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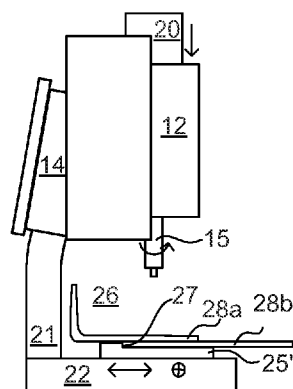


FIG. 2

(57) Abstract: A technique for Friction Stir Working (FSW) a stitch uses a robotic C-frame end effector (CFEE) with a FSW tool and a counter plate at opposite ends of the C-frame. The C-frame has an open center space for receiving an edge of a workpiece. The counter plate has a surface for meeting a distal face of the workpiece. A mover on-board the CFEE is provided for closing and opening the FSW tool with respect to the counter plate, and is adapted to deliver a down-force for FSW. The C-frame has a kinematic structure joining the counter plate to the FSW tool, including a first joint with at least one first traversing DoF with a given range, the DoF is linearly independent of the action of the first mover.



MACHINE, END EFFECTOR AND METHOD FOR ROBOTIC FRICTION STIR STITCH WORKING WITH REDUCED FIXTURING

Field of the Invention

[0001] The present invention relates in general to friction stir stitch or spot working with reduced fixturing and more efficient use of robot control, and in particular to a method and apparatus for such working with a robotic C-frame end effector that supports a workpiece, countering downforce, while allowing a FSW tool to move a limited range over or through the workpiece.

Background of the Invention

[0002] Friction stir welding is an established solid-state thermo-mechanical joining technology that offers advantages over conventional fusion welding technologies and other joining processes, and is understood herein to include any technique that implicates a friction stir tool that uses heat and plasticized stirring to join or add materials to a surface (and therefore includes at least conventional friction stir welding, friction stir diffusion bonding (FSDB), and friction stir additive manufacturing (FSAM)). Friction stir processing (FSP) is a term encompassing a variety of techniques that locally modify material distribution, and control of microstructures of near-surface layers of metal workpieces so that plastic deformation, material mixing, and thermal exposure can be leveraged to achieve significant microstructural refinement, densification, homogenization, and physical or chemical processing of workpieces. Herein friction stir working (FSW) comprehends friction stir welding and FSP, and includes heat assisted forms thereof. FSW can be divided into three regimes: continuous, stitch (herein FS-W) and spot (herein FS-W) working. Continuous FSW has no fixed prescribed length. FS-W works material surrounding the dimensions of the tool (with some margin for error), and FS-W involves in-plane movement, i.e. movement substantially normal to a downforce, in a stitch direction, displacing a FSW tool through the workpiece) of a few mm to a few dm.

[0003] In FS-W, a FSW tool (typically a shouldered tool with a profiled pin extending from a centre of the shoulder) is rotated and plunged into the workpiece until contact is made between the shoulder and the top surface of the workpiece. Herein "plunging" refers to entry of the FSW tool into position inside the workpiece. It includes conventional FSW tools in which the shoulder and pin are fixed (a variety of designs being known for minimizing lost material for different operating regimes of speed, materials, surf angle, etc.), and the pin enters the workpiece before the shoulder contacts the surface, and retractable FSW tools that allow for the pin depth to be varied while the shoulder contacts

the surface. If lap welding is the FS-W operation, the pin typically extends through a top part and into a bottom part to which it is joined. In some descriptions of friction stir welding, if the pin does not extend into the bottom part of the workpiece (which may be one or more pieces), the technique is referred to as FSDB, however for present purposes no distinction is made between FSDB and friction stir welding. After the plunge operation, the FS-W may involve a dwell period, and then the FS-W involves retraction of the tool, leaving an annular heat affected region or nugget surrounding a leaving hole from which the tool was removed. The downforce or forging force applied during plunge and dwell, provides sufficient localized heat to plasticize a volumetric region surrounding the tool, and the mixing of the plasticized material is induced by the rotating tool, but the heat is not sufficient to melt the metal.

[0004] The difference between FS-W and FS-W, is an additional step between the dwell and retraction: while maintaining the downforce, the tool is displaced in-plane. Herein "in-plane" refers to a local direction of movement over a surface of the workpiece with a nominally constant downforce applied, regardless of surface geometry of the workpiece, in a stitch direction; and "transverse" refers to a local direction substantially orthogonal to both the "in-plane" and downforce directions. Stitch working therefore involve plunging at one point, working the workpiece while moving the tool in the in-plane direction, and retracting the tool at the same or another point, where a path length between the plunge and retraction is typically several millimeters to a few decimeters. The heat induced by the downforce softens the material and allows for the in-plane motion with surprisingly little resistance. The in-plane and transverse forces are typically $1/10^{\text{th}}$ the downforce or less for most FS-W. The rotation, downforce, and in-plane forces during working result in material transfer around the periphery of the tool, producing a plastic deformation of the material surrounding the tool bit. For welding embodiments, a sound and homogeneous weld can be produced with improved mechanical properties compared to conventional fusion welding techniques.

[0005] Continuous or stitch butt welding, can also be performed, if gap management is provided. Generally gap management entails clamping the two pieces together with the requisite force in the vicinity of the FSW tool (typically on the order of one fifth to half the downforce), as well as distributed pressure along the whole extent of the weld line. There are a wide variety of additional weld arrangements for parts of various configurations. Neither FSP nor FSAM generally require two separate parts. Any material mixed or added to the single part is provided as a coating, or through a consumable FSW tool. For fast FSW, desirable in automotive and other high part-count application spaces, a low plunge depth is preferred, and so in such contexts, joining is generally limited to workpieces including a top part that is thin, at least where it is welded.

[0006] There are a wide variety of machines adapted to perform FSW. For maximum flexibility for joining processes, robots with FSW end-of-arm tools, generally referred to as “end-effectors”, may be used. Unfortunately this is limiting in at least two ways: only a robot that has sufficient motor torque capability to apply the downforce as well as the in-plane and transverse forces can be used; and massive fixturing is required to support the parts to resist the forces, especially the downforce. The costs of robots do not scale linearly with payload, but rather cost substantially more for higher payload.

[0007] Fixturing is expensive, cumbersome, and unwieldy. Herein fixturing refers to workpiece supports that are not carried by the end effector, whether jointed or not, and whether actuatable or not. Massive fixturing tends to obstruct machines, limiting freedom of mobility of other equipment and machines to access the workpiece for other operations before or after the FSW process. In the worst case, this may require the workpiece or fixturing to be re-positioned and aligned (and usually clamped) in another workspace for different operations, adding costs and time of the repositioning, and any risk of damage, to the overall workpiece fabrication. The size of the fixturing generally is proportional to the force magnitudes it is to resist. Given the several to many kN downforce required by FSW, fixturing often imposes a major impediment to such additional processes. So it is generally desirable to reduce fixturing in order to reduce constraints on machine mobility around the workpiece, and increase the number of processes that can be performed on the workpiece in a given processing station. Furthermore, fixturing is generally geometry-specific, and small changes in a FSW process may require costly changes in fixturing, which might be avoided if fixturing is reduced.

[0008] One way to reduce fixturing may be with the use of C-frame FSW end effectors. EP 1864747 specifically addresses the problem of resisting backup forces in continuous FSW end effectors, and reducing fixturing (support members). Generally C-frame end effectors have a tool end and a counter element (also referred to as an anvil, backing or backup) that are opposed or opposable, for example as opposite jaws. Support members for continuous welding are known to have a rotary member such as a roller, set of rollers, or an endless track (e.g. EP 1864747). The rotary member may be driven to assist the robot's only degree of freedom (DoF) in a plane of the weld.

[0009] While the document claims that reduced or eliminated fixturing is possible with this invention, it is not borne out from the drawings and disclosures. One of ordinary skill in the art, seeing a friction stir welding butt joint shown clearly in FIGs. 1-5, immediately recognizes that gap management is a fundamental problem. The downforce required for welding tends to wedge the two pieces, increasing a gap between the parts. To

counteract this wedging, a local force, especially during plunge (or side entry), when none of the workpieces are already joined, requires a substantial clamping force: in some cases as much as $\frac{1}{2}$ the magnitude of the downforce in the vicinity of the pin. There is nothing in the drawings that begins to explain how this fixturing takes place, except possibly with a second robot that grips one of the workpieces across its full extent as in FIG. 5, or for the particular case of tubular workpieces in FIGs. 8,9. While the roller shown may be sufficient to resist the downforce, greatly simplifying fixturing for some joints (e.g. single, multiple, or T lap joints, none of which were shown), any joint configuration that requires gap management would appear to be impossible if fixturing is eliminated. Consequently, the invention as shown, does not appreciably reduce fixturing.

[0010] Other known C-frame FSW end effectors use the robot only to bring the end effector into place around the parts. On-board actuators are used to supply the downforce as well as the in-plane motion (e.g. JP2004017128, JP2005313227, US20040079787). These fail to leverage the capacity of the robot, and add load, and cost to the end effector for the motors needed to drive the in-plane motions with a desired accuracy.

[0011] Many patents show the use of a counter bearing (support member) that is a separate robot and has roller(s) to be used instead of a C-frame (EP2724810, US6070784, US7748593)

[0012] JP2001121276 appears to teach a machine with a plurality of rollers (7 and 8) on opposite sides of a workpiece and a FSW tool 4 for welding the pieces together, along with parts 6 for clamping the workpiece. It is unclear how many robots are used to produce the machine, but the three parts are moved synchronously. The process appears to be directed toward continuous welding.

[0013] US 9,358,634 teaches a complicated system with an advanced fixture (table) that provides a "correction member" and a collar around a FSW tool on an end effector, that cooperate to guide FSW along a line. The correction member 22 also fixes the workpieces to the table. As such, complex fixturing is required along with the C-frame and a spherical roller member (support member).

[0014] US20040079787 teaches a C-frame FS-W end effector with a backing member 5 and fixing jig 7 for clamping a material to be welded, (and preferably providing an I-shaped groove for guiding the welding of a stitch). This invention requires separate movers onboard the robot end-effector to provide the movement in the welding direction, and thus is included in the class of machines that only use the robot to position the end effector after which point the robot is not engaged in the processing. This adds

complexity (limits to mobility) and weight to the end effector, especially with load and/or position sensors required for monitoring the rate of advance of the FSW tool, and takes poor advantage of the accuracy and power of the robot. This end effector design includes many movers that have to be jointly controlled with the desired accuracy. This patent provides good evidence for stitch welding having better cycle time and bond strength than continuous or spot friction stir welding.

[0015] Accordingly there is a need for an improved C-frame end effector (CFEE) adapted to provide on-board fixturing for stitch and/or spot friction stir working of a workpiece with reduced external fixturing.

Summary of the Invention

[0016] Applicant has devised a C-frame end effector that permits FS-W or FS-W that uses a C-frame structure to bear the downforce, and still allows the robot to control and drive in-plane movement. By frictionally engaging the workpiece with a counter element jointly mounted to the C-frame for at least one (preferably traversing) Degree of Freedom (DoF) movement (preferably in a direction linearly independent of clamp actuation), controlled working of the workpiece can be provided with less fixturing.

[0017] Accordingly a method is provided for Friction Stir Stitch working (FS-W) a workpiece. The method involves: moving a robot-mounted actuatable C-frame end effector (CFEE) into position with respect to a workpiece, with the workpiece between a counter plate and a FSW tool of the CFEE; operating a FSW tool with at least one on-board mover to spin the FSW tool, and press a distal face of the workpiece against the counter plate, while plunging the FSW tool into the workpiece until a shoulder of the FSW tool applies a downforce against a proximal face of the workpiece, wherein the pressing frictionally engages the counter plate and the workpiece; and moving the robot to drive the FSW tool through the workpiece over a surface of the counter plate in at least one direction of an intended stitch while the downforce is applied and the counter plate is frictionally engaged with the workpiece. The robot drives and controls accuracy of the worked stitch within a limited range of motion between the counter plate and FSW tool in a direction that is independent of the downforce, the at least one mover applies downforce, and the counter plate provides substantial fixturing.

[0018] Operating the at least one mover may involve plunging the FSW tool into the workpiece with the counter plate meeting the distal face across a full extent of the workpiece that spans the stitch. Alternatively it may involve operating a clamp carried by the CFEE to press a clamp face against the proximal face. Preferably, operating the

clamp involves applying a clamp force sufficient to frictionally engage the counter plate to the distal face, and fix the counter plate with respect to distal face, prior to plunge. Operating the clamp may involve applying a clamp force prior to a step of retraction, to stabilize the workpiece during retraction. The clamp face may be operated by at least one of the at least one movers via an elastic element, the elastic element applying the clamp force during a first part of a down stroke, prior to plunge. If so, the clamp face may include a rolling element that permits the clamp to apply pressure to the proximal face, while moving across it. Alternatively, the clamp may be mounted to the counter plate.

[0019] The robot may only be free to move across at least 50% of a full extent of the limited range, while pressing the clamp face against the proximal face. While clamped, the FSW tool may be repositionable prior to plunge, the repositioning may be enabled because of a joint between the counter plate and FSW tool that provides the limited range. The limited range joint may be a part of a kinematic structure joining the counter plate and FSW tool. The kinematic structure may have at least 2 DoFs, with at least one DoF being a free joint.

[0020] The proximal face and distal faces may be separate parts of the workpiece, or parts of two or more separate members, that are joined by the FS-W.

[0021] Moving the CFEE into position may involve one or more of: moving the CFEE by operation of the robot; moving the workpiece by a fixturing system; moving separately one of two or more parts of the workpiece into registration with the fixturing; moving separately one of two or more parts of the workpiece into registration with the counter plate; moving separately one of two or more parts of the workpiece into registration with the clamp face; and sensing a registration of the separately moved one or more parts.

[0022] The meeting surface may be substantially planar, simply curved in one direction, bicurved in one direction, convex, concave, or a smooth continuous surface relative to a shoulder of the FSW tool. After the FSW tool is retracted, the distal face of the workpiece may have a shape of the counter plate, which is different than a shape of the workpiece when the CFEE was moved into position.

[0023] Also accordingly, a Friction Stir Working (FSW) C-frame end effector (CFEE) is provided. The CFEE includes: a mounting end for mounting to an end of a robot; a C-frame with mouth for receiving an edge of a workpiece to be friction stir worked between first and second opposing ends; a FSW spindle motor at the first end defining a spindle axis; a counter plate at the second end, the counter plate having a surface for meeting a

distal face of the workpiece, the meeting surface having a first extent in a first parametrized direction that is greater than 2 mm; and a first mover for closing and opening the FSW tool with respect to the counter plate adapted to deliver a downforce for FSW working with the FSW tool. The CFEE comprises a kinematic structure joining the counter plate to the FSW tool, the kinematic structure including a first joint with at least one first traversing degree of freedom (DoF) with a given range, where the traversing DoF is effectively linearly independent of the action of the first mover, and the range is spatially limited to continuously span exactly 25% to 125% of the surface's first extent.

[0024] The first extent is preferably at least 1 cm, or 2 cm or 5 cm.

[0025] The kinematic structure may further include a non-traversing revolute joint that has a revolute axis that meets the spindle axis at or near the surface.

[0026] The first traversing DoF may be provided by a revolute joint having an axis parallel to an axis of the FSW tool, these axes being separated by at least 50% of a maximum extent of the counter plate. One or two traversing DoFs of the kinematic structure may be provided by linear prismatic joints.

[0027] The meeting surface may further have a second extent in a second parametrized direction that is independent of the first parametrized direction, and the kinematic structure may have the first traversing DoF that spans 70-110% of the first parametrized direction, and further comprises a second traversing DoF that spans 5-110% of the second parametrized dimension.

[0028] The kinematic structure may include a plurality of joints spanning 4 DoFs orthogonal to the first mover's action.

[0029] The FSW CFEE may further include a clamp for pressing on a top surface of the workpiece in a direction parallel to an axis of the FSW tool on at least one side of the FSW tool. The clamp may be mounted to one of the first and second ends. If the clamp is mounted to the first end, it may have roller elements for facilitating movement across a surface of the workpiece while clamped. An actuator of the clamp may be operable to latch the counter plate in a fixed position.

[0030] The counter plate may have: a friction coating; a registration feature for meeting the workpiece in a reliable position; a registration sensor for sensing a position and orientation of the workpiece; a curvature to match a distal face of an intended workpiece; a curvature to match an intended form of the workpiece that is different from a

shape of a workpiece as supplied; or a substantially planar surface to match a distal face of an intended workpiece.

[0031] Further features of the invention will be described or will become apparent in the course of the following detailed description.

Brief Description of the Drawings

[0032] In order that the invention may be more clearly understood, embodiments thereof will now be described in detail by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a front view schematically illustrating a 1 DoF CFEE with a Cartesian translational joint, in accordance with a first embodiment of the present invention;

FIG. 2 is a side view schematically illustrating a 2 DoF CFEE with two Cartesian translational joints, further showing workpieces and a counter plate with registration features in accordance with a first variant of the first embodiment of the present invention;

FIG. 3 is a side view schematically illustrating a 1 DoF CFEE with a non-Cartesian traversing joint, in accordance with a second variant of the first embodiment;

FIG. 4 is a front view schematically illustrating a 2 DoF CFEE with translational and rotational DoFs, in accordance with a third variant of the first embodiment;

FIGs. 5A,B are side views schematically illustrating a CFEE with a tool-side clamping mechanism, respectively in two states, in accordance with a fourth variant of the first embodiment;

FIGs. 6A,B are front and side views schematically illustrating a CFEE with a counter-side clamping mechanism, respectively in two states, in accordance with a fourth variant of the first embodiment;

FIG. 7 a side view schematically illustrating a CFEE with an on-board counter-side mechanism for gap management in butt joint applications, in accordance with a fifth variant of the first embodiment;

FIG. 8 a side view schematically illustrating a CFEE with an on-board tool-side mechanism for gap management in butt joint applications, in accordance with a sixth variant of the first embodiment;

FIG. 9 is a flowchart illustrating principal steps in an embodiment of a process of the present invention;

FIGs. 10A,B are a schematic close-up view of a part of a CFEE, and the CFEE mounted and in use on a workpiece with remote fixturing, in accordance with a second embodiment of the present invention;

FIGs. 11A-H are schematic illustrations of the second embodiment in principal steps in performing a FS-W, in accordance with an embodiment of the present invention;

FIGs. 12A,B are schematic illustrations of the second embodiment, showing additional degrees of freedom of motion with respect to a workpiece that is frictionally engaged, in accordance with the present invention; and

FIGs. 13A,B are schematic illustrations of the second embodiment with a modified, bi-curved counter plate, showing an additional degree of freedom of motion with respect to a workpiece that is frictionally engaged, in accordance with the present invention.

Description of Preferred Embodiments

[0033] Herein a C-Frame End Effector CFEE is described that is actuable for friction stir working. The CFEE has the unique feature that it has a counter plate that frictionally engages a distal surface of the workpiece, and is jointedly mounted to the CFEE so that while the distal surface engages the workpiece, a FSW tool of the CFEE can be driven through the workpiece over a range defined by the jointed mounting.

[0034] FIG. 1 is a schematic frontal view of a first embodiment of a CFEE of the present invention. The CFEE comprises a body 10 supporting a spindle motor 12 for friction stir working. A flange 14 for mounting to a robot arm is not in view in FIG. 1, but is in view in variations of the first embodiment. The spindle motor 12 drives rotation of a cylindrical tool body 15 with a shoulder 16 that meets a pin 18 to define a FSW tool (direction shown by arrow). It will be appreciated by those of ordinary skill that there are a variety of FSW tools, some with independent speed control of the shoulder and pin, some with retractable pins, and that the pins can have a variety of shapes, sizes and material compositions. All FSW tools share the property that they communicate a downforce through the shoulder 16 onto the workpiece(s), and that a pin stirs the plasticized, heat-affected, area.

[0035] The mounting of the spindle motor 12 preferably includes a free prismatic joint, which may be provided by vertical guides or rails, and a mechanical attachment of the body 10 to a mover 20. The mover 20 drives the plunge, downforce, and retraction of the FSW tool (direction indicated by double-headed arrow) and can deliver a force commensurate with this task (as noted hereinabove, the downforce may be 10 times the in-plane or transverse forces) so that the robot does not need to effect this motion. The mover 20 has one end secured to the body 10 and a reciprocating end coupled to a rigid casing of the spindle motor 12 via the free prismatic joint.

[0036] The body 10 has an arm 21 that couples to a backup element 22, with sufficient rigidity to communicate the downforce. The backup element 22 includes an at least one Degree of Freedom (DoF) kinematic structure joining a counter plate 25 to the backup element 22. In the embodiment of FIG. 1, the kinematic structure is a prismatic joint with a DoF shown as an arrow before the backup element 22. A range of the prismatic joint in each traversing direction is preferably linked to a dimension of the counter plate 25. The counter plate 25 offers little resistance against the downforce if the pin 18 is more than a short distance away from an edge of the counter plate 25 (the short distance depending mostly on a stiffness of the workpiece), and thus it is preferable that the counter plate 25 extend a full range of the intended weld line. Accordingly, the greater the range of the prismatic joint, and the larger the size of the counter plate 25, the longer a length of stitch can be worked. A range of actuation in the DoF (which is oriented in the direction of the length of the counter plate 25) is preferably between 25% and 125% of the length of the counter plate 25.

[0037] The kinematic structure may be a free kinematic structure, at least in one mode of operation, to minimize weight and complexity of the device, alternatively it may also include driven joints to: improve alignment and registration of the workpieces with the FSW tool 15; speed up, or smooth out in-plane movement; or to take up reaction forces from the in-plane and transverse forces. In some embodiments, the kinematic structure is locked in one (or one of many) positions while the CFEE is moving into place, and it is unlocked once the workpiece is clamped but prior to in-plane movement. The locking can be provided in a variety of ways by commanding the robot to move while the counter plate is contacting a distal face of the workpiece in a known and registered position, with simple mechanized latches, for example. Alternatively sensors can be used to measure the position of the counter plate. A more elaborate motorized position controller can be used alternatively. This motor would only be needed to drive the counter plate, or alternatively could further be used to take up reaction forces.

[0038] FIGs. 1 to 4 show a range of alternative kinematic structures. It will be appreciated that a variety of specific joints and links can be used to construct these variants and there are many mechanical equivalents. It will be noted that different combinations of the DoFs of the counter plate 25 can be provided in other embodiments of the present invention. There are a number of variants of the embodiment of FIG. 1. In each of these variants, similar features and structures are identified by common reference numerals. Descriptions of the structures are not generally repeated herein except to note differences in the variants.

[0039] FIG. 2 schematically illustrates a side view of a 2 DoF kinematic structure in the form of an XY table on backing element 22 supporting the counter plate 25'. The arrows in the drawing show that the counter plate 25' can move into and out of the page (herein the X direction), and can move right to left (herein the Y direction), and thus the downforce is in the Z direction.

[0040] FIG. 3 is a schematic side view of a 1 DoF kinematic structure wherein a pivot plate 25* pivots about an axis centred on arm 21, thus providing an arcuate, traversing DoF that involves linked X and Y movement, and is non-Cartesian. It will be appreciated that additional traversing DoFs would be required to allow for working stitches of different radii. The pivot plate 25* is an alternative form of a counter plate 25.

[0041] While FIGs. 1-3 shows only kinematic structures for in-plane movement, it will be appreciated that the kinematic structure may preferably also have additional DoFs. FSW tools typically come in two kinds: one kind that operates with a small range of "surf" angles (such as 0.5-5°, more typically from about 1.5-4°), and a second that operates at substantially no surf angle. The surf angle is an angle of tilt of the tool with respect to the local normal of the workpiece, in the in-plane direction. Effective working operation (best control of the stitch, in least time and with least reaction forces, and minimization of flashing (loss of the plasticized material)) are achieved by operating the tool with the tilt set within an operating range of surf angles. While this may be conveniently accomplished by a fixed angle of the counter plate 25 with respect to the FSW tool 15, obviating any DoF of the kinematic structure, in other embodiments, where a tool path is complicated and requires changes in rate of advance of the stitch working, or changes in direction during plunge and moving, a very small range tilt DoF may be advantageous, in a direction of the stitching (in-plane). Such small tilt DoFs may not require latching as alignment may be automatically provided by registration with a surface. As no small tilt angle DoFs are provided in variations of FIG. 2, and 3, these embodiments are suitable for FSW tools that operate with no surf angle, otherwise small tilt angle DoFs can be added. In the embodiment of FIG. 2, given that the in-plane stitch direction can at any instant be a linear combination of X and Y directions, the ability to shift these tilt angles (about Y and X) to alter surf angles may be important for FSW tools that require a surf angle. FIG. 4 shows a kinematic structure including a small tilt angle DoF.

[0042] The kinematic structure therefore may include traversing and non-traversing DoFs. The direction of movement of the counter plate 25 is an example of a traversing DoF, in that the motion in this direction allows the FSW tool to scan across the surface of the workpiece to work a stitch, whereas tilting DoFs would only negligibly traverse.

[0043] FIG. 4 is a schematic frontal view of a 2 DoF kinematic structure that includes the movement of counter plate 25 of FIG. 1 and also incorporates a tilt DoF about an axis identified by a curved, two-headed arrow. As suggested hereinabove, this tilt angle may be provided to permit control over a surf angle, in which case the range of the angle may be very small, on the order of a -5 to 5° to permit FSW in either X or -X directions. Alternatively, the tilt angle (rotation about Y) may be substantially larger, to allow for the working of stitches that extend across the workpiece that have curvatures only in this direction (see FIGs. 13a,b). While the counter plate 25 is shown planar, it will be appreciated that a counter plate adapted for a particular workpiece might not be. The embodiment of FIG. 2 with suitable tilt angle DoFs allow for FSW of bicurved workpieces.

[0044] The Y axis of the tilt DoF does move with the counter plate, but rather is fixed with respect to the axis of the FSW tool. As the FSW tool's rotary axis intersects the Y axis, the downforce is linearly independent of the tilt DoF. In all embodiments of the present invention, each of the DoFs of the counter plate 25 provided by the kinematic structure, is linearly independent of the downforce to ensure that none of these DoFs are affected by the downforce applied by the mover 20.

[0045] The Y axis tilt DoF may be supplied by an on-board motor, which may not be very bulky because of the limited range of actuation, however there is substantial advantage to using the robot's position control to ensure a tool path, and free joints have advantages over actuated joints, in terms of compliance, weight, and control complexity.

[0046] FIG. 2 also schematically illustrates a workpiece consisting of two parts 28a,b for lap welding. Only small sections of the parts 28a,b are shown for convenient illustration, closer to dimensions commensurate with of the weld than common parts. It will be appreciated that the parts may have very different shapes and may generally be substantially larger than the counter plate 25'. The variety of shapes of workpieces cannot be covered by reasonable number of drawings, and accordingly, neither can the set of surfaces the counter plate 25' would have to match the parts. Parts 28a,b are shown as generally planar sheets with some measure of forming.

[0047] It will further be appreciated that the parts may be partially formed by the surface of the counter plate 25' which may act as a mold face for the parts to impart a small change in the surface shape while joining or otherwise working.

[0048] An edge 27 is provided for abutment with a bottom part 28b, to facilitate holding the bottom part 28b in registered alignment. It will be appreciated that trivial

modifications could be made to provide for registration of both the parts 28a,b, and these could provide alignment in any number of DoF from 1 to 6. Again, as there are so many parts, and registration may be required in any number of DoFs with respective precisions, no attempt is made to illustrate all such mechanisms.

[0049] A mouth 26 of the CFEE is shown in FIG. 2. The mouth 26 is a volume of space into which an edge of the workpiece can be inserted. As FIG. 2 shows the FSW tool in a substantially retracted or open position, this represents a limit on shapes a leading edge can take and the depth limit of insertion of the workpiece into the CFEE. It will be further noted that the distance the workpiece can move in the Y direction is limited by a range of the XY table, and preferably this is chosen to preclude collision of the workpiece with the arm 21. It will be appreciated that the mouth 26 can only be designed for a range of workpieces. As such, a variety of counter plates 25, and various whole kinematic structures, preferably each have common mounting mechanical interfaces, so that the CFEE can be readily redeployable.

[0050] It will further be appreciated that a variety of counter plate measurement sensors and registration contact sensors may be used to automatically identify positions of the parts 28a,b, although these can equally be mounted to equipment for fixturing (if required) or for moving one or more of the parts into position against the counter plate 25. Furthermore, these can be integrated with mechanisms for detecting or selectively engaging the counter plate 25, to ensure a fixed position thereof, during movement of the robot when the backup element 22 is not engaged with a workpiece.

[0051] The counter plate 25 preferably has surface properties promoting frictional engagement with a variety of metallic workpieces. Herein the term "frictionally engage" is to be understood tribologically, as a surface to surface contact over a non-trivial length in each of two dimensions in which normal force increases static friction resisting transverse movements. As such it excludes rolling frictional coupling of a workpiece to a roller (nominally) at a point or line. The engagement is sufficient to resist all but microscopic relative motion between the workpiece and the counter plate, and is preferably at least one order higher, in each of the X and Y directions, than a resistance of the kinematic structure in the same directions. It may be preferable that the counter plate 25 has a tribological surface for meeting the workpiece, the tribological surface having at least a moderate friction coefficient (0.2, more preferably 0.3), that reduces marking of the workpiece, or exhibits wear resistance.

[0052] A clamping mechanism is not required in all embodiments of the present invention. A clamping mechanism may be advantageous if very light fixturing is provided, at a relatively great distance to the FSW tool, relative to the stiffness of the workpiece. The clamping mechanism may avoid deformation or surface defect of the joined workpiece under retraction forces or springback in the workpiece, if a retractable pin FSW tool is not used. Furthermore, a clamping mechanism that allows for robotic motion is particularly advantageous if: the robot is to be reoriented after frictional engagement of the backing, to change a location of plunge while the workpiece remains in registration; or a FSW process with a constellation of spot workings are required whilst in registration.

[0053] FIGs. 5A,B are side elevation views of a variant with a tool-side mechanism for clamping the workpieces against the counter plate 25, while allowing robotic motion across the surface in two directions. The tool-side mechanism includes a prismatic frame 29 that is mechanically grounded to the rigid casing of the spindle motor 12 (or otherwise to the reciprocating end of the mover 20). The frame 29 consists of four (only two in view) independently sprung housings that are coupled at the bottom edges (although any other number of independently sprung housings could be used, such as 1-10). Each housing is a telescopic joint with inner and outer races 31 that are spaced apart by a respective spring 30. The spring constants of the springs 30 are chosen or calibrated so that frictional engagement of the workpiece to the counter plate 25 is assured prior to contact of the FSW tool with the workpiece.

[0054] Roller elements 32 at the bottom surface of the tool-side mechanism ensure that the FSW tool can move across the surface of the workpiece while contact is maintained. While roller elements 32 may be spherical bearings as shown or U-jointed casters, in lower DoF embodiments they may be wheels, or skids. Preferably this movement does not mark the surface of the workpiece. While the position in FIG. 5A shows the tool-side mechanism significantly reducing access to the mouth 26 of the CFEE, it will be appreciated that the drawings exaggerate the action to make it clear. The springs 30 may be pre-compressed to improve compactness and apply the desired force. FIG. 5B shows the tool-side mechanism frictionally engaging the counter plate 25.

[0055] FIGs. 6A,B are respectively schematic front and side views of a counter-side clamping mechanism. The counter-side mechanism is grounded to the counter plate 25, and consists of two clamps 35a,b and their respective drivers 34a,b. The clamp 35a is shown in a minimally extended position, while clamp 35b is in a more advanced pose. Nonetheless, the clamps may be designed to actuate together. Furthermore the clamps can be different in number, shape, actuation or design. In an alternative embodiment, one or both of the clamps 35a, are further adapted to grip the backup element 22

(latching) when the counter plate 25 is in a predefined position, as this allows for better control over the envelope of the CFEE during movement to and away from the part, and more accurate positioning of the counter plate 25 against the workpiece. For FSP, FSAM, or lap-welding, the clamps would only be needed to supply a force for stabilizing the workpiece against bending, sagging, buckling or crumpling, to further reduce fixturing.

[0056] As indicated hereinabove, butt welding and other configurations that require gap management, call for more substantial clamping between the joining faces. FIGs. 7 and 8 schematically illustrate counter-side, and tool-side butt weld clamps on variants of the present invention, respectively. A longer, narrower tool pin 18' is shown, to ensure deeper penetration into the weld, as the butt weld joins thicker parts 40. It will be appreciated that thinner parts can be butt welded by providing substantial support of the workpieces over more of the workpiece, such that the clamps cover the bottom of both workpieces (side edges opposite the welded edge, if available) and most of the top surfaces of the workpieces away from the shoulder.

[0057] FIG. 7 shows a counter-side (mounted) gap management mechanism with clamps 38 pushed by movers 36. The clamps 38 and movers 36 are carried by the counter plate 25 and do not interfere with the motion of the counter plate 25. In such an embodiment, the robot drives the tool pin 18' maintaining a position straddling the workpieces 40, which is the in-plane direction: at the instant shown, this is the X direction.

[0058] FIG. 8 schematically illustrates a tool-side (mounted) gap management mechanism with casters 42 having bearing rollers 44, that are mechanized to be brought into contact with the sides of the parts 40, and to apply a clamping force to press the parts 40 together, without impeding the robot-applied in-plane and transverse forces, or the mover's C-frame actuation. The mechanization allows for a lowering of the casters 42, as well as their closure, relative to the FSW tool. A symmetric motor 46 is used to drive the opening and closure of the casters 42, via bars 45.

[0059] While it would be very difficult to clearly illustrate, it would be best to incorporate both tool-side and counter-side mechanisms for gap management, as they are substantially complementary. The counter-side mechanism may provide a higher clamp force efficiently to only a relatively small fraction of the extent of the workpiece in the X direction, at a fixed position on the counter plate (where plunge is planned). The tool-side mechanism is adapted to apply clamping force at a fixed distance from the FSW tool, and so applies the clamping force locally, without requiring clamping where it is not called for. As butt welding requires a substantially greater force initially, when no part of

the weld has been established, the joint effects of the counter-side and tool-side mechanisms can be compounded where needed, initially, and the tool-side mechanism and the already established weld, cooperate to provide the required gap management throughout the remainder of the weld. As a result, minimal clamping is provided while meeting the gap management requirements at each point.

[0060] FIG. 9 is a schematic flowchart showing principal steps in an embodiment of a method of FS-W, in accordance with the present invention. The process begins at step 47 when a workpiece is in position between a backup and FSW tool of a CFEE. Accomplishing this step may involve moving the robot over a large workpiece that has no local fixturing, but is supported remotely. Depending on a size, weight and stiffness of the workpiece, different support and fixturing arrangements may be provided.

[0061] In one extreme, a powder-coated, spray coated, or other film-treated thin metallic sheet (or non-coated sheets for microstructure enhancement) for FSP or FSAM is supported substantially only by the backup, with the reaction forces taken up by on-board actuators. A resistance to robotic movement when clamped, in the in-plane and transverse directions, must be provided. While the workpiece cannot move with respect to the counter plate 25 because of Coulomb friction that arises from the substantial downforce, depending on the stiffness of the sheet (workpiece), the whole reaction forces of the in-plane and transverse forces are taken up only by the stiffness of the workpiece and/or the on-board actuators. Alternatively, if on-board actuators are not provided, the sheet may be clamped orthogonal to the in-plane direction at a location upstream of the in-plane direction, so tension in the sheet resists the reaction force. In less extreme examples, the workpiece will have a stiffness that can be leveraged, or more local fixturing can be supplied.

[0062] It should be noted that the in-plane and transverse forces are typically an order of magnitude less than the downforce, and accordingly, the fixturing required to stabilize against the reaction forces are substantially lighter, less obtrusive, and more easily reconfigured than those that support downforce, if on-board actuators are not provided to take up this force, and the stiffness of the workpieces are not sufficient.

[0063] The workpiece, may be arranged by a machine other than the robot, in which case the CFEE may be stationary while the workpiece is moved into position. The same robot with a different end effector might have been used to place the workpiece in a fixturing prior to the CFEE being connected to the robot. Furthermore the CFEE may be equipped with surfaces for registering, aligning or laying the workpiece, or parts thereof.

[0064] In general there are at least two approaches for ensuring that the stitch is well placed. The robot's accuracy may be relied upon and a separate fixturing may be used to provide the workpiece with a suitable accuracy for robotic working. If accuracy of the counter plate positioning is not sensitive (either because the counter plate is larger than the weld pattern or because pressure from the clamps or plunge will automatically seat the workpiece at a given orientation to within satisfactory tolerances), no more registration may be needed. If specific position and orientation of the counter plate is needed, latching, or sensor data can be used to coordinatize the counter plate and effectively select the orientation and alignment of the counter plate as it meets the workpiece.

[0065] A second method for ensuring that the parts are in place, involves reliance on registration features of the counter plate. Once the workpiece is in registration with features of the counter plate, it is no longer relevant where the robot is in space, and relative positions with high accuracy can be chosen relative to the first registered position. Thus any mechanized feed or fixturing can be used to bring the workpiece into registration, and any external or internal robotic sensors can be used to provide the registration. On-board sensors can be used to identify marks or features of the workpiece and guide the robot towards the features, and determine whether alignment is satisfactory, and may further marking may be helpful to identify location for plunge.

[0066] In welding processes, two or more separately movable parts (entirely separate items or edges of a common workpiece) of the workpiece need to be both registered in respective positions. The complication of ensuring position of both of the parts relative to each other, as well as the workpiece to the CFEE may require further equipment. If one of the parts has far greater stiffness than the other, such as often occurs when bonding a sheet to a structural member (e.g. stiffener or rib), the stiffer part may take up the reaction forces. In most weld configurations, downforce is of great assistance in ensuring stability of parts, because the Coulomb friction resulting from the downforce makes sliding of the parts once frictionally engaged, well resisted. Thus, correct initial registration of sheets may be particularly important, and may require some lightweight machines. In some embodiments, machines are used to tension, or even deform, one or more parts of the workpiece before a first stitch is worked, between stitch workings, or even during stitch working to impart a desired stress. In butt joint type configurations, as described above, more substantial clamping is required to provide gap management, but this clamping tends to obviate the need for additional fixturing, at least in the vicinity of the working.

[0067] Once the workpiece is in place within the mouth of the CFEE, on-board movers are used to clamp the workpiece and plunge the FSW tool into the workpiece

(step 48). The clamping may be performed by: a separately operated clamp mounted to the CFEE; a) a clamp mounted to the CFEE that is operated by a same mover that performs plunge, but prior to contact between the FSW tool and the workpiece; b) by the FSW tool that presses the workpiece against the backup during plunge; or c) by the robot which presses the counter plate against a distal face of the workpiece, this pressure being resisted by sufficient weight of the workpiece, or fixturing, to frictionally engage the workpiece to the counter plate. Once the frictional engagement is established, according to a) or c), the FSW tool is advantageously free to move within a range defined by the kinematic structure, in between 1 and 5 DoFs. The only DoF with which the CFEE is constrained not to move in is the Z or plunge direction.

[0068] Once the FSW tool is plunged into the workpiece, under the drive of the on-board mover, the FSW tool continues to maintain downforce, and the rotation of the FSW tool. The robot is then commanded to move in-plane and applies in-plane and transverse forces (step 49) necessary to accomplish a preset tool path, preferably in motion control mode. The FSW tool moves through the plasticized workpiece to stitch a length of work.

[0069] It will be appreciated that the FSW tool may be retracted and plunged at a plurality of points on the workpiece within the ambit of the counter plate. If a clamping mechanism is provided to keep the workpiece in place between retraction and plunge, improved accuracy of positioning can be provided. Additionally, the same CFEE can also be used to spot work any constellation of points within the ambit with the accuracy provided by the robot. An advantage of FS-W over FS-W, is that the in-plane and transverse forces are not applied, and accordingly fixturing required to resist the reaction forces can be avoided. An advantage of FS-W over FS-W is a strength of the joint per processing time.

[0070] FIGs. 10A,B are schematic illustrations of an exemplary CFEE 50 of the present invention that is intended to be built as a prototype. To facilitate viewing, FIG. 10A shows an enlarged view the CFEE 50 mostly below a spindle motor 52 casing, without any robot, to which the CFEE 50 is mounted, and without any workpiece. In FIG. 10B, the CFEE 50 is robot-mounted and a workpiece 68 is provided. Specifically a flange 54 of the CFEE 50 is mounted to a wrist flange 88 of a robot 80, via a 6 DoF force sensor 86. The 6 DoF force sensor 86 is useful for monitoring reaction (in-plane and transverse) forces during stitching, for example, in accordance with the teachings of Applicant's pending PCT patent application WO 2016/151360 (the contents of which are incorporated herein by reference), which will be used to permit accurate stitching with a

robot that exerts a force that exceeds the robot's stiffness limits. The force sensor 86 is rigidly mounted to a frame 63, which is a fixed end of the CFEE 50.

[0071] As seen in FIG. 10B, the spindle motor 52 and mover 60 are mounted to the frame 63. A stator end of the mover 60 is held by the frame 63, via a set of 3 (shear action) load pins 90 that are used to control force feedback to the mover 60 (two in view in FIG. 10B, but all three clearly shown in FIGs. 12A). The load pins 90 output is used for a closed loop feedback system in order to provide an accurate clamping force. Each pin has a capacity of 10 Kn.

[0072] A bottom of the spindle motor 52 is shown in FIG. 10A coupled to a FSW tool 55, with a pin 58 for stirring, and a shoulder 56 for applying the downforce. In the specific example, the spindle motor is a Siemens servomotor model number 1FE1082-6WP30-1BD2. It was chosen over an Etel motor that was selected at first, but the Etel motor had too many poles, and was limited in rotational speed by the maximum frequency output of available drives. The bulkier Siemens motor has fewer poles but has similar power and torque that are more linear through the rpm range. Rated power, torque and rpm are respectively 34 Kw, 65 Nm and 5000 rpm.

[0073] In FIG. 10A the mover 60 is in a retracted pose, whereas in FIG. 10B the mover 60 is in a substantially extended pose. The mover 60 is a ball screw drive linear actuator, with a threaded shaft 61 shown in FIG. 10B, although any other mover could have been used that provides the necessary force, power and control required. It will be appreciated that while the downforce must be maintained at a minimum level during FSW, there is little consequence for incrementally too much force, and accordingly a relatively low accuracy is needed, compared to positioning control, in many applications. In the specific example, the mover 60 is driven by a Siemens servomotor model number 1FW6050-0WB03-0FC1 via a ball screw system. The rated torque of the motor is 22.3 Nm at 940 rpm. The ball screw system is from Bosch Rexroth, model number for nut and screw are respectively FEM-E-S 40x5Rx3.5-5 and SN-R 40x5Rx3.5. A pitch of 5 mm results in an available downforce of 28 Kn.

[0074] The frame 63 further provides two rails 91 (only in view in FIGs. 12A,13A) and runner blocks (not in view) for guiding plunge of the spindle motor 52 in the Z direction, under the mover's drive. The runner blocks are not in view as they are between the frame 63 and the spindle motor casing 52. Projections 93 extends from the spindle motor 52 on opposite sides of the spindle motor 52, passing through guideway 92 without contacting the guideway 92. Thus operation of the plunge causes these projections 93 to reciprocate along the guideway 92. The projections 93 have stops above and below to

mechanically abut against top and bottom surfaces of the guideways 92, to stop plunge or retraction outside of a preset range, in the event of a control failure.

[0075] Below bottoms of the guideways 92, the frame 63 meets respective prismatic, Y-axis joints supports, defined by rails 78a,b, and fitting channels in runner blocks 79a,b. The rails 78a,b are rigidly mounted to respective branched arms of a horseshoe table 51. A pneumatic drive 83 is provided for controlling the Y direction motion, and is coupled to the rails 78a,b and runner blocks 79a,b. The Y direction pneumatic drive is provided by two SMC pneumatic cylinders model CQ2B50 mounted back to back, and will provide three possible positions: fully retracted when both cylinders are in retracted position, fully extended when both cylinders are in extended position and middle when one cylinder is retracted and the other one is extended.

[0076] One advantage of using an on-board drive for the Y Cartesian DoF, is that the placement of the workpiece 68 with respect to the initial disposition of the counter plate 65 is at a known position of the robot end flange 88, which may simplify control for some applications. It should further be noted that a driver is not required, as a simple latching mechanism can suffice. Alternatively the counter plate 65 can be completely free. In such a case, prior to clamping a feeding mechanism may be used to ensure registration of the workpiece 68 with respect to the counter plate 65, at a preset (taught) position and orientation, and the robot then moves the wrist flange 88 to a start position that is within the ambit of the kinematic structure (if necessary) to begin. It will be noted that various control schemes can be used that involve additional sensors and actuators onboard the CFEE, or can be provided by fixturing or other metrology systems.

[0077] A pair of encoders 82a,b are provided to sense a position of the Y direction motion, in conjunction with a strip of sensed medium (which is preferably magnetic, but may also be optical or possibly electric), to provide feedback for the pneumatic drive 83. Specifically Lika SHD2 linear encoders were selected, although a variety of equivalent encoders could have been used. While two of these encoders are shown, only one would typically be called for; the second is used to increase accuracy, and for symmetry.

[0078] A fixed arm 61 extends from the horseshoe table 51, providing a curvature of the C-frame of the CFEE 50 (as best seen in FIG. 12B), and defining the mouth of the CFEE 50. The fixed arm 61 completes a bend of the mouth to bring a backing element 62 (FIG. 10B) in line with the FSW tool 55 axis. Specifically, a revolute joint 74 is mounted to the fixed arm 51 to provide a free rotation about the Z axis (see FIGs. 12A,B). A free end of the revolute joint 74 is coupled to a set of bearing rollers 75 (only one clearly in view). The bearing rollers 75 are mounted in an X direction guideway 76 in a T frame supporting a counter plate 65, which permits translation in the Cartesian X

direction, as well as revolution about the Y axis, of the counter plate 65. The bearing rollers 75 meet the raceway 76 and spin freely. An axis of the bearing rollers is sufficiently perpendicular to an axis of the FSW tool, that the downforce is linearly independent of the movement of counter plate 65, and also with the pivoting of the counter plate 65 along the axis of the bearing rollers 75.

[0079] Thus in the example, a kinematic structure is provided that includes Cartesian Y and then X joints suspended from the frame 63 (the Y joint couples to the horseshoe table 51, which is coupled to a rotary joint 74 for providing a rotation about the Z axis, by a arm 61, and the rotary joint is coupled to a Y axis rotary, X axis Cartesian prismatic joint provided by bearing rollers 75 in a guideway 76) and a Z joint for the spindle motor 52. Each of these joints has a fixed range that is defined for a respective process with a given part configuration.

[0080] The counter plate 65 has, at two opposite ends, automatically actuatable clamping mechanisms 72a,b with clamp faces 71a,b. These permit the clamping of workpieces having a range of dimensions, to the counter plate 65.

[0081] The CFEE 50 includes a kinematic structure of free joints that decouple the FSW tool from the counter plate 65 in X and Y, as well as about Y, and Z, 4 of the 5 DoFs possible are provided. The only DoF unaccounted for is rotation about the X axis.

[0082] The clamps 71,2a,b, counter plate 65, kinematic structure, arm 61 and horseshoe table 51, have considerable inertia and moment. As explained hereinabove, to ensure accurate registration of the FSW tool and counter plate 65, the CFEE 50 may: monitor these independent motions by way of encoders or measurement systems; use a mechanical latching system that allows for registered positioning; or these joints could have low power drivers that either disengage or cooperate with actuation of the robot during FSW. The cooperation may involve moving in a same direction to increase available force and therefore the speed of the working; or alternatively may be in an opposite direction, to take up the reaction forces to the in-plane and transverse forces.

[0083] The latching system preferably is engaged at particular positions of the joints, and can be released automatically, or can be overborne by moving the robot 80 when frictionally engaged, but is not overborne by expected inertial forces applied during free movement of the CFEE 50. Features 84, visible on the underside of the counter plate 65 of FIG. 10B, are a corresponding part of a detent-based latching system that permits the counter plate 65 to be latched in 3 specific positions (right, center, or left). The detent-based latching system shown locks the counter plate 65 in both X position and in rotation about the Y axis. The Y axis motion is controlled by a pneumatic driver described above.

[0084] FIGs. 11A-H collectively show a sequence for FS-W a stitch in accordance with an embodiment of the present invention, using the CFEE 50. FIGs. 11A-C correspond to an example of step 47 of FIG. 9, in which no registration element is used and a position and orientation of the workpiece 68 is ensured by fixturing 85 remote from an intended stitch path 69. Workpiece 68 is provided as two clamped parts for lap welding. The workpiece 68 is stationary as the CFEE 50 is moved into place by moving the counter plate 65 underneath the workpiece 68 at a desired position (FIG. 11B), with the counter plate 65 parallel to a bottom face of the workpiece 68 (below intended stitch path 69). The robot 80 is then actuated to bring a meeting surface of the counter plate 65 against a distal side of the workpiece 68. Specifically, the counter plate 65 might have been slightly below the unflexed workpiece 68, it may meet the workpiece 68, or it may lift the workpiece 68 a desired amount or apply a prescribed force from below, in different processes. In the last case, resistance between the distal side of the workpiece 68 and counter plate 35 may provide reliable frictional engagement. In FIG. 11C, the counter plate 65 is raised to meet the bottom of the workpiece 68.

[0085] With the workpiece 68 now in position, as shown in FIG. 11D, the clamping mechanisms 72a,b are engaged to frictionally engage the workpiece 68 to the meeting surface of the counter plate 65. If there is an actuatable latching system, it is now released as the counter plate 65 is stable with respect to the workpiece 68, and the robot 80 retains the degrees of freedom provided by the kinematic structure, over the respective ranges each DoF allows. As the clamping mechanisms 72a,b in this embodiment allow independent movement of the FSW tool, the FSW tool may move into position with respect to a starting point of the intended stitch path 69. This step may be necessary if there is a low accuracy registration of the clamped workpiece 68 with respect to FSW tool, and the position of the counter plate 65 is not accurately controlled, or the counter plate 65 is adapted to meet the workpiece 68 at only one position, which does not align the FSW tool with the starting point at a latched position.

[0086] The spindle motor 52 is actuated to drive the FSW tool, and the mover 60 is actuated to plunge. With a fixed FSW tool as shown, the tool pin 58 is inserted until the FSW tool shoulder 56 makes contact with a top surface of the workpiece 68. It will be appreciated that some FSW tools are designed with retractable tool pins, that allow for the shoulder of the FSW tool to apply downforce first, and then for plunge of the tool pin. Furthermore, a side entry into the workpiece may be preferred in some embodiments. FIG. 11E shows the result of a plunge operation, actuated by mover 60. The application of downforce once plunged, and the rotation of the FSW tool shoulder, plasticizes the material underneath the shoulder 56. The tool pin 58 stirs the plasticized material. Thus FIGs. 11D,E illustrate an embodiment of step 48 of FIG. 9.

[0100] While maintaining the downforce and rotation, the robot 80 is operated to move in-plane, thereby applying in-plane and transverse forces to keep the tool pin 58 on path (69) through the plasticized material. This is shown with a first segment in the Y direction (completed in FIG. 11F), a second segment in the X direction (completed in FIG. 11G) and a final segment in the X-Y direction (completed in FIG. 11H). The logically following steps of retraction, release of the clamping mechanism, and withdrawal of the CFEE 50 are not shown as they would be identical to FIGs. 11E,D,C,B,A with the exception that the intended stitch path 69 is now stitched, unless the workpiece is deformed by the clamping and/or the downforce applied during the FSW. Applicant notes that instead of returning to the pose in step A, the CFEE 50 may be moved to a second location on the same workpiece 69, or on another workpiece, and recommence. As such the meeting surface of the counter plate 65 may serve as a mold for additional shaping of the workpiece 68.

[0101] FIGs. 12A,B and 13A,B showcase the spatially limited 4 DoF mobility of the CFEE 50 while a workpiece is frictionally engaged. FIGs. 12A,B show variation of a rotation about the Z axis. While this DoF might not appear to strictly be necessary as it doesn't change a set of stitch patterns that can be applied, in a practical embodiment, where there are mobility constraints associated with the workpiece, its tooling, or other obstructions (as the CFEE 50 and workpiece may not be symmetrical about the FSW tool axis), this DoF is likely valuable. Furthermore, this DoF is expected to be used for optimizing actuator utilization within the robot 80 (e.g. to extend service life of the robot).

[0102] FIGs. 13A,B show the robotic freedom to move about a rotation around the Y axis. This is particularly useful if the workpiece is to be worked on a surface that is curved. FIGs. 13A shows a modified counter plate 65* that is curved in the YZ plane. Specifically counter plate 65* is bicurved. No clamping mechanism is shown in this embodiment of the counter plate 65*, and as such the alignment of the workpiece, FSW tool, and counter plate must be adequate for the FSW process, at the start of the plunge, where the frictional engagement is made between the workpiece and a meeting surface of the counter plate 65*.

[0103] While the CFEE 50 has DoFs in the two Cartesian directions X, Y, as well as rotations about Y and Z, a final DoF may be provided. An additional rotation about the X direction can be provided with a joint between the frame 63 and horseshoe table 51, or around where arm 61 is labelled, or between backing element 62 and revolute joint 74 (which can be replaced with a universal joint), for example. However given the limited extent of the counter plate 65 in the Y direction, this DoF is not perceived as highly desirable for a majority of applications.

[0104] Furthermore, the intended stitch path shown was selected to showcase the freedoms of the FSW tool with the illustrated CFEE. A wide variety of stitch paths are contemplated, including non-self intersecting paths, self-intersecting paths, and multiply self-intersecting paths, where the paths may be poly-lines, curves, and line segments.

[0105] The essential features of the CFEEs described herein are shown with a minimum of view-obstructing alternative elements. It will be appreciated by those of skill in the art that a number of sensors, and devices can be added to the CFEE to improve process controls and reliability. For example, temperature control actuators and sensors, such as laser heaters and temperature sensors may improve FSW efficiency and control.

[0106] Other advantages that are inherent to the structure are obvious to one skilled in the art. The embodiments are described herein illustratively and are not meant to limit the scope of the invention as claimed. Variations of the foregoing embodiments will be evident to a person of ordinary skill and are intended by the inventor to be encompassed by the following claims.

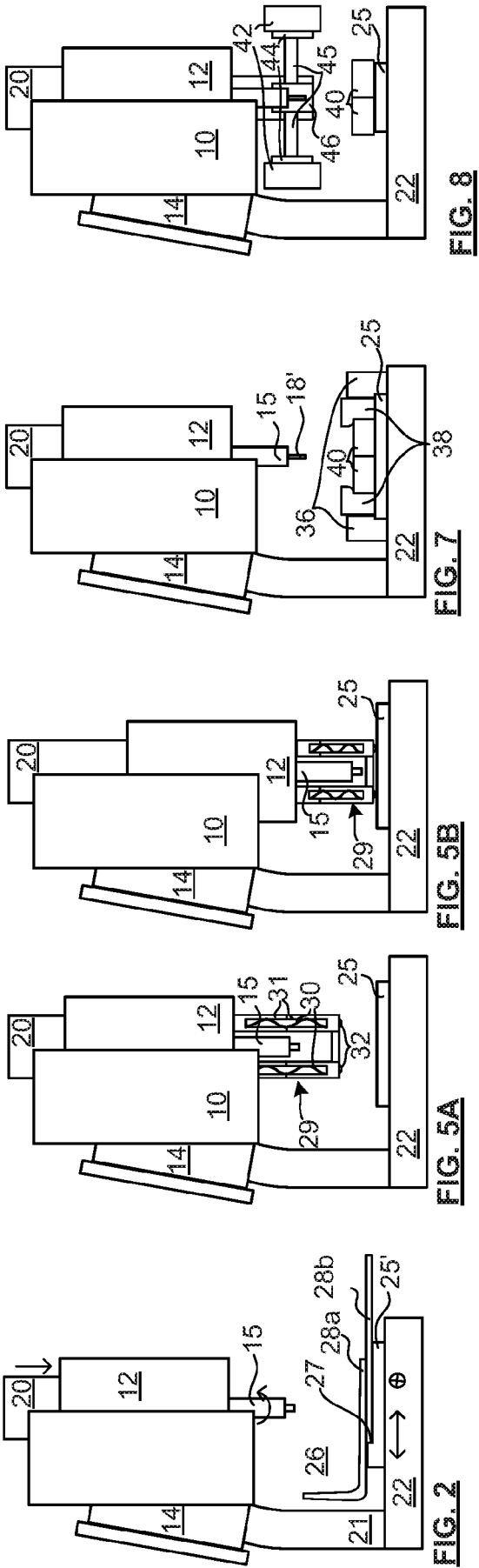
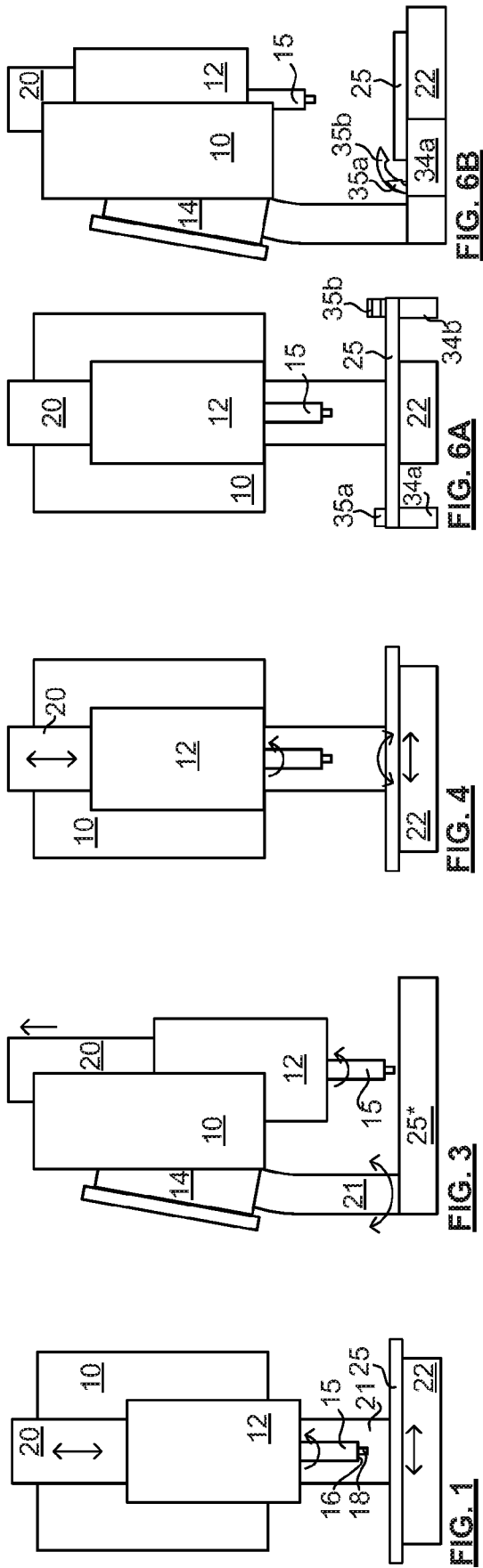
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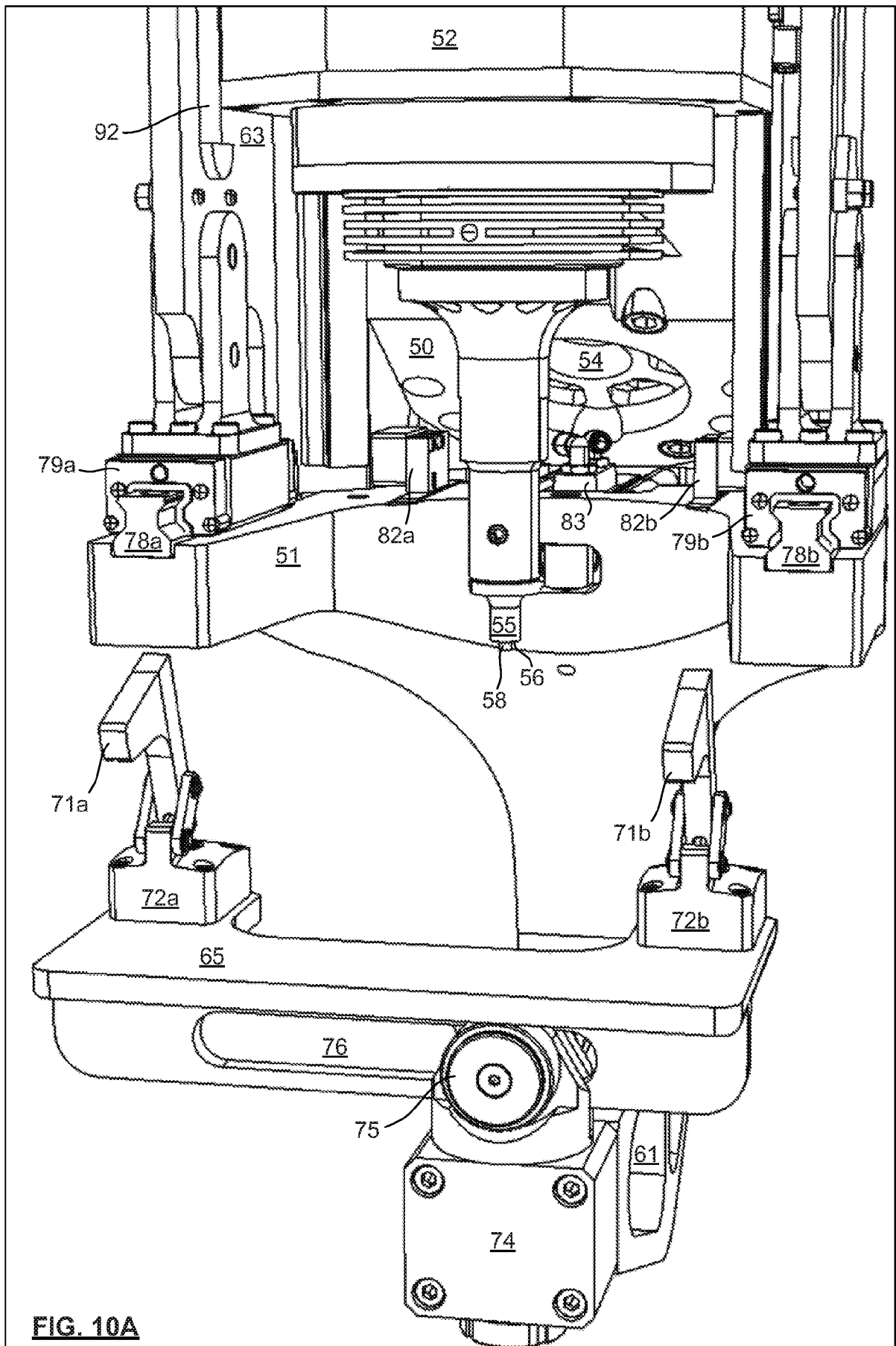
1. Friction Stir Stitch working (FS-W) a workpiece by:
moving a robot-mounted actuable C-frame end effector (CFEE) into position with respect to a workpiece, with the workpiece between a counter plate and a FSW tool of the CFEE;
operating a FSW tool with at least one on-board mover to spin the FSW tool, and press a distal face of the workpiece against the counter plate, while plunging the FSW tool into the workpiece until a shoulder of the FSW tool applies a downforce against a proximal face of the workpiece, wherein the pressing frictionally engages the counter plate and the workpiece; and
moving the robot to drive the FSW tool through the workpiece over a surface of the counter plate in at least one direction of an intended stitch while the downforce is applied and the counter plate is frictionally engaged with the workpiece;
whereby the robot drives and controls accuracy of the worked stitch within a limited range of motion between the counter plate and FSW tool in a direction that is independent of the downforce, the at least one mover applies downforce, and the counter plate provides substantial fixturing.
2. The method of claim 1 wherein operating the at least one mover comprises plunging the FSW tool into the workpiece with the counter plate meeting the distal face across a full extent of the workpiece that spans the stitch.
3. The method of claim 2 further comprising operating a clamp carried by the CFEE to press a clamp face against the proximal face.
4. The method of claim 3 wherein operating the clamp comprises applying a clamp force sufficient to frictionally engage the counter plate to the distal face, and fix the counter plate with respect to distal face, prior to plunge.
5. The method of claim 3 or 4 wherein operating the clamp comprises applying a clamp force prior to a step of retraction, to stabilize the workpiece during retraction.
6. The method of any one of claims 3 to 5 wherein the clamp face is operated by at least one of the at least one movers via an elastic element, the elastic element applying the clamp force during a first part of a down stroke, prior to plunge.
7. The method of claim 6 wherein the clamp face comprises a rolling element that permits the clamp to apply pressure to the proximal face, while moving across it.

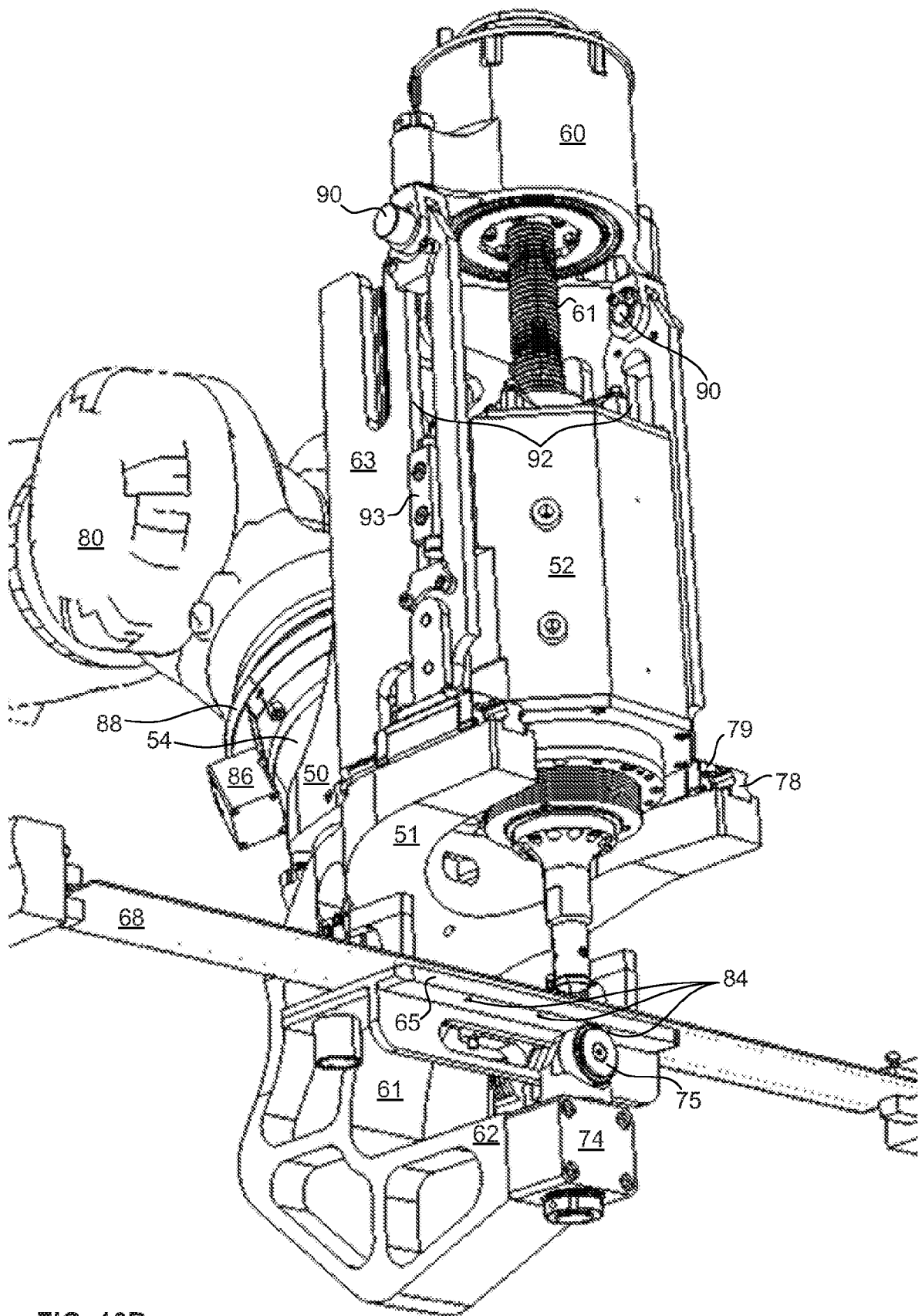
8. The method of any one of claims 3 to 5 wherein the clamp is mounted to the counter plate.
9. The method of any one of claims 3 to 8 wherein the robot is only free to move across at least 50% of a full extent of the limited range, while pressing the clamp face against the proximal face, and repositioning of the FSW tool prior to plunge is permitted because of a joint between the counter plate and FSW tool that provides the limited range.
10. The method of claim 9 wherein the limited range joint is a part of a kinematic structure joining the counter plate and FSW tool, the kinematic structure having at least 2 DoF, and at least one DoF is a free joint.
11. The method of any one of claims 1 to 10 wherein the proximal face and distal faces are of separate parts of the workpiece, or are parts of two or more separate members, that are joined by the FS-W.
12. The method of any one of claims 1 to 11 wherein moving the CFEE into position comprises one or more of:
 - moving the CFEE by operation of the robot;
 - moving the workpiece by a fixturing system;
 - moving separately one of two or more parts of the workpiece into registration with the fixturing;
 - moving separately one of two or more parts of the workpiece into registration with the counter plate;
 - moving separately one of two or more parts of the workpiece into registration with the clamp face; and
 - sensing a registration of the separately moved one or more parts.
13. The method of any one of claims 1 to 12 wherein the meeting surface is substantially planar, simply curved in one direction, bicurved in one direction, convex, concave, or a smooth continuous surface relative to a shoulder of the FSW tool.
14. The method of any one of claims 1 to 13 wherein after the FSW tool is retracted, the distal face of the workpiece has a shape of the counter plate, which is different than a shape of the workpiece when the CFEE was moved into position.
15. A Friction Stir Working (FSW) C-frame end effector (CFEE) comprising:
 - a mounting end for mounting to an end of a robot;

- a C-frame with a mouth for receiving an edge of a workpiece to be friction stir worked between first and second opposing ends;
 - a FSW spindle motor at the first end, the motor defining a spindle axis;
 - a counter plate at the second end, the counter plate having a surface for meeting a distal face of the workpiece, the meeting surface having a first extent in a first parametrized direction that is greater than 2 mm;
 - a first mover for closing and opening the FSW tool with respect to the counter plate adapted to deliver a downforce for FSW working with the FSW tool; and
 - a kinematic structure joining the counter plate to the FSW tool, the kinematic structure including a first joint with at least one first traversing degree of freedom (DoF) with a given range, where the traversing DoF is effectively linearly independent of the action of the first mover, and the range is spatially limited to continuously span all and only 25% to 125% of the surface's first extent.
16. The FSW CFEE of claim 15 wherein the kinematic structure further comprises a non-traversing revolute joint that has a revolute axis that meets the spindle axis at or near the surface.
17. The FSW CFEE of claim 15 wherein the first traversing DoF is provided by a revolute joint having an axis parallel to an axis of the FSW tool, these axes being separated by at least 50% of a maximum extent of the counter plate.
18. The FSW CFEE of claim 15 wherein one or two traversing DoFs of the kinematic structure are provided by linear prismatic joints.
19. The FSW CFEE of any one of claims 15 to 18 wherein the meeting surface further has a second extent in a second parametrized direction that is independent of the first parametrized direction, and the kinematic structure comprises the first traversing DoF that spans 70-110% of the first parametrized direction, and further comprises a second traversing DoF that spans 5-110% of the second parametrized dimension.
20. The FSW CFEE of claim 15 wherein the kinematic structure comprises a plurality of joints spanning 4 DoFs orthogonal to the first mover's action.
21. The FSW CFEE of any one of claims 15-20 further comprising a clamp for pressing on a top surface of the workpiece in a direction parallel to an axis of the FSW tool on at least one side of the FSW tool.

22. The FSW CFEE of claim 21 wherein the clamp is mounted to one of the first and second ends.
23. The FSW CFEE of claim 22 wherein the clamp is mounted to the first end, and has roller elements for facilitating movement across a surface of the workpiece while clamped.
24. The FSW CFEE of claim 22 wherein an actuator of the clamp is operable to latch the counter plate in a fixed position.
25. The FSW CFEE of any one of claims 15-24 wherein the counter plate has:
- a friction coating;
 - a registration feature for meeting the workpiece in a reliable position;
 - a registration sensor for sensing a position and orientation of the workpiece;
 - a curvature to match a distal face of an intended workpiece;
 - a curvature to match an intended form of the workpiece that is different from a shape of a workpiece as supplied; or
 - a substantially planar surface to match a distal face of an intended workpiece.





**FIG. 10B**

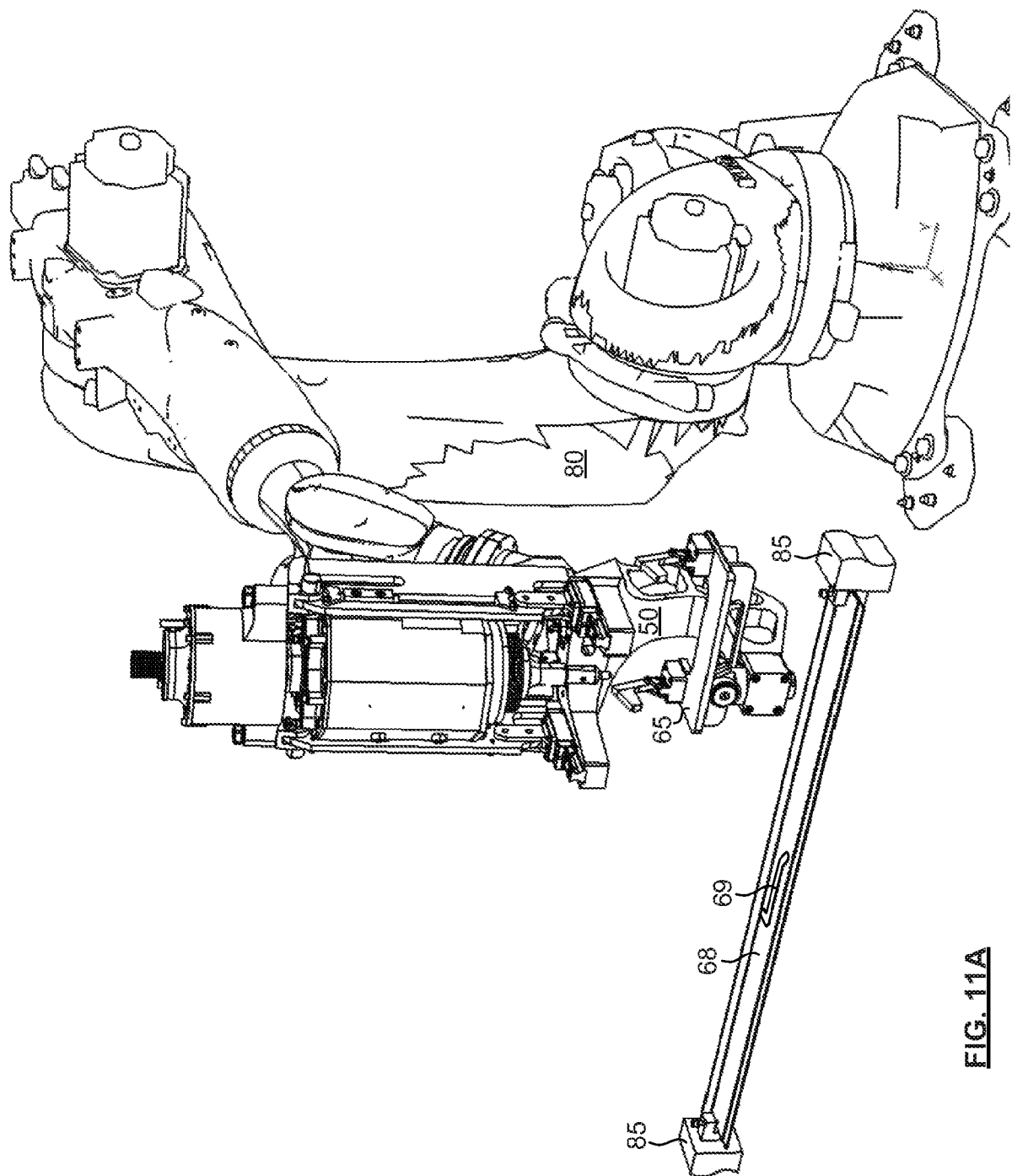


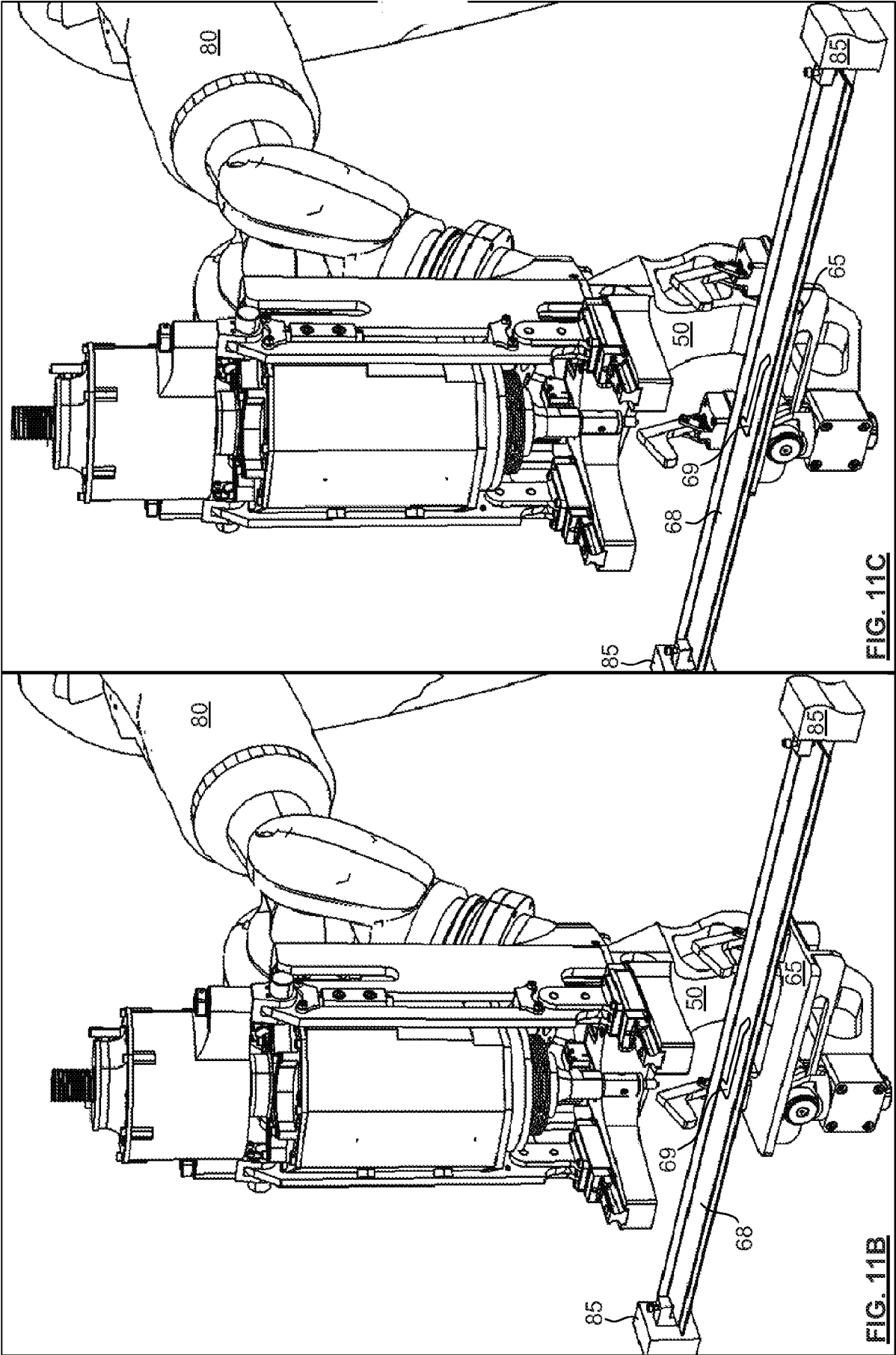
FIG. 11A

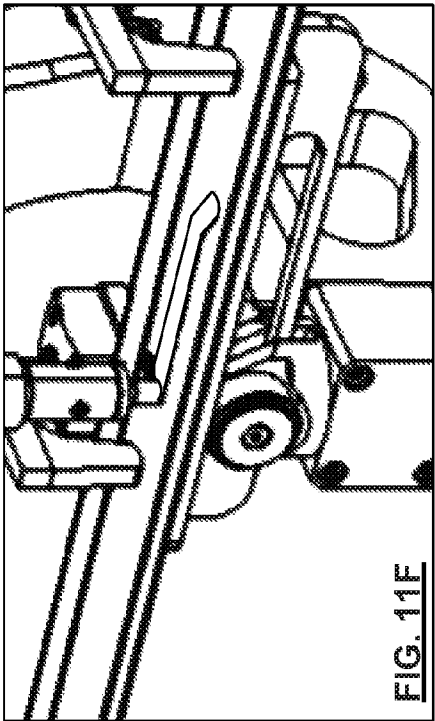
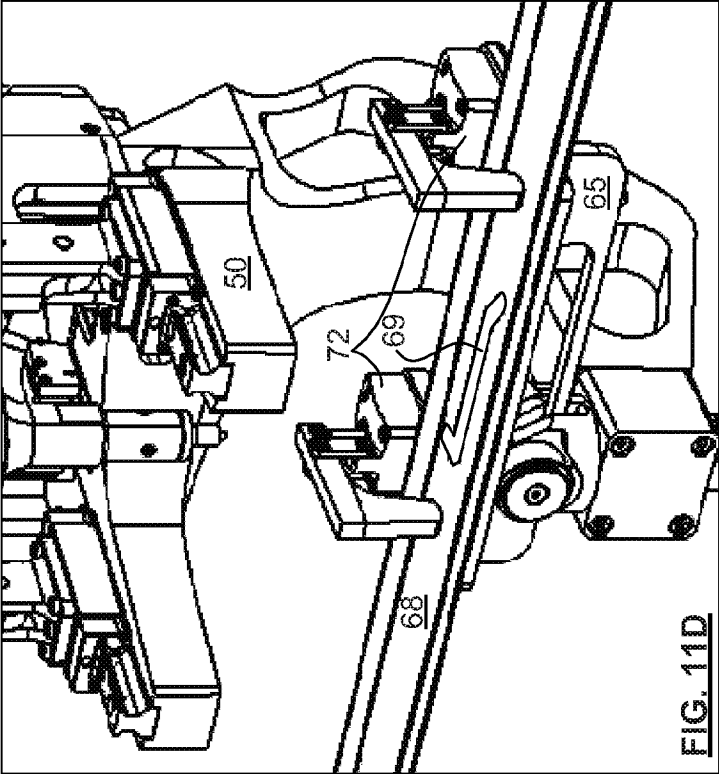
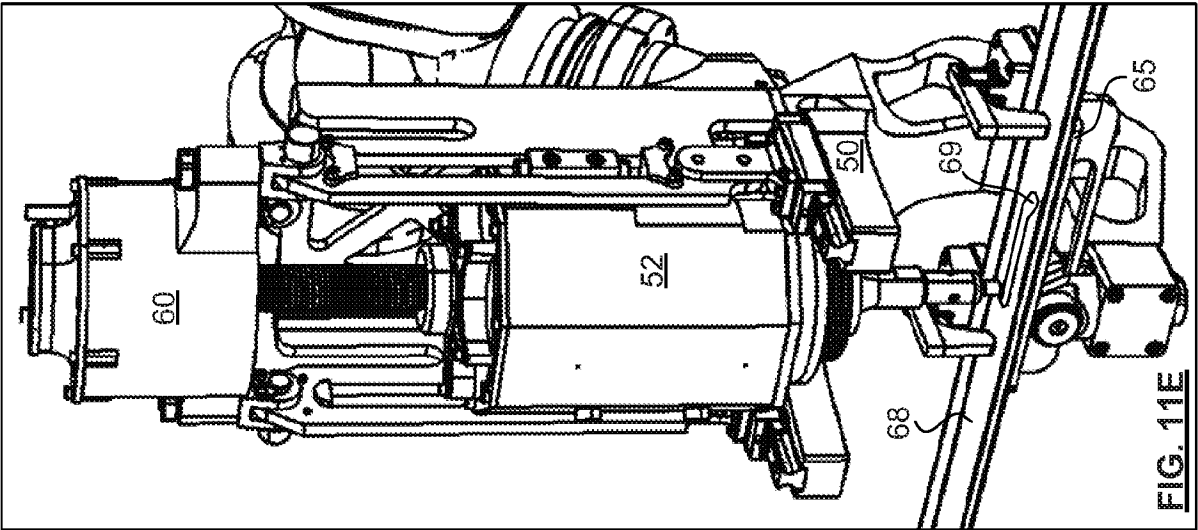
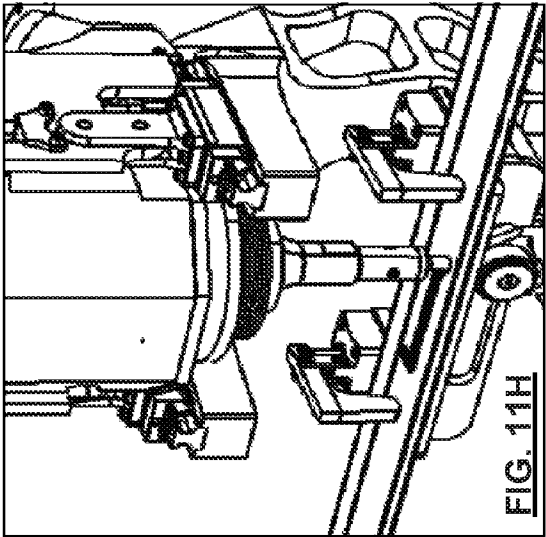
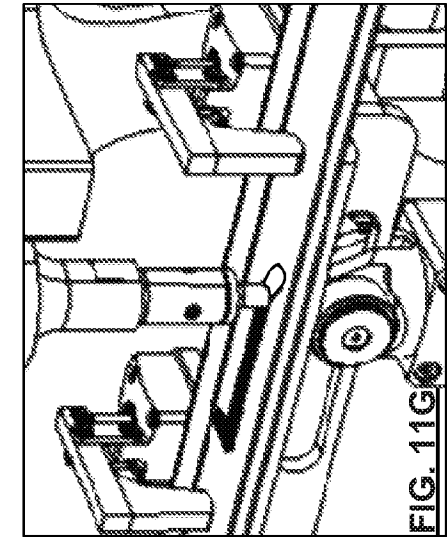
Operate robot and/or
fixturing to bring CFEE
47 into position with
workpiece between
backup and FSW tool

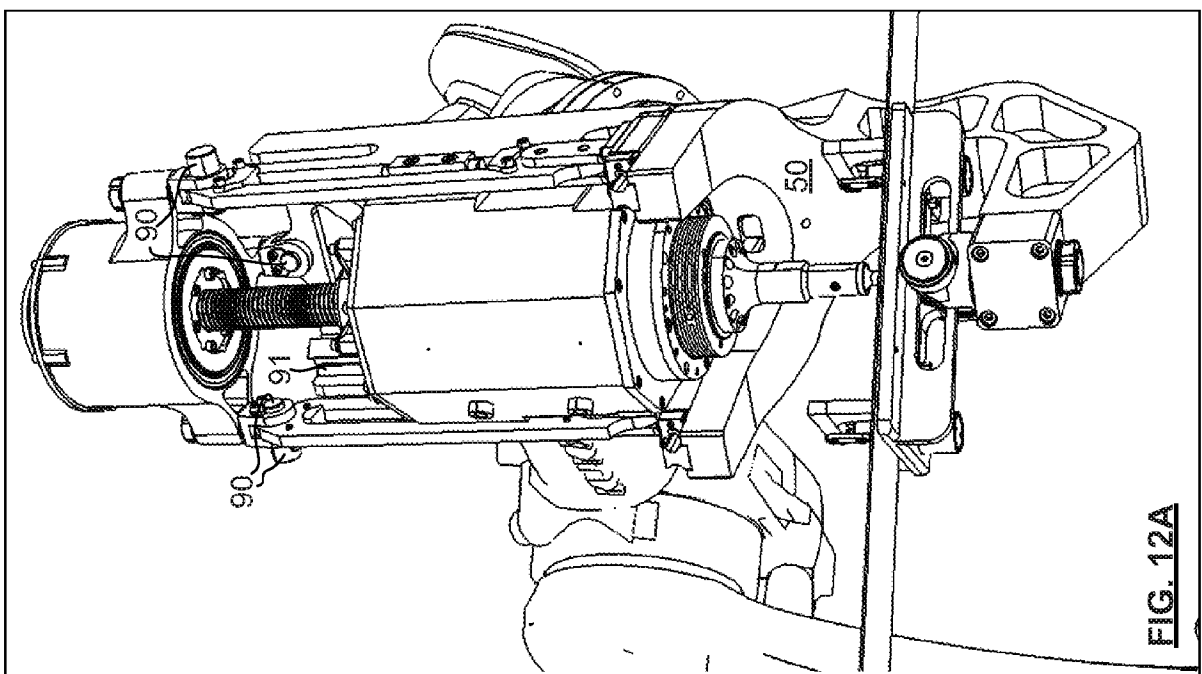
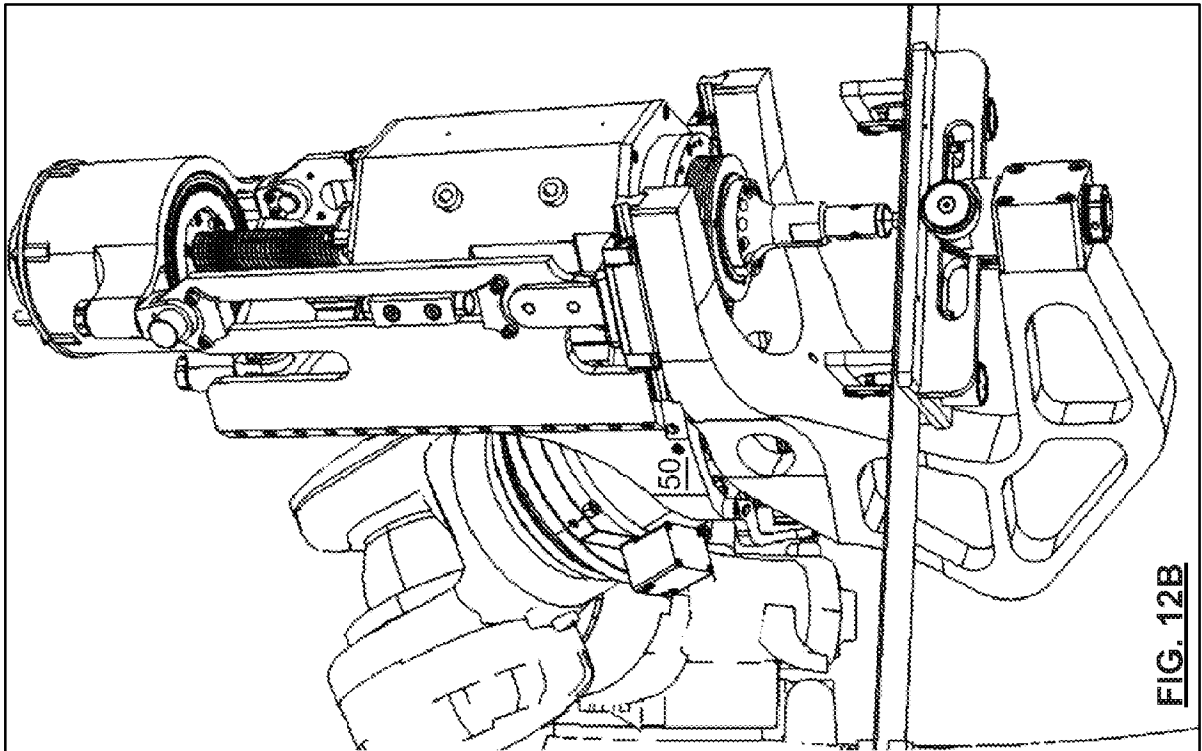
Operate on-board movers
to clamp and plunge, 48
frictionally engaging
backup with workpiece

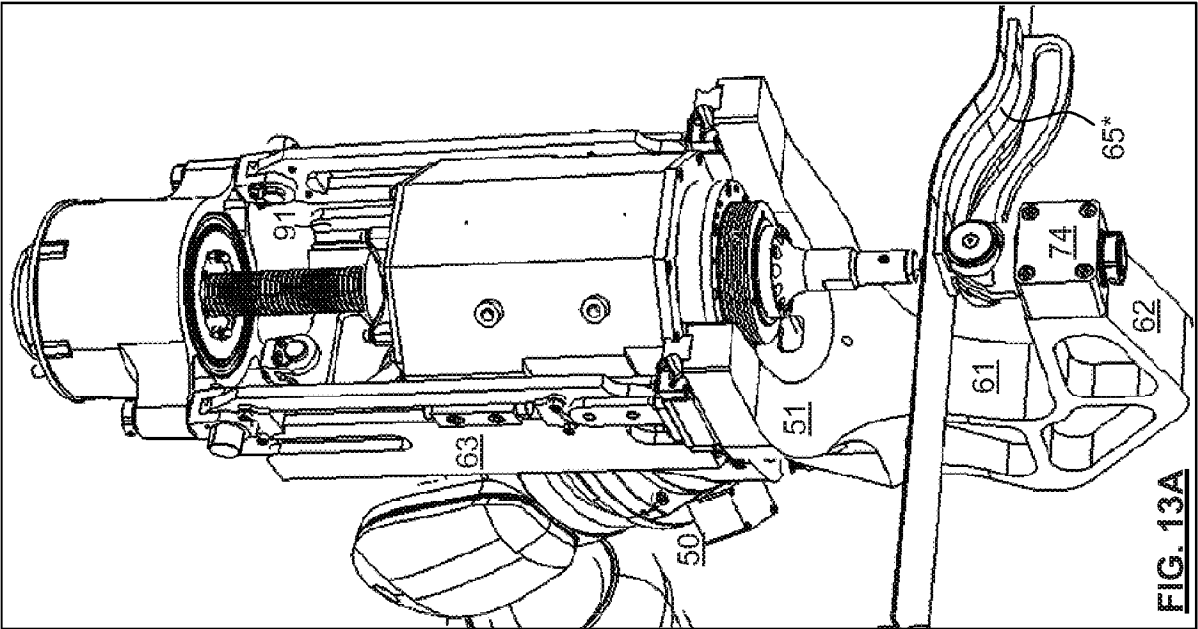
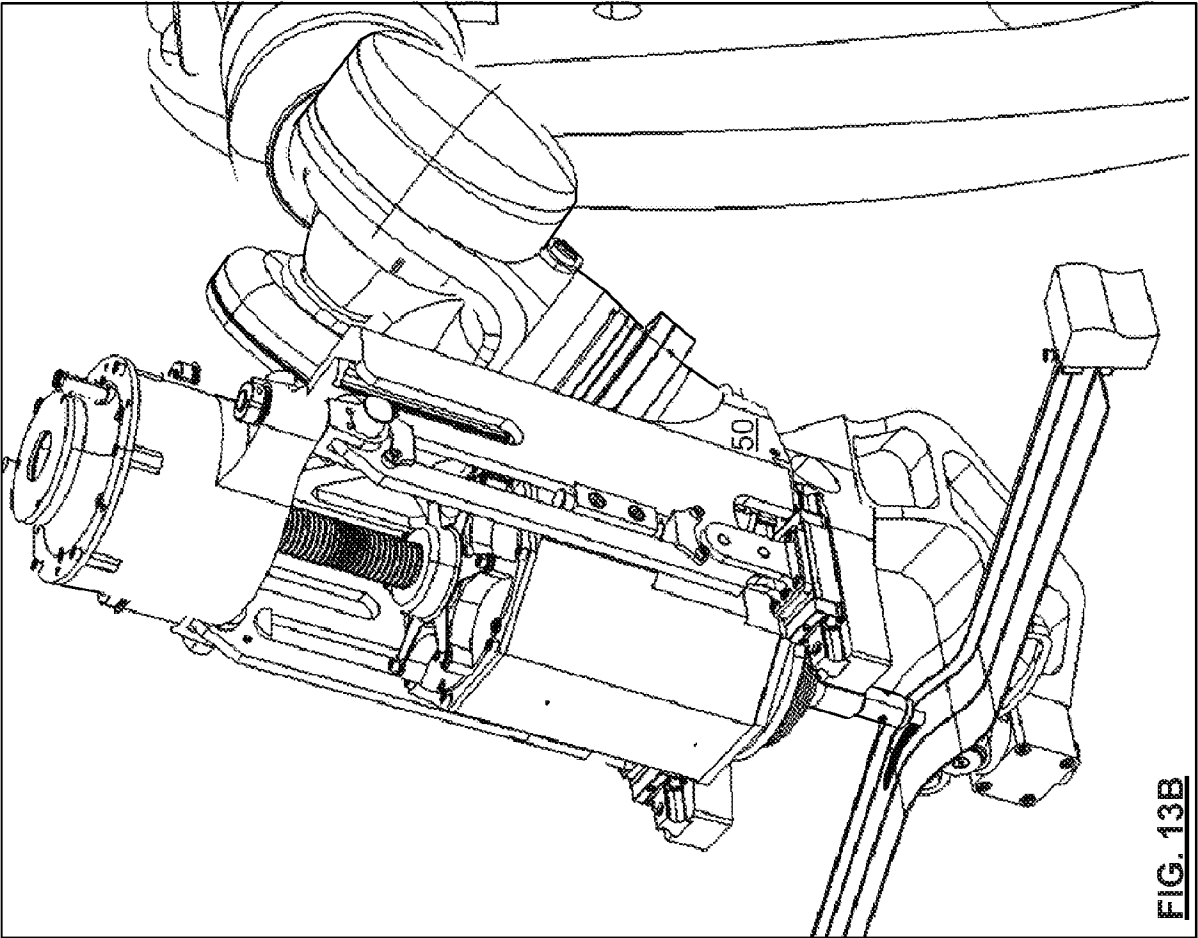
Maintain downforce with movers
and operate robot to apply 49
transverse forces to move the
FSW tool through the workpiece

FIG. 9









INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2018/056498

A. CLASSIFICATION OF SUBJECT MATTER

IPC: **B23K 20/12** (2006.01), **B23K 37/02** (2006.01), **B23K 37/04** (2006.01), **B25J 19/02** (2006.01),**B25J 9/18** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
keywords used across the whole IPC

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
USPTO WEST, Questel Orbit, Japanese patent database, Canadian patent database, IEEE, and Google Keywords: "weld*", "friction", "stir", "welding", "cfee", "c-frame", "end effector", "robot*", "counter plate", "stitch weld", "spot weld", "dot weld", "fixture*", "reduce fixturing", "fsw", "downforce", "friction stir stitch".

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/0079787 A1 (HITACHI LTD.) 29 Apr 2004, whole document.	1 - 25
A	US 9,358,634 B2 (F-TECH, INC.) 07 Jun 2016, whole document.	1 - 25
A	EP 1,864,747 A1 (ABB) 12 Dec 2007, whole document.	1 - 25

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* "A" "E" "L" "O" "P"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance earlier application or patent but published on or after the international filing date document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) document referring to an oral disclosure, use, exhibition or other means document published prior to the international filing date but later than the priority date claimed	"T" "X" "Y" "&"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art document member of the same patent family
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Date of the actual completion of the international search

Date of mailing of the international search report
05 December 2018 (05-12-2018)Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
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Gatineau, Quebec K1A 0C9
Facsimile No.: 819-953-2476

Authorized officer

Ali Mian (819) 639-8519

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2018/056498

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US 2004/0079787 A1	29 Apr 2004	CN 1270863 C JP 2004/141898 A	23 Aug 2006 20 May 2004
US 9,358,634 B2	07 Jun 2016	CN 103567627 A CN 103567627 B EP 2,692,473 A3 JP 5,984,561 B2 US 2014/0034706 A1	12 Feb 2014 13 Jan 2016 07 Dec 2016 06 Sep 2016 06 Feb 2014
EP 1,864,747 A1	12 Dec 2007	EP 2006/0445039	07 Jun 2006