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Fleming et al.

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(54) **LATERAL POSITION DETECTION AND CONTROL FOR FRICTION STIR SYSTEMS**

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B23K 20/12 (2006.01)

(52) **U.S. Cl.** **228/112.1; 228/2.1; 228/103**

(58) **Field of Classification Search** **228/2.1, 228/112.1, 103**

See application file for complete search history.

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Primary Examiner—Kevin P Kerns

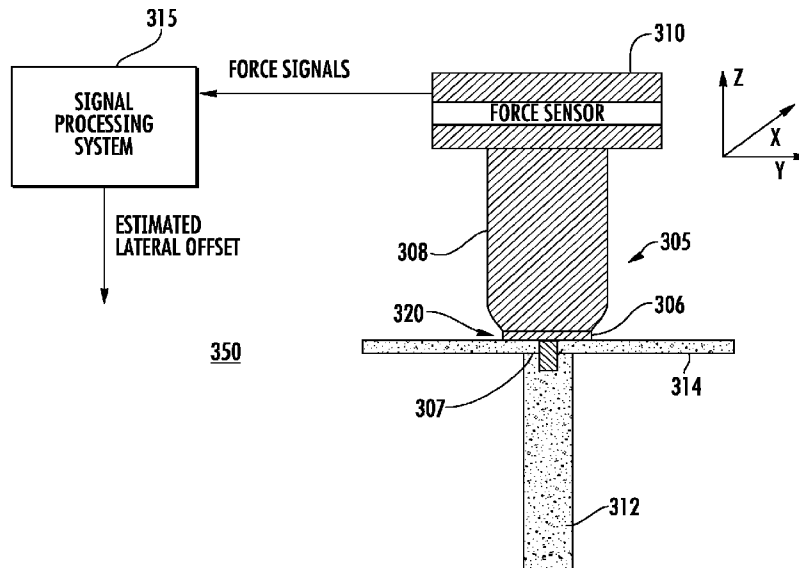
Assistat Examiner—DeVang R Patel

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(57) **ABSTRACT**

A friction stir system for processing at least a first workpiece includes a spindle actuator coupled to a rotary tool comprising a rotating member for contacting and processing the first workpiece. A detection system is provided for obtaining information related to a lateral alignment of the rotating member. The detection system comprises at least one sensor for measuring a force experienced by the rotary tool or a parameter related to the force experienced by the rotary tool during processing, wherein the sensor provides sensor signals. A signal processing system is coupled to receive and analyze the sensor signals and determine a lateral alignment of the rotating member relative to a selected lateral position, a selected path, or a direction to decrease a lateral distance relative to the selected lateral position or selected path. In one embodiment, the friction stir system can be embodied as a closed loop tracking system, such as a robot-based tracked friction stir welding (FSW) or friction stir processing (FSP) system.

33 Claims, 8 Drawing Sheets



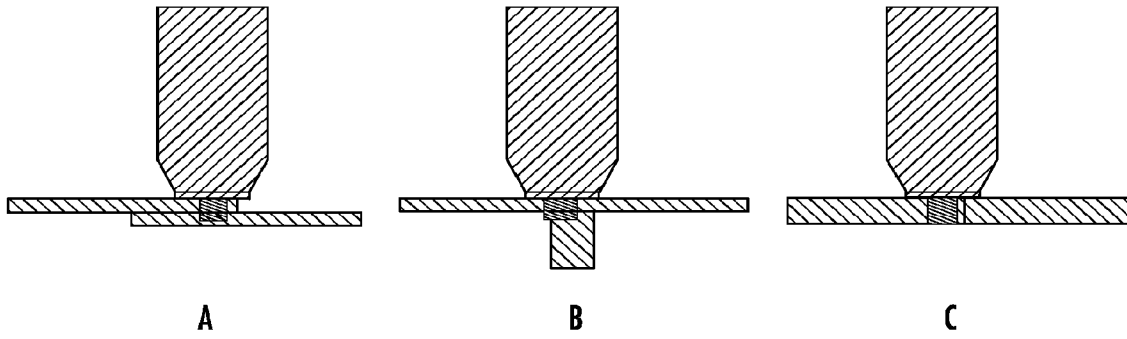


FIG. 1
(PRIOR ART)

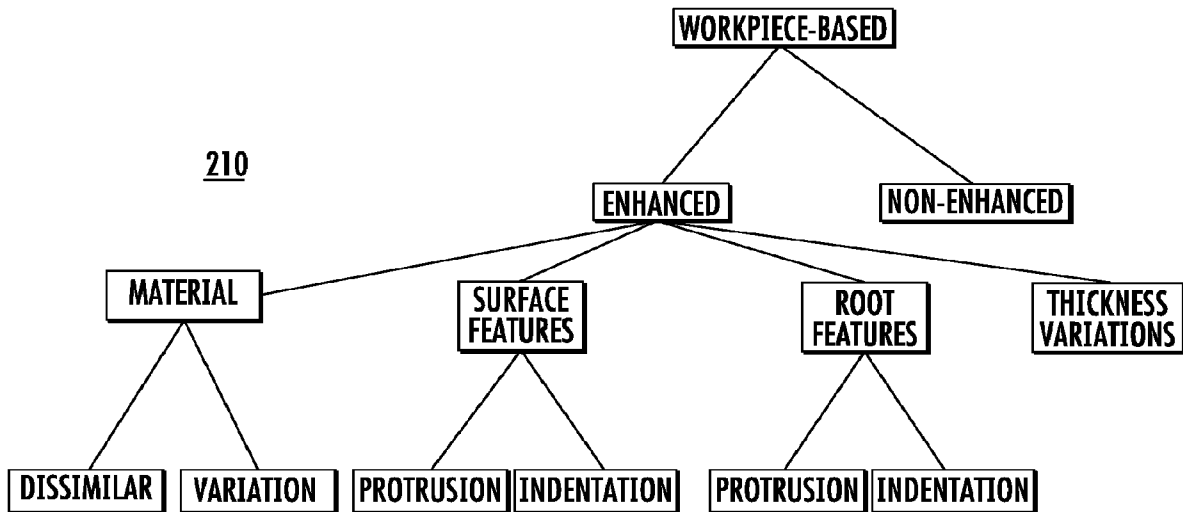


FIG. 2A

**BLIND T-JOINT
SAMPLE-BASED**

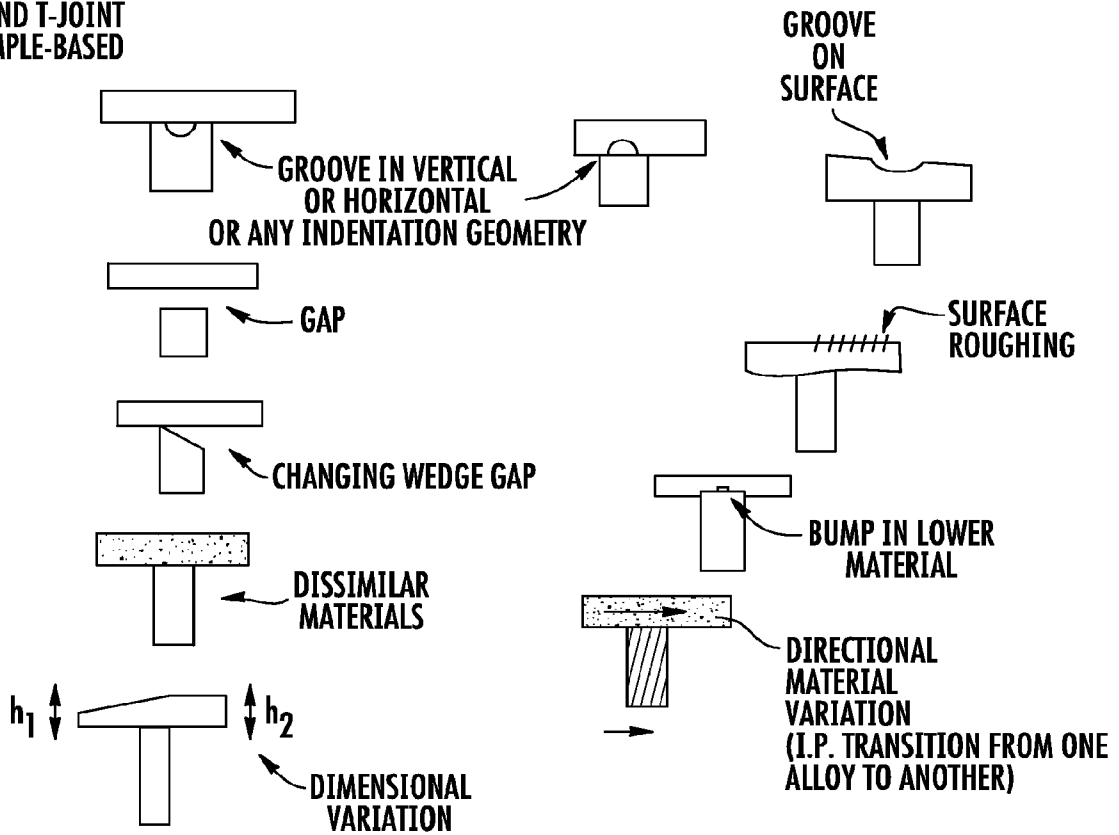
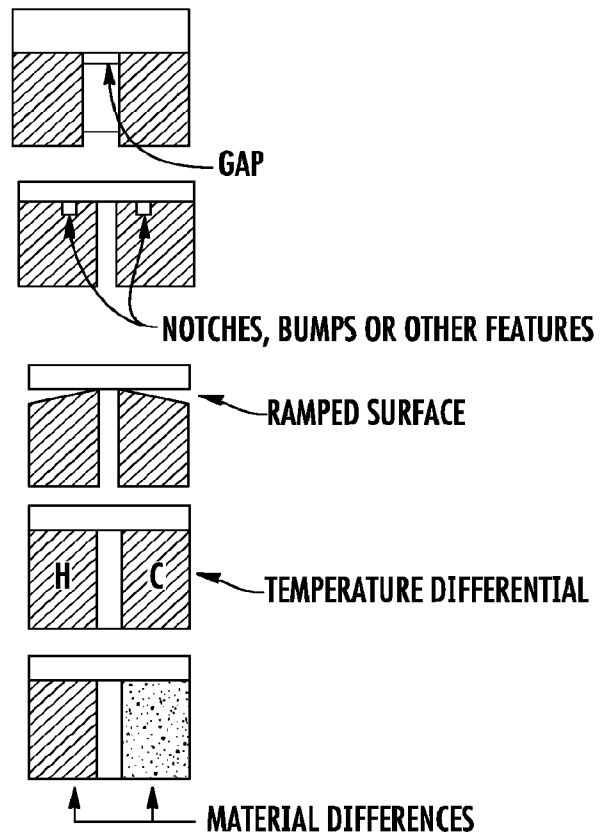
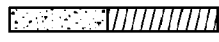


FIG. 2B



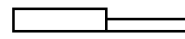
BUTT JOINTS
SAMPLE-BASED



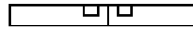
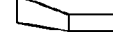
DISSIMILAR MATERIAL



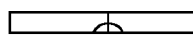
DIRECTIONAL MATERIAL VARIATION



THICKNESS VARIATION

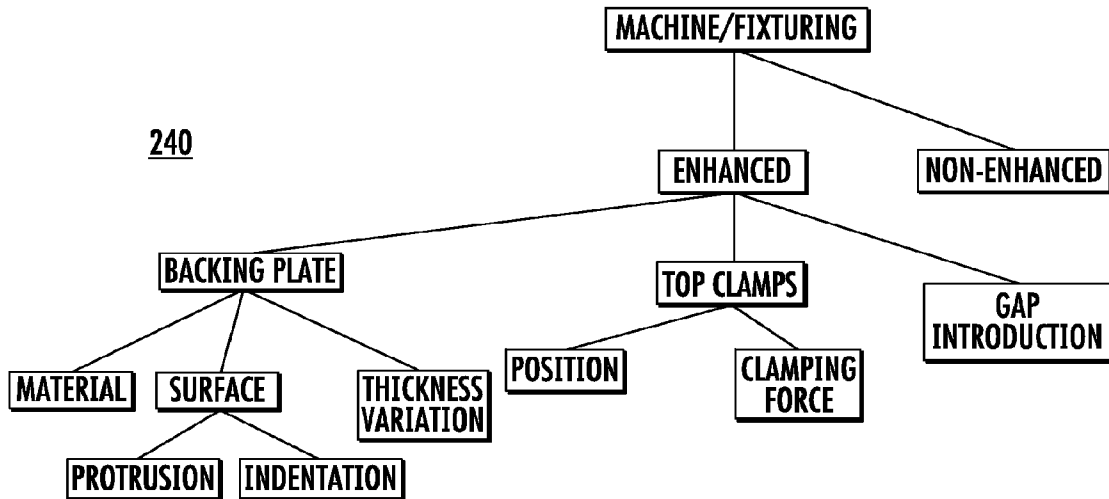


SURFACE FEATURE (ROUGHING INDENTATION PROTRUSION)



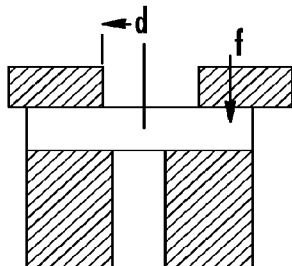
ROOT FEATURE

FIG. 2C



BLIND T-JOINT

MACHINE-FIXTURING BASED, CONTINUED



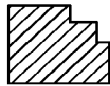
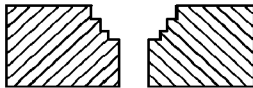
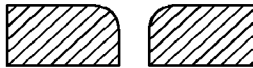
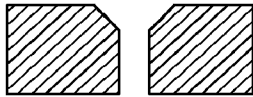
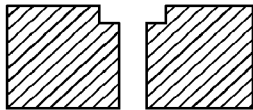
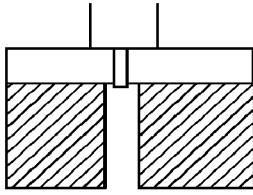
VARYING UPPER CLAMP POSITION

VARYING CLAMPING FORCE

FIG. 2D

BLIND T-JOINT

MACHINE-FIXTURING BASED

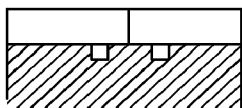


OTHER
COMPLEX
CURVATURES

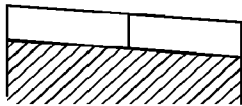
COMPOSITION UNDER SHOULDER
PROXIMITY OF PROBE TO
SAMPLE/AIR OR SAMPLE/CLAMP
BOUNDARY

FIG. 2E

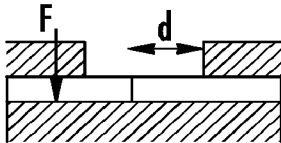
MACHINE/FIXTURING



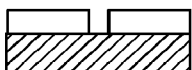
← INDENTATION/PROTRUSION



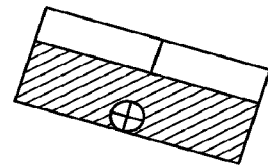
← UNEVEN HAIGHT



TOP CLAMP POSITION/CLAMPING FORCE

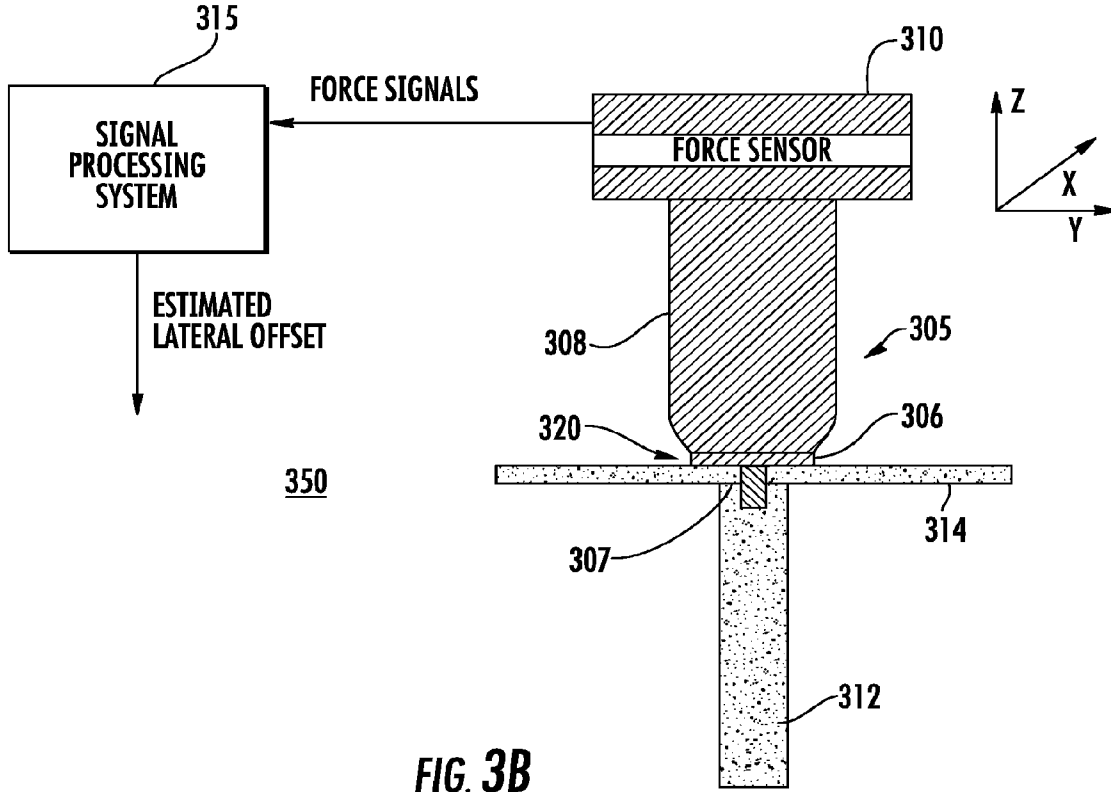
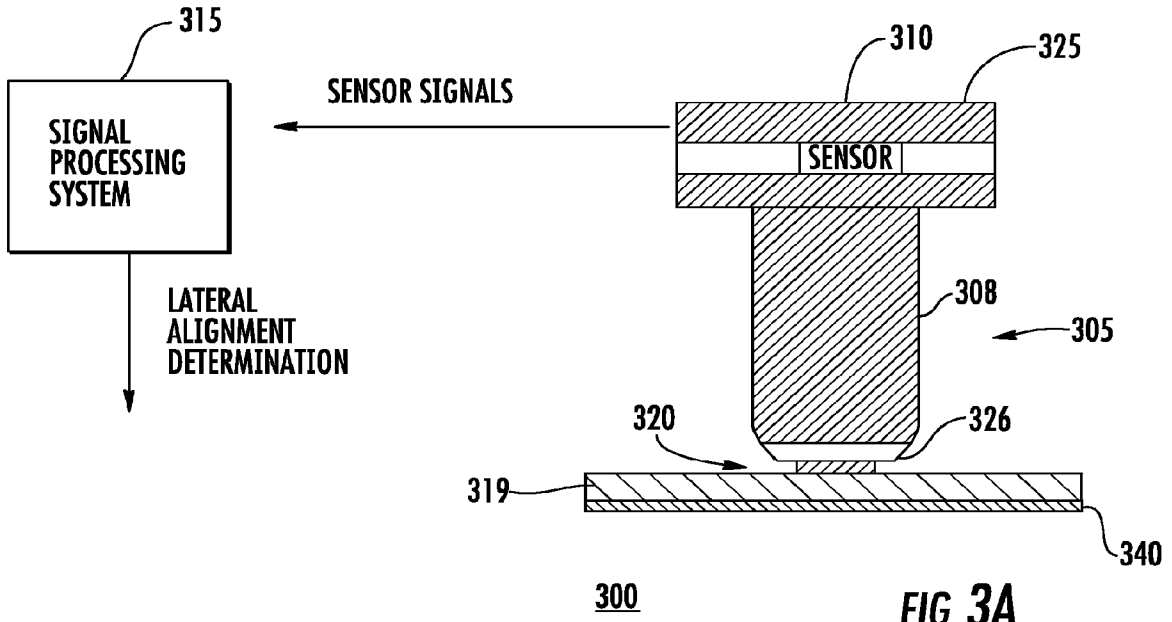


GAP INTRODUCTION



BACKING PLATE ORIENTATION

FIG. 2F



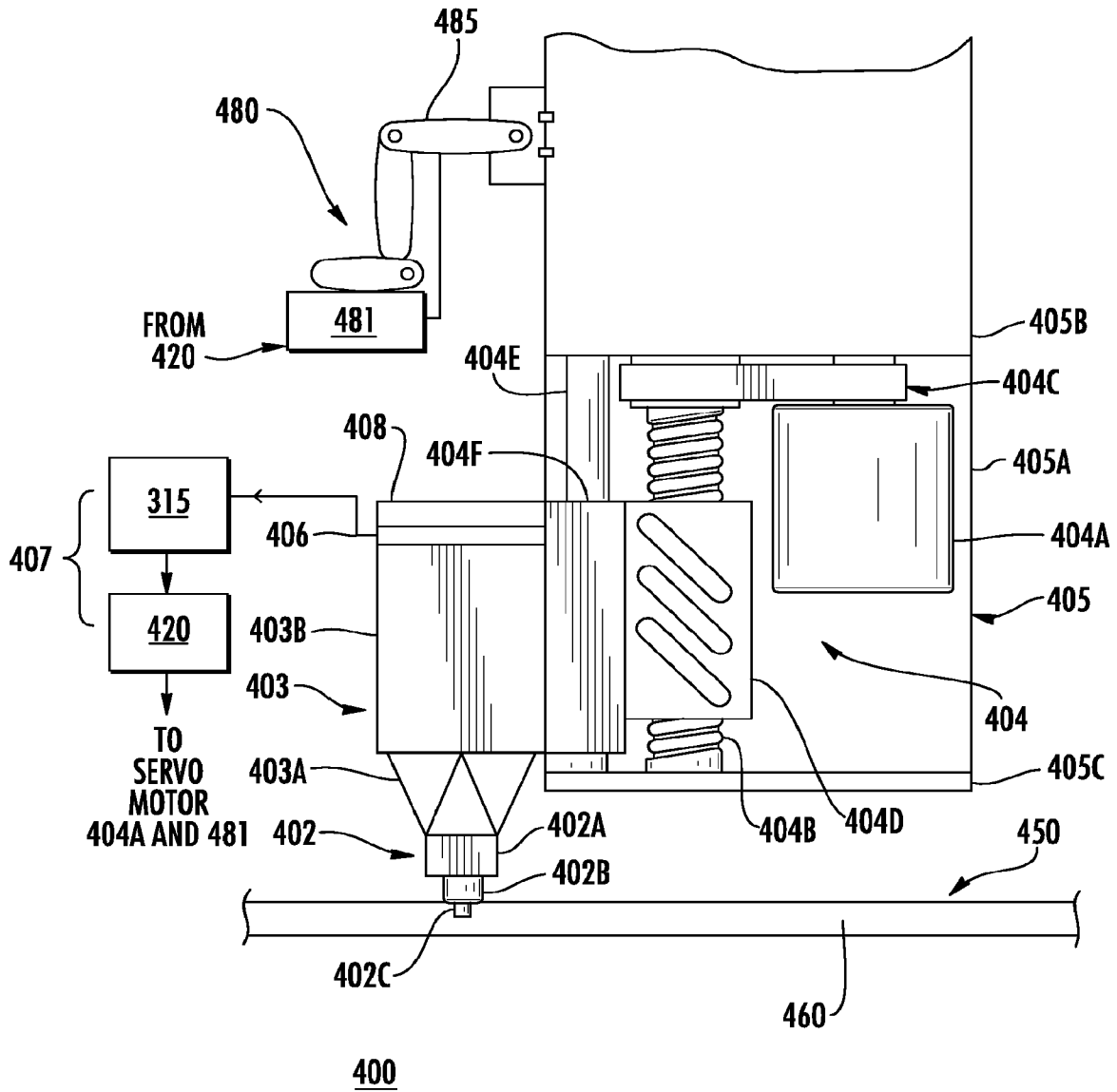


FIG. 4

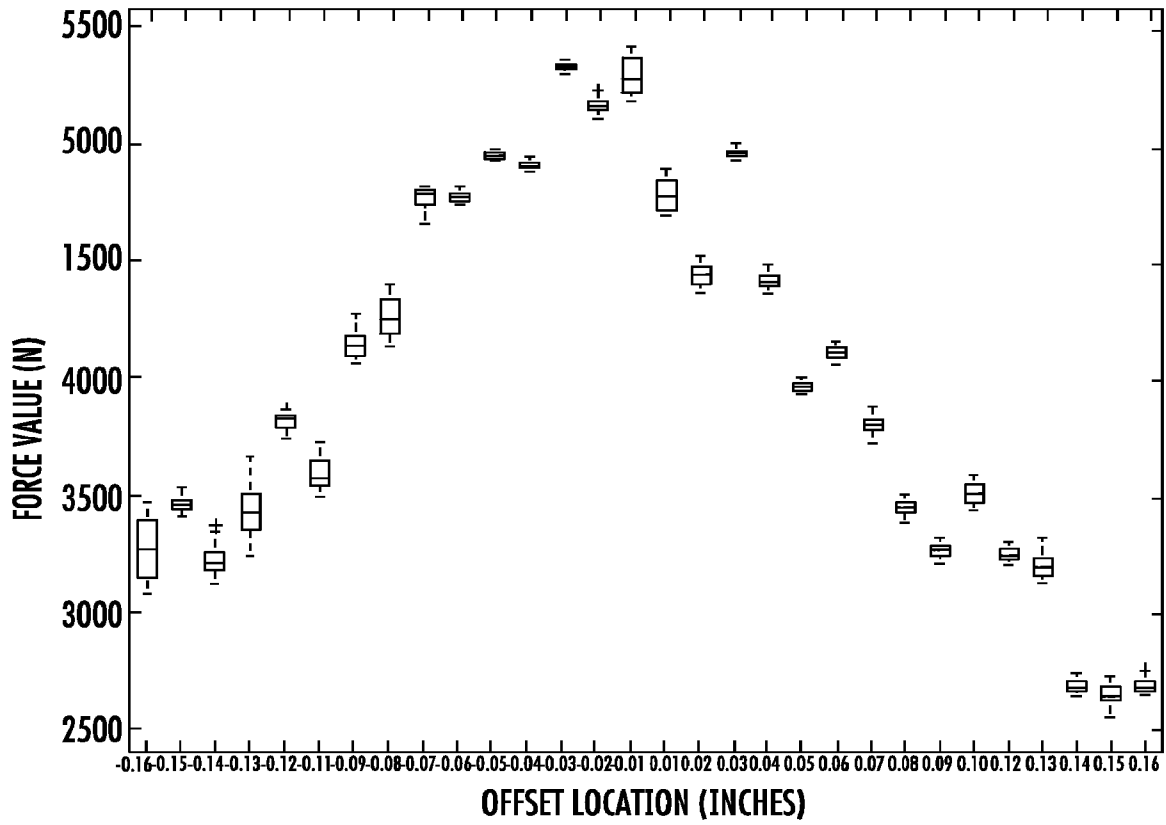


FIG. 5

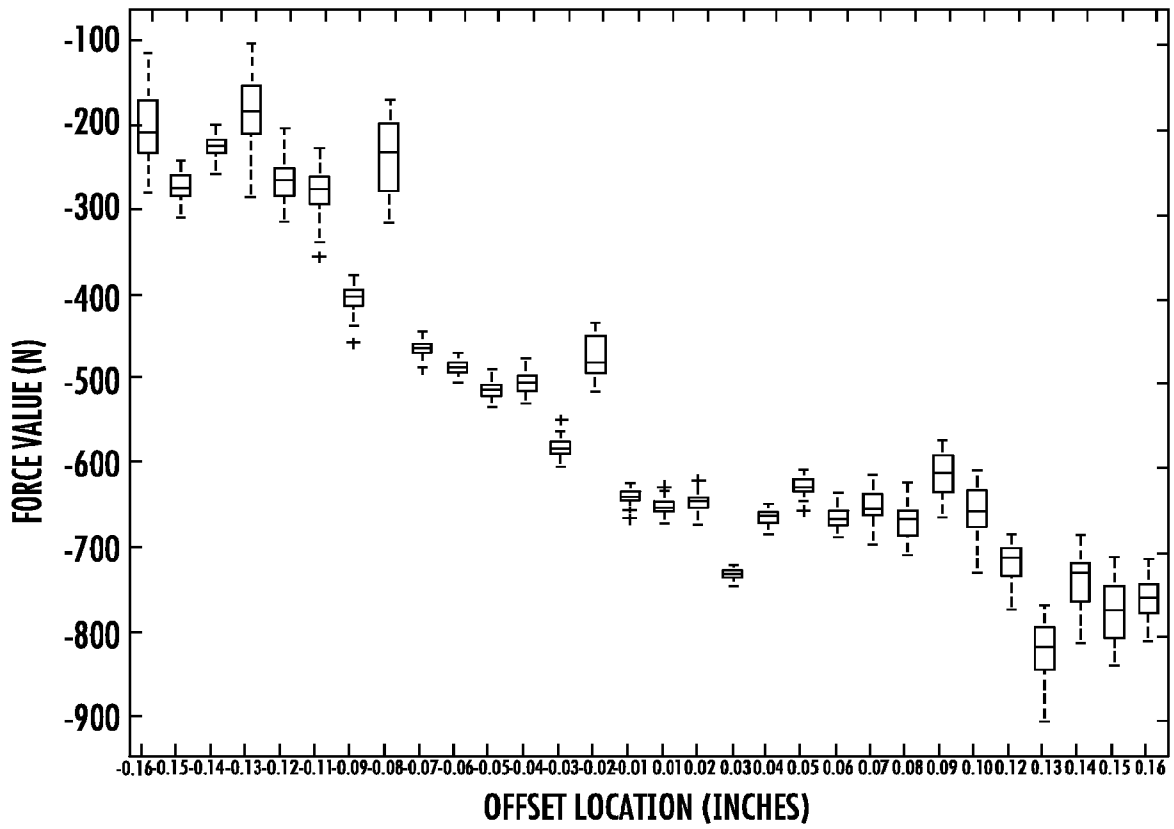


FIG. 6

LATERAL POSITION DETECTION AND CONTROL FOR FRICTION STIR SYSTEMS

RELATED APPLICATIONS

This application is a divisional application of, and claims priority to U.S. Ser. No. 12/130,622, filed May 30, 2008, contents which are incorporated by reference herein.

GOVERNMENT RIGHTS

The United States Government has certain rights in embodiments of the present invention pursuant to prime contract No. W-7405-ENG-36 with the United States Department of Energy.

FIELD OF THE INVENTION

The present invention relates to friction stir systems (FSS) including friction stir welding (FSW) and friction stir processing (FSP) systems, and related position detection methodologies for such systems.

BACKGROUND

One FSS embodiment is FSW. FSW is a joining process where welding is accomplished via mechanical stirring at a temperature that is below the melting point of the material being welded. In FSW, the welding tool comprises a shoulder and a pin (also called a probe). The tool is rotated while traversing the weld line. The shoulder applies pressure and friction induced heat to the surface of the material while the probe plunges into the material and induces material flow.

Another FSS embodiment is referred to as friction stir processing (FSP). FSP is a surface treatment technique which generally uses the same tool body as FSW, but lacks a FSW type probe. FSP is a relatively new surface-engineering technology that can locally eliminate or reduce casting defects and refine microstructures, thus improving strength and ductility, increasing resistance to corrosion and fatigue, enhancing formability, and improving other properties. FSP can also produce fine-grained microstructures through the thickness, imparted by superplasticity. Analogous to FSW, in FSP there is generally substantial and complex material flow.

FSW can be applied in a number of configurations, or positions, of the material to be welded and the FSW tool. One FSW configuration is referred to as butt-weld. In this arrangement the materials to be jointed are generally butted together side by side. The tool traverses the seam between the two samples, welding them together. The probe generally extends nearly to the base of the material. In this case, it is desirable for the probe to be well positioned with respect to the weld line.

Another FSW configuration is referred to as lap weld. In this case, the two samples are laid one on top of the other. The FSW probe extends through the top material and some distance into the second to accomplish the weld. Another FSW configuration is referred to as T-joint. In the T-joint, the materials to be welded are arranged in a T, with a horizontally-oriented sample set on top of a vertically-oriented sample. Other FSW configurations include the corner weld and edge weld.

As known in the art, welds from FSW can experience a loss in weld quality when the system parameters and conditions are not well set. For instance, in the case of FSW, loss of quality can occur if the welding tool rotates too slowly, or too quickly, or if the probe is not the correct length for the mate-

rial (e.g. a probe in butt-welding extends only halfway through the material, leaving the lower half of the seam un-bonded).

One flaw-inducing condition for FSW and FSP systems can be due to lateral misalignment during the FSW or FSP process. Lateral misalignment results when the FSW or FSP tool is offset relative to the selected lateral position or selected path referenced to the workpiece(s). In FSW, lateral misalignment can cause poor quality welds. In FSP, lateral misalignment can cause unintended microstructural results.

In the case of FSW, examples of lateral misalignment for lap weld, T-weld and butt weld (left to right) are shown in FIG. 1 as A, B and C, respectively. In lap-welding, lateral misalignment can arise when the probe is located entirely within the material but the shoulder of the tool is not completely in contact with the upper material. This condition can result in a number of generally undesirable consequences that result from insufficient heat input due to less shoulder contact and thus less friction. Also material could be ejected out into the area under the exposed shoulder. In the T-joint (FIG. 1B), the probe is shown offset to the point where a portion of the probe does not reside in the lower material. In T-joints, the geometry of the material beneath the shoulder is changing with lateral offset, in that the tool is more or less centered over the vertical member. Additionally, the probe moves toward or away from the edges of the vertical member. These changing conditions will cause changes in weld quality. Lateral offset is known to cause deterioration of quality for T-joints in both the extended un-bonded region to the right of the probe as well as the loss of the material which is generally ejected to the left of the probe. Finally in the butt-joint (FIG. 1C), the probe is shown laterally offset relative to the joint line sufficiently so that the probe is only in one of the material pieces. In butt-joints, the composition of the material under the shoulder does not change, but the amount the probe is in each material does. At centered locations, the probe is half in one material and half in another. In an offset position, it is largely in one piece, and only slightly in the other. The resulting weld quality for significant lateral offset in butt-joints will likely be quite low.

Visualization is one known technique for identifying and correcting lateral misalignment. In butt-joint and in some lap welding configurations the alignment of the FSW tool with regard to the weld seam can generally be visually observed. However, in other lap welds including blind T-joint, visualization is not generally possible. In blind T-joints this inability results because the lower vertical member cannot be seen through the upper horizontal member. Similarly, in certain FSP processes, visualization is not generally possible. There is thus a need for a new technique to better maintain FSW and FSP processing tools in a desired lateral alignment during system operation.

SUMMARY

This Summary is provided to comply with 37 C.F.R. §1.73, requiring a summary of the invention briefly indicating the nature and substance of the invention. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

A friction stir system for processing at least a first work-piece comprises a spindle actuator coupled to a rotary tool comprising a rotating member for contacting and processing the first workpiece. A detection system is provided for obtaining information related to a lateral alignment of the rotating member. The detection system comprises at least one sensor for measuring a force experienced by the rotary tool or a

parameter related to the force experienced by the rotary tool during processing, wherein the sensor provides sensor signals. A signal processing system is coupled to receive and analyze the sensor signals and determine a lateral alignment of the rotating member relative to a selected lateral position, a selected path, or a direction to decrease a lateral distance relative to the selected lateral position or selected path. In one embodiment, the friction stir system can be embodied as a closed loop tracking system, such as a robot-based tracked friction stir welding or friction stir processing system.

FIGURES

FIG. 1A-C shows depictions of laterally misaligned friction stir welding (FSW) probes during a lap weld, T-weld and butt weld, respectively.

FIG. 2A shows a classification tree according to an embodiment of the invention for a friction stir system configuration having workpiece-based lateral position detection including an enhanced and a non-enhanced branch, and exemplary material, surface features, root features, and thickness variation for the enhanced branch.

FIG. 2B shows specific exemplary workpiece-based enhancement species for a blind T-Joint FSW configuration.

FIG. 2C shows specific exemplary workpiece-based enhancement species according to an embodiment of the invention for a butt-joint FSW configuration.

FIG. 2D shows a classification tree according to an embodiment of the invention for a friction stir system configuration having machine/fixturing-based lateral position detection including an enhanced and a non-enhanced branch, and exemplary backing plate, top clamps, and gap introduction and species thereof that can be used for the signal enhancement branch.

FIG. 2E shows specific exemplary machine/fixturing-based enhancement species according to an embodiment of the invention for a blind T-Joint FSW configuration.

FIG. 2F shows specific exemplary machine/fixturing-based enhancement species according to an embodiment of the invention for a butt-joint FSW configuration.

FIG. 3A is a simplified depiction of an exemplary FSS system having lateral position detection according to an embodiment of the invention for processing at least a first workpiece.

FIG. 3B is a simplified depiction of an exemplary FSW system having lateral position detection according to an embodiment of the invention.

FIG. 4 shows an exemplary friction stir system having through the tool lateral position tracking according to an embodiment of the invention.

FIG. 5 shows values for the axial forces experienced by an FSW tool vs. varying amounts of lateral offset, according to an embodiment of the invention.

FIG. 6 shows the measured x-axis forces experienced by an FSW tool experienced during welding, according to an embodiment of the invention.

DETAILED DESCRIPTION

The present invention is described with reference to the attached figures, wherein like reference numerals are used throughout the figures to designate similar or equivalent elements. The figures are not drawn to scale and they are provided merely to illustrate the instant invention. Several aspects of the invention are described below with reference to example applications for illustration. It should be understood that numerous specific details, relationships, and methods are

set forth to provide a full understanding of the invention. One having ordinary skill in the relevant art, however, will readily recognize that the invention can be practiced without one or more of the specific details or with other methods. In other instances, well-known structures or operations are not shown in detail to avoid obscuring the invention. The present invention is not limited by the illustrated ordering of acts or events, as some acts may occur in different orders and/or concurrently with other acts or events. Furthermore, not all illustrated acts or events are required to implement a methodology in accordance with the present invention.

The present Inventors have discovered that the lateral alignment for friction stir systems (FSS) comprising a rotary tool including a rotating member can be automatically detected, and optionally quantified and/or tracked by the inclusion of a lateral position detection system. The lateral position detection system measures one or more forces experienced by the rotary tool or a parameter related to the force (e.g. vibration via vibration sensing) experienced by the rotary tool during processing. The lateral alignment is generally based on the location of the rotating member relative to a selected lateral position or path referenced to a first and a second workpiece (e.g. a joint for FSW).

At least one sensor is operable to measure a force experienced by the rotary tool or a parameter related to the force experienced by the rotary tool during processing, wherein the sensor provides sensor signals. A signal processing system is coupled to receive and analyze the sensor signals. The signal processing system can automatically determine the lateral alignment of the rotating member relative to the selected lateral position or selected path, or in the case of the weaving methodology described below, a direction to decrease the lateral distance to the selected lateral position or selected path.

Although embodiments of the present invention are generally described relative to FSW, as will be clear to one having ordinary skill in the art, embodiments of the present invention can be applied to related FSP. As described above, other than the absence of a probe, The FSP system and method is otherwise generally identical to FSW and embodiments of the present invention can be applied in an analogous fashion to FSP. Although the deformation in FSP is generally confined to the workpiece surface, the process forces have been identified by the present Inventors to generally remain sufficiently high for detection thereof.

Automated lateral misalignment detection and optionally lateral alignment tracking systems according to embodiments of the invention can be configured for FSS including robotic based FSS. In a typical embodiment, the force is sensed directly by affixing a force sensor to the shaft of the FSS tool or below the anvil supporting the workpiece(s). In this embodiment, the force sensor can comprise a dynamometer, strain gauge, pressure sensor, load cell or other suitable sensor. Additionally, signals generated which can give information about the force(s) can generally be used, such as vibration signals. Accordingly, vibration sensors for sensing the vibration of the rotating member can also generally be used.

In a typical application, a FSS according to an embodiment of the invention acquires force signals which it uses to determine lateral offset. If the signal changes are symmetric about the desired position (e.g. seam) or path, then the system is generally only able to determine the lateral distance from the desired position, but not direction. In other cases, the signals obtained are non-symmetric and both the distance and the lateral direction can generally be obtained. In another application, an FSS according to an embodiment of the invention can be configured to compare the degree of lateral offsets of

two locations (without knowing the absolute distance) and obtain the desired lateral position or path, or information to reduce the lateral distance to the desired position or path by weaving. Weaving generally comprises moving the rotating member in the lateral direction (thus orthogonal to the translation direction). Weaving is described in more detail below.

Sources of the force or parameter related to force to be sensed by the lateral position detection system can generally be classified as being workpiece-based or machine/fixturing based, or a combination of these. Workpiece-based as used herein refers to signals that arise from characteristics of the workpieces being friction stir processed. Machine/fixturing based as used herein refers to signals that arise from characteristics of the FSS itself, such as the clamping, spacers, or fixturing. Both the workpiece-based and machine/fixturing-based embodiments can also be configured to provide enhanced signals (extrinsic features added) as described below, or operated without any enhancement (intrinsic or non-enhanced). In the enhanced embodiment, the enhanced signal portion is generally due to features or changes in the workpiece and/or FSS inserted purposely to induce the enhanced signal portion. In the non-enhanced embodiment, there is no purposeful features or change in the workpiece and/or FSS introduced to provide an enhanced signal portion.

FIG. 2A shows a classification tree 210 according to an embodiment of the invention for a FSS configuration having workpiece-based lateral position detection including an enhanced and a non-enhanced branch. The non-enhanced branch can be used, for example, in certain FSW configurations, such as lap welding where the two samples overlap only in a region (e.g. as shown in FIG. 1A), so that the composition of material under the shoulder generally changes with lateral position. Lateral offset will thus affect the material composition as the rotating member moves across the surface. The change in material composition results in a change in the force on the FSW tool that the Inventors have found can be related to the lateral position of the tool and a relationship established between these parameters.

However, in certain configurations, such as in the lap weld FSW configuration where two samples are overlapped completely (or other cases so that generally no offset position has the composition of the material under the shoulder change), then the forces will not generally change with lateral offset because nothing about the material being stirred or the fixturing is changing with offset. In such cases, an enhanced branch/configuration can be used.

FIG. 2A also shows examples including material, surface features, root features, and thickness variation that can be used for workpiece-based signal enhancement. Some specific categories for the exemplary material, surface features, root features, and thickness variation are also shown in FIG. 2A. FIG. 2B shows some specific exemplary workpiece-based enhancement species for a blind T-Joint configuration. FIG. 2C shows specific exemplary sample-based enhancement species for a butt-joint configuration.

FIG. 2D shows a classification tree 240 according to an embodiment of the invention for a FSS configuration having machine/fixturing-based lateral position detection having an enhanced and a non-enhanced branch. The non-enhanced configuration can be used when useable signals are due to system characteristics not purposefully inserted to induce signals. In cases where the non-enhanced version does not provide a satisfactory signal level, a machine/fixturing branch/configuration can be used to provide an enhanced signal. FIG. 2D also shows exemplary backing plate, top clamps, and gap introduction that can be used for the

machine/fixturing signal enhancement. Some species for the exemplary backing plate, top clamps, are shown in FIG. 2D.

FIG. 2E shows specific exemplary machine/fixturing-based enhancement species for a blind T-Joint configuration. FIG. 2F shows specific exemplary machine/fixturing-based enhancement species for a butt-joint configuration. It is noted that some of the exemplary enhancements shown in FIGS. 2A-2F can also be applied to lap welds and butt-joints, or FSP.

FIG. 3A is a simplified depiction of an exemplary FSS system 300 having lateral position detection according to an embodiment of the invention for processing at least a first workpiece 319. The workpiece 319 is shown disposed on supporting anvil 340. System 300 can be embodied for FSW or FSP. FSS tool 305 comprises a spindle actuator 308 having a tool chuck (not shown in FIG. 3A) fixed to a rotating shaft thereof for rotational driving rotary tool 320 comprising rotational member 326 including a shoulder for contacting and deforming the workpiece 319. Spindle actuator 308 is generally powered by a motor (e.g. electric) or by a hydraulic. A detection system 310 provides information relating to a lateral alignment of the rotating member 326 relative to a selected lateral position or selected path referenced to the workpiece 319. The detection system 310 comprises at least one sensor 325 operable to measure a force experienced by the rotational member 326 or a parameter related to the force it experiences during FSW or FSP processing, wherein the sensor 325 provides sensor signals. The sensor 325 shown in FIG. 3A can be a force sensor coupled to the tool 305. In this way, forces experienced by the tool 305 are transmitted through the tool to the force sensor 325.

Force sensor 310 can comprise a variety of different load cell configurations, which as known in the art are electronic transducers which convert a force into an electrical signal. This conversion is indirect and can comprise a mechanical arrangement for the force being sensed deforming a strain gauge, wherein the strain gauge converts the deformation (strain) to electrical signals. The electrical signal output is normally on the order of a few millivolts and is generally amplified before it can be used. The output of the transducer corresponds to the force applied to the transducer. Although strain gauge load cells are the most common, hydraulic (or hydrostatic), piezoelectric load cells, and vibrating wire load cells can also generally be used.

In one embodiment, the force sensor 310 comprises a dynamometer. A dynamometer can measure the axial force (F_z), in plane forces F_x and F_y , and the torque around in the axial direction (along the z-axis). For example, the dynamometer can comprise a dynamometer provided by Kistler Instrument Corp., Amherst, N.Y., which measures 4 forces: F_x , F_y , F_z and the Torque around the z-axis.

A signal processing system 315 is coupled to receive and analyze the sensor signals and determine the lateral alignment of the rotating member 326 relative to the selected lateral position or selected path, or a direction to decrease a lateral distance to the selected lateral position or said selected path. Signal processing system 315 can comprise a microprocessor having associated memory, the memory having stored correlation information, such as force vs. lateral offset correlation data. In one example, the correlation data shown in FIG. 5 or FIG. 6 described in the Examples below can be used.

Although connections for communications between components in FSS 300 are generally shown as wired (electrical) connections, optical and over-the-air connections may also generally be used with systems according to embodiments of the invention. In the case of over-the-air connections, receivers, transmitters or transceivers may be provided based on the need to receive information, transmit information, or both

receive and transmit. For example, force sensor **310** can include an associated transmitter and antenna, and signal processing system **315** can include an antenna and a receiver operable to receive the sensed signal transmitted by the transmitter associated with the force sensor.

FIG. **3B** is a simplified depiction of an exemplary FSW system **350** having lateral position detection according to an embodiment of the invention. System **350** is operating on workpieces **311** and **312** arranged in a T-joint configuration. System **350** comprises FSW tool **305** comprising a spindle actuator **308** having a tool chuck (not shown in FIG. **3B**) fixed to a rotating shaft thereof for rotational driving of a rotary tool **320** comprising shoulder **306** and probe **307**. Probe has a length sufficient to extend into workpiece **312**. A force sensor **310** is coupled to tool **305**. A signal processing system **315** is coupled to receive force signals from force sensor **310**. The force sensor **310** shown is affixed to the rotating shaft of tool **305**, and it in turn holds the FSW tool **305**. In this way, forces experienced by the FSW tool **305** are transmitted through the tool to the force sensor **310**.

As described above, the force sensor **310** can be embodied as a variety of different load cells to measure one or more forces. The force signals experienced by rotary tool **320** transmitted through the FSW tool **305** that are sensed by force sensor **310** are transmitted to the signal processing system **315**. As known in the art, the force signals can be filtered, amplified and converted to digital signals. Signal processing system **315** can comprise a microprocessor having associated memory, the memory having stored force vs. lateral offset correlation data, such as based on the data shown in FIGS. **5** and **6** described in the Examples below.

In one embodiment, experiments are performed in the laboratory to gather sufficient data to prepare a general correlation function that relates the measured force (or a force related parameter) experienced by the friction stir tool and the magnitude (and in some embodiments the direction) of lateral offset. One way of measuring the lateral offset to compile data for generating a correlation function is to use a string potentiometric transducer to directly measure the lateral offset of the stage. The string potentiometer uses a string pull to affect the resistance of a potentiometer, which in turn changes the voltage measured by and after signal processing (e.g. analog to digital (A/D) conversion) is translated into a position of the stage. Other methods for directly measuring lateral position include, but are not limited to, a magnetic tape reader, or a relative or absolute shaft encoder fixed to the shaft which moves the stage laterally. Linear position transducers are a general class of transducer which can perform this measurement. It may also be possible for simulations to be used instead of experiments to generate data to compile a correlation function, such as based on computational fluid dynamics to simulate the welds or surface deformation and the measured forces.

The signal processing system **315** having such data CT a correlation function based on such data can determine the lateral offset from collected force signals. In one embodiment, the lateral offset can be reported as a real number which represents the lateral position. In the butt-joint configuration, this measurement is generally in terms of the distance of the location of probe **307** from the joint line center. The offset estimator can be based on a generally non-linear function which maps the input forces to an estimated lateral offset. Such a function could be derived from a data set through regression, or be implemented through a support vector machine, neural network or other suitable method. Alternatively, a function can also be derived from models or physical properties.

As noted above, force sensor **310** measures the magnitude of at least one force, such as the axial force experienced by the probe **307** associated with tool **305**. In the case of T-joints, the force sensor is generally operable to detect a force in the range of about 1 kN up to 40 kN for the axial force. The other forces (in-plane and torque about the axial axis) during T-joint processing tend to be significantly lower in magnitude, generally being 100 N to 5 kN. The axial force magnitude alone for certain T-joint configurations has been found to generally be sufficient to estimate of the degree (magnitude) of lateral offset, but generally not the direction of lateral offset. In order to deduce the side (direction) of the weld an offset is on, in one embodiment force sensor **310** also measures at least one in-plane force, such as the in plane force along the x-axis shown in FIG. **3B**. Alternatively, weaving according to an embodiment of the invention described below can be used to determine the direction.

As briefly described above, weaving comprises the back and forth lateral motion of the probe and monitoring the sensed force, parameter related to force (e.g. vibration) or signal derived therefrom such as the lateral offset signal to determine whether the tool is moving towards or away from a desired location. In weaving, it is generally assumed that the input data is symmetric about the point desired to be maintained. In the case where the axial force is maximized at a particular location (alternatively, it could be minimized, or it could be some other force), then the weaving algorithm can move the probe in a weaving pattern, comparing locations relative to each other, and moving towards the location of maximal axial force. Weaving can thus be used to identify the direction to reach a desired lateral location.

For example, if the only signal available is the axial force, in the case of the T-joint, the relation generally provided would be an inverted parabola centered about the jointline when plotted against the magnitude of the lateral offset (See FIG. **5** described below which provides a relation between values of the axial forces (measured in Newtons) for T-joint welds run and the lateral offset (measured in inches). In this case, the FSW tool can be controlled to weave to maintain maximum axial forces. During the weave, using the sensed axial force, the tool can move toward the advancing side while the axial force is sensed to be increasing, and then reverse directions when the axial force is sensed to begin to decrease. As known in the art, the “retreating side” of a FSW weld joint refers to the transverse side of the weld joint where the tangential direction of the rotational motion of the pin is opposite the direction of the advancement of the pin through the structural members. The side opposite the retreating side, referred to as the “advancing side” is where the tangential direction of the rotational motion of the pin corresponds to the direction of the advancement of the pin.

The output of the misalignment detection system, such as shown in system **300** or system **350**, as described above, is generally a real number which represents the lateral position relative to the location of the rotating member, such as the probe’s location relative to the joint line center in butt-welding. One additional piece of information that can be helpful in certain embodiments of the invention is which side of the center location (which provides the maximum force) the FSS tool is offset. In certain experiments conducted, systems according to embodiments of the invention have been able to discern this. For example, in the case where there are asymmetric forces present (such as demonstrated for the x-force in T-joints; see FIG. **6** described below), then a function, predictor or estimator can generally be configured to predict the location of the probe with respect to the desired location, including information about to which side the probe is offset.

However, in certain configurations, information regarding the side of the center location may prove difficult to determine. In such cases, weaving as described above can be used to determine which side of the center location the rotational tool is on.

Different setups (lap welding, t-joints etc.) and welding parameters (rotation speed, travel speed) are expected to generally impact the magnitude of the recorded sensed force(s) and be accounted for in order to have an estimation process configured for a specific weld scenario. There are a number of possibilities for offset estimation, including estimating the absolute amount of the offset and estimating relatively whether one sensed position is offset by more or less than another and by how much. Because FSS is generally known to have significant process variation including variations arising from different configurations, welding speeds, tool design and so on, different techniques for offset estimation may be used for different FSW or FSP scenarios.

Lateral misalignment detection according to embodiments of the invention can be used for a variety of purpose in a variety of systems. In one embodiment, misalignment detection is used to verify that the FSW or FSP tool is properly laterally aligned relative to a selected lateral position or path referenced to the workpiece(s). This could be used to alert an operator in a conventional system or a robot in a robotic system when a misalignment occurs generally more than a predetermined numerical threshold is detected. Such a misalignment could have serious effects on the weld quality.

In another embodiment of the invention, misalignment detection according to the invention is used as part of a friction stir system having additional components implementing feedback control of the lateral position of the tool. Such systems are referred to herein as a "through the tool tracked FSS". In such a system, misalignment detection is used as a feedback signal for a closed-loop lateral position control system. FIG. 4 shows an exemplary friction stir system 400 having through the tool lateral position tracking according to an embodiment of the invention. Through the tool tracking provides automatic tracking to a desired lateral position (e.g. relative to a joint). Embodiments of the invention may be particularly helpful for successful joining of "blind T joints", and for robotic welding where tolerances in the robot and the fixturing holding the workpiece(s) provided are generally inadequate to ensure proper "tracking" of the joint during processing.

System 400 includes a rotary tool 402 for FSW, a rotational driving unit 403 for rotationally driving the rotary tool 402, a press driving unit 404 having the rotational driving unit 403 mounted thereon for pressing the rotary tool 402 against the surface of a welding portion 460 of a workpiece 450, and a mount bracket 405 for supporting the press driving unit 404. In addition, the friction stir welding system 400 further includes a force sensor 406 for detecting the force experienced by the rotary tool 402 while pressed on the workpiece 450 during operation of system 400.

A control unit 407 comprises a signal processing system 315 for estimating lateral offset and weld controller 420. Control unit 407 is provided for controlling the lateral position of rotary tool 402 so that measured force falls within a predetermined range based on a detection signal from the force sensor 406. The weld controller 420 uses the lateral offset data to control the servo motor 481 which provides power to robotic arm 485 and optionally servo motor 404A. For example, system 400 can be used to actively maintain some lateral position, such as at a seam/joint line in butt-welding. The tracking feature provided by system 400 can be particularly helpful when either the actual lateral position is

difficult to obtain accurately through conventional visual means (e.g. for T-joints), or when the joint line is not a straight line, as can be case in robotic FSW systems, such as system 400 shown in FIG. 4.

The rotary tool 402 is generally made of steel or other material which is harder than the workpiece 450 and has a grip portion 402A adapted to be gripped by a chuck, a shank 402B provided on the grip portion 402A in such manner as to protrude from a distal end face thereof to thereby be pressed against the surface of the welding portion 460 of the workpiece 450, and a probe 402C provided on the shank 402B to protrude from a distal end face thereof to be inserted into the welding portion 460. The rotary tool 402 is caused to travel along the line of the welding portion 460 of the workpiece 450 while being rotationally driven at a speed of about 100 to 10,000 rpm so that the probe 402C softens the welding portion 460 by virtue of friction heat to thereby allow the portion being so softened to be plastically deformed in the vicinity of the traveling probe 402C. Welding portion 460 is welded when cooled and solidified.

The rotational driving unit 403 includes the tool chuck 403A for gripping the grip portion 402A of the rotary tool 402 and a spindle motor 403B having the tool chuck 403A fixed to a rotating shaft thereof for rotational driving. The spindle motor 403B is mounted on the press driving unit 404 at an upper end thereof which is opposite to the tool chuck 403A via a mounting plate 408. In this case, the spindle motor 403B is fixed to the mounting plate 408 at the upper end thereof with fasteners such as bolts and nuts while compressibly holding the force sensor 406 between the mounting plate 408 and itself. In the embodiment shown the sensor 406 is positioned between the tool and the vertical shaft. It is also generally possible for the force sensor to be in a number of other locations including below the material, elsewhere on the shaft, or even embedded in the tool.

The press driving unit 404 includes a servo motor 404A affixed to the mounting bracket 405 with a rotating shaft thereof being oriented upwardly, a ball screw shaft 404B rotatably supported on the mount bracket 405 at upper and lower ends thereof, a belt power transmission mechanism 404C for constituting a power transmission between an upper end portion of the ball screw shaft 404B and the rotating shaft of the servo motor 404A, a ball screw nut 404D adapted to thread fit on the ball screw shaft 404B in such a manner as to be movable vertically, a direct driven bearing rail 404E disposed in parallel with the ball screw shaft 404B and fixed to the mounting bracket 405 at upper and lower ends thereof and a direct driven bearing 404F adapted to fit on the direct driven bearing rail 404E in such a manner as to be movable vertically there along and integrally coupled to the ball screw nut 404D. Then, fixed to this direct driven bearing 404F is the mounting plate 408 to which the spindle motor 403B of the rotational driving unit 403 is fixed in turn.

The mounting bracket 405 has a side wall 405A to which the servo motor 404A is fixed, and an upper wall 405B and a lower wall 405C on which the ball screw shaft 404B and the direct driven bearing rail 404E are supported at the upper and lower ends thereof, respectively. The upper wall 405B is shown detachably attached (e.g. via bolts and nuts) to a robotic module 480 comprising robotic arm 485 and servo motor 481 for moving the robotic arm 485 and thus the rotational driving unit 403 and rotary tool 402 laterally or vertically.

The force sensor 406 outputs a detected force signal to the controller 420. The controller 420 is configured to provide a control signal to control the lateral position of rotary tool 402 relative to a joint or other location of the workpiece 450, such

as via movement of arm 485 based on input signals from the force sensor 406 and a stored correlation relation between force and lateral position. Controller can also control servo motor 404A of the press driving unit 404, such as to change the rotation speed of rotary tool or the height of the rotary tool.

Controller 420 generally comprises a feedback control unit, a motor control signal output unit and a motor driving circuit. In addition, the controller generally includes memory such as Read Only Memory (ROM) for storing various types of data and programs, such as the force to lateral alignment correlation data or a function therefrom, a Random Access Memory (RAM) for temporarily storing various types of data and the like and a Central Processing Unit (CPU) for performing various types of operations as well as an input/output interface I/O between the force sensor 406 controller 420. An A/D converter (not shown) is generally included for converting the analog signal from the force sensor 406 into a digital signal. The feedback control unit can perform proportional, integral and differential (PID) operations relative to a deviation of the actual force relative to a target force to converge the deviation towards zero.

In one embodiment, through the tool tracking according to an embodiment of the invention enables automatic joint line tracking in FSW. Through the tool tracking also enables more complicated weld-seams to be obtained (e.g. a curved weld path). Further the robustness of the process can be improved by monitoring the lateral offset even in cases where the location of the weld-seam is known, such as by providing an assurance that proper alignment was maintained throughout the welding operation. Moreover, a feature of through the tool tracking is that it generally does not require added external sensors outside of force sensors on the tool, which are common in FSW and FSP. This can represent a significant savings in both cost and system complexity.

Other operational parameters can change the force sensed by force sensors according to the invention. However, it is generally possible to separate out changes in force due to other effects, such as due to a change in pin penetration depth which can change the measured axial force. In one embodiment of the invention, a two step process is repeated throughout the welding process. In the first step, the forces (including but not limited to axial force) are used to determine a particular lateral location relative to a joint, such as center of the weld which provides a maximum axial force. In this case, when the FSW tool is at the weld center, then a load-control function can be performed. The load control function can comprise changing some parameter (such as the vertical position which changes the pin penetration depth) to set the axial force to the desired load at the centered position. This sequence can be repeated throughout the weld.

Although the embodiments of the invention have generally been described relative to blind T-joint FSW where the system can detect offset both in direction from the seam and the magnitude of the lateral offset, embodiments of the invention are generally applicable to any type of weld joint or FSP, and are particularly helpful for automated robotic welding for FSW or FSP configurations.

Although not described herein, FSW or FSP according to the invention can be use to join different sample compositions. Moreover, active cooling can be performed during performing FSW to avoid melting the sample. For example, a backing plate (or anvil) which has coolant tubes running through it can be used for cooling.

FIG. 5 shows values of the axial forces (measured in Newtons) for FSW runs with varying amounts of offsets (measured in inches) obtained by the present Inventors. The welds run in this example were T-joint welds using aluminum work-

pieces. A string potentiometer transducer was attached to the lateral position to directly measure the lateral offset of the stage. The function can be seen to be in the shape of an inverted parabola. The maximum force is obtained very near the center of the seam, shown as a lateral offset of nearly zero. More generally, for FSW welds other than T-joints, the best position for the tool is generally not at the exact center, but instead is slightly offset toward the advancing side.

FIG. 6 shows the measured in-plane x-axis forces (measured in Newtons) for FSW runs with varying amounts of offsets (measured in inches) experienced by an FSW tool on the plane of the horizontal member (perpendicular to the axial force) obtained by the present Inventors. As with the data shown in FIG. 5, a string potentiometer transducer was attached to the lateral position to measure the lateral offset of the stage. The function obtained is in a shape characterized by near constant force levels at the offset location extremes, with a force of between about -200 and -300 N for lateral offsets between -0.16 to -0.07 inches and a force between -600 to -800 N for an offset of between 0.03 and 0.16 inches. A transition region between the location extremes has a force that generally decreases with increasing (more positive) lateral offset. A force of about -650 N corresponds to a lateral offset of nearly zero.

The data shown in FIGS. 5 and 6 demonstrates that lateral offset estimator can be configured by generating a generally non-linear function which maps at least one sensed force to a lateral offset. Such a function could be derived from a data set through regression, or be implemented through a support vector machine, neural network or other suitable method. In addition to regression methods, simulations, models and physical principles may also generally be used to derive predictive functions as well.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Numerous changes to the disclosed embodiments can be made in accordance with the disclosure herein without departing from the spirit or scope of the invention. Thus, the breadth and scope of the present invention should not be limited by any of the above described embodiments. Rather, the scope of the invention should be defined in accordance with the following claims and their equivalents.

Although the invention has been illustrated and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In particular regard to the various functions performed by the above described components (assemblies, devices, circuits, systems, etc.), the terms (including a reference to a "means") used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (e.g., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary implementations of the invention. In addition, while a particular feature of the invention may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. Furthermore, to the extent that the terms "including", "includes", "having", "has", "with", or variants thereof are used in either the detailed description and/or the claims, such terms are intended to be inclusive in a manner similar to the term "comprising."

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The Abstract of the Disclosure is provided to comply with 37 C.F.R. §1.72(b), requiring an abstract that will allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the following claims.

What is claimed is:

1. A friction stir method for processing at least a first workpiece, wherein a system for said method comprises a spindle actuator coupled to a rotary tool comprising a rotating member for contacting and processing said first workpiece, comprising:

measuring at least one force signal or a parameter related to said force experienced by said rotary tool during said processing, and

estimating a lateral position of said rotating member relative to a selected lateral position or a selected path, wherein said estimating comprises comparing stored lateral position correlation data or lateral position correlation data based on a stored correlation function to said force experienced by said rotary tool to determine a lateral position of said rotating member with respect to the selected lateral position or the selected path and determining lateral offset values based on said lateral position; and

decreasing a lateral distance between the rotating member and the selected lateral position or the selected lateral path based on the lateral offset values.

2. The method of claim 1, wherein said rotating member comprising a shoulder and a probe extending outwardly from said shoulder, whereby said method comprises friction stir welding (FSW).

3. The method of claim 1, wherein said method comprises friction stir processing (FSP).

4. The method of claim 1, further comprising the step of weaving to direct said rotary tool in a direction to decrease a lateral distance relative to said selected lateral position or said selected path.

5. The method of claim 1, wherein said system includes at least one sensor signal enhancement feature based on said system.

6. The method of claim 5, wherein said system further comprises a backing plate under said workpiece, wherein said sensor signal enhancement feature comprises a material variation of said backing plate, a surface indentation or protrusion in said backing plate, or thickness variation of said backing plate.

7. The method of claim 1, wherein said at least a first workpiece comprises said first workpiece and a second workpiece, wherein at least one of said first workpiece and said second workpiece includes at least one sensor signal enhancement feature.

8. The method of claim 1, wherein said method comprises welding a blind T-joint.

9. The method of claim 1, wherein said method comprises welding a butt joint.

10. The method of claim 1, wherein said method comprises welding a lap joint.

11. The method of claim 1, wherein said method comprises the step of controlling a lateral position of said rotary tool based on said lateral alignment.

12. The method of claim 1, wherein said controlling comprises sending control signals to cause a servo motor coupled to a robotic arm to automatically control said lateral position of said rotary tool so that said sensor signals are within a predetermined range or said lateral alignment is maintained within a predetermined limit or range.

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13. The method of claim 1, wherein said force comprises an axial force.

14. The method of claim 1, wherein said force comprises an in-plane force.

15. The method of claim 1, further comprising the step of issuing an alert to an operator of said system when said lateral alignment is outside a predetermined limit or range.

16. A friction stir method for processing at least a first workpiece using a friction stir weld system comprising a spindle actuator coupled to a rotary tool comprising a rotating member for performing said processing, the method comprising:

measuring a force experienced by said rotary tool or a parameter related to said force experienced by said rotary tool during said processing, said force based on a plurality of force sensor signals associated with said measured force or said measured parameter at a plurality of locations on said first workpiece,

comparing said plurality of force sensor signals to stored lateral position correlation data or lateral position correlation data based on a stored correlation function to discern a lateral position of said rotating member with respect to a selected lateral position or a selected path, determining at least one lateral alignment offset value for said rotating member based at least on said discerned lateral position, and

decreasing a lateral distance between said rotary tool and said selected lateral position or said selected path based on said lateral alignment offset value.

17. The method of claim 16, further comprising providing a backing plate under said first workpiece comprising a force sensor signal enhancement feature, said force sensor signal enhancement feature comprising a material variation of said backing plate, a surface indentation or protrusion in said backing plate, or thickness variation of said backing plate.

18. The method of claim 16, wherein said adjusting further comprises:

moving an arm driven by a servo motor coupled to said rotary tool arm to automatically control said lateral position of said rotary tool based on said lateral alignment offset value.

19. The method of claim 18, wherein said moving further comprises moving said rotary tool along said first workpiece in a weaving pattern.

20. The method of claim 16, wherein said plurality of force sensor signals are associated with at least one among an axial force, an in plane force, and a torque experienced by said rotary tool.

21. The method of claim 16, further comprising selecting said feature of said first workpiece to comprise at least a portion of said first workpiece contacting at least one second workpiece.

22. The method of claim 16, wherein determining is further based on a direction of rotation of said rotating member.

23. The method of claim 16, wherein said comparing further comprises comparing said plurality of force sensor signals at consecutive ones of said plurality of locations.

24. The method of claim 16, wherein said determining further comprises determining a direction towards a location of maximal or minimal force relative to said current location of said rotating member.

25. A friction stir welding method for welding at least a first and a second workpiece using a tracked friction stir weld tool comprising a spindle actuator coupled to a rotary tool having a rotating member with a shoulder and a probe extending outwardly from said shoulder for contacting and processing said first and second workpiece, the method comprising:

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measuring a force experienced by said rotary tool during said processing, said force based on a plurality of force sensor signals associated with said measured force at a plurality of locations on said first and second workpiece; comparing said plurality of force sensor signals to stored lateral position correlation data or lateral position correlation data based on a stored correlation function to discern a lateral position of said rotating member with respect to a joint line for said first and second workpiece; determining lateral alignment offset values for said rotating member based at least on said discerned lateral position; and decreasing a lateral distance between said rotating member and said joint line by adjusting a lateral position of said rotary tool based on said lateral alignment offset values.

26. The method of claim 25, wherein said adjusting further comprises:

- operating a servo motor to move an arm coupled to said rotary tool to change said lateral position of said rotary tool.

27. The method of claim 25, further comprising:

- providing a backing plate under at least one of said first and second workpiece, wherein said backing plate comprises a force sensor signal enhancement feature, said

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force sensor signal enhancement feature comprising a material variation of said backing plate, a surface indentation or protrusion in said backing plate, or thickness variation of said backing plate.

28. The method of claim 25, wherein said adjusting further comprises moving said rotary tool along said first workpiece in a weaving pattern.

29. The method of claim 25, wherein said plurality of force sensor signals are associated with at least one among an axial force, an in plane force, and a torque experienced by said rotary tool.

30. The method of claim 25, further comprising selecting said feature to comprise at least a portion of at least one second workpiece contacting said first workpiece.

31. The method of claim 25, wherein determining is further based on a direction of rotation of said rotating member.

32. The method of claim 25, wherein said comparing further comprises comparing said plurality of force sensor signals at consecutive ones of said plurality of locations.

33. The method of claim 25, wherein said determining further comprises determining a direction towards a location of maximal or minimal force relative to said current location of said rotating member.

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