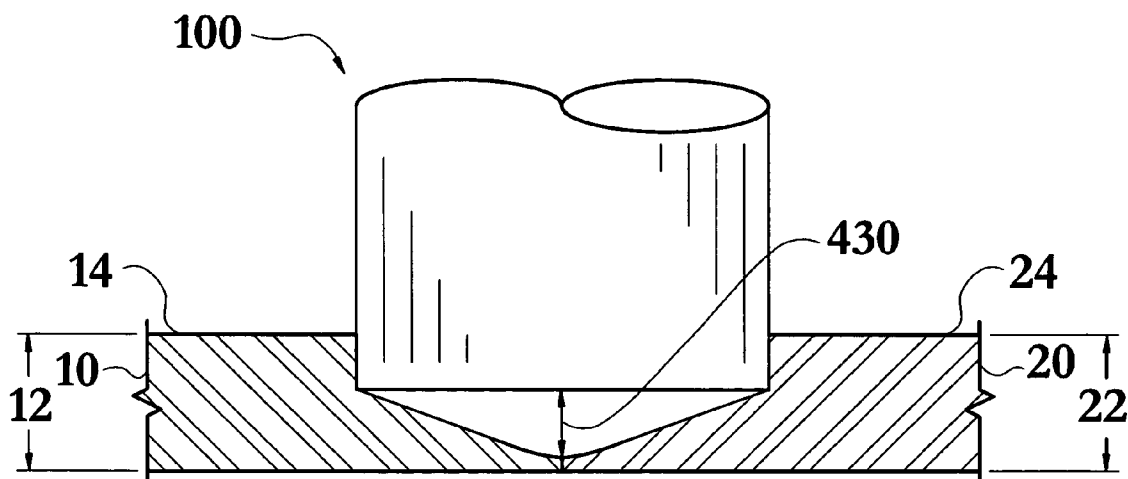
**FIG. 4**



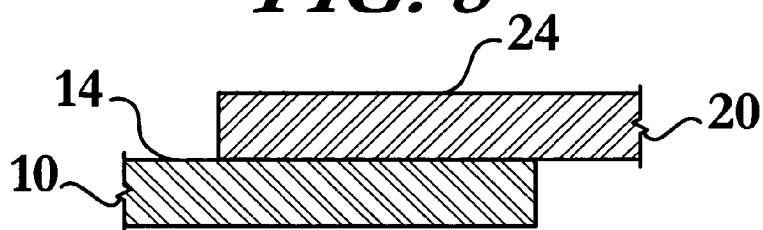
**FIG. 6**



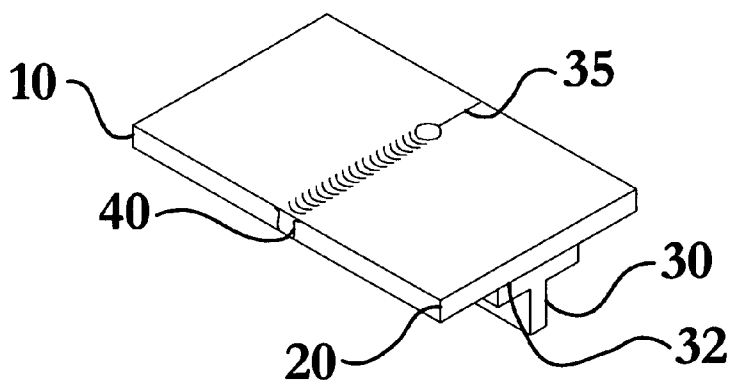
**FIG. 7**



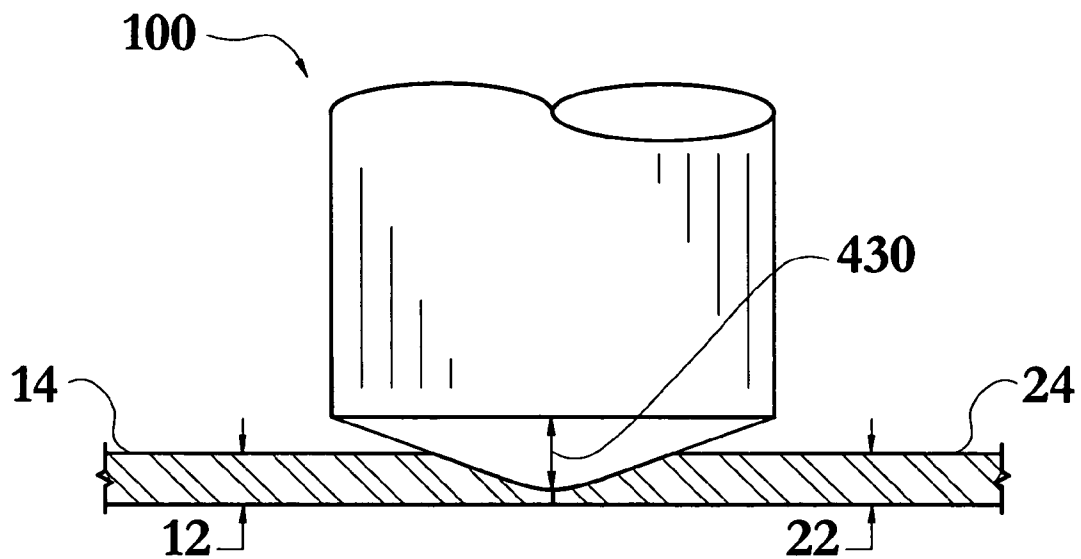
**FIG. 8**



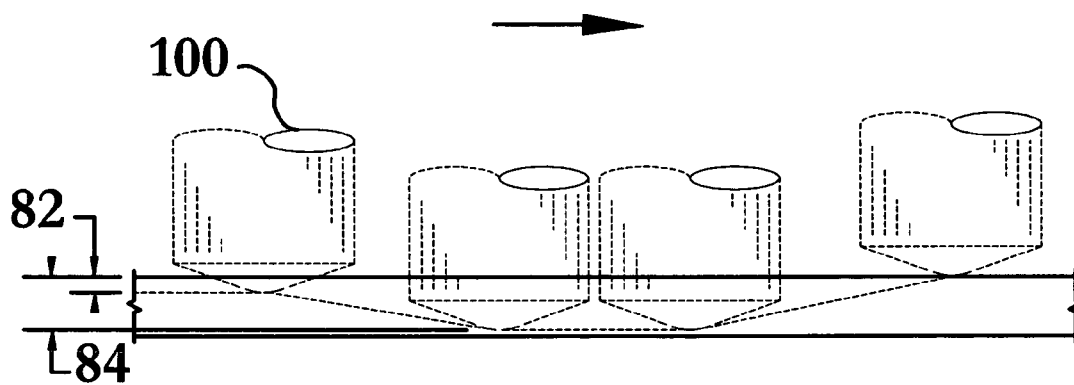
**FIG. 9**



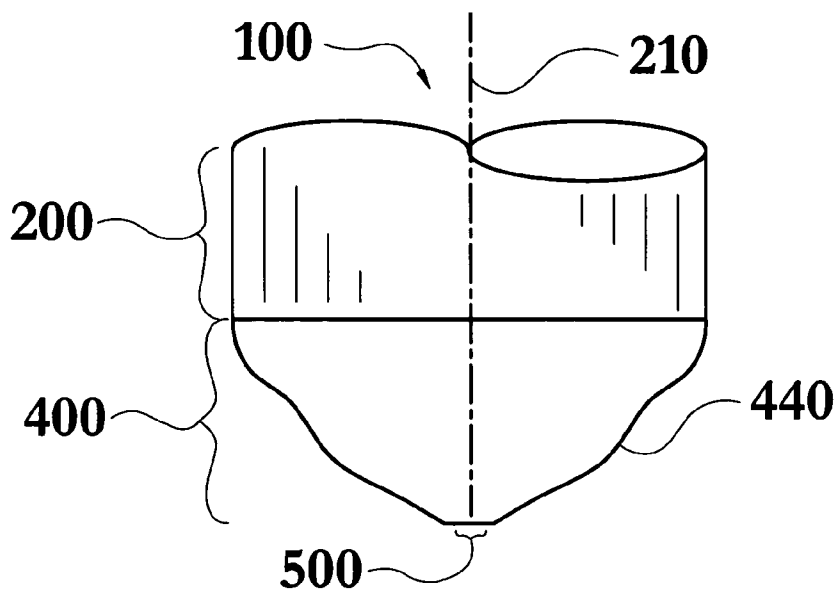
**FIG. 10**



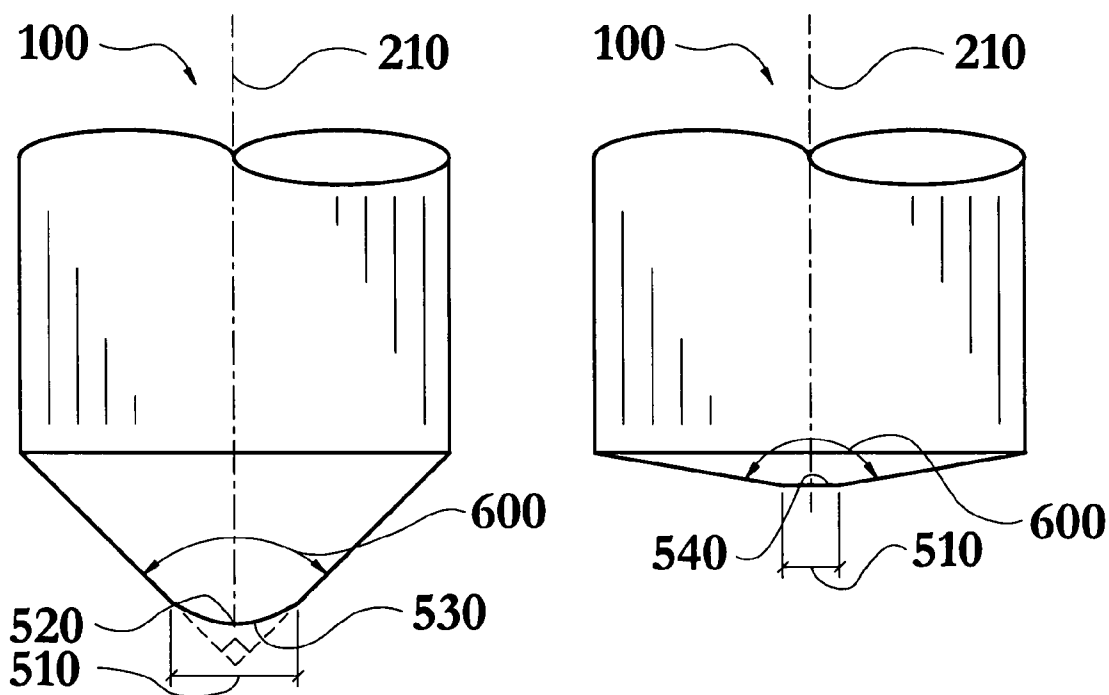
**FIG. 11**



**FIG. 12**

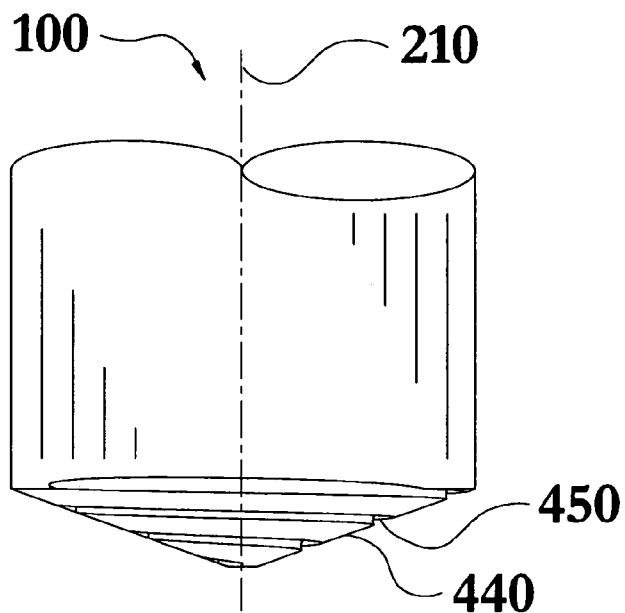


**FIG. 13**

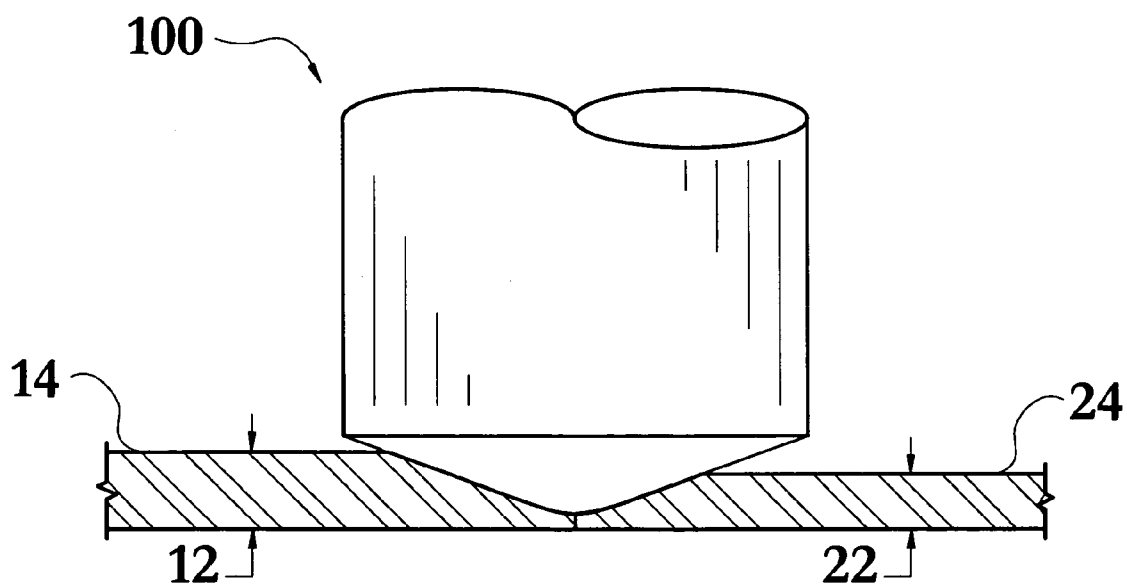


**FIG. 14**

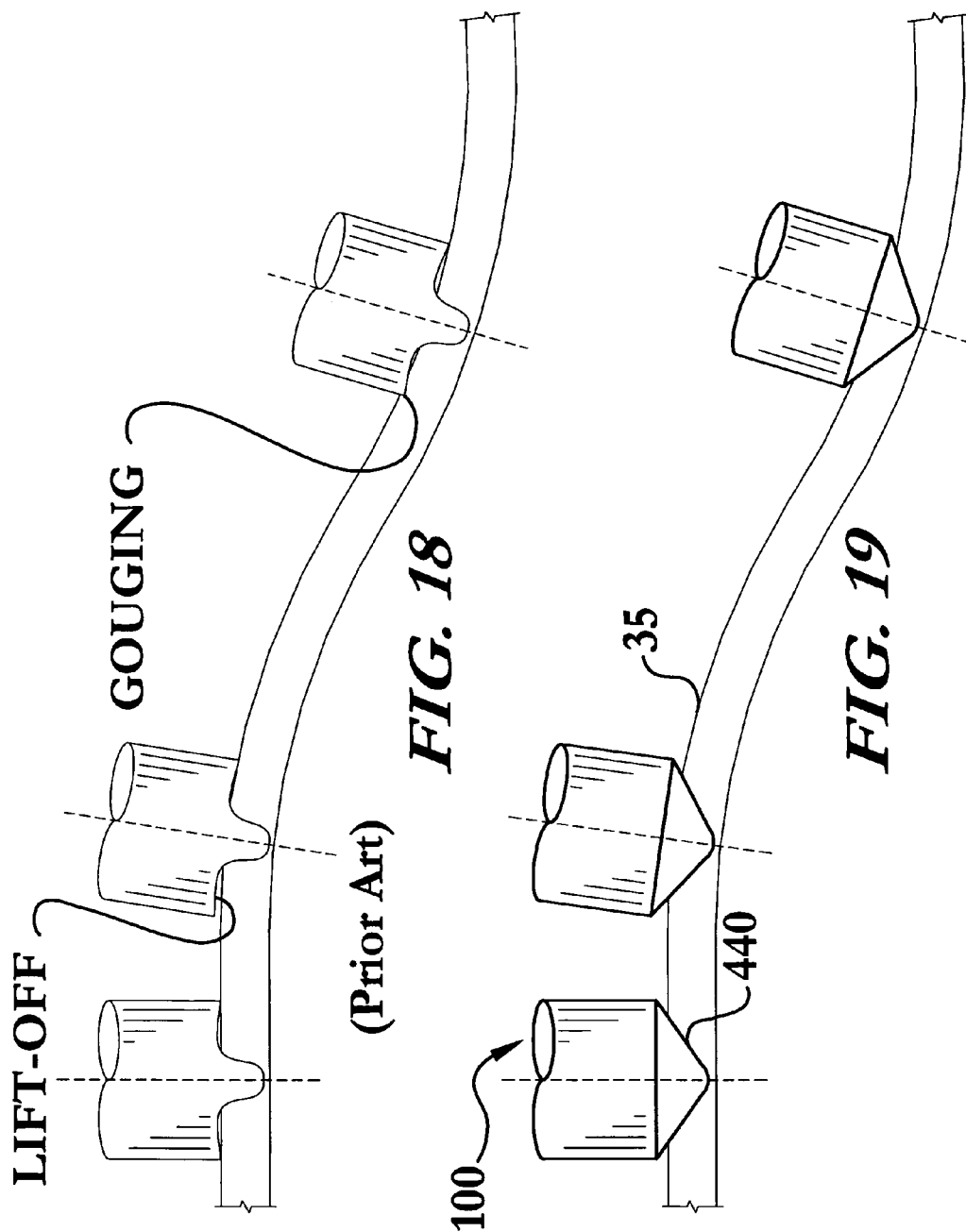
**FIG. 15**



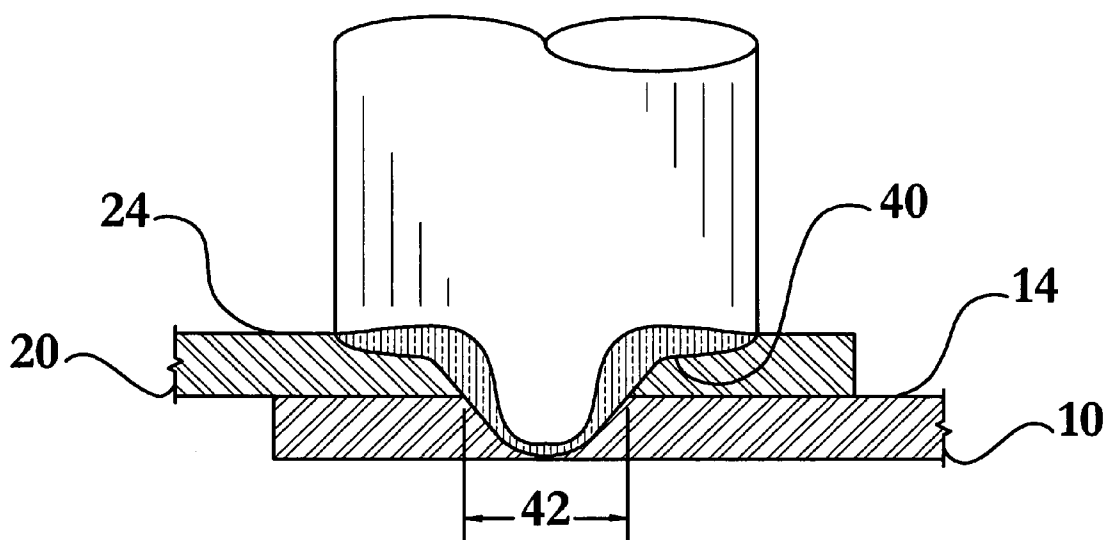
**FIG. 16**



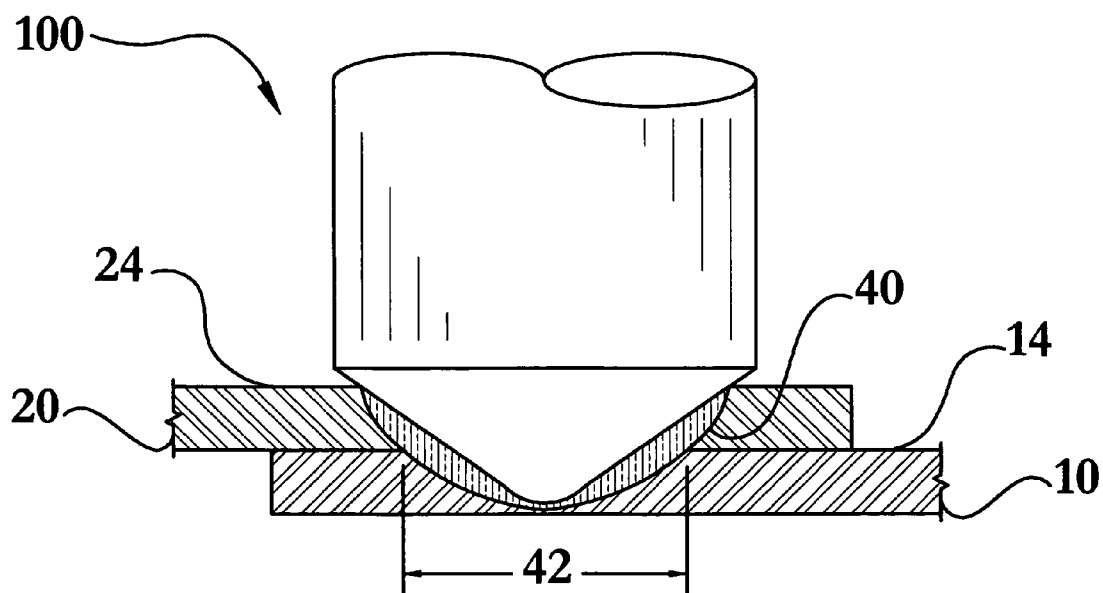
**FIG. 17**



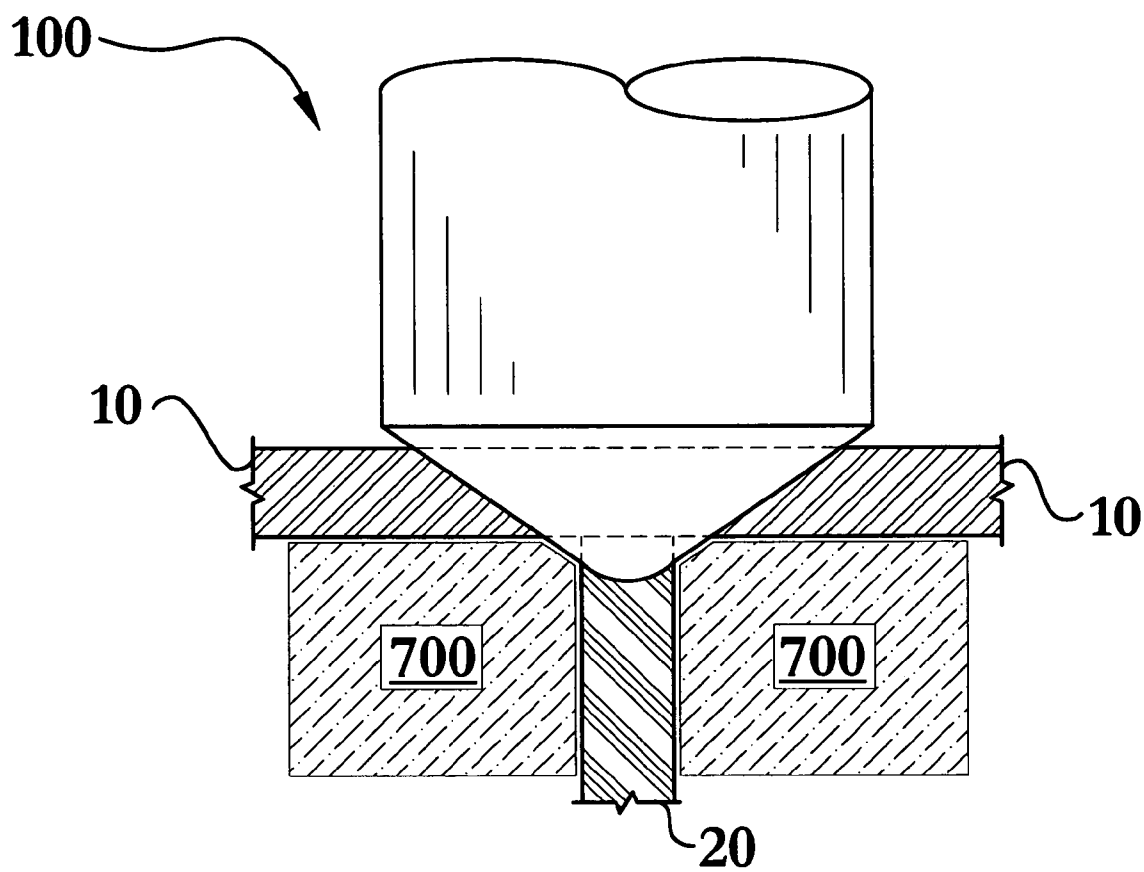




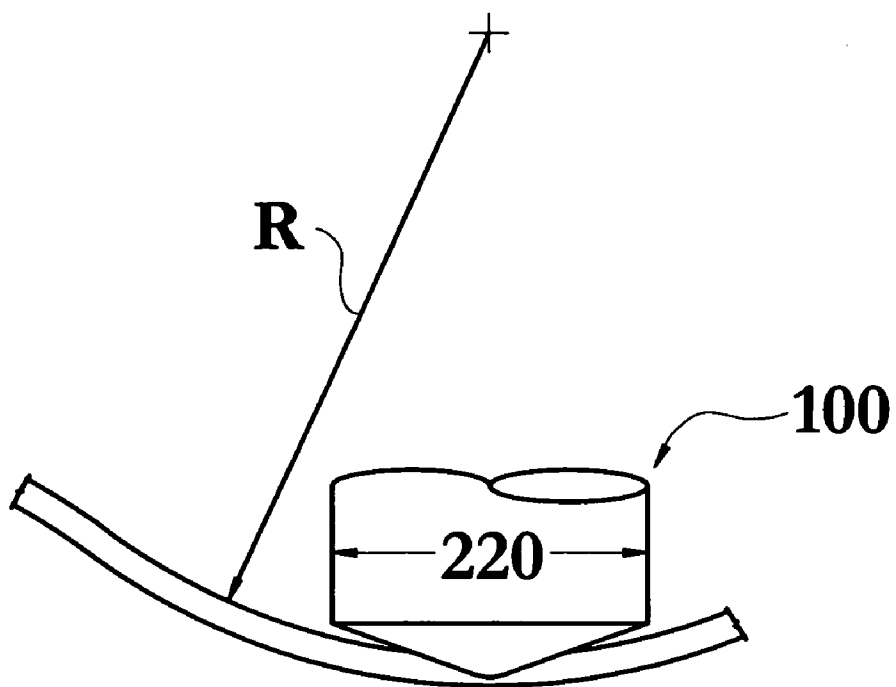
**FIG. 20**



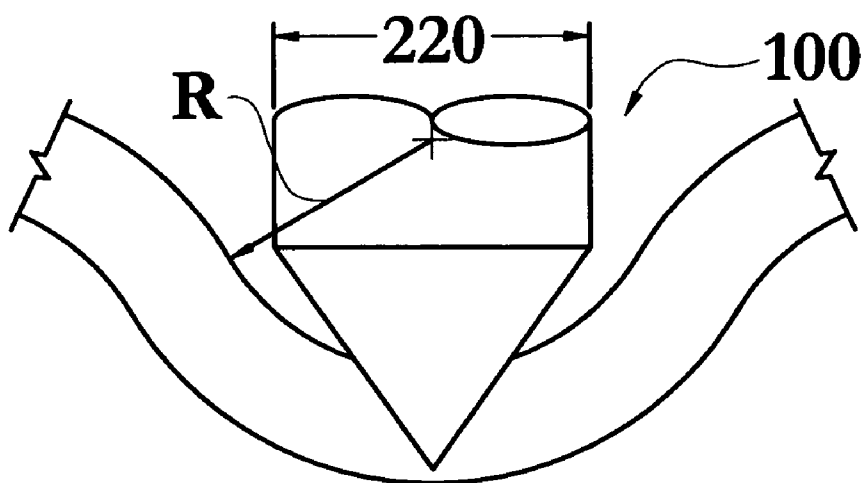
**FIG. 21**



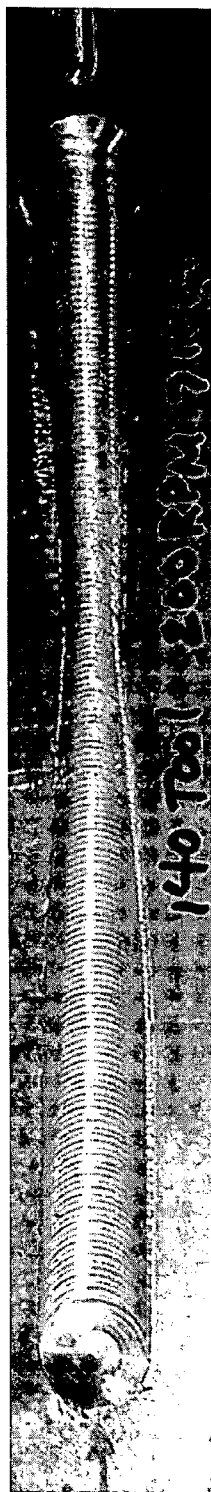
**FIG. 22**



**FIG. 23**



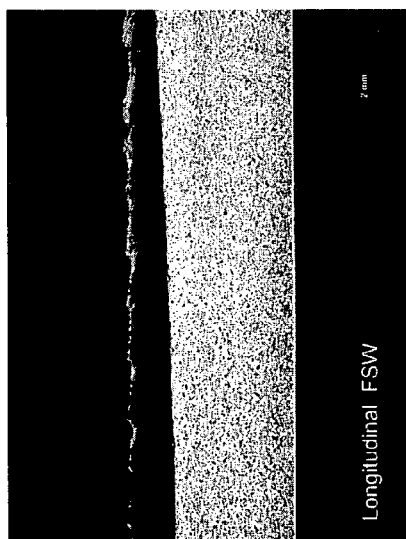
**FIG. 24**



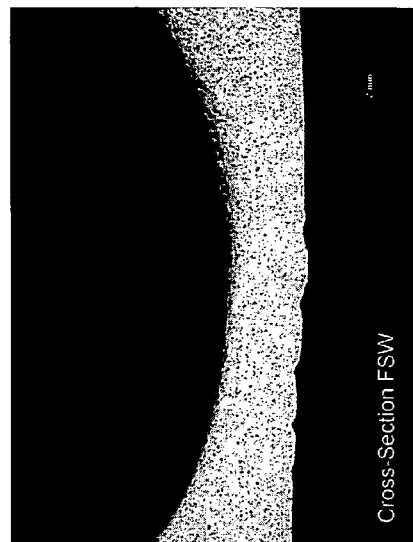
**FIG. 25**



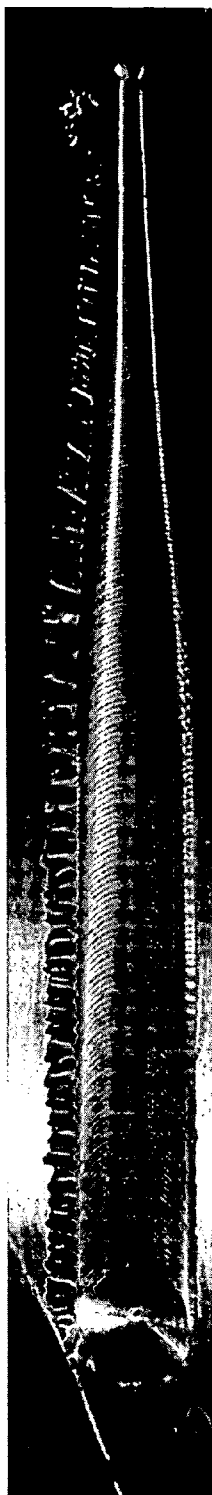
**FIG. 26**



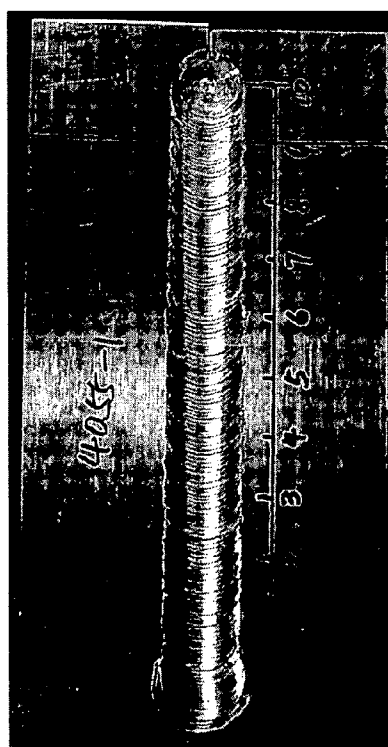
**FIG. 27**



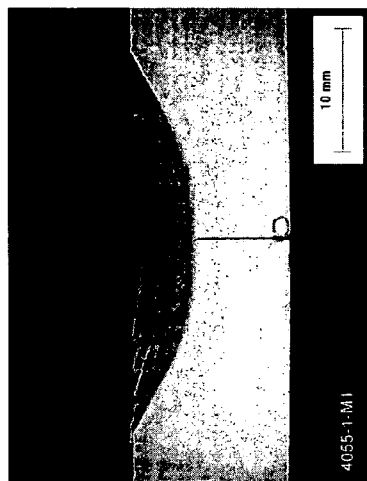
**FIG. 28**



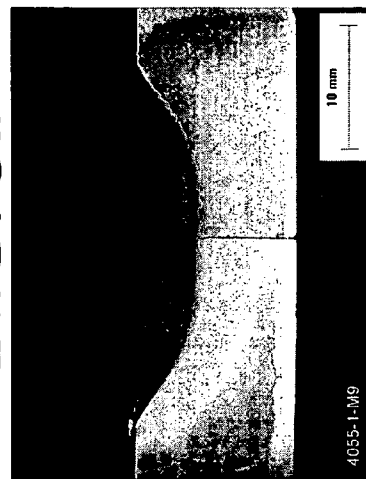
*FIG. 29*



*FIG. 30*



*FIG. 31*



*FIG. 32*

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**METHOD OF FRICTION STIR WELDING  
AND RETRACTABLE SHOULDERLESS  
VARIABLE PENETRATION FRICTION STIR  
WELDING TOOL FOR SAME**

STATEMENT REGARDING FEDERALLY  
SPONSORED RESEARCH OR DEVELOPMENT

This invention was not made as part of a federally sponsored research or development project.

TECHNICAL FIELD

The present invention relates to the field of friction stir welding; particularly, to a single piece non-consumable shoulderless friction stir welding tool and methods that can perform variable penetration welds, variable width welds, weld workpieces of differing thicknesses, weld workpieces having complex curvature, retract from the weld during welding without producing an exit hole, and improve the quality of friction stir welds.

BACKGROUND OF THE INVENTION

Those in the wide ranging materials joining industries have recognized the benefits of friction stir welding (FSW) since its invention, only to be precluded from widespread application due to a number of factors. FSW is a relatively simple method of solid phase welding developed by The Welding Institute in the early 1990's. The conventional process utilizes a specially shaped nonconsumable cylindrical tool with a profiled pin, often threaded, extending from a shoulder of the tool, that is rotated and plunged into a joint formed by abutting edges of the workpieces that are to be joined until a surface of the shoulder contacts the surface of the workpieces. The rotating tool plasticizes a region of the workpieces around the pin and beneath the shoulder. The tool is then advanced along the joint. The rotation of the tool develops frictional heating of the workpieces, from both shoulder friction and pin friction, as well as adiabatic heating, and the tool forces plasticized workpiece material from the leading edge of the tool to the rear of the tool where it consolidates and cools to form a high quality weld.

The FSW tool is generally a cylindrical piece with a shoulder face that meets a pin that projects from the shoulder face at a right angle, as illustrated in U.S. Pat. Nos. 5,460,317 and 6,029,879. In some instances, the pin actually moves in a perpendicular direction in an aperture formed in the face of the shoulder, as illustrated in U.S. Pat. Nos. 5,611,469, 5,697,544, and 6,053,391. The face of the shoulder may be formed with an upward dome that is perpendicular to the pin, as illustrated in U.S. Pat. Nos. 5,611,479, 5,697,544, and 6,053,391. The dome region and an unobstructed shoulder face to pin interface have been considered essential for the proper frictional heating of the workpiece material. Traditional thinking held that dome region of the shoulder serves to constrain plasticized material for consolidation at the trailing edge of the FSW tool so as to prevent it from extruding out from under the sides of the tool. For example, U.S. Pat. No. 5,813,592 states at column 1, lines 42-51, that "In order to achieve a proper consolidation of the weld metal the probe bottom part (shoulder) must maintain during the whole welding operation (forward movement) in an intimate contact with [the] surface of the joined members. If the probe shoulder during this forward movement even temporarily "lifts" from the surface a small amount of plasticised welding material will be expelled behind the

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probe thus causing occurrence of voids in the weld since there is no available material to fill the vacant space after the expelled material." The present invention proves this long-held belief false.

Since FSW is a solid-state process, meaning there is no melting of the materials, many of the problems associated with other fusion welding methods are avoided, including solidification cracking, shrinkage, and weld pool positioning and control. Additionally, FSW minimizes distortion and residual stresses. Further, since filler materials are not used in FSW, issues associated with chemical segregation are avoided. Still further, FSW has enabled the welding of a wide range of alloys that were previously unweldable. Yet another advantage of FSW is that it does not have many of the hazards associated with other welding means such as welding fumes, radiation, high voltage, liquid metals, or arcing. Additionally, FSW generally has only three process variables to control (rotation speed, travel speed, and pressure), whereas fusion welding often has at least twice the number of process variables (purge gas, voltage, amperage, wire feed speed, travel speed, shield gas, and arc gap, just to name a few). Perhaps most importantly, the crushing, stirring, and forging of the plasticized material by the FSW tool often produces a weld that is more reliable than conventional welds and maintains material properties more closely to those of the workpiece properties, often resulting in twice the fatigue resistance found in fusion welds.

Despite all the advantages of FSW, it has only found very limited commercial application to date due to many difficulties associated therewith. One early problem associated with single-piece FSW tools **90**, as seen in FIG. **1**, was that they leave an exit hole **80** in the weld **40**, as seen in FIG. **5**, that must be filled after completion of the friction stir weld. Such single-piece FSW tools **90** are also plagued with premature breakage of the pin **92** during welding, resulting in the pin **92** being permanently lodged in the weld **40**. Such breakage is often attributed to tool design that has relatively poor heat distribution and areas of high stress concentration, such as at the pin **92** to shoulder **91** interface, also known as the transition region **93**, seen in FIG. **1**. In an effort to eliminate exit holes **82** the retractable pin tool **95** was developed, as seen in FIG. **2**. The retractable pin tool **95** essentially splits the conventional shouldered FSW tool **90** into two separate components, namely a shoulder portion **96** that is hollow and receives the pin **97** that may extend and retract from the shoulder **96**. The independent movement of the pin **97** permits the pin **97** to be gradually withdrawn from the weld **40** while the shoulder **96** remains in contact with the workpieces **10**, **20**, thereby eliminating the exit hole **80**.

While the retractable pin tool **95** may eliminate the exit hole **82**, it has several drawbacks. The retractable pin tool **95** is prone to breakage due to the high stress concentrations at the shoulder **96** to pin **97** interface. The retractable pin tool **95** is also susceptible to binding between the pin **97** and the shoulder **96** as stirred weld metal can be forced into the gap between the pin **97** and the shoulder **96**.

Another problem with both conventional shouldered FSW tools **90** and retractable pin tools **95** is the overheating caused by the shoulder **91**, **96**. During FSW with conventional shouldered FSW tools **90**, **95** the weld **40** is repeatedly subjected to the pressure and rotation of the tool shoulder **91**, **96**. As a conventional FSW tool **90**, **95** traverses a joint **35** the material is first exposed to the leading edge of the shoulder **91**, **96** that is generally exerting a downward force on the workpieces **10**, **20** of several hundred pounds, often several thousand pounds, and is rotating at RPM's ranging from under 100 rpm to over 1000 rpm, while traversing the

joint 35 rather slowly, generally less than ten inches per minute (IPM), depending on the materials being joined and their thickness. Taking for example a simple illustrative case of a conventional tool 90, 95 traversing a joint 35 at 6 IPM and 800 RPM, it takes 10 seconds to traverse a one inch section of the joint 35 during which 80 revolutions of the tool 90, 95 are made, resulting in 160 exposures of weld 40 to the shoulder 91, 96 (an exposure at the leading edge and the trailing edge for each revolution). Such repeated exposure to the shoulder 91, 96 results in the overheating of the weld 40 and the associated drawbacks. Prior methods and apparatus have indicated that such top surface friction heating and weld material containment contributed by the shoulder were essential to FSW. In fact, the definition of friction stir welding in most welding references includes the mention of a tool having a pin and a shoulder, thus a tool lacking a shoulder, or a shoulderless tool, as in the present invention is a completely new concept.

Further, conventional shouldered FSW tools 90 and retractable pin tools 95 are generally ineffective at joining workpieces 10, 20 of different thickness, as seen in FIG. 6. This is due in large part to the fact that such tools 90, 95 are designed for a specific pin 92, 97 length for a particular material thickness. Such designs necessitate a unique tool for each thickness of material to be joined. The retractable pin tool 95 may reduce the number of tools needed to make welds in materials having differing thicknesses, but it too is limited in that each retractable pin tool 95 has a limited useful range established by the diameter of the shoulder. For instance, if the material is too thick or thin then underheating or over-heating will occur. Additionally, one can easily appreciate that the pin 97 of a retractable pin tool 95 designed for use in joining 1/8" thick sheets will be ineffective and will fail if it is simply further extended from the shoulder 96 in trying to join 1/2" thick plates.

Additionally, conventional shouldered FSW tools 90 and retractable pin tools 95 cannot be used in joining workpieces having more than slight curvature. Such tools 90, 95 provide inadequate contact, also referred to as lift-off, or result in gouging of the workpieces, as seen in FIG. 18. Such lift-off and gouging results in welds having reduced aesthetic qualities that often require grinding of the surface and diminish the mechanical properties of the weld.

Yet another problem associated with conventional shouldered FSW tools 90 and retractable pin tools 95 is the flow characteristics imparted on the weld material due to the transition region 93, labeled in FIG. 1, between the shoulder 91 and the pin 92. The transition region 93 in shouldered tools 90, 95 often causes dead zones and eddies in the material flow resulting in subsurface voids and lack of fusion in the weld 40. Such problems greatly limit the robustness of the conventional tools and methods, particularly on joints that vary in geometry or heat distribution due to part shape or tooling.

A friction stir weld 40 created with conventional shouldered FSW tools 90, 95 have several distinct regions, as seen in FIG. 3, where the direction of travel of the tool 90 is into the paper. First, the metal away from the immediate vicinity of the weld 40 that is not affected by the weld is known as the base metal 50. Closer to the actual weld 40 is the heat affected zone (HAZ) 60 where the material has experienced a thermal cycle that has modified the microstructure and/or mechanical properties, yet has no plastic deformation. Next, closer to the tool 90, 95 is the thermomechanically affected zone (TMAZ) 70 where the material has seen limited plastic deformation by the tool 90, 95, and the heat from the process has also exerted some influence on the material. With the

exception of aluminum, most materials exhibit recrystallization throughout the TMAZ 70. Aluminum often exhibits recrystallization in only a portion of the TMAZ, often referred to as the nugget. Within the TMAZ 70 is the stir zone 75, seen in FIG. 4, having non-uniform grain structure from the violent deformation that materials in this region undergo while hot. The stir zone 75 has a shoulder region 76 and a pin region 77. The pin region 77 is that region that has been directly exposed to the pin 92, whereas the shoulder region 76 is the region just outside of the pin region 77 and below the shoulder 91, 96 of the tool 90, 95. The shoulder region 76 flares out further away from the pin 92, 97 near the surface of the workpiece nearest the shoulder 91, 96, due to the effects of the shoulder 91, 96. This flared-out portion of the shoulder region 76, or re-stir area, near the surface of the weld 40 is the area most commonly exposed to overheating and the associated annealing and overageing effects that reduce the weld properties.

Additionally, the design of conventional shouldered FSW tools 90, 95 are prone to excessive wear and poor heat and load distribution. These problems are largely attributable to the longstanding belief that FSW tools must have a relatively narrow pin and wide shoulder.

Accordingly, the art has needed a tool, and associated methods, that eliminate the need for a shoulder and thereby eliminate the multitude of problems associated with the shoulder. An ideal tool would be simple in design and construction; inexpensive; allow for retractability during welding thereby eliminating the exit hole; accommodate joining materials of differing thicknesses; facilitate variable penetration depth; improve weld quality by reducing internal voids and lack of fusion; and eliminate the re-stir area of the stir region. While some of the prior art devices attempted to improve the state of the art, none has achieved the unique and novel configurations and capabilities of the present invention. With these capabilities taken into consideration, the instant invention addresses many of the shortcomings of the prior art and offers significant benefits heretofore unavailable. Further, none of the above inventions and patents, taken either singly or in combination, is seen to describe the instant invention as claimed.

#### SUMMARY OF INVENTION

In its most general configuration, the present invention advances the state of the art with a variety of new capabilities and overcomes many of the shortcomings of prior methods in new and novel ways. In its most general sense, the present invention overcomes the shortcomings and limitations of the prior art in any of a number of generally effective configurations.

In one of the many preferable configurations, the non-consumable retractable shoulderless variable penetration friction stir welding tool includes a substantially cylindrical body portion, a head portion, and a tip section, each integral to the tool. The body portion has a longitudinal axis about which it is rotatable, a diameter, a sidewall substantially parallel to the longitudinal axis, a proximal end, and a distal end.

The head portion has a base with a diameter substantially equal to the diameter of the body portion, thereby forming a transition between the body portion and the head portion. The head portion includes a face that converges to the tip section. The transition from the body portion to the head portion is smooth in that it is uninterrupted by a shoulder or other projection. This lack of a shoulder has numerous advantages that have long been overlooked by those in the

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FSW industry. Prior methods and apparatus have indicated that top surface friction heating and weld material containment were essential to FSW.

The present invention's elimination of any portion of the tool that contacts the top surface of either workpiece away from the point at which the tool enters the workpiece(s) has several advantages. One such advantage is the elimination of the primary source of overheating. Additionally, another advantage of the present tool is the reduction of internal voids and lack of fusion that are associated with the transition region between the shoulder and the pin, as well as the transition from the pin to the pin tip. Further, the present design allows the use of a single tool in performing welds of varying depth and/or width, performing welds to join workpieces having differing thicknesses, performing welds to join workpieces having complex curvatures, and in retracting the tool to leave a weld free of an exit hole.

Numerous variations, modifications, alternatives, and alterations of the various preferred embodiments, processes, and methods may be used alone or in combination with one another as will become more readily apparent to those with skill in the art with reference to the following detailed description of the preferred embodiments and the accompanying figures and drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Without limiting the scope of the present invention as claimed below and referring now to the drawings and figures:

FIG. 1 shows a cross-section of a typical conventional shouldered FSW tool, not to scale;

FIG. 2 shows a cross-section of a typical conventional shouldered retractable pin tool, not to scale;

FIG. 3 shows a cross-section of a first workpiece and a second workpiece as they are joined by FSW, not to scale;

FIG. 4 shows an enlarged cross-section of a portion of FIG. 3, not to scale;

FIG. 5 shows an elevated perspective view of a first and second workpiece being joined by FSW and the associated exit hole left by conventional shouldered FSW tools, not to scale;

FIG. 6 shows a cross-section of a typical conventional shouldered FSW tool and a first and second workpiece of differing thicknesses, not to scale;

FIG. 7 shows a front elevation view of an embodiment of the tool of the present invention, not to scale;

FIG. 8 shows a partial cross-section of a joint with the tool of FIG. 7 joining a first and a second workpiece by FSW, not to scale;

FIG. 9 shows a first and a second workpiece configured in a lap joint, not to scale;

FIG. 10 shows a first and a second workpiece configured in butt joint arrangement with a third workpiece below to be joined by a lap joint;

FIG. 11 shows a partial cross-section of a joint with an embodiment of the tool of FIG. 7 joining a first and a second workpiece by FSW, not to scale;

FIG. 12 shows a partial cross-section of an embodiment of the tool of the present invention as it traverses a joint from left to right while changing from a first penetration depth to a second penetration depth and then is retracted from the workpieces, not to scale;

FIG. 13 shows a front elevation view of an embodiment of the tool of FIG. 7, not to scale;

FIG. 14 shows a front elevation view of an embodiment of the tool of FIG. 7, not to scale;

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FIG. 15 shows a front elevation view of an embodiment of the tool of FIG. 7, not to scale;

FIG. 16 shows a front elevation view of an embodiment of the tool of FIG. 7, not to scale;

FIG. 17 shows a partial cross-section of a joint with the tool of FIG. 7 joining a first and a second workpiece of differing thicknesses by FSW, not to scale;

FIG. 18 shows a partial cross-section of typical conventional shouldered FSW tool traversing an undulating joint, not to scale;

FIG. 19 shows a partial cross-section of one embodiment of the tool of FIG. 7 traversing an undulating joint, not to scale;

FIG. 20 shows a partial cross-section of a first and a second workpiece configured in a lap joint being welded by a typical conventional shouldered FSW tool, not to scale;

FIG. 21 shows a partial cross-section of a first and a second workpiece configured in a lap joint being welded by an embodiment of the present invention, not to scale;

FIG. 22 shows a partial cross-section of a first and a second workpiece configured in tee joint arrangement being welded by an embodiment of the present invention, not to scale;

FIG. 23 shows a partial cross-section of one embodiment of the tool traversing an undulating joint, not to scale;

FIG. 24 shows a partial cross-section of one embodiment of the tool traversing an undulating joint, not to scale;

FIG. 25 is a photograph in top plan view, not to scale, of a weld made using the tool and method of the present invention;

FIG. 26 is a photograph in top plan view, not to scale, of a weld made using the tool and method of the present invention;

FIG. 27 is a cross-section taken along section lines A-A in FIG. 26, not to scale;

FIG. 28 is a cross-section taken along section lines B-B in FIG. 26, not to scale;

FIG. 29 is a photograph in top plan view, not to scale, of a weld made using the tool and method of the present invention;

FIG. 30 is a photograph in top plan view, not to scale, of a weld made using the tool and method of the present invention;

FIG. 31 is a cross-section taken along the one inch line in FIG. 30, not to scale; and

FIG. 32 is a cross-section taken along the nine inch line in FIG. 30, not to scale.

#### DETAILED DESCRIPTION OF THE INVENTION

The non-consumable retractable shoulderless variable penetration friction stir welding tool and methods of friction stir welding of the present invention enable a significant advance in the state of the art. The preferred embodiments of the method and apparatus accomplish this by new and novel methods that are configured in unique and novel ways and which demonstrate previously unavailable but preferred and desirable capabilities. The description set forth below in connection with the drawings is intended merely as a description of the presently preferred embodiments of the invention, and is not intended to represent the only form in which the present invention may be constructed or utilized. The description sets forth the designs, functions, means, and methods of implementing the invention in connection with the illustrated embodiments. It is to be understood, however, that the same or equivalent functions and features may be



accomplished by different embodiments that are also intended to be encompassed within the spirit and scope of the invention.

The present invention includes several methods of friction stir welding (FSW) and a non-consumable retractable shoulderless variable penetration friction stir welding tool **100** for performing the methods. The non-consumable retractable shoulderless variable penetration friction stir welding tool **100** is used in joining a first workpiece **10** and a second workpiece **20** with a friction stir weld **40**. The tool **100** includes a substantially cylindrical body portion **200**, a head portion **400**, and a tip section **500**, each integral to the tool **100**, as seen in FIG. 7. The body portion **200** has a longitudinal axis **210** about which it is rotatable, a diameter **220**, a sidewall **230** substantially parallel to the longitudinal axis **210**, a proximal end **240**, and a distal end **250**.

The first workpiece **10** has a first thickness **12** and a top surface **14**. Similarly, the second workpiece **20** has a second thickness **22** and a top surface **24**, as seen in FIG. 8. The tool **100** and methods of the present invention work equally as well on butt joints, as seen in FIG. 5; lap joints, as seen in FIG. 9; combination butt and lap joints, as seen in FIG. 10; tee joints, as seen in FIG. 22; corner joints, not illustrated but understood by one with skill in the art; as well as bead on plate welds to alter the local characteristics of a plate due to friction stir processing of the material with the tool.

Referring again to FIG. 7, the head portion **400** is located at the distal end **250** of the body portion **200**. The head portion **400** has a base **410** with a diameter **420** substantially equal to the diameter **220** of the body portion **200** thereby forming a transition **300** between the body portion **200** and the head portion **400**. The head portion **400** includes a face **440** that converges to the tip section **500**. The tip section **500** has a diameter **510** and a center **520** wherein the center **520** is located substantially on the longitudinal axis **210**, illustrated in FIGS. 14 and 15. Referring again to FIG. 7, the head portion **400** and the tip section **500** define a height **430** from the distal-most portion of the tip section **500** to the base **410** along the longitudinal axis **210**. The transition **300** from the body portion **200** to the head portion **400** is smooth in that it is uninterrupted by a shoulder or other projection. The transition **300** may incorporate a smooth curve between the body portion **200** and the head portion **400**, but it is not required.

The substantially equal diameters **220**, **420** of the body portion **200** and the head portion **400**, along with the transition **300** therebetween, establish that the present invention lacks a shoulder as is present in prior art friction stir welding tools **90**, **95**, as seen in FIGS. 1 and 2. This lack of a shoulder has numerous advantages that have long been overlooked by those in the FSW industry.

The shoulder **91**, **96** of conventional shouldered FSW tools **90** as well as retractable pin tools **95**, as seen in FIGS. 1 and 2, is the source of many problems and confusion in FSW, which have been previously explained in the Background of the Invention herein. In short, the present tool **100** does not require a shoulder **91**, **96** to retain the plasticized material of the FSW, contrary to the teachings of the leaders in the field. Referring to FIG. 11, the present invention's elimination of any portion of the tool **100** that contacts the top surface **14**, **24** of either workpieces **10**, **20** away from the point at which the tool enters the workpiece(s) **10**, **20** has several advantages.

One such advantage is the elimination of the primary source of overheating. Referring again to FIGS. 1-3, during FSW with prior shouldered FSW tools, the weld **40** is repeatedly subjected to the pressure and rotation of the tool

shoulder **91**, **96**. As a conventional FSW tool **90**, **95** traverses a joint **35** the material is first exposed to the leading edge of the shoulder **91**, **96** that is generally exerting a downward force on the workpieces **10**, **20** of several hundred pounds, often several thousand pounds, and is rotating at several hundred RPM, while traversing the joint rather slowly, generally less than ten inches per minute (IPM). One with skill in the art will understand that such characteristics are dependent on a number of factors including the material being joined and its thickness. Taking, for example, a simple illustrative case of a conventional tool **90**, **95** traversing a joint **35** at 6 IPM and 800 RPM, it takes 10 seconds to traverse a one inch section of the joint **35** during which 80 revolutions of the tool **90**, **95** are made, resulting in 160 exposures of weld **40** to the shoulder **91**, **96** (an exposure at the leading edge and the trailing edge of each revolution). Such repeated exposure to the shoulder **91**, **96** results in the overheating of the weld **40** and the associated drawbacks, as previously explained. The present invention includes a method of reducing the amount of overheating experienced by a friction stir weld **40** by ensuring that while traversing the joint **35** with the rotating tool **100**, no portion of the tool **100**, away from the entry penetration of the tool **100** into the workpieces **10**, **20**, comes in contact with the top surface **14**, **24** of either workpiece **10**, **20**. Prior methods and apparatus have indicated that such top surface friction heating and weld material containment were essential to FSW.

Another advantage of the present tool **100** and methods is the reduction of internal voids and lack of fusion that are associated with the transition region **93**, labeled in FIG. 1, between the shoulder **91**, **96** and the pin **92**, **97** of traditional friction stir welding tools **90**, **95**. As previously discussed in the Background of the Invention herein, the transition region **93** between the shoulder **91**, **96** and the pin **92**, **97** is the source of many problems in tool design and affects the characteristics of the resulting weld. Such problems are particularly pronounced in conventional retractable pin tools **95**, illustrated in FIG. 2, because the transition region changes as the pin **97** enters the workpieces **10**, **20** or retracts from the workpieces **10**, **20**.

Yet another advantage of the present non-consumable retractable shoulderless variable penetration tool **100** and methods of the present invention is that the elimination of a shoulder **91**, or similar projection, allows the use of a single tool **100** in performing welds **40** of varying depth, performing welds **40** to join workpieces having differing thicknesses, and in retracting the tool **100** to leave a weld **40** free of an exit hole **80**, as seen in FIG. 5. Conventional single-piece shouldered FSW tools **90**, as seen in FIG. 1, have a fixed pin length projecting from the shoulder **91** and therefore are limited to performing welds of a single penetration depth. The present tool **100** is designed such that the height **430** of the head portion **400** may be (i) less than or equal to the lesser of the first workpiece thickness **12** or the second workpiece thickness **22** such that the entire tip section **500**, head portion **400**, and a portion of the body portion **200** are in the friction stir weld **40** during welding, as seen in FIG. 8 or alternatively (ii) greater than or equal to the greater of the first workpiece thickness **12** or the second workpiece thickness **22** such that the entire tip section **500** and a portion of the head portion **400** are in the friction stir weld **40** during welding, as seen in FIG. 11. This ability to submerge a portion of the body portion **200** into the weld **40** permits use of the tool **100** in creating spot welds. Additionally, the tool **100** permits the joining of a first workpiece **10** and a second workpiece **20** wherein they have unequal thicknesses **12**, **14**, as shown in FIG. 17.

Along with the ability to perform ability to perform variable depth welds comes the ability to vary the width of the welds. As one with skill in the art can appreciate, the further the tool **100** of the present invention penetrates into the joint **35** the wider the weld **40** becomes. This, along with the ability of the present invention to be plunged into the joint **35** as it is traversing the joint **35**, permits the economical use of friction stir welding in performing tack welds. Such tack welds are particularly useful in holding parts in the tooling.

Additionally, one with skill in the art can appreciate that cooperating tools may be used in creating full penetration welds in thicker workpieces with one tool penetrating half way into the joint from one side of the joint and the second tool penetrating half way into the joint from the opposite side of the joint.

The shoulderless design of the present tool **100** permits the friction stir welding of workpieces **10**, **20** having significant curvature. In the past conventional shouldered friction stir welding tools **90**, **95** have not been able to join workpieces **10**, **20** having more than slight undulation because of shoulder **91**, **96** interference. As seen in FIG. **18**, while traversing down a slope the shoulder **91**, **96** of conventional tools **90**, **95** would lift-off, or separate from the joint **35**, at either the leading edge of the shoulder **91**, **96** or the trailing edge of the shoulder **91**, **96** depending on the motion control system. Alternatively, while traversing down into a valley or up from a valley, the shoulder **91**, **96** of conventional tools **90**, **95** would gouge into the joint at either the trailing edge of the shoulder **91**, **96** or the leading edge of the shoulder **91**, **96** depending on the motion control system. Such lift-off and gouging results in welds having reduced aesthetic qualities that often require grinding of the surface and diminish the mechanical properties of the weld.

FIG. **19** illustrates how the present tool **100** eliminates such gouging and lift-off problems and permits the joining of workpieces **10**, **20** having aggressive curvature. Selecting a tool **100** of the present design such that a portion of the head portion **400**, and therefore a portion of the face **440**, does not penetrate the joint **35** when joining a flat portion of the workpieces **10**, **20** ensures that the body portion **200** to head portion **400** interface, or transition **300**, does not gouge the joint **35**, while the face **440** remains in contact with the joint at both the leading and trailing edges of the tool **100**. The curve of FIG. **19** is rather gradual, yet illustrates the point. The tool **100** of the present invention may be utilized in joining workpieces having complimentary curves that are much more severe. In fact, the present tool **100** may be used in configurations where the radius **R** of the at least one cooperating curve is less than approximately two times the diameter **220** of the body portion **200** and greater than one-half the diameter **220** of the body portion **200**. The present tool **100** is illustrated in FIG. **23**, with an opening angle **600** of 140 degrees, traversing a curve with a radius **R** equal to twice the diameter **220** of the body portion **200**. Similarly, a tool **100** with an opening angle **600** of 70 degrees is shown in FIG. **24** traversing a curve with a radius **R** equal to approximately seventy-five percent of the diameter **220** of the body portion **200**.

Still further, another advantage of the present tool **100** is that it produces wider welds **40** than those produced by conventional shouldered friction stir welding tools **90**, **95** of the same exterior diameter. FIGS. **20** and **21** illustrate that the lap joint weld width **42**, being the width of the weld **40** at the interface between the first and second workpieces **10**, **20**, is much greater when using a tool **100** of the present invention, as seen in FIG. **21**, than when using a conven-

tional tool, as seen in FIG. **20**. The improved weld width **42** is a result of the relatively flat head portion **400**, when compared to prior art shouldered tools **90**, **95**, and results in more bonded area between the first and second workpieces **10**, **20**, and thus a higher load capacity.

The relatively flat head portion **400** is also beneficial when performing welds along tee joints, as seen in FIG. **22**, and along corner joints. The large opening angle **600** of the tool **100** results in greater, and more complete, mixing of material between the first and second workpieces **10**, **20**. Additionally, the backing tool **700** may be selected to match the opening angle **600** of the tool **100** so that the face **400** may be parallel to an edge of the backing tool **700** and either touch the backing tool **700** or come into close proximity thereto, thereby minimizing or eliminating the potential for dead zones. Further, such a configuration has the additional benefit of aiding in the root side fillet/chamfer formation.

Further, the design of the present invention, namely the shoulderless transition **300** from the head portion **400** to the body portion **200**, allows the weld penetration depth to change on the fly. For instance, the tool **100** may first be plunged into the workpiece(s) **10**, **20** to a first penetration depth **82** and travel for a particular distance (left to right) before further extending, or retracting, into the workpiece(s) **10**, **20** to a second penetration depth **84**, as seen in FIG. **12**. It is important to note that the present tool **100** is capable of entering the joint **35** as it is moving along the joint **35**, and need not be first plunged to a particular depth and then traversed, as with prior tools. For instance, the far left tool **100** of FIG. **12** could have started its descent to the second position from the top surface rather than an initial depth. This can be particularly advantageous in welding lap joints, as seen in FIG. **9**, and combination butt and lap joints, as seen in FIG. **10**. It is significant to note that the tool **100** of the present invention is capable of plunging into the joint **35** as it is moving along the joint **35**, it need not be first plunged into a joint **35** and then moved along the joint **35**. Therefore, when joining the elements of FIG. **10** the tool **100** would first enter the joint **35** between the first and second workpieces **10**, **20** to a first depth and then penetrate to a deeper depth in the vicinity of the third workpiece **30** so as to not only join the first workpiece **10** to the second workpiece **20** but to also join each of them to the third workpiece **30**. Such adaptability is not found in the prior art tools.

As previously expressed, the head portion **400** includes a face **440** that converges to the tip section **500**. This convergence may be in any manner and need not be uniform or continuous, as seen in FIG. **13**. In one embodiment, the head portion **400** is substantially frustoconical in shape with the face **440** converging to the tip section **500** at an opening angle **600**, as seen in FIGS. **14** and **15**. The opening angle **600** may be virtually any angle but the range of between approximately 70 degrees and approximately 160 degrees, illustrated in FIG. **15**, has been found to be effective, with the range of approximately 100 degrees and 140 degrees even more preferred. An opening angle **600** of 90 degrees is illustrated in FIG. **14**. The relatively flat head portion **400** and tip section **500** of the present invention also flies in the face of traditional FSW teachings.

In one embodiment the tip section **500** is a flat shape **540**, as seen in FIGS. **7** and **15**. Alternatively the tip section **500** may be a curved shape **530**, as seen in FIGS. **14** and **11**. Still further, the tip section **500** may be pyramidal in shape, or virtually any other shape imaginable. Since the head portion **400** converges to the tip section **500** there will always be tip section diameter **510** at the interface between the tip section **500** and head portion **400**, as seen in FIGS. **14** and **15**. It is

at the tip section diameter **510** that the tip section **500** transitions to the head portion **400**. In one embodiment the tip diameter **510** is less than approximately forty percent of the body portion diameter **220** or the head portion diameter **420**. Such an aggressive convergence is unlike prior FSW tools. In some embodiments the tip section **500** continues to converge at the same angle as the head portion **400** and is therefore indistinguishable from the head portion **400**, as in the case of a simple cone seen in FIG. **24**.

The face **440** of the head portion **400** and the sidewall **230** of the body portion **230** may be substantially smooth or contain friction and/or plunge control features. For instance, in one embodiment the face **440** of the head portion **400** is formed with at least one recess **450**, as seen in FIG. **16**, to aid in heat generation; stirring of the weld **40**; reduction of surface flash formation; and improved stability of the tool **100** during the plunge. Alternatively, the face **440** may include projections extending from the face **440** such as threads or stipples, as disclosed in the prior art.

The present tool **100** also eliminates the points of high stress concentration present in conventional prior art shouldered tools **90**, **95**. Typically the pin **92**, **97** of conventional prior art shouldered tools **90**, **95** is approximately one-third the diameter of the overall tool diameter, as seen in FIGS. **1** and **2**. This change in diameter occurs at the shoulder **91**, **96** and is a point of particularly high stress in the pin **92**, **97**. Obviously, the present design seen in FIG. **11** does not contain such points of high stress concentration. Further, the useful life of a tool **100** of the present design is significantly greater than that of conventional prior art shouldered tools **90**, **95**.

FIGS. **25-29** illustrate welds made using the tool and methods of the present invention on 0.125" thick **7075** aluminum. The direction of travel of the tool when performing the illustrated welds was from right to left. First, FIG. **25** illustrates a variable-depth variable-width weld having a reduced depth and width near the middle of the weld traverse and a weld produced having no exit hole. Next, FIG. **26** illustrates a weld where the tool was gradually tapered out of the joint during the last one-third of the traverse leaving no exit hole. The section line labeled section A-A in FIG. **26** is shown in FIG. **27** and illustrates the changing depth of the weld. Further, FIG. **28** is a cross-section taken along section line B-B in FIG. **26** showing no internal voids or lack of fusion, as other leaders in the field would expect from such a tool and method. Further, FIG. **29** illustrates a weld produced with the tool gradually entering into the joint as it traverses the joint, rather than the conventional approach of first plunging the tool to the desired depth and then traversing the joint. Lastly, FIGS. **30-32** illustrate a constant penetration constant width weld traversing from left to right in FIG. **30**. The weld was produced with the tool rotating at 135 rpm, traversing the joint at 2.2 inches per minute, and having a penetration depth of 0.170 inches. A cross-section taken along the one inch marker line in FIG. **30** is shown in FIG. **31** and one taken along nine inch marker line is shown in FIG. **32**, both cross-sections being free of internal voids and lack of fusion. Cross-sections in FIGS. **28**, **31**, and **32** show no evidence of re-stir, discussed above, near the surface of the weld **40** commonly characterized by overheating and the associated annealing and overageing effects that reduce weld properties.

While the disclosure herein refers generally to a first workpiece **10** and a second workpiece **20**, the present invention may be used in joining more than just two workpieces or in the repair of a single workpiece. For example, the tool and methods of the present invention may be used

in friction stir processing of a single workpiece to improve its properties. Numerous alterations, modifications, and variations of the preferred embodiments disclosed herein will be apparent to those skilled in the art and they are all anticipated and contemplated to be within the spirit and scope of the instant invention. For example, although specific embodiments have been described in detail, those with skill in the art will understand that the preceding embodiments and variations can be modified to incorporate various types of substitute and or additional or alternative materials, relative arrangement of elements, and dimensional configurations. Accordingly, even though only few variations of the present invention are described herein, it is to be understood that the practice of such additional modifications and variations and the equivalents thereof, are within the spirit and scope of the invention as defined in the following claims. The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or acts for performing the functions in combination with other claimed elements as specifically claimed.

We claim:

**1.** A method for creating a friction stir weld free of an exit hole thereby joining a first workpiece, having a first thickness, and a second workpiece, having a second thickness, without using a conventional shouldered retractable pin tool and reducing the amount of overheating, comprising the steps of:

plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into a joint to be welded wherein the tool comprises a substantially cylindrical body portion, a head portion, and a tip section, each integral to the tool, the body portion having a longitudinal axis about which it is rotatable, a diameter, a sidewall substantially parallel to the longitudinal axis, a proximal end, and a distal end, the head portion located at the distal end of the body portion having a base with a diameter substantially equal to the diameter of the body portion forming a smooth transition between the body portion and the head portion, a face that converges to the tip section having a diameter and a center wherein the center is located substantially on the longitudinal axis, a height from the distal-most portion of the tip section to the base along the longitudinal axis;

traversing the joint with the rotating tool ensuring that no portion of the tool, away from the entry penetration of the tool into the workpieces, comes in contact with the top surface of either workpiece; and

gradually retracting the portion of the rotating tool from the workpieces while traversing the joint so that the tool exits the workpieces at a predetermined exit point leaving a friction stir weld free of an exit hole.

**2.** The method of claim **1**, wherein the step of plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into a joint consists of gradually forcing the tool into the joint while traversing the joint.

**3.** The method of claim **1**, wherein the portion of the rotating non-consumable shoulderless variable penetration friction stir welding tool that is plunged into the joint is a portion of the head portion such that a portion of the face is within the first and second workpieces and a portion of the face is outside the first and second workpieces.

**4.** The method of claim **1**, wherein the portion of the rotating non-consumable shoulderless variable penetration

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friction stir welding tool that is plunged into the joint includes the entire tip section, head portion, and a portion of the body portion.

5. The method of claim 1, wherein the head portion is substantially frustoconical in shape with the face converging to the tip section at an opening angle.

6. The method of claim 5, wherein the opening angle is between approximately 70 degrees and approximately 160 degrees.

7. The method of claim 1, wherein the thickness of the first workpiece and the thickness of the second workpiece are unequal.

8. The method of claim 1, wherein the tip diameter is less than approximately forty percent of the body portion diameter or the head portion diameter.

9. A method for improving the quality of a friction stir weld by reducing internal voids and lack of fusion, characteristic of the transition region between the shoulder and the pin of traditional friction stir welding tools, during the joining of a first workpiece, having a first thickness and a top surface, and a second workpiece, having a second thickness and a top surface, comprising the steps of:

plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into a joint to be welded, the tool having no projections substantially orthogonal to a longitudinal axis of the tool or substantially parallel to the top surfaces of the first or second workpieces such that no portion of the tool, away from the entry penetration of the tool into the workpieces, comes in contact with the top surface of either workpiece, the tool comprising a substantially cylindrical body portion, a head portion, and a tip section, each integral to the tool, the body portion having a longitudinal axis about which it is rotatable, a diameter, a sidewall substantially parallel to the longitudinal axis, a proximal end, and a distal end, the head portion located at the distal end of the body portion having a base with a diameter substantially equal to the diameter of the body portion forming a smooth transition between the body portion and the head portion, a face that converges to the tip section having a diameter and a center wherein the center is located substantially on the longitudinal axis, a height from the distal-most portion of the tip section to the base along the longitudinal axis, wherein the lack of projections reduces dead zones, eddies, internal voids, and lack of fusion in the weld;

traversing the joint with the rotating tool; and

gradually retracting the portion of the rotating tool from the joint while traversing the joint so that the tool exits the joint at a predetermined exit point leaving a friction stir weld free of an exit hole.

10. The method of claim 9, wherein the step of plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into a joint consists of gradually forcing the tool into the joint while traversing the joint.

11. The method of claim 9, wherein the portion of the rotating non-consumable shoulderless variable penetration friction stir welding tool that is plunged into the joint is a portion of the head portion such that a portion of the face is within the first and second workpieces and a portion of the face is outside the first and second workpieces.

12. The method of claim 9, wherein the portion of the rotating non-consumable shoulderless variable penetration

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friction stir welding tool that is plunged into the joint includes the entire tip section, head portion, and a portion of the body portion.

13. The method of claim 9, wherein the head portion is substantially frustoconical in shape with the face converging to the tip section at an opening angle.

14. The method of claim 13, wherein the opening angle is between approximately 70 degrees and approximately 160 degrees.

15. The method of claim 9, wherein the thickness of the first workpiece and the thickness of the second workpiece are unequal.

16. The method of claim 9, wherein the tip diameter is less than approximately forty percent of the body portion diameter or the head portion diameter.

17. A method for joining curved workpieces by friction stir welding, comprising the steps of:

placing a first workpiece having a first thickness in close proximity to a second workpiece having a second thickness thereby creating a joint, wherein the first workpiece and second workpiece each have at least one cooperating curve;

plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into the joint to be welded to a first penetration depth wherein the tool comprises a substantially cylindrical body portion, a head portion, and a tip section, each integral to the tool, the body portion having a longitudinal axis about which it is rotatable, a diameter, a sidewall substantially parallel to the longitudinal axis, a proximal end, and a distal end, the head portion located at the distal end of the body portion having a base with a diameter substantially equal to the diameter of the body portion forming a smooth transition between the body portion and the head portion, a face that converges to the tip section having a diameter and a center wherein the center is located substantially on the longitudinal axis, a height from the distal-most portion of the tip section to the base along the longitudinal axis;

traversing the joint and the at least one cooperating curve with the rotating tool ensuring that no portion of the tool, away from the entry penetration of the tool into the workpieces, comes in contact with the top surface of either workpiece and no gouging occurs; and

gradually retracting the portion of the rotating tool from the workpieces while traversing the joint so that the tool exits the workpieces at a predetermined exit point leaving a friction stir weld free of an exit hole.

18. The method of claim 17, wherein the radius of the at least one cooperating curve is less than approximately two times the diameter of the body portion and greater than one-half the diameter of the body portion.

19. The method of claim 17, wherein the step of plunging a portion of a rotating non-consumable shoulderless variable penetration friction stir welding tool into a joint consists of gradually forcing the tool into the joint while traversing the joint.

20. The method of claim 17, wherein the portion of the rotating non-consumable shoulderless variable penetration friction stir welding tool that is plunged into the joint is a portion of the head portion such that a portion of the face is within the first and second workpieces and a portion of the face is outside the first and second workpieces.

21. The method of claim 17, wherein the head portion is substantially frustoconical in shape with the face converging to the tip section at an opening angle.

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22. The method of claim 21, wherein the opening angle is between approximately 70 degrees and approximately 160 degrees.

23. The method of claim 17, wherein the thickness of the first workpiece and the thickness of the second workpiece 5 are unequal.

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24. The method of claim 17, wherein the tip diameter is less than approximately forty percent of the body portion diameter or the head portion diameter.

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