Innovation, Sciences et Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 2937013 C 2021/06/08

(11)(21) **2 937 013**

(12) **BREVET CANADIEN
CANADIAN PATENT**

(13) **C**

(22) Date de dépôt/Filing Date: 2016/07/22
(41) Mise à la disp. pub./Open to Public Insp.: 2017/04/28
(45) Date de délivrance/Issue Date: 2021/06/08
(30) Priorité/Priority: 2015/10/28 (US14/925,458)

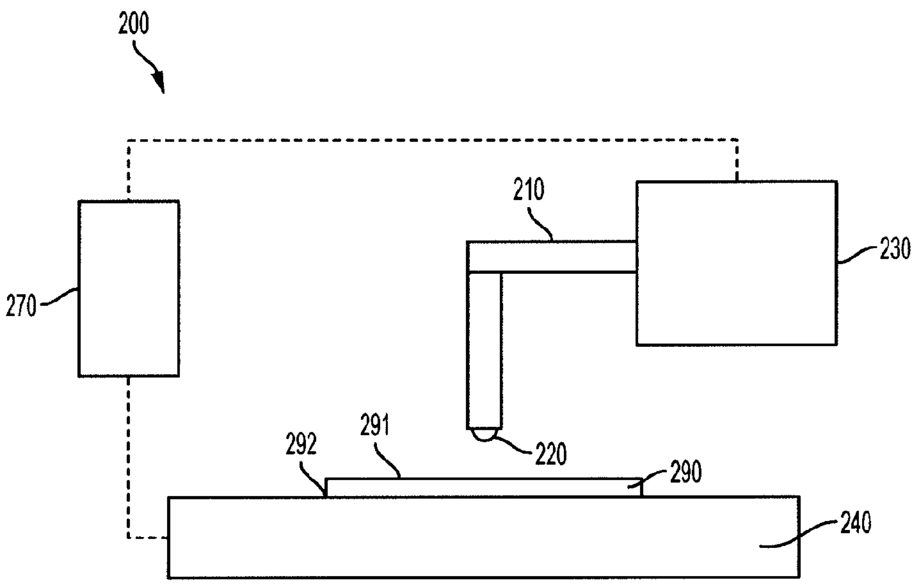
(51) Cl.Int./Int.Cl. *B21D 5/08* (2006.01), *B21B 1/38* (2006.01), *B21D 11/00* (2006.01), *B64C 1/12* (2006.01)

(72) Inventeurs/Inventors:
ZHANG, HAO, US;
QUARBERG, RYAN PAUL, US

(73) Propriétaire/Owner:
THE BOEING COMPANY, US

(74) Agent: SMART & BIGGAR LLP

(54) Titre : FORMAGE DE LAMINAGE EN PROFONDEUR
(54) Title: DEEP ROLLING FORMING



(57) Abrégé/Abstract:
Disclosed are a method and system to form a contoured structure using deep rolling. The method includes using deep rolling to introduce plastic deformation to one or more portions of a work piece to form a convex contour in the work piece. The work piece, and subsequently formed contoured structure, can be metal or composite. The disclosed deep rolling systems and methods form, for example contoured aircraft panels, while also providing fatigue strength improvement and low level of work hardening during the forming process rather than as a post-production surface treatment.

ABSTRACT

Disclosed are a method and system to form a contoured structure using deep rolling. The method includes using deep rolling to introduce plastic deformation to one or more portions of a work piece to form a convex contour in the work piece. The work piece, and subsequently formed contoured structure, can be metal or composite. The disclosed deep rolling systems and methods form, for example contoured aircraft panels, while also providing fatigue strength improvement and low level of work hardening during the forming process rather than as a post-production surface treatment.

DEEP ROLLING FORMING

Technical Field

The present teachings relate generally to forming contoured structures and, more particularly, to using deep rolling to form contoured structures.

Background

Modern aircraft utilize contoured structures, e.g. curved metal panels, in a variety of applications including skins, access panels, wing flaps, and fuselage sections. Conventional methods for forming the contoured metal panels include shot peening and laser shock peening. In shot peen forming, a flow of metal, glass or ceramic shot impacts a surface of a metal work piece to elastically and plastically stretch that surface and introduce local low plastic deformation that manifests itself as a residual compressive stress. The combination of elastic and plastic stretching and compressive stress generation causes the metal panel to develop a concave curvature on the shot peened side. Problems arise with shot peening because of process variability. Moreover, shot peening uses small shots typically made of cast iron, cut wire steel, glass or ceramics that often break and need periodic replacement. Handing and disposal of the replaced shot can cause environment problems.

Laser shock peening operates similarly to shot peening, but uses a pulsed laser instead of steel or ceramic pieces to impact the work piece. Laser shock peening, however, requires expensive equipment and time consuming masking/unmasking steps before and after forming.

These methods also increase the surface roughness of the work piece, thereby requiring additional time consuming and costly surface treatment after the contours are introduced into the metal panel. An improved method for forming contoured metal panels would be desirable.

Summary

The following presents a simplified summary in order to provide a basic understanding of some aspects of one or more embodiments of the present teachings. This summary is not an extensive overview, nor is it intended to identify key or critical elements of the present teachings, nor to delineate the scope of the disclosure. Rather, its primary purpose is merely to present one or more concepts in simplified form as a prelude to the detailed description presented later.

In one embodiment, there is provided a method for forming a contoured structure from a work piece. The method involves providing the work piece comprising a first side and a second side, the work piece having a thickness of about two inches or less, positioning the work piece on a fixture, such that the first side of the work piece is accessible to a deep rolling tool, and applying a compressive force to the first side of the work piece with the deep rolling tool. The method further involves moving the deep rolling tool relative to the work piece while continuing to apply the compressive force to introduce a residual compressive stress localized at or near a surface of a first portion of the work piece, and adjusting the deep rolling tool to contact a second portion of the work piece and moving the deep rolling tool relative to

Date Reçue/Date Received 2020-06-04

the work piece to introduce a residual compressive stress localized at or near a surface of the second portion of the work piece. The method further involves adjusting the deep rolling tool to contact one or more additional portions of the work piece and moving the deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the one or more additional portions of the work piece and to introduce a convex contoured surface into the work piece.

The convex contoured surface may have a radius of from one inch to 300 feet.

The first portion, second portion, and additional portions of the work piece each may include a plurality of parallel adjacent line segments.

The first portion, second portion, and additional portions of the work piece each may include a square or rectangular shaped area on the first side of the work piece.

The deep rolling tool may include a spherical ball having a diameter from 0.05 inches to 1 inch or one or more cylinders each cylinder having a dimension of 0.1 inch diameter by 0.25 inches length to 3.0 inches diameter by 12 inches length.

An amount of compressive force applied by the deep rolling tool to portions of the work piece may range from 0.1 ksi to 30 ksi

Moving the deep rolling tool relative to the work piece may include moving the deep rolling tool at a rate of 0.01 inch/second to 10 inch/second.

Moving the deep rolling tool relative to the work piece to introduce the residual compressive stress localized at or near the surface of the first, the second, or the one

Date Reçue/Date Received 2020-06-04

or more additional portions of the work piece may include moving the deep rolling tool over a same portion of the work piece from 1 to 10 times.

A surface roughness of the first side of the convex contoured surface subsequent to introduction of the residual compressive stress by the deep rolling tool may be equal to or less than a surface roughness of the first side of the work piece prior to introduction of the residual compressive stress by the deep rolling tool.

The work piece may include a metal or composite.

An amount of force applied by the deep rolling tool to introduce the residual compressive stress to the first portion of the work piece may vary.

The method may involve applying another compressive force to the second side of the work piece with a second deep rolling tool to introduce a residual compressive stress localized at or near a surface of a portion of the second side of the work piece.

The applying of the another compressive force to the second side of the work piece may occur simultaneously as the compressive force is applied to the first side.

In another embodiment, there is provided a contoured structure made by any of the methods described above.

The structure may include a panel having a thickness of 2 inches or less, a length of 1 foot or more, and a width of 0.5 feet or more. A first side of the panel may comprise a convex contour with a radius from about 1 inch to about 300 feet, wherein the convex contour on the first side is formed by the deep rolling process. The first side of the panel comprising the convex contour may further comprise a surface

Date Reçue/Date Received 2020-06-04

roughness value Ra_2 that is less than or equal to a surface roughness value Ra_1, where Ra_1 is a surface roughness of the panel prior to the deep rolling process and Ra_2 is the surface roughness value after deep rolling.

The panel may have a residual stress that is more than between about -10 ksi and about -20ksi at a depth of 0.02 inches from a surface of the panel.

In another embodiment, there is provided a system for forming a contoured structure from a work piece comprising a first side and a second side, the work piece having a thickness of about two inches or less. The system includes a first deep rolling tool, means for positioning the work piece on a fixture, such that the first side of the work piece is accessible to the first deep rolling tool, and means for applying a first compressive force to the first side of the work piece with the first deep rolling tool. The system further includes means for moving the first deep rolling tool relative to the work piece while continuing to apply the first compressive force to introduce a residual compressive stress localized at or near a surface of the first portion of the work piece, and means for adjusting the first deep rolling tool to contact a second portion of the work piece. The means for moving the first deep rolling tool is configured to move the first deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the second portion of the work piece. The means for adjusting the first deep rolling tool is operable to adjust the first deep rolling tool to contact one or more additional portions of the work piece. The means for moving the first deep rolling tool is also configured to move the first deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or

Date Reçue/Date Received 2020-06-04

near a surface of the one or more additional portions of the work piece and to introduce a convex contour into the work piece, wherein the convex contour has a radius of from one inch to 300 feet.

The first deep rolling tool may include a tool element capable of applying the first compressive force to the first side of the work piece, wherein the first compressive force is in a range of 0.1ksi to 30ksi.

The means for moving the first deep rolling tool may be operable to move the first deep rolling tool at a rate of 0.01inch/second to 10 inch /second relative to the workpiece.

The means for moving the first deep rolling tool and the means for adjusting the first deep rolling tool may include a first computer numerically controlled (CNC) machine.

The first CNC machine may be configured to control movement of the first deep rolling tool to cause the first deep rolling tool to produce a contour in the first side of the workpiece, the contour having a radius of about 1 inch to about 300 feet.

The system may include a second deep rolling tool and a second CNC machine, wherein the second deep rolling tool is positioned by the second CNC machine to apply a second compressive force to the second side of the work piece.

The first and second CNC machines may be configured to cause the first deep rolling tool to apply the first compressive force to the first side of the work piece simultaneously as the second deep rolling tool applies the second compressive force to the second side of the work piece.

Date Reçue/Date Received 2020-06-04

Brief Description of the Drawings

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the present teachings and together with the description, serve to explain the principles of the disclosure. In the figures:

FIGS. **1**A and **1**B depict an aircraft including various contoured metal panels;

FIG. **2** depicts an exemplary system for forming a contoured structure from a work piece according to the present teachings;

FIGS. **3**A-B depict exemplary deep rolling tool elements according to the present teachings;

FIG. **4** depicts an exemplary method for using deep rolling to produce a contoured structure according to the present teachings;

FIGS. **5**A-C depict exemplary deep rolled portions of a metal work piece and paths of a deep rolling tool during formation of a contour in a work piece according to the present teachings;

FIG. **6** schematically depicts a contoured metal structure formed by deep rolling according to the present teachings;

FIG. **7** depicts another exemplary system for forming a contoured structure from a work piece according to the present teachings.

FIG. **8** shows surface roughness measured on **7075** aluminum samples before and after deep rolling; and

FIG. **9** shows measured residual stress profiles for machined, deep rolled, and shot peened **7075** aluminum samples.

It should be noted that some details of the figures have been simplified and are drawn to facilitate understanding of the present teachings rather than to maintain strict structural accuracy, detail, and scale.

Detailed Description

Reference will now be made in detail to exemplary embodiments of the present teachings, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

Deep rolling is a mechanical surface treatment that has been used to improve fatigue strength of metal parts that have been previously formed by, for example, casting, forging, etc. The previously formed metal parts typically include bolts, axles, wheel rims and other parts that require improved fatigue strength. In deep rolling, a tool element, such as a spherical ball or cylinder, moves over the surface of, for example, an axle while at the same time applying a compressive force to the surface of the axle. This causes low plastic deformation localized near the surface of the axle and results in improved fatigue performance of the part. Use of deep rolling, however, has been limited to improving fatigue performance of previously formed metal parts.

Systems and methods of the present teachings utilize deep rolling to form contoured structures from flat and curved work pieces. Use of the system and method is not limited to forming contoured structures from metal work pieces and can be used, for example, on composites. The exemplary deep rolling systems and methods disclosed herein avoid the process variability, expensive equipment, and subsequent surface roughness treatments associated with shot peening and laser shock peening. Furthermore, the exemplary systems and methods disclosed herein provide fatigue strength improvement and low level of work hardening during the forming process rather than as a post production surface treatment.

FIG. **1**A depicts an aircraft **100** that includes a number of contoured metal structures such as aircraft skins, access panels, wing flaps, wingskins, and fuselage sections. An aluminum skin panel **110** shown in FIG. **1**B is an example of a metal structure that is contoured for aerodynamic reasons. The description below may reference a metal skin panel for an aircraft as an example to illustrate the exemplary methods, however, one of ordinary skill in the art will understand that metal structures used on other vehicles are contemplated and other types of materials besides aluminum are contemplated including, but not limited to titanium, steels, carbon-fiber-reinforced polymer composites, other polymer/plastic matrix composites, metal matrix composites, and ceramic matrix composites.

FIG. **2** depicts an exemplary deep rolling system **200** that can be used to form a contoured structure from a work piece. As used herein, the term “work piece” refers to an initial structure, e.g. a metal panel or plate, on which deep rolling will introduce a contour or contours to form a contoured structure, e.g., a metal skin panel for an aircraft. The work piece can be flat or can already include contours. As used herein, the term “contoured structure” refers to a work piece on which deep rolling has introduced one or more curves/curvatures. Deep rolling system can include a fixture **240**, a deep rolling tool **210** and a computer numerically controlled (CNC) machine **230**. Deep rolling system **200** can further comprise a control system **270** that includes, for example, a hydraulic pressure pump, instruments, and sensors that in-situ monitor, control, and record the process parameters. Control system **270** can be connected to control fixture **240**, deep rolling tool **210**, and/or CNC machine **230**. Fixture **240** can position a work piece **290** so that one side is accessible to deep rolling tool **210**. Fixture **240** and deep rolling tool **210** can be configured so that one moves while the other is stationary. In another example, fixture **240** and deep rolling tool **210** can be configured so that both move.

Deep rolling tool **210** can include a deep rolling head **220**. Deep rolling head **220** includes an element, typically spherical or cylindrical in shape, to contact the surface of work piece **290** to introduce localized low plastic deformation to the surface of work piece **290**. FIG. 3A depicts an exemplary head **320** comprising a spherical ball element **322** that can be hydrostatically suspended by a ball retainer **324**. A cavity **326** can hold pressurized liquid, such as a coolant or oil. Spherical ball **322** can rotate in any direction within ball retainer **324**. Spherical ball **322** can have a diameter, for example, from about **0.05** inches to about **1** inch.

Deep rolling tool can alternatively comprise a cylindrically shaped element. FIG 3B depicts a cylindrical element **321** that can rotate about a fixed axis, shown as axis **325**. Cylindrical element **321** can have a dimension, for example, of **0.1** inch diameter by **0.25** inches length to **3.0** inches diameter by **12** inches length.

Deep rolling system **200** can include a computer numerically controlled (CNC) machine **230**. Although referred to as a CNC machine herein, one of ordinary skill in the art will understand that CNC machine **230** can include multi-axis CNC machines as well as conventional machines. CNC machine **230** can be, for example, a turning machine, drilling machine, milling machine, machining centers, or a conventional machine tool. CNC machine **230** can control the location and force deep rolling tool **210** exerts on the surface of work piece **290**.

FIG. **4** depicts an exemplary method **400** for forming a contoured structure according to the present teachings. Although exemplary method **400** describes forming a contoured metal structure from a metal work piece, other work pieces and contoured structures are contemplated including composite work pieces and contoured composite structures. At **410**, a metal work piece is provided that will be formed into a contoured metal structure. A metal work piece **290**, shown in FIG. **5**A, can be a metal structure made of aluminum, titanium, steel or other metals that can be formed into a contoured metal structure for use on a vehicle such as an aircraft. The metal work piece can be flat or include contours/curves. It can also include other structural elements such as, for example, openings, windows and the like. Metal work piece **290**, shown in a side view in FIG. **2**, can include a first side **291** and a second side **292**. First side **291** corresponds to the top surface in FIG. **2** and second side **292** corresponds to the bottom surface facing fixture **240**. Metal work piece **290** can have a thickness of about **2** inches or less, a length of about **1** foot or more, and a width of about **0.5** feet or more. An exemplary work piece to be formed into an aircraft wing structure can have a length of up to about **150** feet and a width of up to about **40** feet.

At **420** of FIG. **4**, the metal work piece can be positioned on a fixture so that one side is accessible to a deep rolling tool. For example, referring back to FIG.**2**, fixture **240** can position work piece **290** so that deep rolling tool **210** can physically contact top surface **291** of work piece **290**.

At **430**, the deep rolling tool can introduce plastic deformation to the work piece by applying a compressive force to the surface of the work piece. Referring back to FIG. **2**, CNC machine **230** can be programmed so that deep rolling tool **210** applies a compressive force ranging from **0**.**05** ksi to **150** ksi to first surface **291** of work piece **290**. For example, a compressive force of **0**.**1** ksi to **15** ksi can be applied to an aluminum alloy or a compressive force of **0**.**1** ksi to **30** ksi can be applied to a titanium alloy.

Plastic deformation can be introduced to a first portion of the work piece by moving the deep rolling tool relative to the work piece while continuing to apply the compressive force. By controlling, among other parameters, the force applied by the deep rolling tool to the surface and the path of the deep rolling tool as it moves along the surface, a contour can be introduced to the work piece to form the contoured structure. For example, CNC machine **230** can be programmed to move deep rolling tool **210** relative to work piece **290** while continuing to apply the compressive force to surface **291**. For example, deep rolling tool **210** can move at a rate of **0**.**01** inch/second to **20** inch/second relative to work piece **290**.

CNC machine **230** can be programmed to control a path of deep rolling tool **210** as it travels along first surface **291**. For example, the CNC machine can control movement of the deep rolling tool so that plastic deformation can be introduced to one or more portions of the work piece. As used herein, the term portion refers to a part of the work piece being subject to deep rolling. For example, a portion can be a circular or polygon shaped area on the work piece. A portion can also be a line segment or line segments over which the deep rolling tool travels. FIGS. **5**A-C shows a top view of first surface **291** of work piece **290**. Several exemplary paths **510**, **520**, and **530** on first surface **291**are shown. Each of the examples represents the path a deep rolling tool can travel as it introduces plastic deformation into portions of the surface of the work piece. FIG. **5**A shows a plurality of paths **510**a, **510**b, **510**c . . . **510**n, where each path corresponds to a portion of the work piece. For example, first portion **515**a, second portion **515**b, and third portion **515**c represent portions of work piece **290** in which plastic deformation has been introduced. Each of portions **515**a, **515**b, and **515**c correspond to paths **510**a, **510**b, and **510**c, respectively. For example, plastic deformation can be introduced into first portion **515**a of work piece **290** by applying a compressive force while moving deep rolling tool along path **510**a.

FIG. **5**B depicts another example path **520**. Although depicted as a single path, deep rolling tool **210** is adjusted to change its direction and/or location to treat multiple portions of work piece **290**. FIG. **5**C depicts yet another example path. Paths **530**a, **530**b and **530**c are rectangular shaped and each treat separate portions of work piece **290**. One of ordinary skill in the art will understand that other shaped paths, for example circular or spiral paths, are contemplated and depend on a number of factors including the desired contour, type of material, size of the work piece, orientation of the work piece on the fixture, and specific application for the contoured structure. For example, different paths can be used to introduce the same contour to a work piece.

Deep rolling tool **210** can move along a same path one or more times, for example, **1** to **10** times, while applying compressive stress. Moreover, the amount of compressive force applied by deep rolling tool **210** can vary as it moves along a path.

At **440** of FIG. **4**, the deep rolling tool can be adjusted so compressive force is applied to a second portion of the work piece. Referring to FIG. **5**A, subsequent to deep rolling tool **210** moving along path **510**a one or more times, it can be adjusted so that it applies compressive force while moving along path **510** b one or more times. This introduces plastic deformation to second portion **515**b of metal work piece **290**. As previously discussed, the compressive stress applied by deep rolling tool **210** can be constant or varied as it moves along path **510**b. The compressive stress applied by deep rolling tool **210** as it moves along path **510**b can be the same or different than the compressive stress applied along path **510**a. While depicted as parallel paths, one ordinary skill in the art will understand that the direction of the paths can vary dependent on the contour(s) desired.

At **450**, the deep rolling tool can be adjusted so compressive force is applied to one or more additional portions of the work piece. Referring to FIG. **5**C, deep rolling tool **210** can be adjusted so that it applies compressive force while moving along path **510**c one or more times. This introduces plastic deformation to third portion **515**c of metal work piece **290**. One of ordinary skill in the art will understand that the number of portions, the locations of the paths, the number of passes along each path, and the compressive stress can be varied to form the desired contour or contours.

Subsequent to the application of compressive force to the first, second, and one or more additional portions of the work piece, a contour is introduced. As shown in FIG. **6**, a contoured metal structure **600** can be formed from metal work piece **290**. First surface **291** of work piece corresponds to convex contoured surface **691** of metal structure **600**. In other words, application of compressive force in a certain range on first surface **291** of work piece **290** results in a convex contour in metal structure **600**. The convex contour can have a radius from about **1** inch to about **300** feet, or about **5** inches to **200** feet, or about **12** inches to about **50** feet. Deep rolling can be used to form contoured metal structures **600** having a width of about **2** inches or less, a length of about **1** foot or more, and a width of about **0.5** feet or more.

FIG. **7** depicts another deep rolling system that includes two tools to introduce compressive residual stress to both sides of a work piece simultaneously. An exemplary deep rolling system **700** can include a first deep rolling tool **710** having a first element **720**, a first computer numerically controlled (CNC) machine **730**, and a first control system **770** that can include, for example, a hydraulic pressure pump, instruments, and sensors that in-situ monitor, control, and record the process parameters. Deep rolling system **700** can further include a second deep rolling tool **712** having a second element **722**, a second computer numerically controlled (CNC) machine **732**, and a second control system **772** that can include, for example, a hydraulic pressure pump, instruments, and sensors that in-situ monitor, control, and record the process parameters.

Deep rolling system **700** can include a fixture **740** that can position a work piece **790** so that a first side **791** is accessible to first deep rolling tool **710** and a second side **792** is accessible to second deep rolling tool **712**. Although depicted in a vertical configuration, one of ordinary skill in the art will understand that other configurations are contemplated. Deep rolling system **700** can be used to form a contour or contours on work piece **790** by introducing compressive residual stress on side **791** and **792** simultaneously or sequentially. In another example, contours can be formed in work piece **790** by alternatingly introducing compressive residual stress first into side **791** and then into side **792**, and then repeating as desired.

The disclosed deep rolling system can be incorporated into existing workflows for manufacturing contoured structures, such as, for example, metal panels for use as aircraft skins. Referring back to FIGS. **4** and **6**, forming contoured structures using deep rolling method **400** may provide additional advantages. For example, the surface roughness of contoured structure **600** remains the same or can be improved compared to the surface roughness prior to deep rolling. FIG. **8** shows results of surface roughness measurements before and after deep rolling of **7050** aluminum. Surface roughness was measured on four samples, numbered **1** thru **4**, prior to deep rolling. Measurements were taken at four different locations. The surface roughness prior to deep rolling varied from about **70-130** micro-inch as shown on the left side of FIG. **8**. After deep rolling and prior to any surface treatment that would alter surface roughness, measurements were made at the same four locations. As shown on the right side of FIG. **8**, the surface roughness decreased to about **30-55** micro-inch. In contrast, forming a curved structure by shot or laser shock peening significantly increases the surface roughness and requires subsequent surface treatment to reduce the surface roughness before moving onto the next step in the manufacturing work flow.

Using deep rolling to form contoured structures can also provide higher and deeper residual stress. This can improve the productivity and efficiency of contour forming and allow formation of a wider range of contour curvatures. Fatigue properties can also be enhanced by deeper and higher residual stress. FIG. **9** shows residual stress profiles for machined, shot peened, and deep rolled 7050 aluminum samples. Residual stress measured for samples deep rolled were higher and extended further into the sample compared to machining and shot peening. For samples deep rolled at 0.7 ksi, the residual stress was about -10 ksi or more at a depth of 0.02 inches from the surface of the sample. For samples deep rolled at 1.5 ksi, the residual stress was about -20 ksi or more at a depth of 0.02 inches from the surface of the sample. In contrast, the machined and shot peened samples showed residual stress of less than about -5 ksi at a depth of 0.02 inches.

Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the present teachings are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. Moreover, all ranges disclosed herein are to be understood to encompass any and all sub-ranges subsumed therein. For example, a range of "less than 10" can include any and all sub-ranges between (and including) the minimum value of zero and the maximum value of 10, that is, any and all sub-ranges having a minimum value of equal to or greater than zero and a maximum value of equal to or less than 10, e.g., 1 to 5. In certain cases, the numerical values as stated for the parameter can take on negative values. In this case, the example value of range stated as "less than 10" can assume negative values, e.g. – 1, -2, -3, -10, -20, -30, etc. It will be appreciated that while the process is described as a series of acts or events, the present teachings are not limited by the ordering of such acts or events. Some acts may occur in different orders and/or concurrently with other acts or events apart from those described herein. Also, not all process stages may be required to implement a methodology in accordance with one or more aspects or embodiments of the present teachings. It will be appreciated that structural components and/or processing stages can be added or existing structural components and/or processing stages can be removed or modified. Further, one or more of the acts depicted herein may be carried out in one or more separate acts and/or phases. Furthermore, to the extent that the terms “including,” “includes,” “having,” “has,” “with,” or variants thereof are used in either the detailed description and the claims, such terms are intended to be inclusive in a manner similar to the term “comprising.” The term “at least one of” is used to mean one or more of the listed items can be selected. Further, in the discussion and claims herein, the term “on” used with respect to two materials, one “on” the other, means at least some contact between the materials, while “over” means the materials are in proximity, but possibly with one or more additional intervening materials such that contact is possible but not required. Neither “on” nor “over” implies any directionality as used herein. The term “conformal” describes a coating material in which angles of the underlying material are preserved by the conformal material. The term “about” indicates that the value listed may be somewhat altered, as long as the alteration does not result in nonconformance of the process or structure to the illustrated embodiment. Finally, “exemplary” indicates the description is used as an example, rather than implying that it is an ideal. Other embodiments of the present teachings will be apparent to those skilled in the art from consideration of the specification and practice of the disclosure herein. It is intended that the specification and examples be considered as exemplary only.

Terms of relative position as used in this application are defined based on a plane parallel to the conventional plane or working surface of a workpiece, regardless of the orientation of the workpiece. The term “horizontal” or “lateral” as used in this application is defined as a plane parallel to the conventional plane or working surface of a workpiece, regardless of the orientation of the workpiece. The term “vertical” refers to a direction perpendicular to the horizontal. Terms such as “on,” “side” (as in “sidewall”), “higher,” “lower,” “over,” “top,” and “under” are defined with respect to the conventional plane or working surface being on the top surface of the workpiece, regardless of the orientation of the workpiece.

EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method for forming a contoured structure from a work piece, the method comprising:

providing the work piece comprising a first side and a second side, the work piece having a thickness of about two inches or less;

positioning the work piece on a fixture, such that the first side of the work piece is accessible to a deep rolling tool;

applying a compressive force to the first side of the work piece with the deep rolling tool;

moving the deep rolling tool relative to the work piece while continuing to apply the compressive force to introduce a residual compressive stress localized at or near a surface of a first portion of the work piece;

adjusting the deep rolling tool to contact a second portion of the work piece and moving the deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the second portion of the work piece; and

adjusting the deep rolling tool to contact one or more additional portions of the work piece and moving the deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the one or more additional portions of the work piece and to introduce a convex contoured surface into the work piece.

Date Reçue/Date Received 2020-06-04

2. The method of claim **1**, wherein the convex contoured surface has a radius of from one inch to **300** feet.

3. The method of claim **1** or **2**, wherein the first portion, second portion, and additional portions of the work piece each comprise a plurality of parallel adjacent line segments.

4. The method of claim **1** or **2**, wherein the first portion, second portion, and additional portions of the work piece each comprise a square or rectangular shaped area on the first side of the work piece.

5. The method of claim **1** or **2**, wherein the deep rolling tool comprises a spherical ball having a diameter from **0**.**05** inches to **1** inch or one or more cylinders each cylinder having a dimension of **0**.**1** inch diameter by **0**.**25** inches length to **3**.**0** inches diameter by **12** inches length.

6. The method of claim **1** or **2**, wherein an amount of compressive force applied by the deep rolling tool to portions of the work piece range from **0**.**1** ksi to **30** ksi

7. The method of claim **1** or **2**, wherein moving the deep rolling tool relative to the work piece comprises moving the deep rolling tool at a rate of **0**.**01** inch/second to **10** inch/second.

8. The method of claim **1** or **2**, wherein moving the deep rolling tool relative to the work piece to introduce the residual compressive stress localized at or near the surface of the first, the second, or the one or more additional portions of the work piece comprises moving the deep rolling tool over a same portion of the work piece from **1** to **10** times.

Date Reçue/Date Received 2020-06-04

9. The method of claim **1** or **2**, wherein a surface roughness of the first side of the convex contoured surface subsequent to introduction of the residual compressive stress by the deep rolling tool is equal to or less than a surface roughness of the first side of the work piece prior to introduction of the residual compressive stress by the deep rolling tool.

10. The method of claim **1** or **2**, wherein the work piece comprises a metal or composite.

11. The method of claim **1** or **2**, wherein an amount of force applied by the deep rolling tool to introduce the residual compressive stress to the first portion of the work piece varies.

12. The method of any one of claims **1**-**11**, further comprising:

applying another compressive force to the second side of the work piece with a second deep rolling tool to introduce a residual compressive stress localized at or near a surface of a portion of the second side of the work piece.

13. The method of claim **12**, wherein the applying of the another compressive force to the second side of the work piece occurs simultaneously as the compressive force is applied to the first side.

14. A contoured structure made by the method of any one of claims **1**-**13**.

15. The contoured structure of claim **14**, wherein the structure comprises:

a panel having a thickness of **2** inches or less, a length of **1** foot or more, and a width of **0**.**5** feet or more; and

Date Reçue/Date Received 2020-06-04

a first side of the panel comprises a convex contour with a radius from about **1** inch to about **300** feet, wherein the convex contour on the first side is formed by the deep rolling process;

and wherein the first side of the panel comprising the convex contour further comprises a surface roughness value Ra_2 that is less than or equal to a surface roughness value Ra_1, where Ra_1 is a surface roughness of the panel prior to the deep rolling process and Ra_2 is the surface roughness value after deep rolling.

16. The contoured structure of claim **15**, wherein the panel has a residual stress that is more than between about -**10** ksi and about -**20**ksi at a depth of **0**.**02** inches from a surface of the panel.

17. A system for forming a contoured structure from a work piece comprising a first side and a second side, the work piece having a thickness of about two inches or less, the system comprising:

a first deep rolling tool;

means for positioning the work piece on a fixture, such that the first side of the work piece is accessible to the first deep rolling tool;

means for applying a first compressive force to the first side of the work piece with the first deep rolling tool;

means for moving the first deep rolling tool relative to the work piece while continuing to apply the first compressive force to introduce a residual

Date Reçue/Date Received 2020-06-04

compressive stress localized at or near a surface of the first portion of the work piece;

means for adjusting the first deep rolling tool to contact a second portion of the work piece,

wherein the means for moving the first deep rolling tool is configured to move the first deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the second portion of the work piece;

wherein the means for adjusting the first deep rolling tool is operable to adjust the first deep rolling tool to contact one or more additional portions of the work piece; and

wherein the means for moving the first deep rolling tool is configured to move the first deep rolling tool relative to the work piece to introduce a residual compressive stress localized at or near a surface of the one or more additional portions of the work piece and to introduce a convex contour into the work piece, wherein the convex contour has a radius of from one inch to **300** feet.

18. The system of claim **17** wherein the first deep rolling tool comprises a tool element capable of applying the first compressive force to the first side of the workpiece, wherein the first compressive force is in a range of **0**.**1**ksi to **30**ksi.

19. The system of claim **18** wherein the means for moving the first deep rolling tool is operable to move the first deep rolling tool at a rate of **0**.**01**inch/second to **10** inch /second relative to the workpiece.

Date Reçue/Date Received 2020-06-04

20. The system of claim **19** wherein the means for moving the first deep rolling tool and the means for adjusting the first deep rolling tool comprises a first computer numerically controlled (CNC) machine.

21. The system of claim **20** wherein the first CNC machine is configured to control movement of the first deep rolling tool to cause the first deep rolling tool to produce a contour in the first side of the workpiece, the contour having a radius of about **1** inch to about **300** feet.

22. The system of claim **21**, further comprising a second deep rolling tool and a second CNC machine, wherein the second deep rolling tool is positioned by the second CNC machine to apply a second compressive force to the second side of the work piece.

23. The system of claim **22**, wherein the first and second CNC machines are configured to cause the first deep rolling tool to apply the first compressive force to the first side of the work piece simultaneously as the second deep rolling tool applies the second compressive force to the second side of the work piece.

Date Reçue/Date Received 2020-06-04

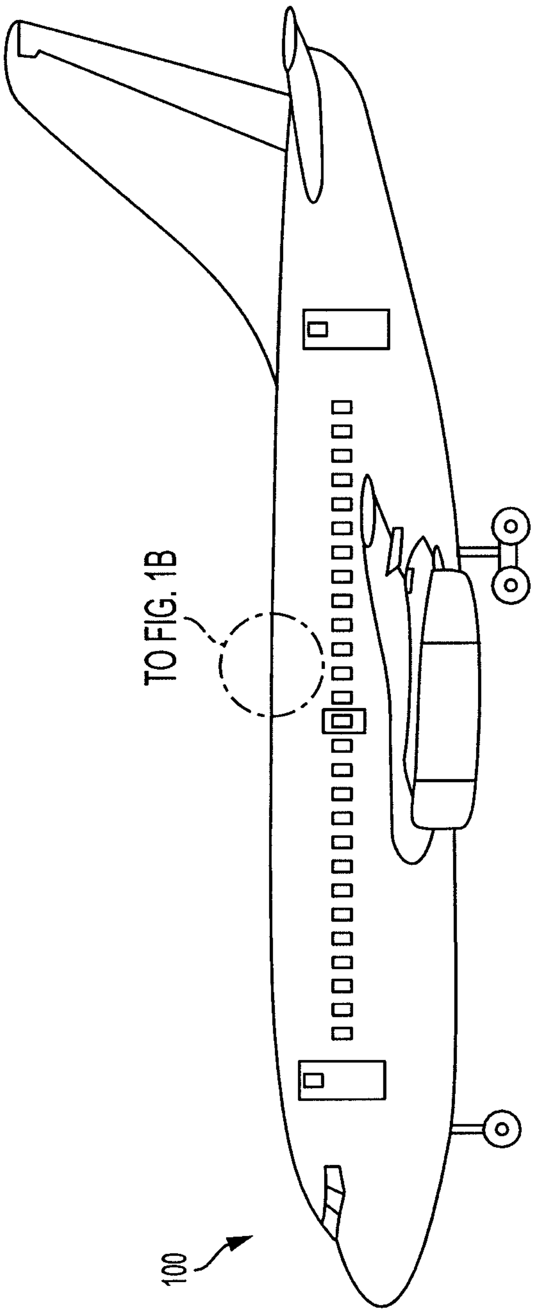


FIG. 1A

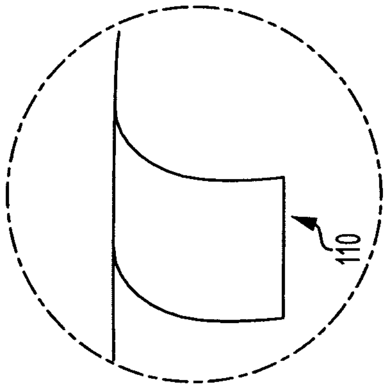


FIG. 1B

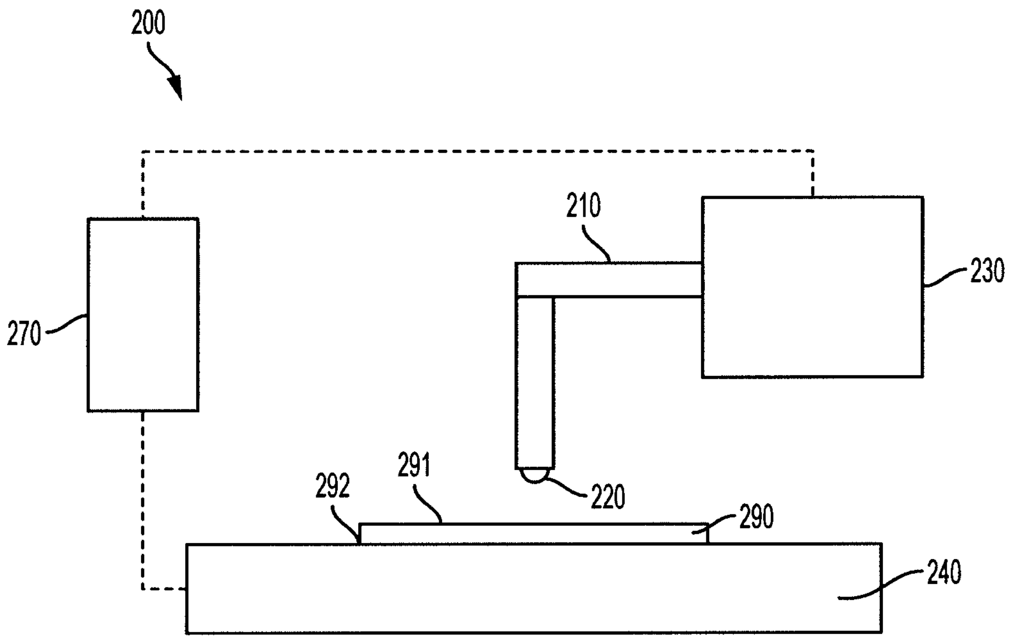


FIG. 2

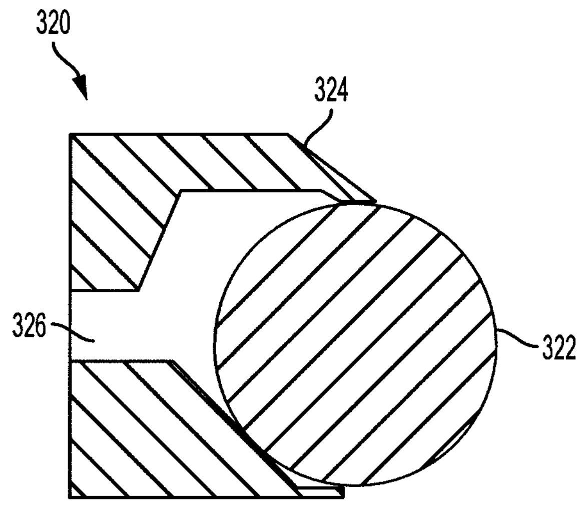


FIG. 3A

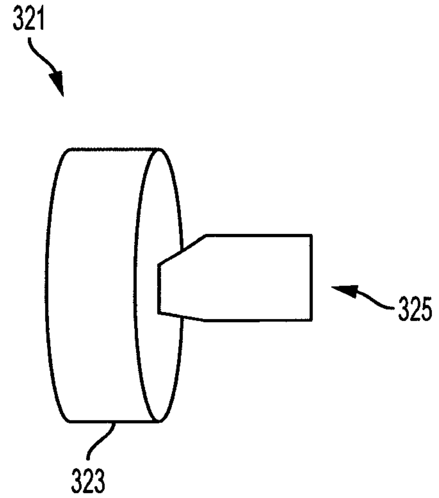


FIG. 3B

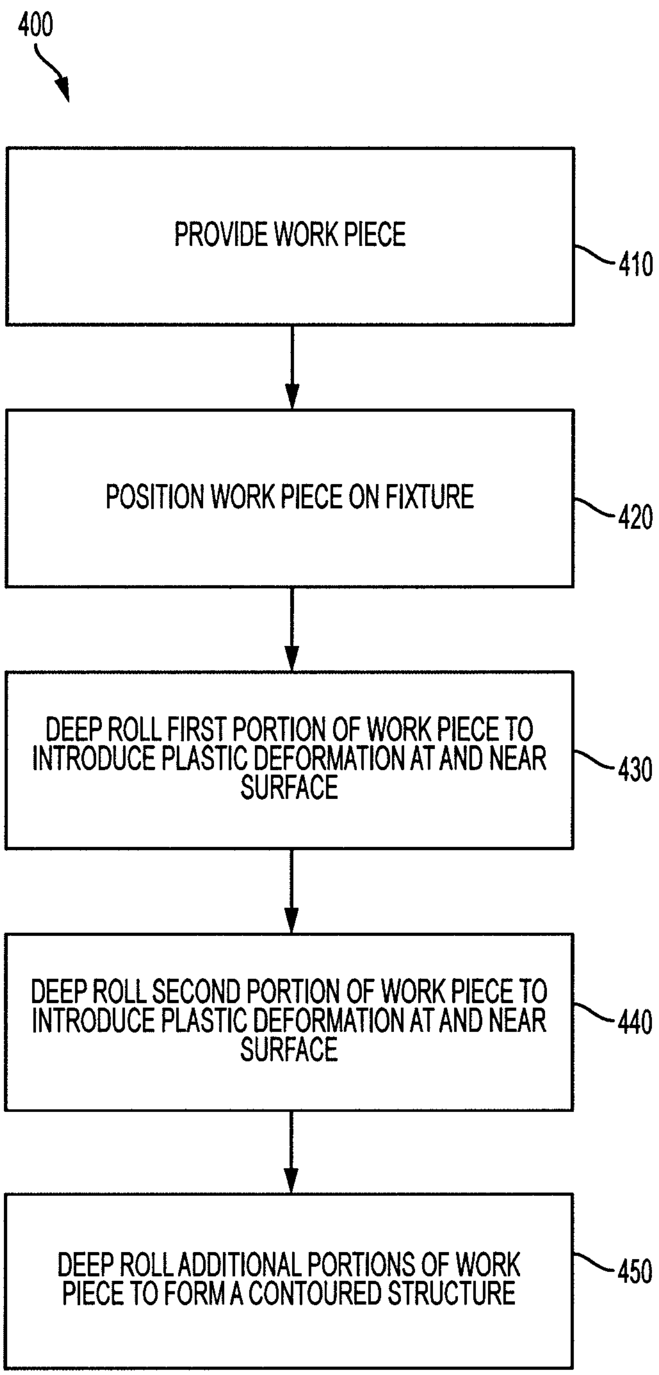

400
PROVIDE WORK PIECE
410
POSITION WORK PIECE ON FIXTURE
420
DEEP ROLL FIRST PORTION OF WORK PIECE TO INTRODUCE PLASTIC DEFORMATION AT AND NEAR SURFACE
430
DEEP ROLL SECOND PORTION OF WORK PIECE TO INTRODUCE PLASTIC DEFORMATION AT AND NEAR SURFACE
440
DEEP ROLL ADDITIONAL PORTIONS OF WORK PIECE TO FORM A CONTOURED STRUCTURE
450

FIG. 4

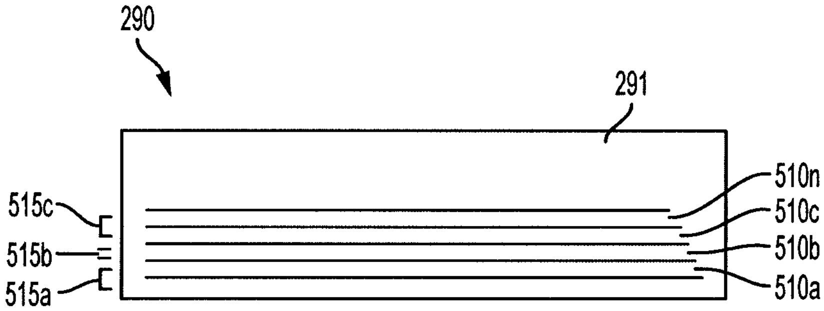


FIG. 5A

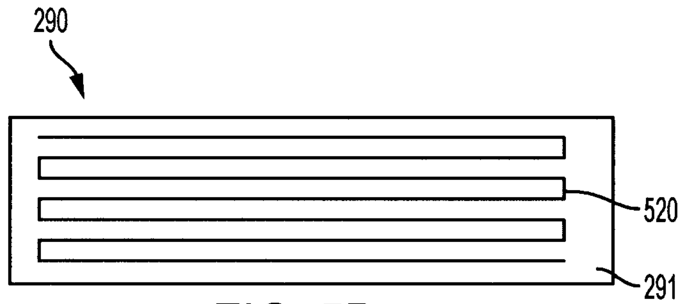


FIG. 5B

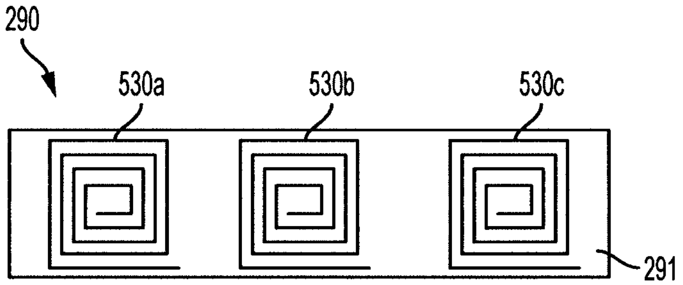


FIG. 5C

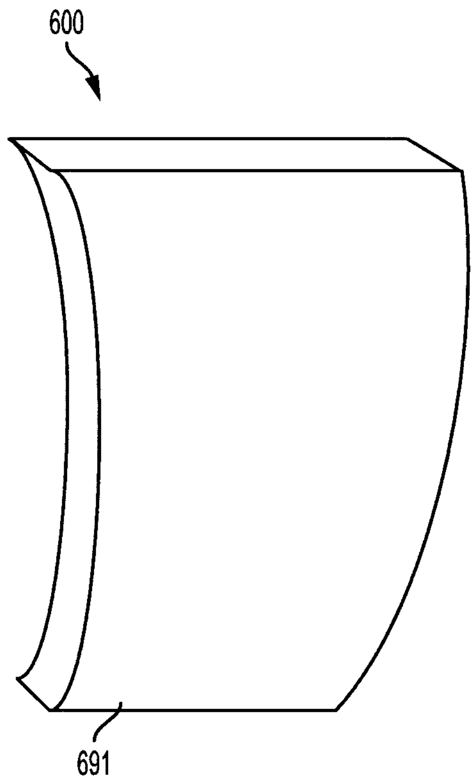


FIG. 6

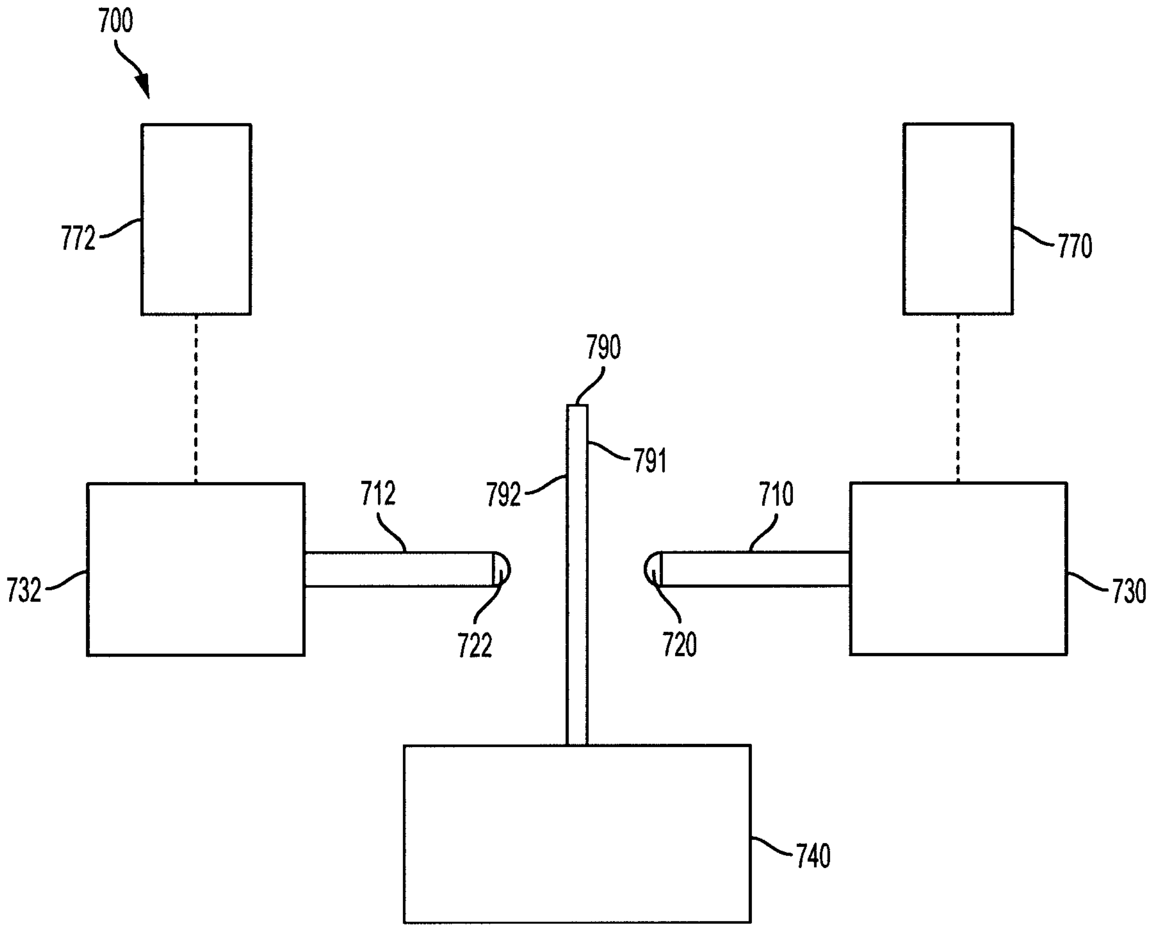


FIG. 7

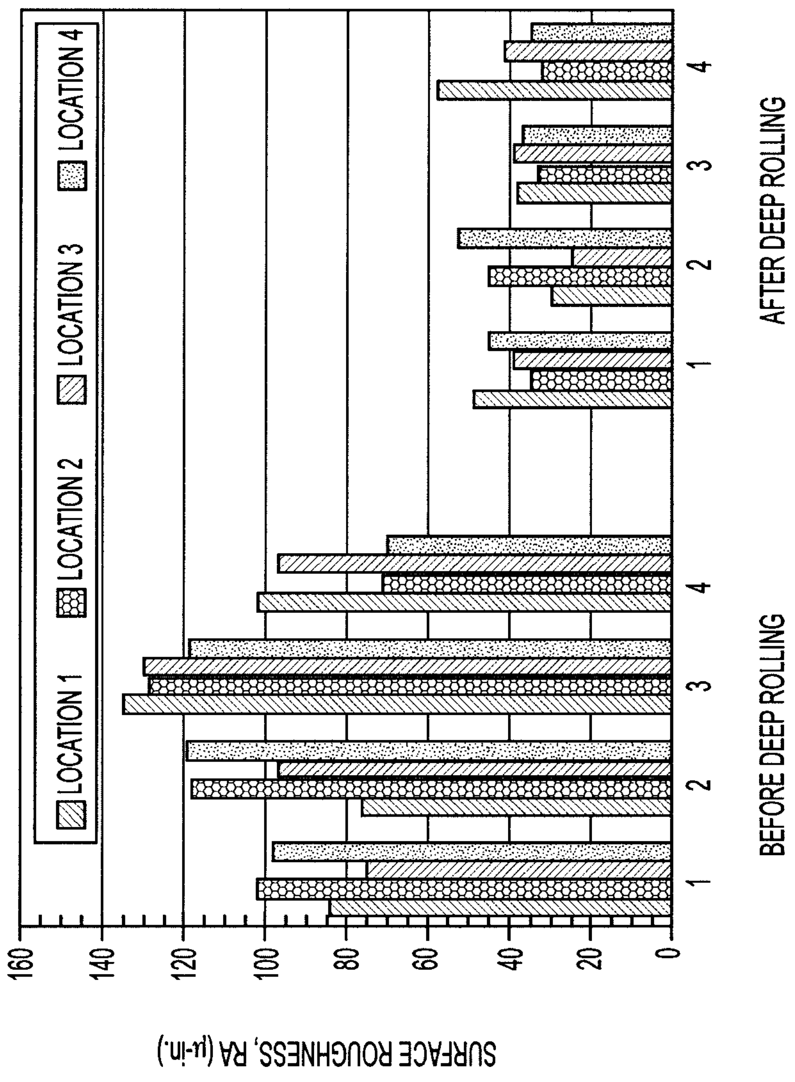
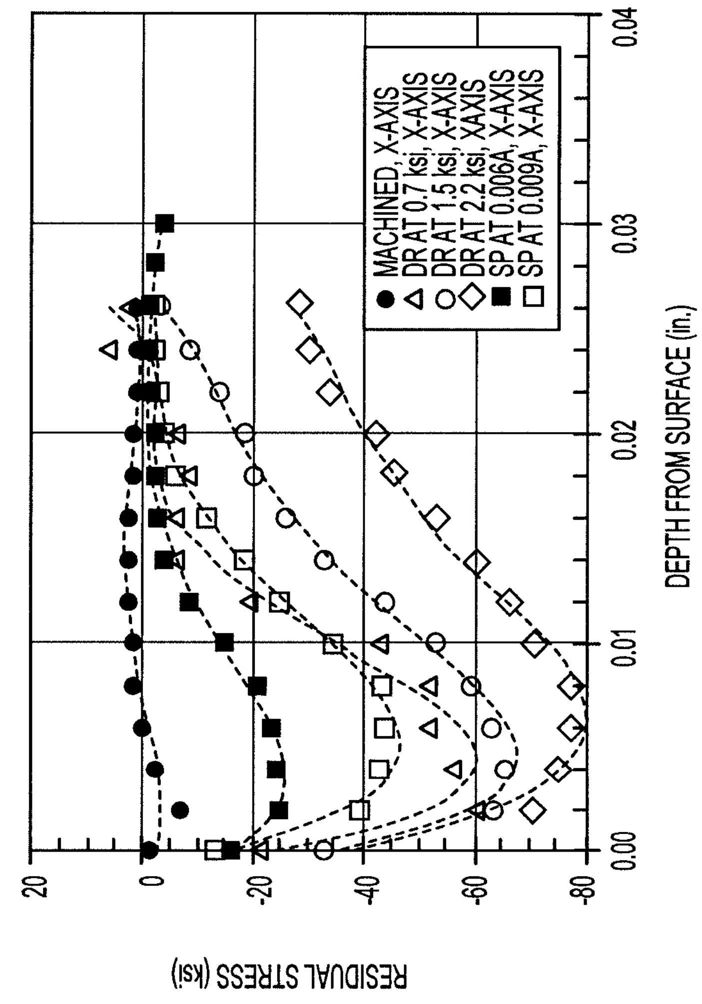
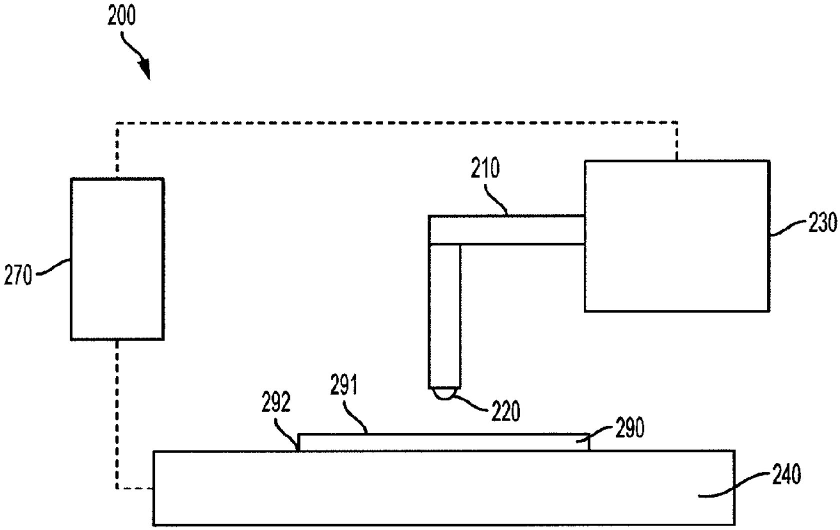

LOCATION 1
LOCATION 2
LOCATION 3
LOCATION 4
SURFACE ROUGHNESS, RA (μ-in.)
160
140
120
100
80
60
40
20
0
1
2
3
4
BEFORE DEEP ROLLING
1
2
3
4
AFTER DEEP ROLLING

FIG. 8



RESIDUAL STRESS (ksi)
20
0
-20
-40
-60
-80
DEPTH FROM SURFACE (in.)
0.00
0.01
0.02
0.03
0.04
MACHINED, X-AXIS
DR AT 0.7 ksi, X-AXIS
DR AT 1.5 ksi, X-AXIS
DR AT 2.2 ksi, XAXIS
SP AT 0.006A, X-AXIS
SP AT 0.009A, X-AXIS

FIG. 9


200
210
230
270
291
292
220
290
240