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Modular workholding apparatus

Abstract

A workholding apparatus for components having complex geometries or surfaces, which components are difficult constrain for the purpose of inspection, addresses the problem of adequately constraining such components in a convenient and cost-effective manner so that they do not move during inspection, while also making all or most critical features accessible to the inspection instruments being used. A method teaches how to eliminate setup changes between different components through the use of inexpensive modular attachments. These attachments are in the form of a single piece thermoplastic part which is affixed to each component having also reference features that can be interlocked into a common base fixture for more efficient inspection operations.

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Background/Summary

RELATED APPLICATIONS (1) This application is a divisional application from U.S. patent application Ser. No. 16/563,448, filed Sep. 6, 2019, now U.S. Pat. No. 11,498,133, and titled “Modular Workholding Apparatus” and naming Jonathan J. O'Hare and Jonathan Dove as inventors, and claims priority to U.S. Provisional Application No. 62/728,414, filed Sep. 7, 2018 and titled “Modular Workholding Method for the Inspection of Manufactured Components” and naming Jonathan J. O'Hare and Jonathan Dove as inventors. The disclosure of each of the foregoing applications is incorporated herein by reference, in its entirety.

FIELD OF THE INVENTION

(1) The present invention relates to coordinate measuring machines, and more particularly to workholding for coordinate measuring machines.

BACKGROUND OF THE INVENTION

(2) Workholding refers to the methods and tooling used to constrain components during various manufacturing processes. Tooling used for the purpose of workholding is also often referred to in industry as ‘fixtures’ or ‘fixturing.’

(3) Methods for workholding include clamping, screwing, vacuum holding, magnetic locking, gluing, etc. The development of workholding solutions is often expensive and time consuming because there is no one-size-fits-all or single general-purpose method to hold every type of component being manufactured. For example, flexible parts such as those in plastic medical devices may not be clamped or screwed down applying point loads since they would bend non-uniformly and deflect beyond an acceptable level. In such cases alternative methods such as vacuum holding is often used in place of clamps or other hard tooling devices.

(4) Moreover, the manufacturing process for a single component may require a unique workholding solution for each operation. For example, a component may be sandcast in a first operation, then held in a large cradle fixture to mill some faces on one side in a second operation, then clamped down flat on that milled face for boring holes in a third operation. In this example each operation would have a different workholding solution since the component geometry changes with each operation.

(5) It may also be noted that some components have features on all sides so that no one workholding solution can be used to make all the features of a component accessible at one time. This is particularly true for components at the end of the manufacturing process where final inspection is required. Inspection of components may be performed at any point during the manufacturing process, but final inspection is often the last operation and involves a more comprehensive inspection of a component's features. At final inspection workholding is critical so that as many component features can be accurately inspected in the same setup as possible. The final inspection of manufactured components mostly involves dimensional measurements performed by coordinate measuring machines (CMMs), though other modes of inspection may also be performed. The present invention relates to coordinate measuring machines, and more particularly to workholding for coordinate measuring machines.

SUMMARY OF VARIOUS EMBODIMENTS

(6) In accordance with one embodiment, a fixture (which may be referred-to as a “workholder”) includes a workpiece interface shaped to receive and secure a target portion of a workpiece, and a base having a second interface configured to securely couple to a clamping system. The workholder is configured for use as an intermediary between a workpiece and coordinate measuring machine, and is not part of the workpiece and is not part of the coordinate measuring machine.

(7) In some embodiments, the workpiece interface is shaped and sized, relative to the target portion of the workpiece, to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the workpiece interface. In some embodiments, the workpiece interface has a contour that is complementary to the shape of the target portion of a workpiece. In some

embodiments, the workpiece interface includes (e.g., is made of) thermoplastic.

(8) In some embodiments, the base has a bottom face, and the fixture further includes a plurality of cavities in the bottom face. The plurality of cavities are arranged in a pattern to match a corresponding pattern of dowels on a storage plate.

(9) Some embodiments include a plurality of base magnets coupled to the base. That plurality of base magnets are arranged in a base pattern to match a corresponding pattern of storage magnets arranged on a storage plate. In some such embodiments, at least one of the base magnets is disposed in a polarity complementary to a corresponding storage magnet, in a storage system, which corresponding storage magnet is counterpart to the at least one of the base magnet. In some embodiments, each of a plurality of the base magnets is disposed in a polarity complementary to a corresponding counterpart storage magnet in a storage system.

(10) In some embodiments, the base includes a set of base features, which base features are configured to interlock with counterpart features on a robotic gripper, and the same base features are configured to interlock with jaw reference features of a clamp, wherein the clamp is not the same as the robot gripper. In other embodiments, the base includes a plurality of base features, a first subset of which are configured to interlock with counterpart features on a robotic gripper, and a second subset of which are configured to interlock with jaw reference features of a clamp, where the first subset is not identical to the second subset.

(11) The workpiece interface of the workholder may also be described as having one or more of the following properties: (a) the workpiece interface is shaped and sized, relative to the target portion of the workpiece, to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the first interface; (b) the workpiece interface includes (e.g., is made of) thermoplastic; and (c) the workpiece interface has a contour that is complementary to the shape of the target portion of a workpiece; and the base of the workholder may be described as having one or more of the following features: (i) the base has a bottom face, the fixture further including a plurality of cavities in the bottom face, the plurality of cavities arranged in a pattern to match a corresponding pattern of dowels on a storage plate; and (ii) a plurality of base magnets coupled to the base, the plurality of base magnets arranged in a base pattern to match a corresponding pattern of storage magnets arranged on a storage plate.

(12) Another embodiment is directed to methods of producing a single-piece workholding apparatus. For example, one embodiment of a method of producing a single-piece workholding apparatus (for holding a workpiece during inspection by a coordinate measuring machine, wherein the workpiece has a target portion having a complex geometry) includes the following steps: measuring the complex geometry of the target portion to obtain a measured element; and creating a digital template by digitally subtracting the measured element from a template blank; and producing, from the digital template, the single-piece workholding apparatus comprising an interface having a fixed shape, the interface adapted to couple to the target portion of the workpiece.

(13) In some embodiments, the template further comprising a standard clamping interface, and the method further includes producing, from the digital template, the single-piece workholding apparatus having a standard clamping interface.

(14) Some embodiments produce the single-piece workholding apparatus by 3D printing the digital template. For example, some embodiments 3D print the single-piece workholding apparatus from thermoplastic. To that end, in some embodiments, the thermoplastic is one of ABS, HIPS, and Nylon (polyamide).

(15) In some embodiments, 3D printing the digital template includes producing the single-piece workholding apparatus via fused deposition modeling (FDM).

(16) Yet another embodiment is directed to a workholder for holding a workpiece during inspection by a coordinate measuring machine, the workpiece having a target portion. The workholder includes: a base means for securely coupling to a clamping system; and a workpiece interface

means for receiving and securing the target portion of the workpiece.

(17) In some such embodiments, the base means has a bottom face, and a base means includes a plurality of cavities in the bottom face, the plurality of cavities arranged in a pattern to match a corresponding pattern of dowels on a storage plate. In some embodiments, the base further includes a plurality of base magnets coupled to the base means, the plurality of base magnets arranged in a base pattern to match a corresponding pattern of storage magnets arranged on a storage plate.

(18) In some embodiments, the workpiece interface means is shaped and sized, relative to the target portion of the workpiece, to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the workpiece interface means. Moreover, in some embodiments the workpiece interface means has a contour that is complementary to the shape of the target portion of a workpiece.

(19) The workpiece interface means in some embodiments of the workholder may be described as having one or more of the following properties: (a) the workpiece interface means is shaped and sized, relative to the target portion of the workpiece, to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the first interface; (b) the workpiece interface means includes (e.g., is made of) thermoplastic; and (c) the workpiece interface means has a contour that is complementary to the shape of the target portion of a workpiece; and the base means may be described as having one or more of the following features: (i) the base means has a bottom face, the fixture further comprising a plurality of cavities in the bottom face, the plurality of cavities arranged in a pattern to match a corresponding pattern of dowels on a storage plate; and (ii) a plurality of base magnets coupled to the base, the plurality of base magnets arranged in a base pattern to match a corresponding pattern of storage magnets arranged on a storage plate.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) Those skilled in the art should more fully appreciate advantages of various embodiments of the invention from the following “Description of Illustrative Embodiments,” discussed with reference to the drawings summarized immediately below.

(2) FIG. 1A schematically illustrates a coordinate measuring machine, a robot and a storage unit for storing workpieces;

(3) FIG. 1B schematically illustrates an embodiment of a storage plate for storing workpiece holding apparatuses;

(4) FIG. 1C schematically illustrates another embodiment of a storage plate for storing workpiece holding apparatuses;

(5) FIG. 1D and FIG. 1E schematically illustrate another embodiment of a storage plate for storing workpiece holding apparatuses;

(6) FIG. 2A, FIG. 2B, and FIG. 2C schematically illustrates an embodiment of a workpiece holding apparatus;

(7) FIG. 3A schematically illustrates an embodiment of a workholder adapted to receive a workpiece;

(8) FIG. 3B schematically illustrates an embodiment of a workholder holding a workpiece;

(9) FIG. 3C schematically illustrates an embodiment of a workholder;

(10) FIG. 3D and FIG. 3E each schematically illustrates an embodiment of a workholder;

(11) FIG. 3F schematically illustrates an embodiment of a workpiece;

(12) FIG. 3G schematically illustrates embodiments of finger features of a robot gripper;

(13) FIG. 4A schematically illustrates an embodiment of a clamping system;

(14) FIG. 4B schematically illustrates an embodiment of a clamping system receiving a workholder;

- (15) FIG. 5A schematically illustrates a clamping system serially receiving a first workholder and a second workholder;
- (16) FIG. 5B is a flow chart that illustrates a method of using a plurality of non-identical workholders without changing a clamping setup;
- (17) FIG. 6A is a flow chart that illustrates a method of fabricating a workholder; and
- (18) FIG. 6B schematically illustrates templates and components at various stages of the fabrication process.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

- (19) Illustrative embodiments provide an apparatus (which may be referred-to as a workholder) for constraining a workpiece (e.g., an object or manufactured component) during a manufacture process, such as inspection by a coordinate measuring machine. In illustrative embodiments, the workholder is configured for use as an intermediary between a workpiece and coordinate measuring machine, and is not part of the workpiece and is not part of the coordinate measuring machine.
- (20) Preferred embodiments have a workpiece interface (e.g., a slot, cavity or aperture) having a shape that is complementary to the shape of a target portion (e.g., a root form) of the workpiece, such that the workpiece can be press-fit into the workpiece interface.
- (21) Illustrative embodiments also have a clamp interface configured to securely couple to a clamping system. Each of a variety of workholders may have identical clamp interfaces so that each may securely couple to the same clamping system.
- (22) Illustrative embodiments take advantage of several benefits afforded by FDM (fused deposition modeling) technology. Although thermoplastics may seem unsuitable for many workholding applications in manufacturing, the inventors have recognized that these materials are flexible, durable, inexpensive and easy to form into any shape with accuracies better than 0.5 mm, and have recognized that these properties make thermoplastics desirable for use in the apparatuses and methods described herein, and in particular for inspection operations in manufacturing. This is so, in part, for inspection operations (such as measuring a workpiece using a CMM **100**) since the loads imposed by most inspection instruments are quite low compared with that of tooling used in other manufacturing operations.
- (23) Definitions. As used in this description and the accompanying claims, the following terms shall have the meanings indicated, unless the context otherwise requires: The term “complex geometry” means a geometry which is non-prismatic, and/or is bound by a multitude of non-orthogonal and or curved surfaces.
- (24) The term “ABS” means acrylonitrile-butadienestyrene.
- (25) The term “HIPS” means high impact polystyrene.
- (26) A “digital template” is a digital data file from which a workholder may be produced (e.g., machined, subtractively produced, additively produced, 3D-printed).
- (27) The term “fixed shape” means that the shape (e.g., of a feature of an apparatus) is fixed, and not adjustable. In some embodiments, a feature having a fixed shape may be pliable so that the apparatus can flex when accepting a workpiece, and yet the feature is still considered to have a fixed shape.
- (28) A “set” includes at least one member.
- (29) The term “target portion,” in reference to a workpiece, means that portion of the workpiece that fits into a corresponding slot in an attachment. For example, but without limitation, in some workpieces the target portion may be a root form. In some workpieces, the target portion may have a shape described as a “complex geometry.”
- (30) A “target workpiece” is a workpiece for which a workholder has a complementary shape.
- (31) A “template blank” is an object capable of being configured as a workholder apparatus. In some embodiments, a template blank is a digital data file capable of being modified, through a computer process, to form a template that includes an interface shaped to receive a target portion of

a workpiece. In some embodiments, a template blank includes a standard clamping interface.

(32) The term “workpiece” means an object to be held and constrained during a manufacturing operation. A workpiece may be an object to be measured by a coordinate measuring machine, such as a manufactured component, for example.

(33) The workpieces in some illustrative embodiments described below include jet turbine blades. Some such jet turbine blades include complex geometry known in the aerospace industry as the “root form” of the blade. The depicted components in these examples are only meant to show a typical example of a component having complex geometry and is in no way intended to limit the application of the concepts disclosed herein to a single type of manufactured component having complex geometry or single industry. Other types of manufactured components where these concepts, methods and apparatuses may be successfully applied include orthopaedic implants, automotive powertrain components, and consumer electronics, to name but a few examples.

(34) Environment

(35) FIG. 1A schematically illustrates a working environment for various embodiments. As shown the environment includes a coordinate measuring machine **100**, and robot **180**, and a storage facility **190**.

(36) As known by those in the art, a coordinate measuring machine (or “CMM”) is a system configured to measure one or more features of a workpiece. Coordinate measuring machines are represented in FIG. 1A by coordinate measuring machine **100**.

(37) In the illustrative embodiment of FIG. 1A, the CMM **100** includes a base **110** having a table **111**. The table **111** of the CMM **100** defines an X-Y plane **112** that typically is parallel to the plane of the floor **101**, and a Z-axis normal to the X-Y plane, and a corresponding X-Z plane and Y-Z plane. The table **111** also defines a boundary of a measuring space **113** above the table **111**.

(38) The CMM **100** also has movable features (collectively, **120**) arranged to move and orient a measuring sensor **140** (and in some embodiments, a plurality of such devices) relative to the workpiece. The features of the CMM **100** are configured to move and orient the measuring sensor **140**, relative to the workpiece, in one dimension (X-axis; Y-axis; or Z-axis), two dimensions (X-Y plane; X-Z plane; or Y-Z plane), or three dimensions (a volume defined by the X-axis, Y-axis, and Z-axis).

(39) One or more workpieces **90** are stored in storage system **190**. In this embodiment, the storage system **190** includes one or more drawers (or shelves) **191**.

(40) Robot **180** is disposed so that it can reach the drawer or shelf **191**, as well as the table **111** of the coordinate measuring machine **100**, so that the robot **180** can transport a workholder **200** (e.g., carrying a workpiece **90**) the drawer or shelf **191** to the measuring space **113** of the coordinate measuring machine **100**, and so that it can transport a workholder **200** (e.g., carrying a workpiece **90**) from the measuring space **113** of the coordinate measuring machine **100** to the drawer or shelf **191**. To that end, the robot **180** in this embodiment has a gripper **181** at the end of a movable, articulated arm **182**.

(41) In some embodiments, the gripper **181** has two or more fingers **184**, **185** separated by a gap **187**. The gripper **181** is configured to controllably close and open the fingers **184**, **185** to decrease or increase the gap **187** (respectively) so as to grasp and release (respectively) a workholder **200**. Illustrative embodiments of the fingers **184**, **185** include finger features **186** configured to mate with corresponding base reference features **320** on a workholder **200**, as schematically illustrated in FIG. 3G. In illustrative embodiments, the finger features **186** have a shape that is complementary to the shape of corresponding base reference features **320** on an external surface **202** of a workholder **200**. For example, as schematically illustrated in FIG. 3G, each of the base reference features **320** disposed on a side surface **202** is concave and has a triangular cross-section, and each of the finger features **186** is convex and also has a triangular cross-section. In operation, the fingers **184**, **185** close on the workholder **200**, and each finger feature **186** enters into and mates with a corresponding the base reference feature **320**. When so mated, the gripper **181** has a secure, and

releasable, grip on the **20**) workholder **200**, and can move the workholder **200** from a drawer or shelf **191** to the measuring space **113** of the coordinate measuring machine **100**, and/or from a measuring space **113** of the coordinate measuring machine **100** to a drawer or shelf **191**. In other embodiments, the finger features **186** are concave and the base features **320** are convex. In other embodiments, one or more of the finger features **186** is concave and one or more of the finger features **186** is convex; and one or more of the base features **320** is convex and one or more of the base features **320** is concave, in each case so that each base feature has a shape that is complementary to the shape of a corresponding finger feature.

(42) As can be understood from the foregoing description, the base **240** of the workholder **200**, in such embodiments, includes base features **320** configured to interface with counterpart features on the gripper **181**, and specifically on the gripper fingers **184** and **185**, so as to enhance the accessibility and reliability of robotic gripping of the workholder **200** at their particular locations on the base **240**. Moreover, in preferred embodiments the base features **320** serve a dual purpose: to interlock with the finger features **186** of the gripper **181**, and also to interlock with jaw reference features **420** of a clamp **400**, wherein the clamp **400** is not another robot gripper, and is not the same as, and not identical to, the robot gripper **181**.

(43) In other embodiments, the base **240** includes a plurality of base features **320**, wherein a first subset of the base features **320** are configured to interlock with counterpart features **186** on a robotic gripper **181**, and a second subset of the base features **320** are configured to interlock with counterpart jaw reference features **420** of a clamp **400**, where the first subset is not identical to the second subset. For example, a first set of the base features **320** may include the groove feature **321** (configured to mate with counterpart feature **186** gripper **181**), and a second set of the base feature **320** may include semi-circular feature **322** (configured to mate with semi-circular convex feature **422** on the clamp **400**), in which case the first set is not identical to the second set. As another example, a first set of the base features **320** may include the groove feature **321**, and a second set of the base feature **320** may include both the groove feature **321** and semi-circular feature **322**, in which case the first set is not identical to the second set, even though they have a feature (in this example, groove feature **321**) in common.

(44) For purposes of this description and any claims, a surface of a gripper finger having a flat or planar face is not considered to have finger features.

(45) Storage System

(46) As schematically illustrated in FIG. **1A**, each drawer or shelf **191** of a storage system **190** may have one or more storage plates **192** configured and disposed to hold the one or more workpieces **90**. A storage plate **192** may have a plate surface **193**.

(47) In some embodiments, a storage plate **192** has a metal surface **193** such that a magnet would be attracted to the surface **193** of the storage plate. In other embodiments, the storage plate **192** has a non-metal and non-magnetic surface, which surface neither attracts nor repels a magnet.

(48) Another embodiment of a storage plate **192** is schematically illustrated in FIG. **1B**, and includes in or at its surface **193** a set of metal buttons **194**. In one embodiments, the metal button **194** is a magnet **194**. Each magnet **194** has a positive polarity on one surface, and a negative polarity on the opposing surface. The metal buttons **194** serve to hold a workholding apparatus **200** to the surface **193**, for example when placed on the surface **193** by the robot **180**. For example, in embodiments in which the metal button **194** is a magnet, each metal button **194** may be magnetically attracted to a counterpart metal button or magnet on the surface **193**. In embodiments in which the metal button **194** is a not magnet, each such metal button **194** may be magnetically attracted to a counterpart magnetic button on the surface **193**.

(49) In preferred embodiments, several magnets **194** are arranged in a magnet group **195**, and the storage plate **192** includes several such magnet groups. In illustrative embodiments, the magnets **194** in each magnet group **195** are arranged in a magnet pattern that mirrors a pattern of holder magnets **310** (described below as an embodiment of an alignment feature **250**) in a workholder

apparatus **200**.

(50) Another embodiment of a storage plate **192** is schematically illustrated in FIG. 1C, and includes, extending from its surface **193**, several dowels **197**.

(51) In preferred embodiments, several dowels **197** are arranged in a dowel group **198**, and the storage plate **192** includes several such dowel groups. In illustrative embodiments, the dowels **197** in each dowel group **198** are arranged in a dowel pattern that mirrors a pattern of dowel reception cavities in a holding apparatus **200**.

(52) In some embodiments, the arrangement of the plate alignment structures (e.g., magnets or metal buttons **194**; dowel **197**) are configured such that a workholder **200** may be placed on the alignment structures in only a single way. In other words, in such embodiments, the workpiece **200** will not fit on the alignment fixture in any position except the pre-defined orientation.

(53) For example, in some embodiments, the magnets **194** of a magnet group **195** are arranged to define the three vertexes of an isosceles triangle (not an equilateral triangle), so that the corresponding base magnets **310** on a workpiece holder **200** align with the magnets of a magnet group only in one orientation. Moreover, in embodiments in which the alignment structures **250** are base magnets **310**, the base magnets **310** may be disposed on or in the base **240** in a first polarity, and the magnets **194** on or in the plate **191** may be disposed in a second, opposite polarity, so that each of the base magnets **194** exhibits a magnetic attraction to its counterpart **310** magnet. In this way, if a workholder **200** is placed close to, but not exactly aligned with, the plate **194** magnets, the attraction between the base magnets **310** and the plate magnets **194** will serve to align the workholder **200** to its desired (proper) orientation.

(54) As another example, in some embodiments the dowels **197** of a dowel group **198** are arranged to define the three vertexes of an isosceles triangle (not an equilateral triangle), so that the corresponding dowel cavities **250** (or “base” cavities) on a workholder **200** align with the dowels of a dowel group **198** only in one orientation. For example, FIG. 1D schematically illustrates an embodiment of a storage plate **192** in which dowels **197** in each dowel group **198** are arranged in an asymmetrical pattern to define a specific orientation of a workholder **200**.

(55) For example, FIG. 1E schematically illustrates a pattern of alignment structures **199** (which in various embodiments could be metal buttons **194** or dowels **197**), which pattern defines the three vertexes of an isosceles triangle. A first leg of the triangle has a length **188** that is not equal to the length **189** of a second leg of the triangle, where neither the first leg nor the second leg is the hypotenuse.

(56) In embodiments in which the alignment structures **199** are dowels **197**, a workholder **200** has corresponding dowel cavities **250** arranged in the same triangle so that when dowels **197** engage the dowel cavities **250**, the workholder **200** fits onto the dowel group **198** in only one orientation.

(57) In embodiments in which the alignment structures **199** are metal buttons, a workholder **200** may have counterpart securing structure **250**, such as a magnet or non-magnetic metal.

(58) Although the foregoing examples illustrate alignment structures arranged to form the vertexes of an isosceles triangle, embodiments are not limited to that geometric shape. Other embodiments may arrange or configure the alignment structures **250** to form other shapes, as long as those shapes do not permit a workholder **200** to be coupled to the alignment structures in more than one orientation. Other embodiments arrange the alignment structures to form other triangles or a trapezoid, or a trapezium, to name but a few examples.

(59) Workholder

(60) FIG. 2A, FIG. 2B, and FIG. 2C schematically illustrate an embodiment of a workholder **200**. FIG. 3A, FIG. 3B, FIG. 3C, FIG. 3D and FIG. 3E schematically illustrate other embodiments of a workholder **200**.

(61) A workholder **200** includes a workpiece interface **210**, configured to secure a workpiece **90** to the workholder **200**, and a base **240** configured to secure the workholder **200** to another object, such as a clamp **400** for example. Consequently, the base **240** may be referred to as a “clamp

interface,” although embodiments of workholder **200** do not necessarily require a clamp to be secured, for example, to a coordinate measuring machine.

(62) Various embodiments of workholders **200**, workpiece interfaces **210** and bases **240** are described below. A workholder **200** may include any workpiece interface **210** and any base **240**. Each of the embodiments of workholder **200** may be a single-piece apparatus in which the workpiece interface **210** is integral with the base **240**. For example, a workholder **200** fabricated by 3D printing may be such a single-piece apparatus. Embodiments of workholders **200** are not limited to such printed apparatuses, however. In some embodiments, the workpiece interface **210** is a separate part from the base **240**. In such embodiments, the workpiece **210** may be coupled or affixed to the base **240** to form a single-piece workholder **200**.

(63) Workpiece Interface

(64) FIG. 2A and FIG. 2B schematically illustrate an embodiment of a workholder **200** having an embodiment of a workpiece interface **210**.

(65) The workpiece interface **210** includes a workpiece slot **211** (or cavity), which slot **211** is configured to securely hold the workpiece. For example, in some embodiments, the slot **211** has a shape or contours that are complementary to the shape or contours of a target portion of a target workpiece **90**. In other words, in such embodiments, the workholder and target workpiece have a complementary relationship. Indeed, with some embodiments, the workpiece interface **210** is configured to fit exclusively to a specific target workpiece **90**.

(66) In this way, the workholder **200** in effect takes the place of (the complex geometry of) the workpiece **90**, as a reference surface, making it much easier to handle or clamp the workpiece **90** into a standard vise. In other words, rather than clamp the (complex geometry of a portion of) the workpiece **90** into a vise, the workholder **200** acts as an intermediary between the workpiece **90** and the vise (or other clamping device) **400**. To that end, in some embodiments the base **240** of the workholder **200** has a clamp interface, embodiments of which are described in more detail below.

(67) FIG. 2C schematically illustrates a view of the top **201** of the workholder **200**. To secure the workpiece **90**, e.g., by providing a tight fit, in some embodiments, the slot **211** of the workpiece interface **210** is extruded in a shape that is complementary to the profile of the target portion of the workpiece **90** to being held (the target workpiece) but with one or more dimensions configured to provide a small amount interference so that the walls **212** of the slot **211** apply a preload against the workpiece **90** sufficient to restrain (or prevent movement of) the workpiece **90** to a degree sufficient for measuring the workpiece **90** by a coordinate measuring machine **100**.

(68) FIG. 3A, FIG. 3B, FIG. 3C, FIG. 3D and FIG. 3E schematically illustrate other embodiments of a workholder **200**. In these embodiments, the workpiece interface **210** may be formed of thermoplastic. Preferred thermoplastic materials for this method are ABS, HIPS and Nylon although other materials, including those containing carbon or glass fibers, may also be used.

(69) To achieve such a tight fit, the workpiece interface **210** is designed having a slot **211** extruded in the same shape or profile as the workpiece **90** to be held, but with a small amount physical interference so that the walls **212** of the thermoplastic slot **210** apply enough preload against the workpiece **90** to prevent movement.

(70) The amount of interference can be made gradual by tapering the extrusion between -1 and -5 degrees so that it is easier to insert the component initially, but gets tighter as it is inserted all the way into the workholder **200**. Such a taper is schematically illustrated in FIG. 2C, which includes a dashed arrow **216** to indicate a longitudinal axis of the slot **211** (and which also represents the direction of insertion of a workpiece), and a dotted line **217** to indicate the angle **215** formed by the axis **216** (or direction of insertion) and a wall **212** of the slot **211**. As a workpiece **90** is inserted into the slot **211**, by moving the workpiece in the direction of insertion **216**, the workpiece **90** enters the slot **211**. As a leading edge of the workpiece **90** proceeds into and along the slot **211**, the width of the slot **211** narrows, thereby getting tighter by gradually increasing the pressure from the walls **212** onto the workpiece **90**.

(71) That taper angle **215** may be, in illustrative embodiments, -1 degree, or -5 degrees, or any angle between -1 and -5 degrees (e.g., -2 degrees, -3 degrees, -4 degrees, etc.). For a workpiece interface **210** made of thermoplastic, the inventors have discovered that the upper limit for such a taper angle **215** is -5% over a 25 mm extrusion; otherwise the thermoplastic material will likely exceed its yield point and fracture.

(72) Another feature of some embodiments of workholder **200** is one or more relief openings **220** below the insertion slot **211**. Such a relief opening **220** is ideally a cylindrical bore, although other (potentially less effective) shapes may be used. The purpose of a relief opening **220** is to allow for flexure and stress distribution in the workpiece interface **210** (e.g., when the workpiece interface **210** is made of thermoplastic), which may arise due to the forces being applied by a workpiece **90** is compression fitted into it. A person of ordinary skill in the art, in possession of this description, would be able to determine and apply acceptable shapes and dimension of one or more relief openings **220** (e.g., the correct radius for a bore), based on the material, loading and deflection requirements. The principals are the same as employed in the art of designing relief springs for other applications.

(73) In preferred embodiments, the relief opening, **220**, is connected to the insertion slot **211** via a keyway, **221**, such that, in an embodiment in which the relieve opening **220** includes a cylindrical bore, all features are parallel with the cylinder axis of the relief opening **220**. This relief opening **220** is also positioned such that it is approximately equidistant from all of the external sides (**201**, **202**, **203**, **241**) of the attachment workholder **200** so that the stresses are more evenly distributed throughout the material.

(74) Preferred embodiments of a workholder **200** include (to help with constraining the workpiece **90** within the slot **211**) one or more locating datum points **231** disposed such that they are distributed across one or more surfaces **212** of the workpiece **90**, to interface **210** between such one or more surfaces of the workpiece **90** and the workpiece interface **210**. These locating points, **231** in FIG. 3C, may be or include raised surfaces in the form of spherical, cylindrical or square bumps or otherwise protruding high points in the surface **212** in order to distribute contact loading and prevent any movement between the workpiece **90** and the workpiece interface **210**.

(75) Further to the purpose of constraining the workpiece **90** in the workholder **200**, some embodiments include at least one reference feature **232** that acts as a datum for the purpose of constraining the last remaining degree of freedom of the workpiece **90** within the workpiece interface **210**. In the FIG. 3C, that degree of freedom is in the direction of the Y axis, and the described reference feature, **232**, is depicted as a rectangular stop to define the end of travel of a workpiece **90** through the slot **211**, but in other embodiments may be in the form of some other geometry which has the same purpose.

(76) Some embodiments of the workholder **200** include an undercut or countersink area **225** (schematically illustrated in FIG. 3A) to allow access (for example, by the probe of a coordinate measuring machine) to the complex geometry of a workpiece **90** while that workpiece **90** is secured in the workpiece interface **210**.

(77) Base (Clamp Interface)

(78) Illustrative embodiments of the base **240** of a workholder **200** include reference surfaces and or base reference features, **320** in FIG. 3D and FIG. 3E, by which the workholder **200** may be repeatably and securably placed into a common clamping device, **400** in FIG. 4A and FIG. 4B, to be held during an inspection operation. For example, in illustrative embodiments, the clamp **400** is configured to rest on a coordinate measuring machine **100**, to hold a workpiece **90** in position on the table **111** of a coordinate measuring machine **100** as the coordinate measuring machine **100** takes measurements of or otherwise inspects the workpiece **90**.

(79) The common clamping device, **400**, may be in the form of a vise with jaws with jaw reference features, **420**, as depicted in FIG. 4A and FIG. 4B, which interface with, interlock with, or otherwise lock onto the reference features, **320**, of the workholder **200**. To that end, in preferred

embodiments, the shape(s) of the base reference features **320** on the workholder **200** are complementary to the shape(s) corresponding jaw reference features **420** of the clamping device **400**. For example, convex jaw reference feature **421** of FIG. 4A (which may be referred-to as a “ridge”) has a triangular cross-section that mates with the concave base reference feature **321** (which may be described as a “groove”) of the base **240**, which has a concave triangular cross-section. As another example, convex jaw reference feature **422** of FIG. 4A has a semi-circular cross-section that mates with the base reference feature **322** of the base **240** (FIG. 3D), which has a concave circular cross section.

(80) A plurality of workholders **200** may have identical clamp interfaces **240** (in other words, they may have the same reference surfaces for clamping), even though each of the plurality of workholders **200** is configured to hold a different workpiece **90** (in other words, each of the plurality of workholders **200** is configured to hold a different target workpiece (see, e.g., workpieces **90A** and **90B**), the target workpieces each having a different complex geometry). In this way, the workholders **200** are modular in that any variant of workpieces **90** with a corresponding variant of workpiece geometry may be held for inspection using the same clamping device **400** by using, between the workpiece **90** and the clamping device **400**, a corresponding workholder **200**, all without having to change, retool or adapt the clamping device **400**.

(81) In some embodiments, the base reference features **320** are configured to interface with both the jaw reference features **420** of the clamping device **400** as well as the finger features **186** of gripper fingers **184**, **185**, as described above in connection with FIG. 3G.

(82) Some embodiments of the workholder **200** include one or more alignment features **250** on or in the bottom **241** of the base **240**.

(83) For example, in some embodiments an alignment feature **250** is a magnet **310** in the bottom of the workholder **200**. Such magnets **310** may be part of the base **240**, but may have function not related to the clamp interface. For example, magnets **310**, which in preferred embodiments are permanent magnets, assist with securing the workholder **200** flat on a metallic or magnetic surface **193** of a storage apparatus **191**, so that the workholder **200** remains, reliably, in the location where it is place (e.g., by a robot **180**) so that the workholder **200** is available at that known location when the workholder **200** (or a workpiece **90** secured in the workholder **200**) next needed, and/or does not slide around during movement or transport of the storage apparatus **192**. Such magnets **310** may also prevent the components **90** (workpieces) from toppling over if they are top-heavy.

(84) In some embodiments, the alignment feature **250** is a dowel receiving cavity **251** configured to receive a dowel, such as a dowel **197** extending from a storage plate **192**. A plurality of such dowel receiving cavities may be arranged in a pattern to mirror a dowel patten **198**, so that the base **240** fits onto the dowel patten **197**.

(85) Clamping Device

(86) In FIG. 5A, two different workpieces (**90A** and **90B**, respectively) having different complex geometries, are each shown attached to a flexible attachment (**200A** and **200B**, respectively), with insertion slots (**211A** and **211B**, respectively) suited for constraining complex geometries, **91A** and **91B**. Each attachment **200A** and **200B** is also shown having the same reference surfaces, **320**, for modular clamping into a common clamping device, **400**.

(87) FIG. 5A illustrates that present embodiments enable a way to eliminate setup changes between different components through the use of inexpensive modular attachments.

(88) For example, a method **500** of using a plurality of non-identical workholders without changing a clamping setup may be described by the flow chart in FIG. 5B.

(89) At step **510**, if a first workholder **200A** is not already in a clamp **400**, a workholder **200A** carrying a workpiece **90A** is secured to a clamp **400**.

(90) The first workholder **200A** has a first workpiece interface **210A** configured to secure the first workpiece **90A**. For example, in preferred embodiments, the first workpiece interface **210A** is customized to mate to a first target portion **91A** of the first workpiece **90A**.

(91) The first workholder **200A** has a first clamp interface **240A** configured to mate with jaw reference features **420** of the clamp **400**. For example, the first clamp interface **240A** may have attachment reference features **320** as described herein.

(92) At step **520**, a manufacturing operation is performed on the workpiece **90A**, while the workpiece **90A** is secured to the workholder **200A**, and the workholder **200A** is secured to the clamp **400** via clamp interface **240**. For example, a manufacturing operation may include measuring the workpiece **90A** using a coordinate measuring machine **100**.

(93) At step **530**, the workholder **200A** is removed from the clamp **400**. The clamp **400** is now free to accept another workholder.

(94) At step **540**, a second workholder **200B**, carrying a workpiece **90B**, is secured to the clamp **400**, without changing the clamp **400** or the setup of the clamp **200**. The second workholder **200B** has a second workpiece interface **210B** configured to secure the second workpiece **90B**. For example, in preferred embodiments, the second workpiece interface **210B** is customized to mate to a second target portion **91B** of the second workpiece **90B**, wherein the second target portion **91B** is not identical to the first target portion **91A**.

(95) In illustrative embodiments, the second workpiece **90B** is not identical to the first workpiece **90A**, and thus the second workholder **200B** is not identical to the first workholder **200A** at least in that the second workholder **200B** has a second workpiece interface **240B** that is not identical to the first workpiece interface **240A**.

(96) The second workholder **200B** has a second clamp interface **240B** configured to mate with the same attachment reference features **320** of the clamp **400**. In illustrative embodiments, the second clamp interface **240B** is functionally identical to the first clamp interface **240A**, in that each of the second clamp interface **240B** and the first clamp interface **240A** mate to at least some of the same attachment reference features **320** of the clamp **400**. In preferred embodiments, the second clamp interface **240B** is physically identical to the first clamp interface **240A**, in that the attachment reference features **320** of the first clamp interface **240A** are identical to the attachment reference features **320** of the second clamp interface **240B**.

(97) At step **550**, the method performs a manufacturing operation on the second workpiece **90B**, which manufacturing operation may be referred-to as a second manufacturing operation.

(98) At step **560**, the second workholder **200B** is removed from the clamp **400**. The clamp **400** is now free to accept another workholder.

(99) As can be understood from the foregoing, FIG. 5A presents a securing system (which may be secured to a coordinate measuring machine **100**), which systems is configured to receive serially, and without changing the setup of the securing system, a first workholder **200A** (and its workpiece **90A**) and a second workholder **200B** (and its workpiece **90B**).

(100) A Method of Fabricating a Workholder

(101) FIG. 6A schematically illustrates a process **600** for producing a workholder **200** to hold a workpiece **90**, and FIG. 6B schematically illustrates templates and components at various stages of the fabrication process. In the following description, the workpiece **90** is referred to as the “component” or as “new component.”

(102) The process begins at step **610** by providing a computer-based template blank **700** of a workholder **200**. In illustrative embodiments, the computer-based template blank **700** is a CAD model or other digital representation of the modular workholding attachment whereby the slot or cavity, **211**, into which the component, **90**, is inserted does not exist in the digital model template blank **700**. In illustrative embodiments, the digital model template blank **700** specifies solid material in place of (what will eventually be) the insertion slot or cavity, **211**, from which any new complex geometry form (i.e., the slot **211**) may be cut, printed, fabricated, or otherwise formed using a CAD model of a new component (i.e., the target workpiece for which the workholder is to be adapted to hold), **95**, thereby leaving a new slot **211** for the insertion of the new component.

(103) In preferred embodiments, the template blank **700** already includes a standard clamp

interface **240**, as described above, but other embodiments of the method include fabricating such an interface **240** in addition to fabricating the workpiece interface **210**.

(104) At step **620**, the process **600** also provides or obtains a nominal or measured representation of the complex geometry of the new component (e.g., the target portion; the root form of the new component, if the component has a root form). In preferred embodiments, a nominal representation is obtained from computer-aided design (CAD) model of the new component, rather than on an actual, physical new component. In illustrative embodiments, this may be described as measuring the complex geometry of the target portion to obtain a measured element.

(105) At step **630**, the process **600** defines the shape of the slot **211** based on the measured element. The shape of the slot **211** is, in preferred embodiments, complementary to the shape of the measured element.

(106) To facilitate a tight (snug) fit of the workpiece **90** into the slot **211** of the workholder **200**, there preferably is interference of material in the slot or cavity **211**. To that end, some embodiments include step **640**, which provides either (A) a slight modification of the measured element using its CAD model or other digital form to taper, stretch, shrink or otherwise reduce material from its form so that a slot **211** generated from the measured element is slightly reduced in size as compared to a slot generated by the un-modified measured element, (B) a slight modification to a slot **211** generated to in a shape complementary to the measured element, to produce, between the slot **211** and the given portion of the a component **90** inserted into the slot **211**, an interference, as allowable by the material of the workpiece interface **210**.

(107) Once the digital form **97** of the slot **211** that is complementary to the target portion, **96**, is defined as described above, the slot **211** can be added at step **650** to the digital model template blank **700** of the workholder **200**, and consequently used to remove (or never provide, such as in the case of additive manufacturing) that material from the template blank **700** by a Boolean subtraction of the solid or surfaces in digital form, to produce a customized template **720**. In some embodiments, this may be described as subtracting, from a digital template blank **700**, the measured element, to produce a customized digital template **720** in which the slot **211** has a shape that is complementary to the measured element.

(108) Once the shape for the slot **211** in the customized (and still digital) template **720** has been made for new component, the new template (or digital model) **720** of the workholder for that specific workpiece is complete, and a physical workholder **200** can be produced at step **660**, for example via FDM or other 3D printing method. Preferred materials for fabricating a physical attachment are thermoplastic, such as one of ABS, HIPS, and Nylon, or other polycarbonate or copolyester material.

(109) Some embodiments include a step **670**, in which one or more alignment features **250** (e.g., magnetic metal button; non-magnetic metal button) are attached-to or embedded-in the bottom surface **241** of the base **240**.

(110) A listing of certain reference numbers is presented below. **90**: Workpiece (e.g., manufactured component); **90A**: An illustrative embodiment of workpiece; **90B**: An illustrative embodiment of workpiece; **91**: Target portion of workpiece; **95**: Illustrative embodiment of workpiece; **96**: Illustrative embodiment of target portion of workpiece; **97**: Tapered extrusion shape; **100**: Coordinate measuring machine; **110**: Base; **111**: Table; **112**: Plane; **113**: Measurement envelope; **120**: Moveable features; **140**: Measuring sensor; **180**: Robot; **181**: Robot gripper; **182**: Robot arm; **190**: Storage facility; **191**: Drawer or shelf; **192**: Storage plate; **193**: Surface of storage plate; **194**: Metal button (e.g., magnetic or non-magnetic); **195**: Button group; **197**: Dowel; **198**: Dowel group; **199**: Alignment structure (e.g., metal button; dowel) **200**: Attachment (or “workholder”); **200A**: Illustrative embodiment of attachment; **200B**: Illustrative embodiment of attachment; **201**: Top of workholder; **202**: External side surface of workholder; **203**: External front surface of workholder; **204**: External rear surface of workholder; **210**: Workpiece interface; **211**: Complementary slot (or cavity or aperture); **212**: Interface wall (e.g., slot wall); **215**: Taper angle; **216**: Axis of insertion

(direction of insertion); **217**: Line illustrating direction of slot wall; **220**: Strain relief cavity or aperture; **221**: Keyway; **225**: Undercut (or countersink); **231**: Locating point; **232**: Reference feature; **240**: Base (clamp interface); **241**: Bottom of base; **250**: Securing structure (e.g. magnet; non-magnetic metal; dowel cavity); **320**: Attachment reference surfaces and/or reference features; **400**: Clamping device (e.g., clamp system); **420**: Jaw reference features; **700**: Template blank; **720**: Customized template.

(111) Various embodiments may be characterized by the potential claims listed in the paragraphs following this paragraph (and before the actual claims provided at the end of this application). These potential claims form a part of the written description of this application. Accordingly, subject matter of the following potential claims may be presented as actual claims in later proceedings involving this application or any application claiming priority based on this application. Inclusion of such potential claims should not be construed to mean that the actual claims do not cover the subject matter of the potential claims. Thus, a decision to not present these potential claims in later proceedings should not be construed as a donation of the subject matter to the public.

(112) Without limitation, potential subject matter that may be claimed (prefaced with the letter “P” so as to avoid confusion with the actual claims presented below) includes:

(113) P1. A single-piece workholding apparatus for holding a workpiece during inspection by a coordinate measuring machine, the workpiece having a target portion having a complex geometry, the apparatus comprising: a first interface having a fixed shape, the first interface adapted to couple to the target portion of the workpiece; and a second interface adapted to securely couple to a clamping system.

(114) P2: The workholding apparatus according to P1, wherein the first interface is flexible so as to accept the target portion of the workpiece and hold the target portion via compression fitting.

(115) P3: The workholding apparatus according to any of P1-P2, wherein the first interface has a shape that is complementary to a shape of the target portion.

(116) P4: The workholding apparatus according to any of P1-P3, wherein the first interface is shaped to provide a small amount interference so that the first interface applies preload against the workpiece to constrain and preferably prevent movement of the workpiece during inspection.

(117) P5: The workholding apparatus according to any of P1-P4 wherein the workholding apparatus comprises thermoplastic.

(118) P6: The workholding apparatus according to any of P1-P5, further comprising a set of magnets disposed to magnetically secure the workholding apparatus to a surface.

(119) P10. A workholding system for holding each of a plurality of workpieces during inspection by a coordinate measuring machine, each workpiece having a target portion having a complex geometry, the system comprising: a first holding apparatus having: a first holding interface adapted to couple to a given portion of a first workpiece, the given portion of a first workpiece having a first complex geometry; and a first securing interface; a second holding apparatus having: a second holding interface adapted to couple to a given portion of a second workpiece, the given portion of a second workpiece having a complex geometry that is different from the first complex geometry; and a second securing interface; and a securing system secured to the coordinate measuring machine, and configured to serially receive and secure, without changing the setup of the securing system, the first securing interface and the second securing interface.

(120) P20: A method of providing a single-piece workholding apparatus for holding a workpiece during inspection by a coordinate measuring machine, the workpiece having a target portion having a complex geometry, the method comprising: measuring the complex geometry of the target portion to obtain a measured element; and creating, from a template, single-piece workholding apparatus comprising an interface having a fixed shape, the interface adapted to couple to the target portion of the workpiece.

(121) P21: The method of P20, wherein creating the single-piece workholding apparatus comprises

creating, from the template, a standard clamping interface configured to interface to a clamping system.

(122) P22: The method of P20, wherein creating the single-piece workholding apparatus comprises: subtracting, from a digital template, the measured element, to produce a customized digital template in which the interface has a shape that is complementary to the measured element; and 3D printing the customized digital template.

(123) P23: The method of P22, wherein 3D printing the customized digital template comprises producing the single-piece workholding apparatus from thermoplastic.

(124) P24: The method of P22, wherein the thermoplastic is one of ABS, HIPS, and Nylon.

(125) P25: The method of P22, wherein 3D printing the customized digital template comprises producing the single-piece workholding apparatus via fused deposition modeling (FDM).

(126) P40: A workholding method whereby a modular single piece attachment of flexible material is affixed to a component by a compression fitting and is interchangeable with a common clamping device having reference features that match the single piece attachment.

(127) P41: Method of P40, whereby the flexible material of the single piece attachment is of thermoplastic.

(128) P42: Method of P40, whereby the single piece attachment has a slot or cavity into which a component may be inserted.

(129) P43. Method of P42, whereby the slot or cavity has a tapered angle of between 0 and -5 degrees in the direction of insertion to ensure gradually increasing compression as a component is inserted.

(130) P44: Method of P40, whereby the single piece attachment has a relief hole, **120**, in the form of a cylindrical or other curved profile to relief stresses while a component is compression fit within the single piece attachment.

(131) P45: Method of P40, whereby the single piece attachment has an undercut or countersink area to allow access to the component's complex geometry while affixed to the single piece attachment.

(132) P46: Method of P40, whereby the reference features of the flexible attachment are small raised bumps in spherical, cylindrical, cubic or other protruding surface forms used to make contact with the component, at precise places on its complex geometry.

(133) P47: Method of P40, whereby the single piece attachment has reference features, for repeatable positioning and clamping of the single piece attachment and affixed component within a clamping device.

(134) P48: Method of P47, whereby the clamping device is a vise, chuck or other standard mechanism with two or more moving parts used for workholding purposes.

(135) Various embodiments of the invention may be implemented at least in part in any conventional computer programming language. For example, some embodiments may be implemented in a procedural programming language (e.g., "C"), or in an object-oriented programming language (e.g., "C++"). Other embodiments of the invention may be implemented as preprogrammed hardware elements (e.g., application specific integrated circuits, FPGAs, and digital signal processors), or other related components.

(136) In an alternative embodiment, the disclosed apparatus and methods may be implemented as a computer program product for use with a computer system. Such implementation may include a series of computer instructions fixed either on a tangible medium, such as a non-transient computer readable medium (e.g., a diskette, CD-ROM, ROM, FLASH memory, or fixed disk). The series of computer instructions can embody all or part of the functionality previously described herein with respect to the system.

(137) Those skilled in the art should appreciate that such computer instructions can be written in a number of programming languages for use with many computer architectures or operating systems. Furthermore, such instructions may be stored in any memory device, such as semiconductor,

magnetic, optical or other memory devices, and may be transmitted using any communications technology, such as optical, infrared, microwave, or other transmission technologies.

(138) Among other ways, such a computer program product may be distributed as a removable medium with accompanying printed or electronic documentation (e.g., shrink wrapped software), preloaded with a computer system (e.g., on system ROM or fixed disk), or distributed from a server or electronic bulletin board over the network (e.g., the Internet or World Wide Web). Of course, some embodiments of the invention may be implemented as a combination of both software (e.g., a computer program product) and hardware. Still other embodiments of the invention are implemented as entirely hardware, or entirely software.

(139) Computer program logic implementing all or part of the functionality previously described herein may be executed at different times on a single processor (e.g., concurrently) or may be executed at the same or different times on multiple processors and may run under a single operating system process/thread or under different operating system processes/threads. Thus, the term “computer process” refers generally to the execution of a set of computer program instructions regardless of whether different computer processes are executed on the same or different processors and regardless of whether different computer processes run under the same operating system process/thread or different operating system processes/threads.

(140) The embodiments of the invention described above are intended to be merely exemplary; numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in any appended claims.

Claims

1. A method of producing a single-piece workholding apparatus for holding a workpiece during inspection by a coordinate measuring machine, the workpiece having a target portion having a complex geometry, the method comprising: measuring the geometry of the target portion to obtain a measured element; and creating a digital template by digitally subtracting the measured element from a template blank; and producing, from the digital template, the single-piece workholding apparatus comprising an interface having a fixed shape, the interface adapted to couple to the target portion of the workpiece.
2. The method of claim 1, wherein the digital template further comprises a standard clamping interface, and the method further comprises producing, from the digital template, the single-piece workholding apparatus having a standard clamping interface.
3. The method of claim 1, wherein producing the single-piece workholding apparatus comprises 3D printing the digital template.
4. The method of claim 3, wherein 3D printing the digital template comprises producing the single-piece workholding apparatus from thermoplastic.
5. The method of claim 4, wherein the thermoplastic is one of ABS, HIPS, and polyamide.
6. The method of claim 3, wherein 3D printing the digital template comprises producing the single-piece workholding apparatus via fused deposition modeling (FDM).
7. The method of claim 1, wherein the interface has a contour that is the complement of the target portion shape of the target portion such that the contour is complementary to the shape of the target portion.
8. The method of claim 1, wherein the interface is flexible so as to accept the target portion of the workpiece and so as to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the workpiece interface so as to hold the target portion via compression fitting.
9. The method of claim 1, wherein the interface has a contour that is the complement of the target portion shape of the target portion such that the contour is complementary to the shape of the target

portion, and wherein the workpiece interface is flexible so as to accept the target portion of the workpiece and so as to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the workpiece interface so as to hold the target portion via compression fitting.

10. The method of claim 1, wherein the interface comprises a slot having a tapered angle of between 0 and -5 degrees in a direction of insertion of a workpiece to ensure gradually increasing compression as the workpiece is inserted.

11. The method of claim 1, wherein the single-piece workholding apparatus further comprises a relief hole in the form of a cylindrical or other curved profile to relieve stresses while a workpiece is compression fit into the interface.

12. The method of claim 1, wherein the single-piece workholding apparatus further comprises an undercut or countersink area to allow access to a complex geometry of the workpiece while the workpiece is secure in the interface.

13. The method of claim 1, further comprising coupling the single-piece workholding apparatus to a base having a second interface configured to securely couple to a clamping system.

14. The method of claim 13, wherein the base has a bottom face comprising a plurality of cavities, the plurality of cavities arranged in a pattern to match a corresponding pattern of dowels on a storage plate.

15. The method of claim 13, wherein the base comprises a plurality of base magnets arranged in a base pattern to match a corresponding pattern of storage magnets arranged on a storage plate.

16. The method of claim 13, wherein the base comprises: a first set of base features, which first set of base features is configured to interlock with counterpart features on a robotic gripper; and a second set of base features, which second set of base features is configured to interlock with counterpart jaw reference features of a clamp, wherein the first set of base features is not identical to the second set of base features.

17. The method of claim 13, wherein the base comprises: base features, which base features are configured to interlock with counterpart features on a robotic gripper, and the same base features are configured to interlock with counterpart jaw reference features of a clamp.

18. The method of claim 1, wherein the target portion has a complex geometry defined by a plurality of curved surfaces, and the interface is shaped and sized to have a contour that is the complement of said complex geometry, to provide a compressive force on the target portion of the workpiece when the workpiece is disposed in the interface.

19. The method of claim 4, wherein the thermoplastic is acrylonitrile-butadienestyrene.

20. The method of claim 4, wherein the thermoplastic is polyamide.
