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(54) **POST MACHINING MULTI-STEP MATERIAL WORKING TREATMENT OF FLUID END HOUSING**

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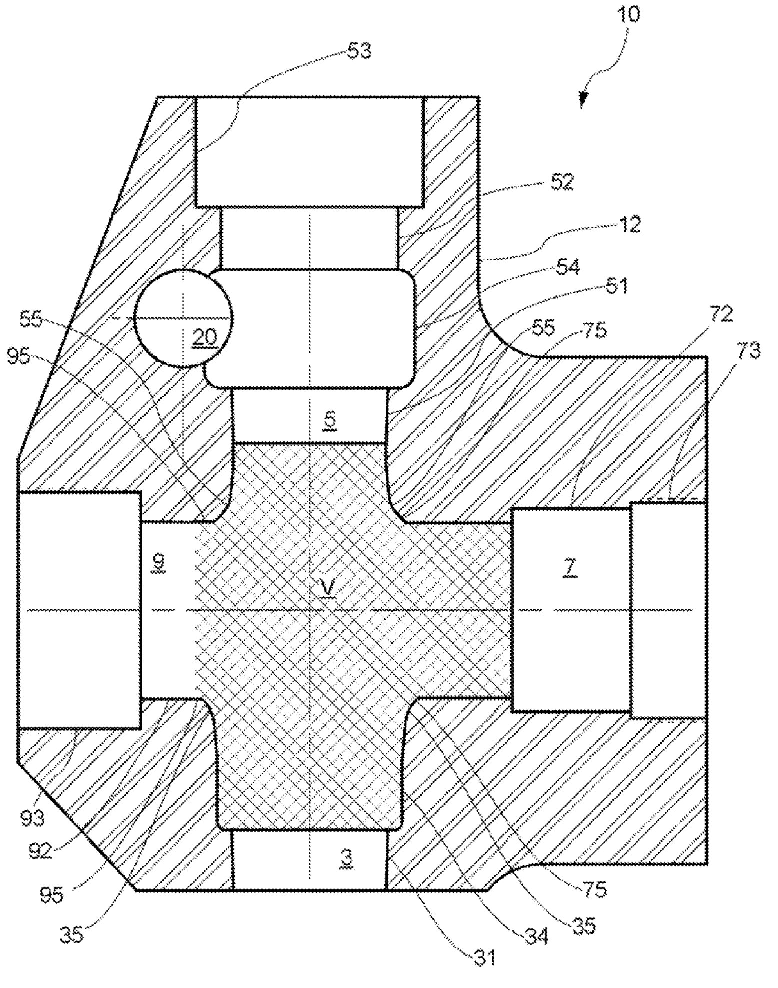
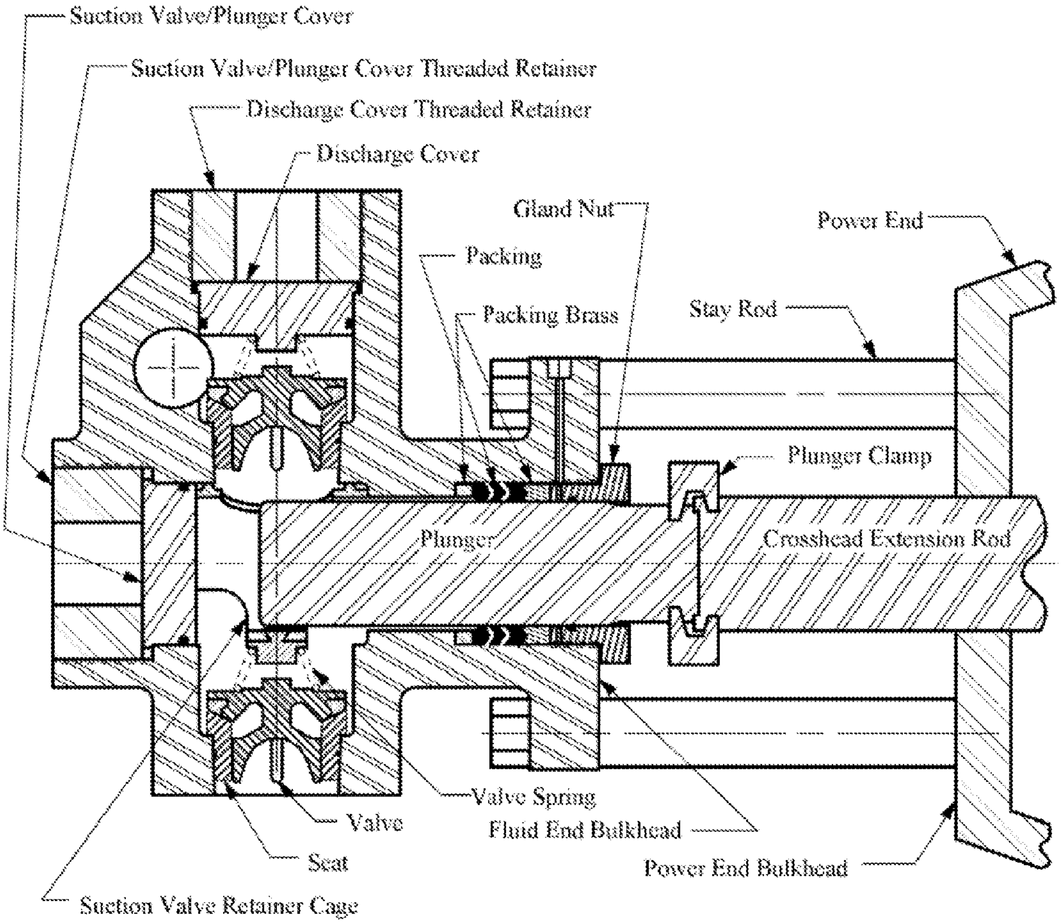
(57) **ABSTRACT**

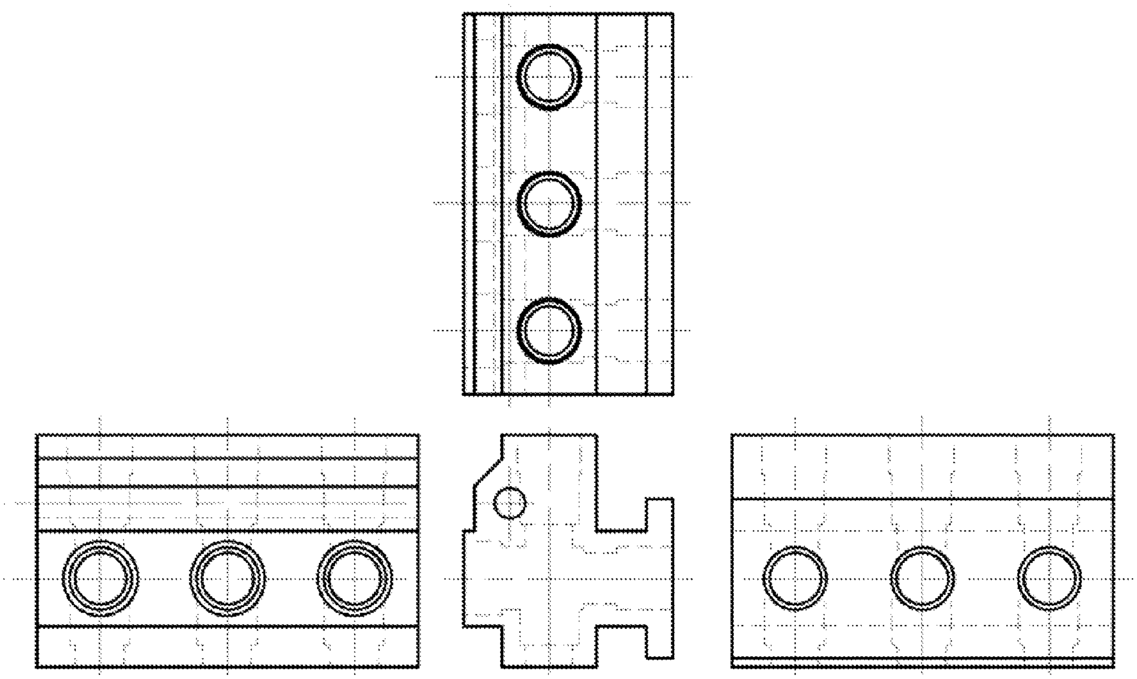
A method for post machining treatment of the interior surfaces of the access, suction, and discharge bores within each fluid chamber of the fluid end housing of a plunger pump that includes a three (3) step cold and hot working process. The treatment processes include a first shot peening of selected sections of said interior surfaces of each fluid chamber; a quench-polish-quench process whereby an anticorrosion nitride surface layer is added to the interior surfaces of each fluid chamber; and a second shot peening of the selected sections of the interior surfaces of each fluid chamber.





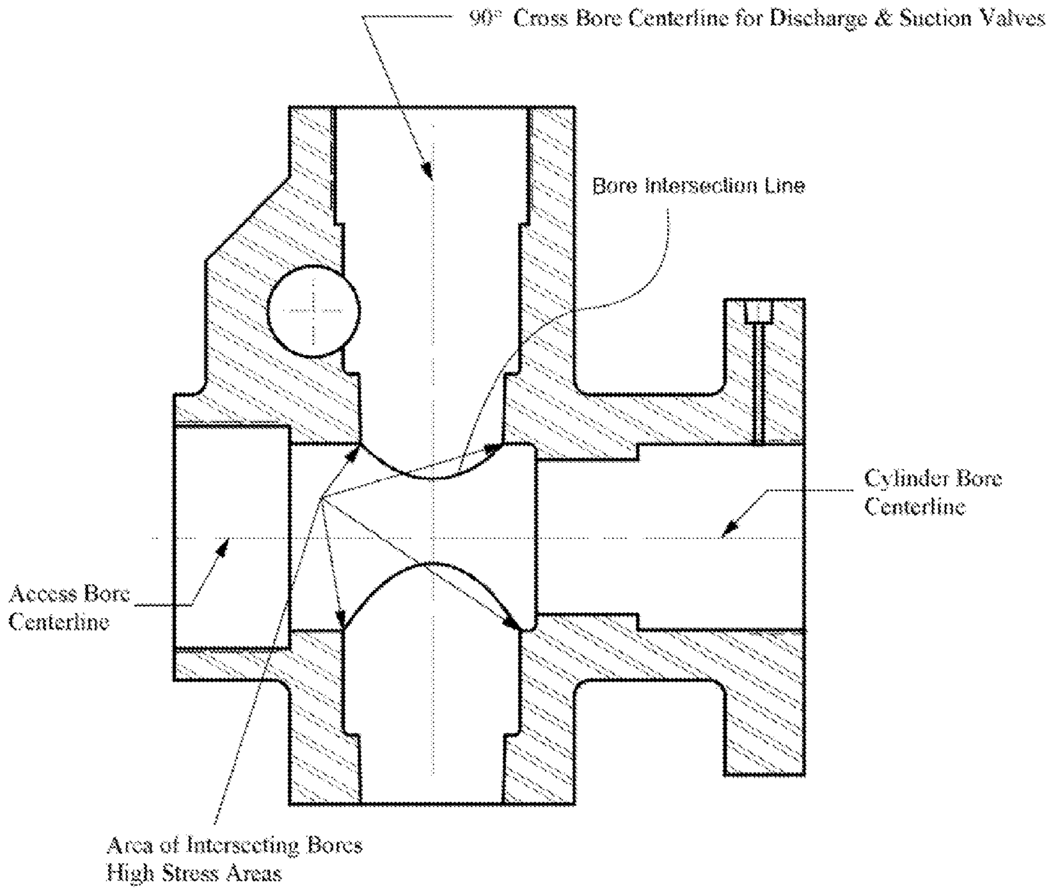
Prior Art

Figure 1



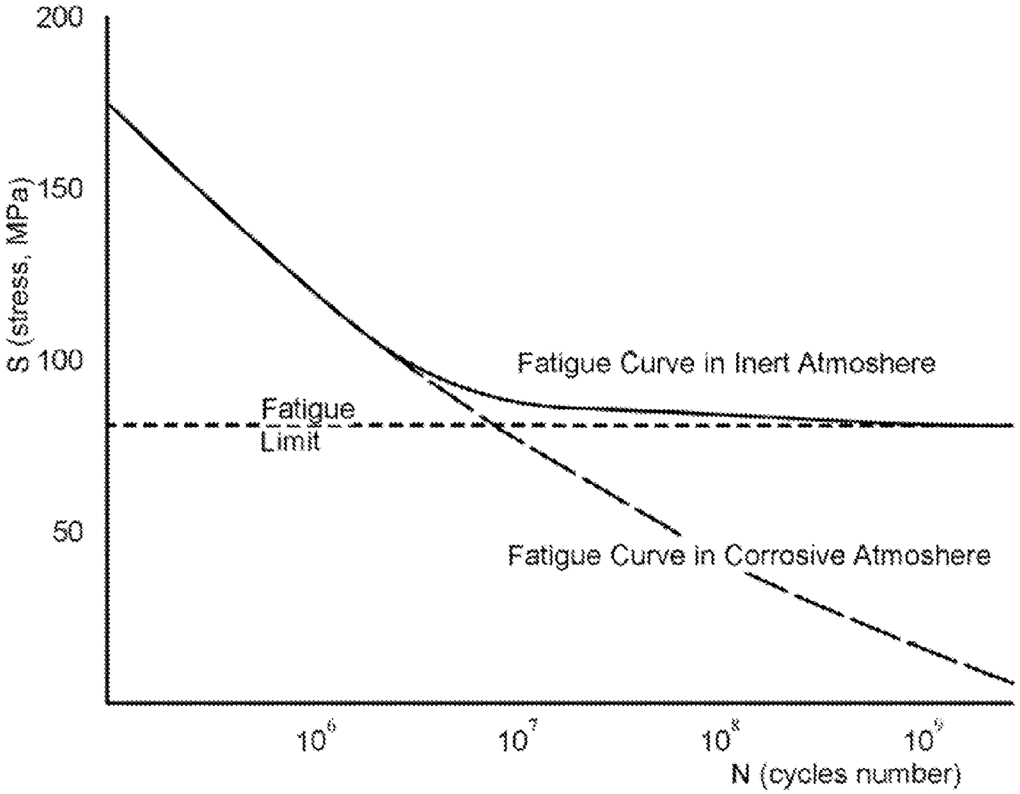
Prior Art

Figure 2



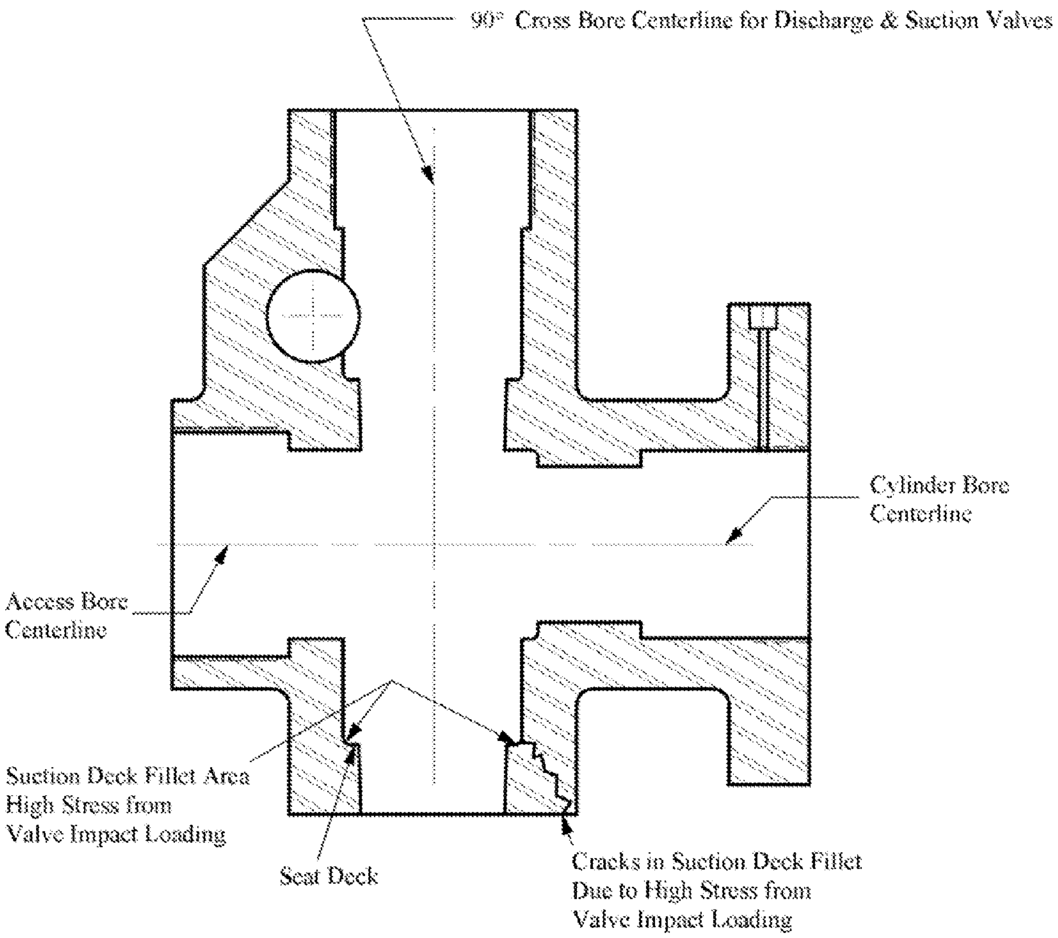
Prior Art

Figure 3



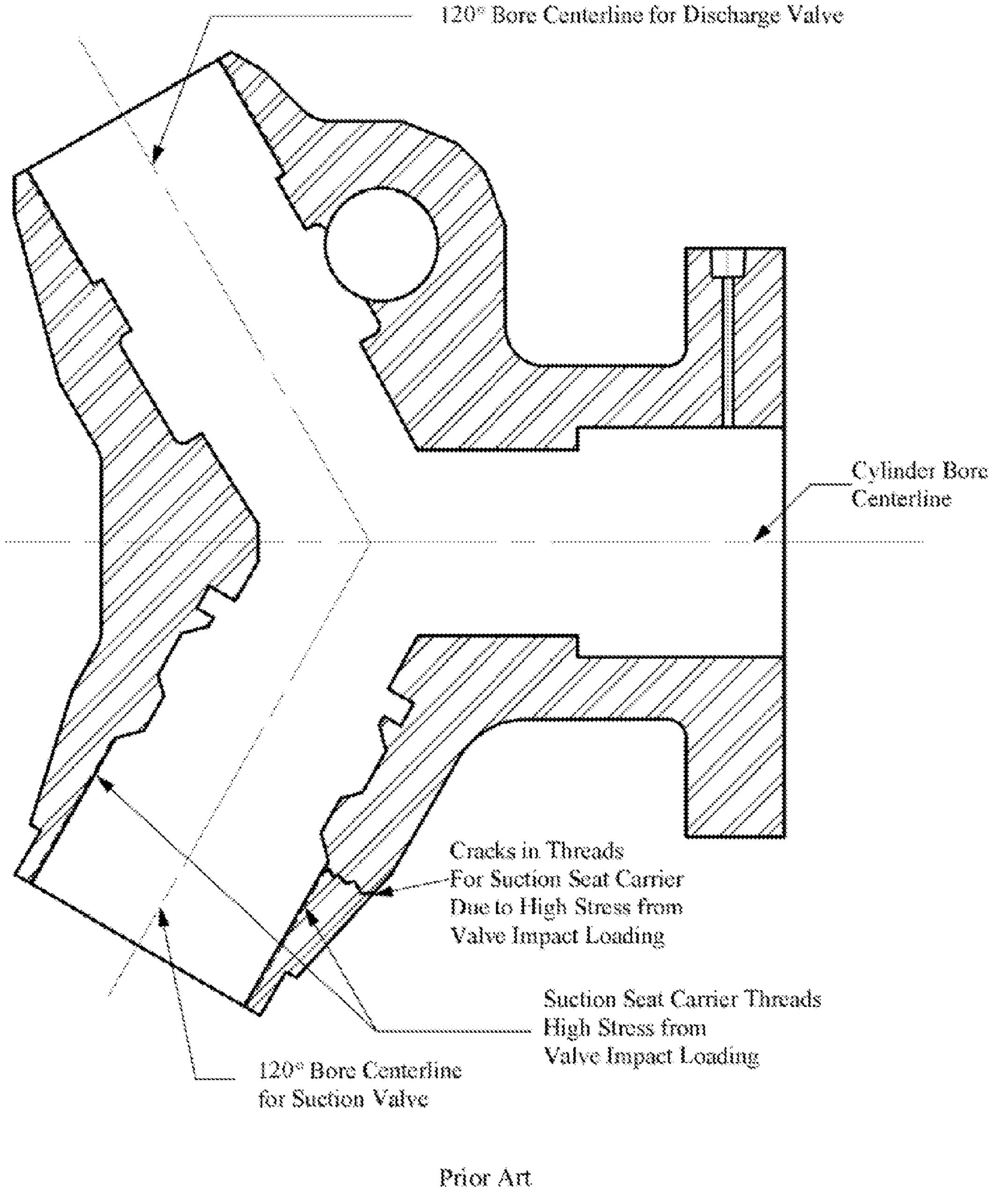
Applied Stress vs Cycles to Failure

Figure 4



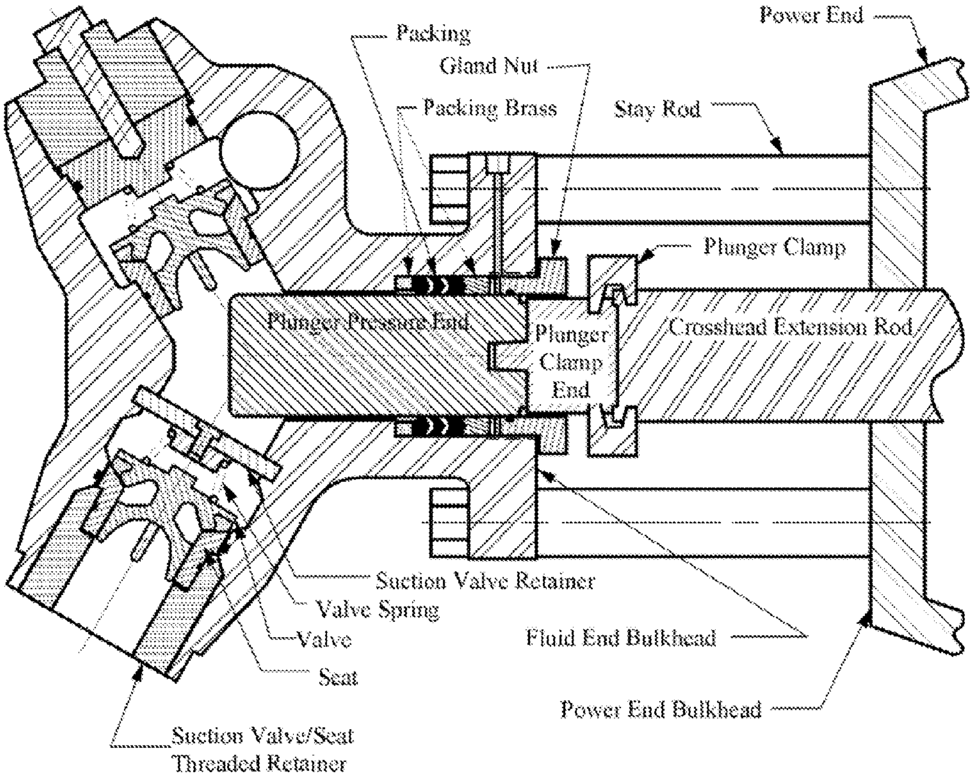
Prior Art

Figure 5



Prior Art

Figure 6A



Prior Art

Figure 6B

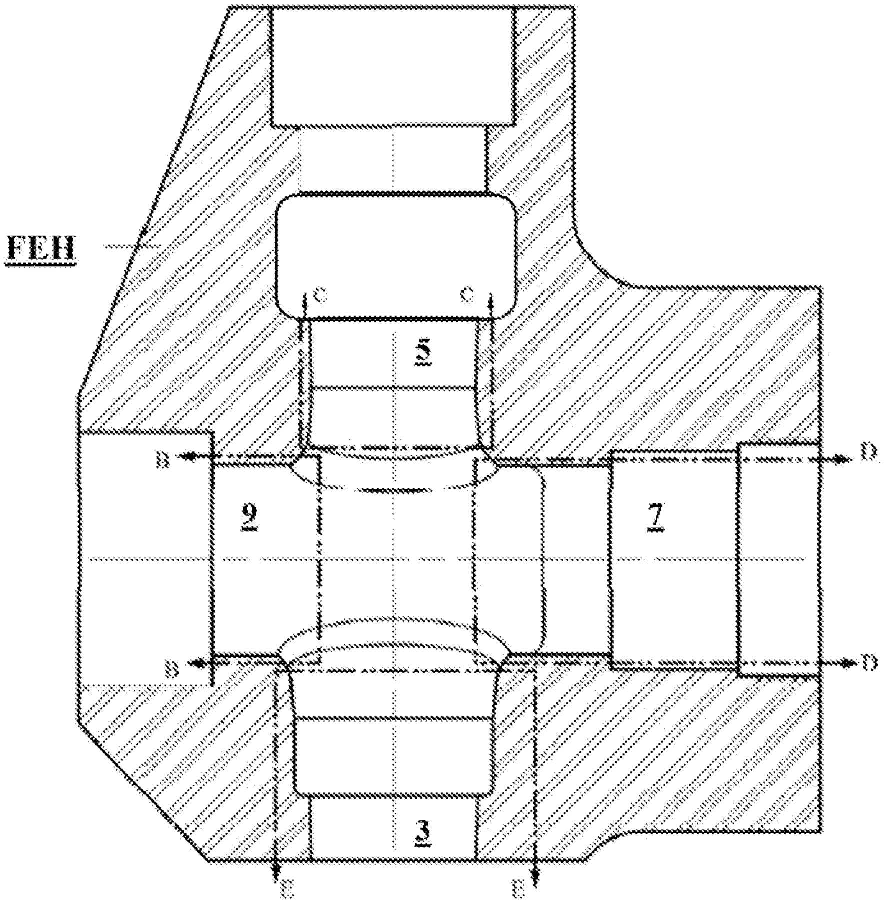
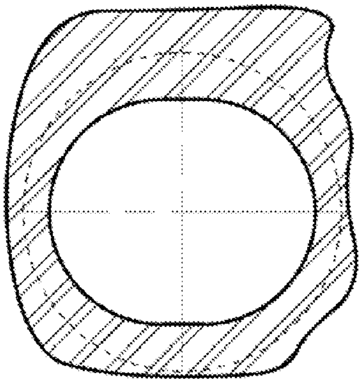
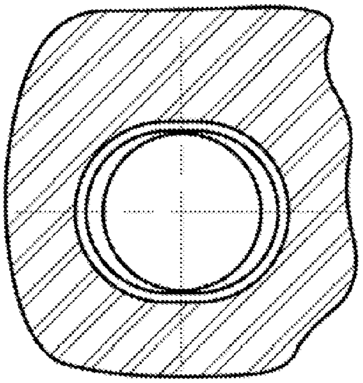


Figure 7A



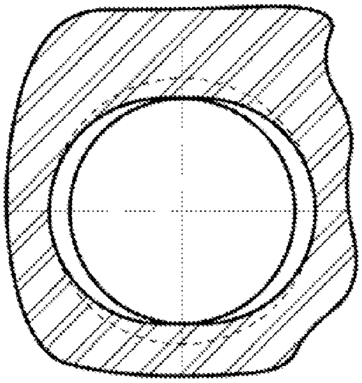
(Section B-B of Figure 7A)

Figure 7B



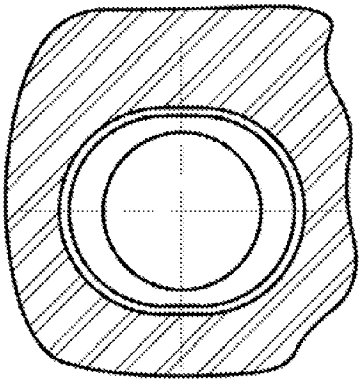
(Section C-C of Figure 7A)

Figure 7C



(Section D-D of Figure 7A)

Figure 7D



(Section E-E of Figure 7A)

Figure 7E

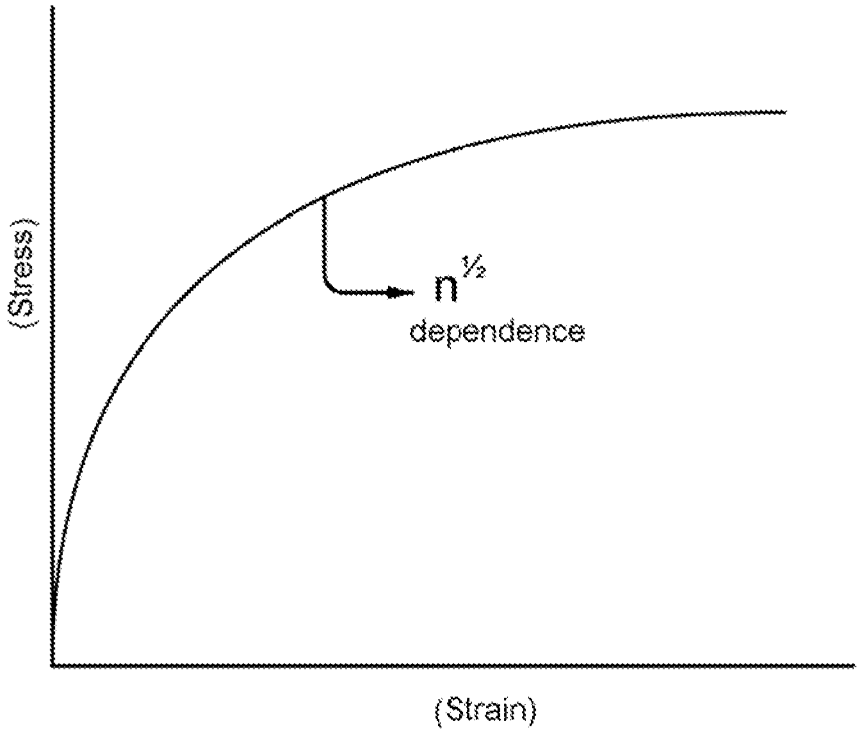


Figure 8

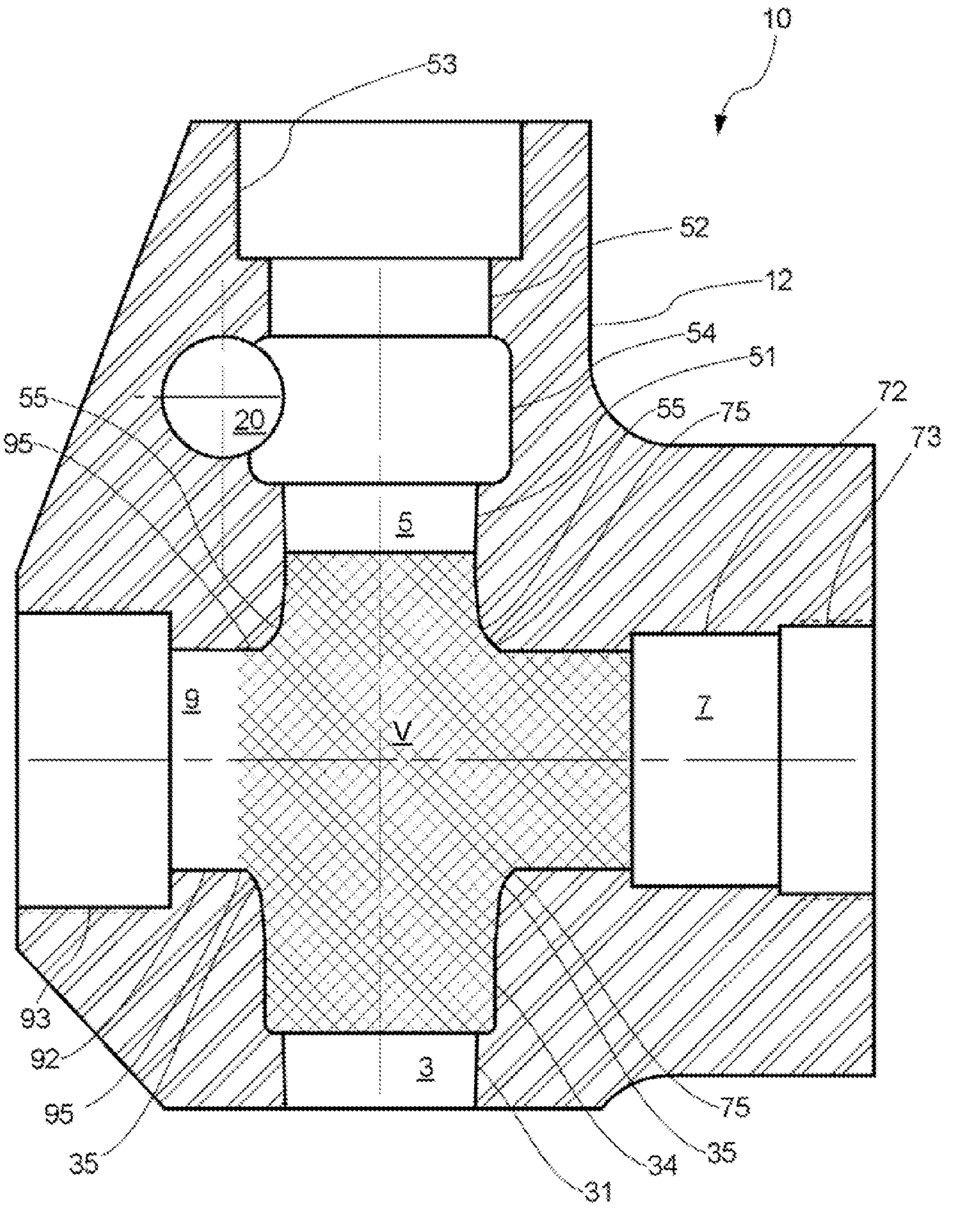
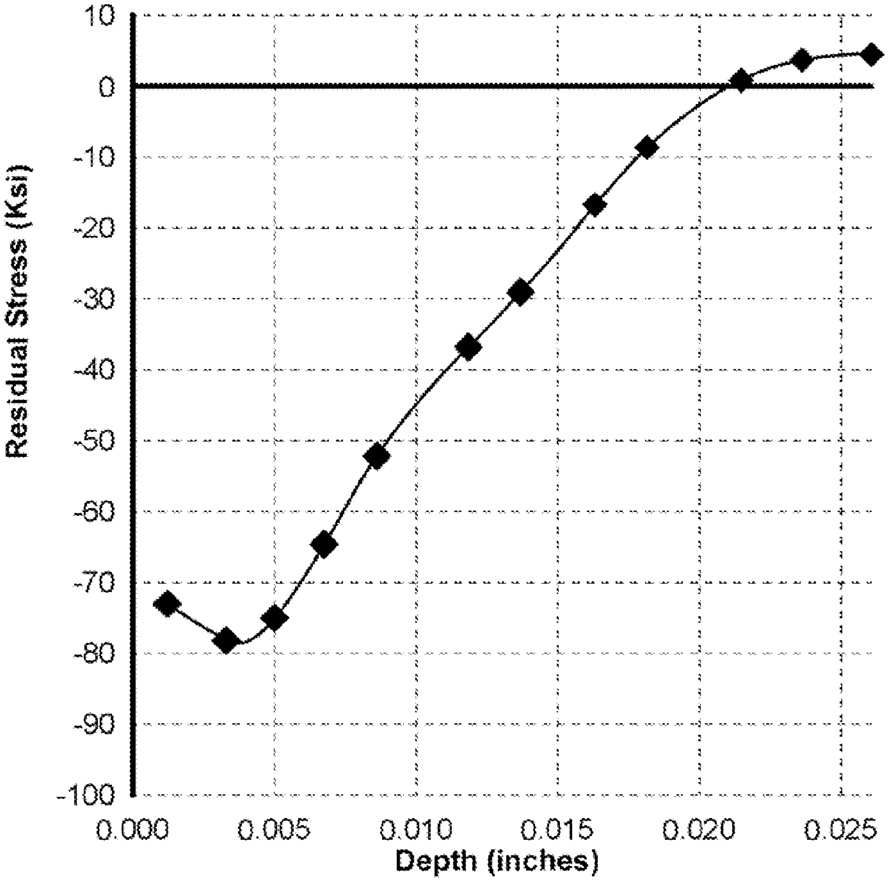
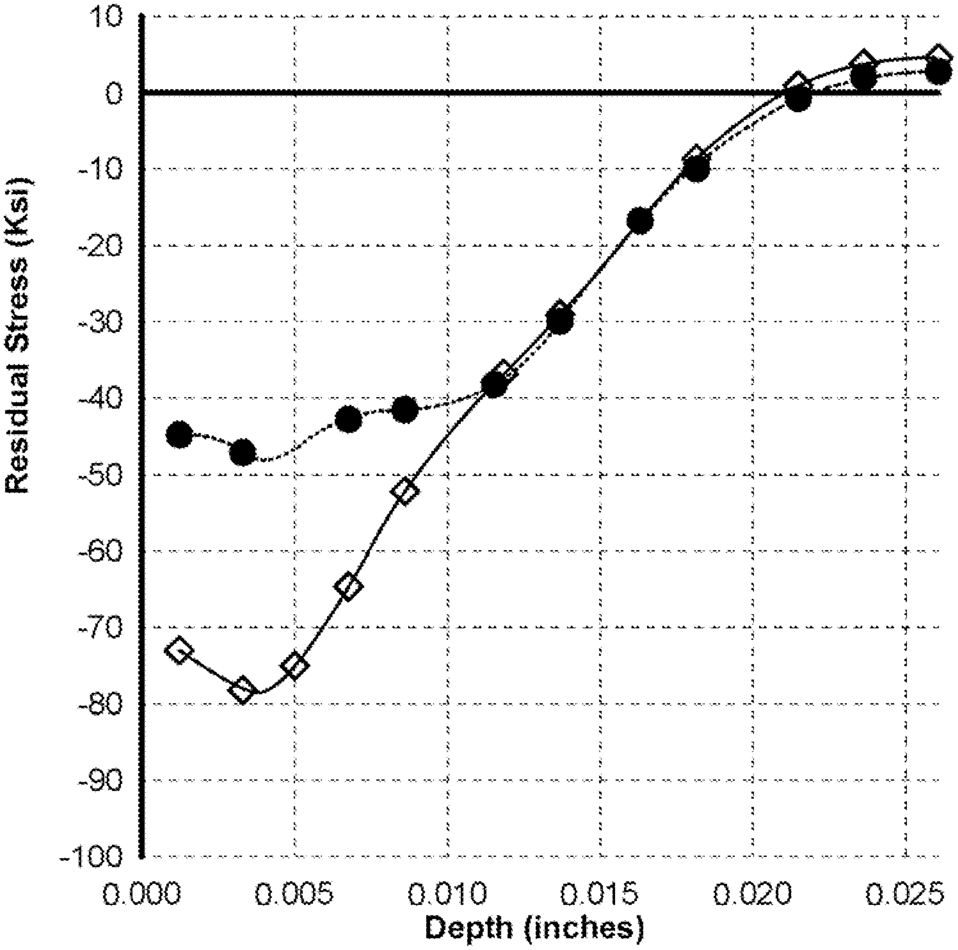


Figure 9



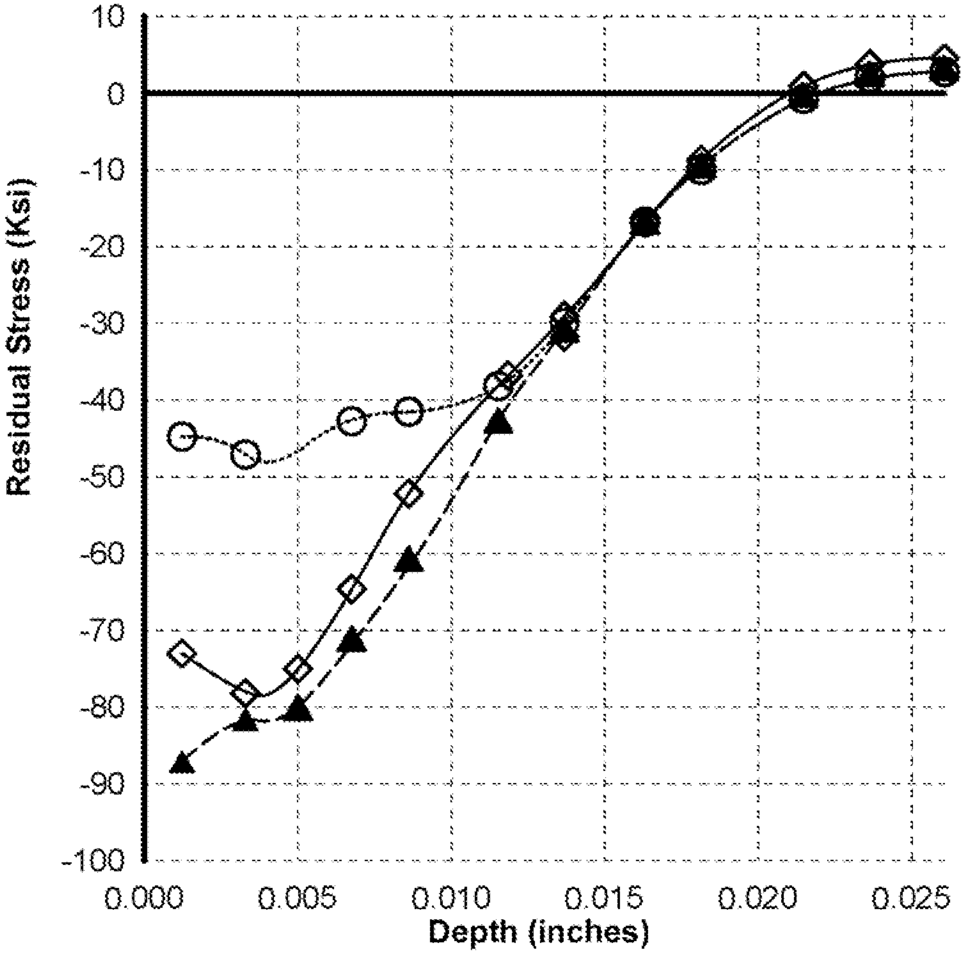
Compressive Stresses Initial Shot Peen

Figure10



Compressive Stresses Initial Shot Peen & Post QPQ Treatment

Figure 11



Compressive Stresses Initial Shot Peen,
Post QPQ Treatment,
& Post Final Shot Peen

Figure 12

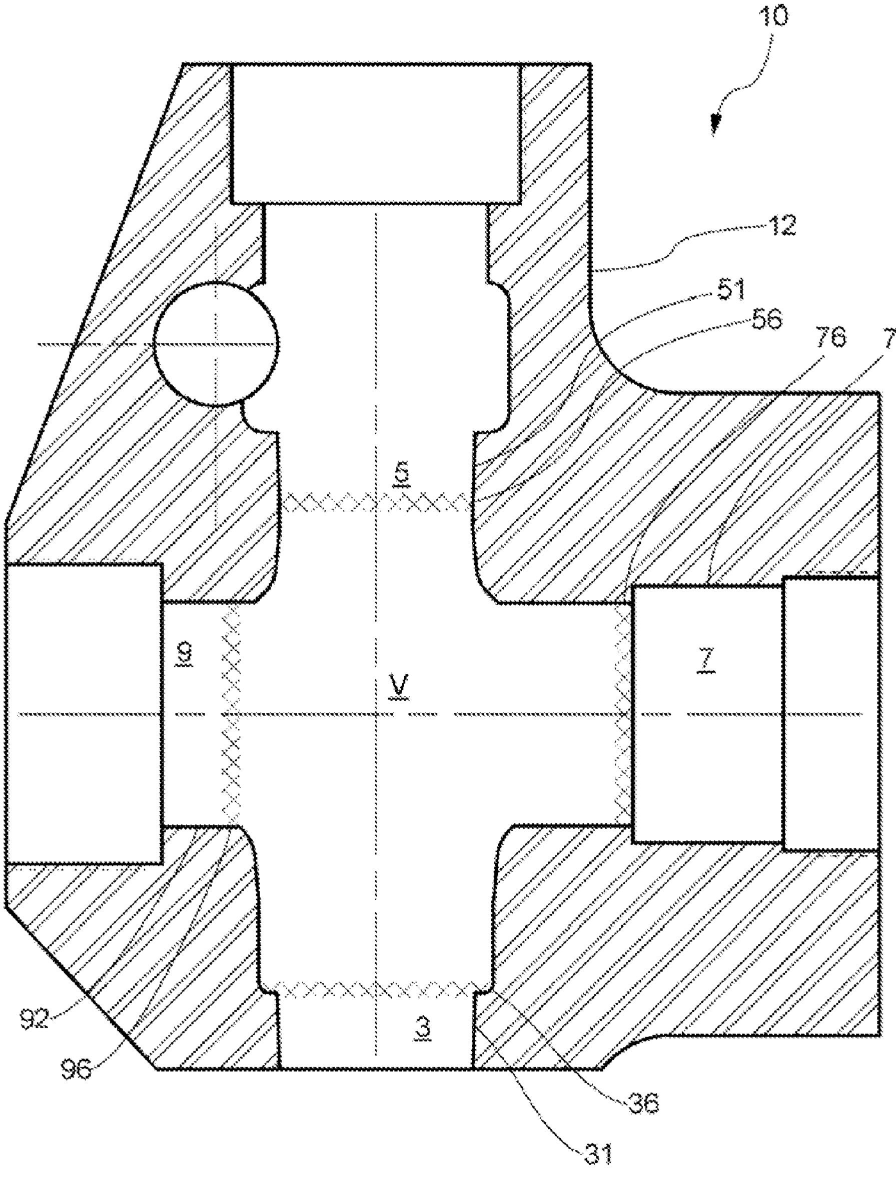


Figure 13

POST MACHINING MULTI-STEP MATERIAL WORKING TREATMENT OF FLUID END HOUSING HAVING MACHINED INTERNAL SURFACES

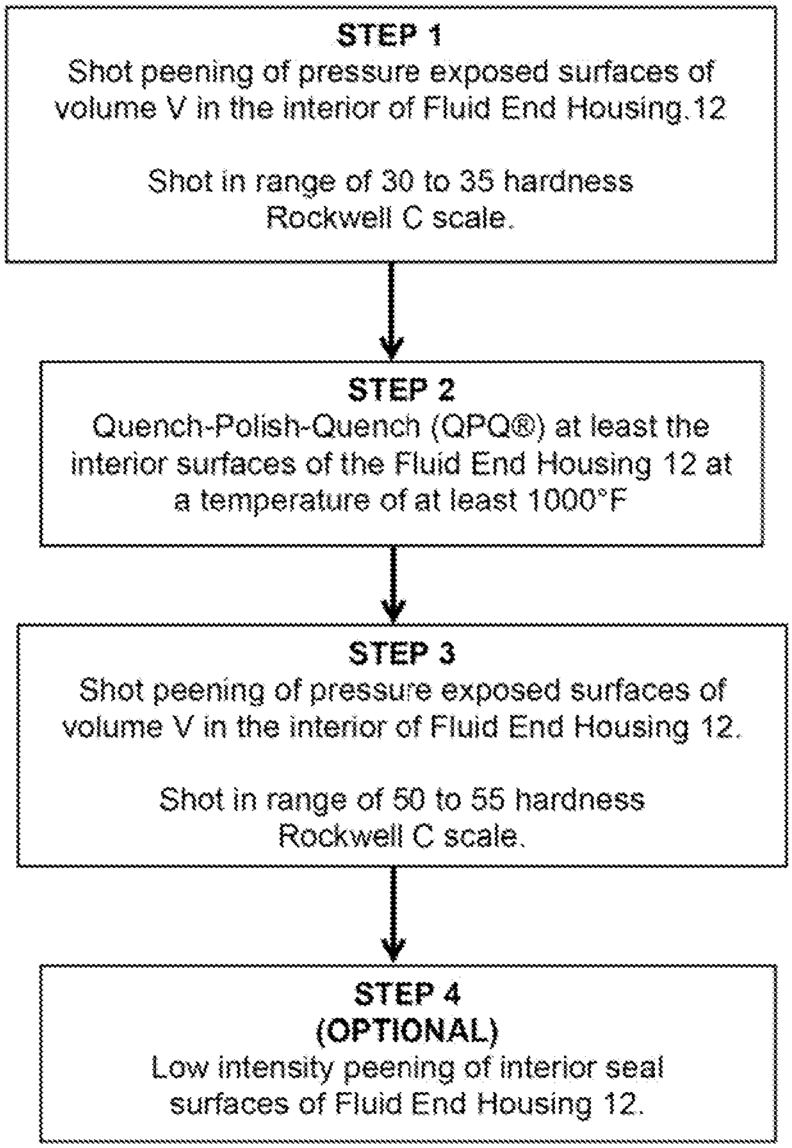


Fig. 14

POST MACHINING MULTI-STEP MATERIAL WORKING TREATMENT OF FLUID END HOUSING

PRIORITY

[0001] This application claims priority to U.S. provisional application Ser. No. 62/078,689 filed Nov. 13, 2014 entitled "Post Machining Multi-Step Material Working Treatment of Fluid End Housing", the entire content of which is incorporated by reference.

FIELD OF THE INVENTION

[0002] The invention relates to the manufacturing of high-pressure plunger pumps used, for example, in oil field operations. More particularly, the invention relates to a three-step process of cold working and hot working the finish of the machined internal surfaces of the fluid end housing of high-pressure plunger pumps.

BACKGROUND

[0003] Engineers typically design high-pressure oil field plunger pumps in two sections; the (proximal) power section and the (distal) fluid section. The power section, referred to by users and in this application as the power end, usually comprises a crankshaft, reduction gears, bearings, connecting rods, crossheads, crosshead extension rods, etc. The fluid section, referred to by the users and in this application to as the fluid end, usually comprises a plunger pump housing having a suction valve in a suction bore, a discharge valve in a discharge bore, an access bore, and a plunger in a plunger bore, plus high-pressure seals, retainers, etc.

[0004] FIG. **1** is a cross-sectional schematic view of a typical fluid end showing its connection to a power end by stay rods. FIG. **1** also illustrates a fluid chamber which is one internal section of the housing containing the valves, seats, plungers, plunger packing, retainers, covers, and miscellaneous seals as previously described. A plurality of fluid chambers similar to that illustrated in FIG. **1** may be combined, as suggested in the Triplex fluid end housing schematically illustrated in FIG. **2**. It is common practice for the centerline of the plunger bore and access bore to be collinear. Typically, the centerlines of the plunger bore, discharge bore, suction bore, and access bore are all arranged in a common plane.

[0005] Valve terminology varies according to the industry (e.g., pipeline industry or oil field service industry) in which the valve is used. In some applications, the term "valve" means just the moving element or valve body. In the present application, however, the term "valve" includes other components in addition to the valve body (e.g., various valve guides to control the motion of the valve body, the valve seat, and/or one or more valve springs that tend to hold the valve closed, with the valve body reversibly sealed against the valve seat).

[0006] Each individual bore in the plunger pump fluid end housing is subject to fatigue due to alternating high and low pressures which occur with each stroke of the plunger cycle. Fatigue is the weakening of a material that occurs when a material is subjected to repeated loading and unloading. When a material is subjected to such repeated or cyclic loading, progressive and localized structural damage occurs. This damage may be caused by nominal maximum stress values that are much less than the strength of the material typically quoted as the material's ultimate tensile stress limit, or the yield stress limit.

[0007] When cyclic loading is above a certain threshold, microscopic cracks in the material will form where the loading stresses are concentrated such as at the material surface, at persistent slip bands (PSBs), and at grain interfaces. Eventually a crack will reach a critical size, propagate suddenly, and the structure will fracture. Conventional plunger pump fluid end housings typically fail due to cracks from fatigue in one of the areas defined by the intersecting suction, plunger, access and discharge bores as schematically illustrated in FIG. **3**.

[0008] The top curve (solid) in FIG. **4** illustrates the fatigue curve or the relationship between applied stress plotted against the number of cycles that a structure is subjected to the applied stress. Note that in a vacuum or inert or non-corrosive median, the stress curve for steel flattens out to infinity after 10^7 cycles. The fatigue limit is illustrated by the dashed horizontal line (small dashed) in FIG. **4**. If the applied stress can be limited to the stress level at 10^7 cycles then a fatigue limit can be established. When the applied stress is kept below the fatigue limit, the structure should not fail in fatigue.

[0009] Corrosion Fatigue is the mechanical degradation of a material under the joint action of corrosion and cyclic loading. When cyclic loading occurs in a corrosive environment, the fatigue curve is downward sloping and the fatigue limit decreases with every cycle. Cracking due to fatigue will invariably occur when sufficient cycles are achieved. This phenomenon limits the ultimate life of any carbon steel plunger pump fluid end housing. The bottom curve (large dashed) in FIG. **4** illustrates the fatigue curve for a structure subjected to repeated cycles in a corrosive environment such as water. In such an environment this fatigue curve never flattens. A structure subjected to cyclic loads in a corrosive environment will eventually fail at approximately 10^9 cycles even with a minimum applied stress. In corrosion fatigue there is no fatigue limit and all structures will fail regardless of the applied stress level. Stainless steel cylinders are resistant but not immune from corrosion fatigue. Even water with a neutral pH level is corrosive.

[0010] Stress Corrosion Cracking occurs in high alloy steels and stainless steels when the material is subjected to corrosive fluids in conjunction with static tensile stresses. Such stresses can result from the manufacturing process (welding, grinding, aggressive machining). Cracks initiate from general corrosion pits, abrasions from slurries, dings/dents from maintenance activities and/or machining imperfections. Propagation and failure can occur quickly even with only a modest number of cycles.

[0011] Fluid end housings suffer from high stresses and fatigue cracks at the suction deck fillet in addition to the high stresses and fatigue cracks that develop at the intersecting bores shown in FIG. **3**. Fatigue cracks at the suction deck fillet of a fluid end housing due to valve impact loads are illustrated in FIG. **5**.

[0012] To reduce fatigue cracking in the high pressure plunger pump fluid end housings described above, a Y-block fluid end housing design has been proposed. The Y-block design, schematically illustrated in FIG. **6**A, reduces stress concentrations in a plunger pump housing such as that shown in FIG. **3** by increasing the angles of bore intersections above 90°. In the illustrated example of FIG. **6**A, the bore intersection angles are approximately 120°. A more complete cross-sectional view of a Y-block plunger pump fluid end assembly is schematically illustrated in FIG. **6**B.

[0013] Although several variations of the Y-block design have been evaluated, none have become commercially successful for several reasons. One reason is that mechanics find field maintenance on Y-block fluid ends difficult. Replacement of plungers and/or plunger packing is significantly more complicated in Y-block designs than in earlier designs such as those depicted in FIG. **1**. In the earlier designs, provision is made to push the plunger distally through the plunger bore and out through an access bore (see, e.g., FIG. **3**). This operation, which would leave the plunger packing easily accessible from the proximal end of the plunger bore, is impossible to perform in a Y-block fluid end housing that incorporates the Y-block design. Consequently, a fluid end housing having a Y-block configuration, while reducing stress in plunger pump fluid end housings relative to earlier designs, has significant disadvantages.

[0014] New high pressure plunger pump fluid end housings that provide both improved internal access and superior stress reduction are described in U.S. Pat. Nos. 8,147,227; 7,513,759; 6,910,871; 6,623,259; 6,544,012; and 6,382,940; which are incorporated by reference. One embodiment of such a high pressure plunger pump fluid end housing is incorporated in the right angular plunger pump described in U.S. Pat. No. 8,147,227 (the '227 patent) which is schematically illustrated in FIG. **7**A. As shown in FIG. **7**A, the right-angular plunger pump fluid end housing FEH has a suction valve bore (suction bore **3**), discharge valve bore (discharge bore **5**), plunger bore **7** and access bore **9**.

[0015] Suction bore **3** and discharge bore **5** may have cylindrical or slightly conical portions for accommodating a valve seat. Bores **3** and **5** with slightly conical portions with substantially circular cross-sections facilitate secure placement of a valve seat in the pump fluid end housing FEH by press-fitting a valve seat having an interference fit with the pump housing. Further, suction bore **3**, discharge bore **5**, plunger bore **7** and access bore **9** comprises an intersection area which interfaces with other bore intersection areas.

[0016] Each bore intersection area of the right-angular pump fluid end housing of FIG. **7**A has a stress-reducing feature comprising an elongated (e.g., elliptical or oblong) cross-section that is substantially perpendicular to each respective bore's longitudinal axis. Respective elongated sections of each bore are shown in FIGS. **7**B, **7**C, **7**D, and **7**E. Intersection bore areas are chamfered, the chamfers comprising additional stress-reducing features. Further, the long axis of each such elongated cross-section is substantially perpendicular to a plane that contains, or is parallel to, the longitudinal axes of suction bore **3**, discharge bore **5**, plunger bore **7** and access bore **9**.

[0017] Manufacture of fluid end housings can be very expensive because they are typically machined from very large steel forgings that must be first manufactured and procured. Usually a fluid end housing is machined from an open die forging because of the large size of a typical fluid end. By definition, open die forgings are made without dies and can be produced in only rectangular prism or block shapes. While a near net shape of the raw material used in manufacturing the housing can be achieved with a casting, castings have poor elongation properties compared with forgings. Plastic elongation of forged fluid end steel material is 10% or greater. While the plastic elongation of similar material in a cast condition approaches 0%. A minimum plastic elongation of 10% is required for high pressure cyclic fatigue resistance.

[0018] In addition to the geometric variations discussed above, engineers have also tried various heat treat options and post heat treat techniques that induce beneficial compressive stresses to the inner chamber walls of fluid end housings. In continuum mechanics, stress is a physical quantity that expresses the internal forces that neighboring particles of a continuous material exert on each other. Stress that exceeds certain strength limits of the material will cause permanent deformation (such as plastic flow) or even change the crystalline structure of the material. It is well documented in various industries that induced compressive stresses that result in plastic deformation of the surface improve the fatigue life of the effected structure such as the internal cavity of a fluid end housing.

[0019] In manufacturing the steel blocks used to machine fluid end housings, cast steel ingots are reshaped into bars after casting by hammering, pressing, and rolling in numerous repetitions; metallurgist call this "working" the steel. There is both hot working and cold working, i.e. the working is performed at hot and cold temperatures. Hot working improves the crystalline structure, breakups impurities, and relieves stresses in the steel. Such hot working has the added benefit of increasing the elongation properties and the fatigue resistance of the steel. In ancient times, artisans using hammers and small furnaces worked the steel, through repeated hammerings, into swords of incredible strength & durability.

[0020] When a steel object is uniformly heated to a temperature slightly above its upper transformation temperature, all of the steel in the object assumes a face-centered cubic crystal lattice structure known as austenite. When the object is quenched below this temperature, other crystal lattice structures are possible. If quenched uniformly, the other crystal lattice structures tend to appear uniformly throughout the object. But if certain portions of the object are cooled at rates different from those applicable to other portions of the object, then the crystal lattice structure of the cooled object may be non-uniform.

[0021] If steel is heated too far above its upper transformation temperature before quenching, its grain structure may be unnecessarily coarsened, meaning that the steel will then be less tough and more brittle after quenching than it would have been had its maximum temperature been closer to its upper transformation temperature. It is important for heat treatments for a particular steel to be applied uniformly when uniform results are desired, and it is further important that maximum temperatures not be so high as to adversely affect the grain structure of the steel.

[0022] Maximum heat-treatment temperatures for different steels vary because they are closely related to a steel's upper transformation temperature which depends on a steel's composition. Carbon steel may have an upper transformation temperature as low as about 1333 degrees F., whereas high-alloy steels may have upper transformation temperatures of more than 2000 degrees F. The upper transformation temperature of the steel traditionally used in manufacturing high-pressure fluid end housings is about 1650 degrees F.

[0023] As an example of changes that can occur in the crystal lattice structure of a particular steel at temperatures around its upper transformation temperature, consider a low-carbon steel. Such steels, commonly comprising iron and about 0.2-0.4% carbon with small amounts of alloying elements, are often used when heat treating is desired for hardening. As this steel begins cooling from a temperature slightly above its upper transformation temperature, its crystal lattice is 100% face-centered cubic (i.e., austenite), but as the steel cools begins to assume other crystal lattice structures (typically referred to as martensite). Body-centered cubic forms are favored by relatively slow cooling, whereas body-centered tetragonal forms are favored by faster cooling. As cooling progresses, the percentage of austenite tends to decrease and by the time the steel cools to a temperature of about 1333 degrees F. (called the lower transformation temperature), most of the austenite has been transformed to one or more other crystal lattice forms. Hence, at temperatures below about 1333 degrees F., little or no austenite exists and there are no further significant changes in the relative percentages of other crystal lattice forms present.

[0024] The above example of progressive changes in the crystal lattice of low-carbon steel differs considerably from the changes that would occur in higher alloy types of steel. Certain stainless steels can retain an austenitic lattice structure even at room temperature. The presence of nickel in steel alloys is observed to be associated with retention of austenitic lattice structure at temperatures below the lower transformation temperature.

[0025] The ability to predict the relative percentages of different crystal lattice forms present at different stages of a heat treatment allows adjustment of a wide variety of steel's important physical properties to adapt it for specialized applications. An example of such an adaptation process comprises heating steel to a predetermined temperature to within or slightly above a particular range (called the transfer temperature range) between the steel's upper transformation temperature and about 1333 degrees F. Following such heating, the steel is cooled (quenched) according to protocols developed to enhance physical properties such as hardness.

[0026] Quenching is performed primarily to influence the formation of a desirable crystal lattice and/or grain structure in a cooled metal, a grain being a portion of the metal having external boundaries and a regular internal lattice. Quenching may be accomplished by immersion of a heated metal object in water or oil. Certain tool steels and other high alloy steels may even be quenched by gas, but the carbon steels traditionally used for fluid end housings cannot be gas-quenched if they are to develop the hardness, strength and toughness necessary for use in high-pressure housings.

[0027] Intersections between crystal structures that occur in association with quenching are not instantaneous, so the rate of cooling may be adjusted to favor development of more desirable crystal and/or grain structures with their corresponding beneficial material properties (e.g., tensile strength, hardness, ductility, toughness, etc.). Further, quenching may optionally be followed by tempering, wherein metal is reheated to a temperature below its lower transformation temperature before finally returning to room temperature. Tempering is particularly useful with relatively high-strength alloy steels because it makes the steel tougher and more ductile (as in tempered martensite) by reducing internal stresses that would otherwise make steel brittle and prone to cracking (e.g., untempered martensite).

[0028] Hot rolling temperatures being below the transformation temperature of steel allow for stress relief but do not alter the grain refinement attained from the previous hot rolling treatment. Multiple hot rolling applications are particularly effective in grain refinement and improving toughness in steel because the temperature of the hot working relieves stresses associated with hot rolling.

[0029] Work hardening, also known as strain hardening or cold working, is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements and dislocation generation or grain structure realignment within the crystalline structure of the material. Work hardening is a consequence of plastic deformation, a permanent change in shape. This is distinct from elastic deformation, which is reversible. Most materials do not exhibit only one or the other, but rather a combination of the two. An example of desirable work hardening is that which occurs in metalworking processes that intentionally induce plastic deformation to exact a shape change. These processes are known as cold working or cold forming processes. They are characterized by shaping the work piece at a temperature below its recrystallization temperature, usually at the ambient temperature. Cold forming techniques are usually classified into four major groups: squeezing, bending, drawing, and shearing.

[0030] Before work hardening, the lattice of the material exhibits a regular, nearly defect-free pattern (almost no dislocations). The defect-free lattice can be created or restored at any time by annealing. As the material is work hardened it becomes increasingly saturated with new dislocations, and more dislocations are prevented from nucleating (a resistance to dislocation-formation develops). This resistance to dislocation-formation manifests itself as a resistance to plastic deformation; hence, the observed strengthening.

[0031] In metallic crystallines, irreversible deformation is usually carried out on a microscopic scale by defects called dislocations, which are created by fluctuations in local stress fields within the material culminating in a lattice rearrangement as the dislocations propagate through the lattice. At normal temperatures the dislocations are not annihilated by annealing. Instead, the dislocations accumulate, interact with one another, and serve as pinning points or obstacles that significantly impede their motion. This leads to an increase in the yield strength of the material and a subsequent decrease in ductility. Such deformation increases the concentration of dislocations which may subsequently form low-angle grain boundaries surrounding sub-grains. Cold working generally results in higher yield strength because of the increased number of dislocations and the Hall-Petch effect of the sub-grains. Multiple cold working applications are beneficial in increasing yield strength and material fracture toughness.

[0032] As shown in FIG. **8**, the yield stress of an ordered material has a half-root dependency on the number of dislocations present. An increase in the number of dislocations is a quantification of work hardening. Plastic deformation occurs as a consequence of work being done on a material; energy is added to the material. In addition, the energy is almost always applied fast enough and in large enough magnitude to not only move existing dislocations, but also to produce a great number of new dislocations by jarring or working the material sufficiently enough. New dislocations are generated in proximity to a "Frank-Read source" as proposed circa 1950, by British physicists Charles Frank and Thornton Read. The stress, τ, of dislocation is dependent on the shear modulus, G, the magnitude of the Burgers vector, b, the dislocation density, $\rho\perp$, the intrinsic strength of the material with low dislocation density, τ_0, and a correction factor specific to the material, α, as expressed by the equation:

$$\tau=\tau_0+G\alpha b\rho_\perp^{1/2}.$$

[0033] Materials exhibits higher strength and improved cyclic fatigue resistance if there are high levels of dislocations (greater than 10^{14} dislocations per m^2) as described above. The best known methods of adding high levels of dislocations and thus compressive stresses to the outer skin of the steel are shot peening and autofrettage.

[0034] Shot peening is one of the oldest know methods of adding compressive stresses to a fluid end housing; shot peening is a cold working process used to produce a compressive residual stress layer and modify mechanical properties of the steel. It entails impacting a surface with shot (round metallic, glass, or ceramic particles) with force sufficient to create plastic deformation. It is similar to sandblasting, except that it operates by the mechanism of plasticity rather than abrasion: each particle functions as a ball-peen hammer. Peening a surface spreads it plastically, causing changes in the mechanical properties of the surface. Its main application is to avoid the propagation of micro cracks from a surface. Such cracks do not propagate in a material that is under a compressive stress; shot peening can create such a stress in the surface. Shot peening is often called for in repairs to relieve tensile stresses built up in machining processes and replace them with beneficial compressive stresses. Depending on the part geometry, part material, shot material, shot quality, shot intensity, shot coverage, shot peening can increase fatigue life significantly. Plastic deformation induces a residual compressive stress in a peened surface, along with tensile stress in the interior. Surface compressive stresses confer resistance to metal fatigue and to some forms of stress corrosion. The tensile stresses deep in the part are not as problematic as tensile stresses on the surface because cracks are less likely to start in the interior.

[0035] Shot peening has shown to be a very effective method of reducing stress risers in fluid end housings from machining imperfections such as micro tears and grooves in the machined surface. Metals benefit from shot peening through a combination of multiple plastic stretching of the near surface and plastic flow beneath the surface in the area of maximum shear stresses. Damage generally only occurs in case of the so called over-peening which involves fatigue failure of the near surface by too many impacts. Multiple shot peening applications without intervening stress relieving would result in over-peening and fatigue failure.

[0036] Autofrettage is an alternate method of applying induced compressive stresses in fluid end housing. Autofrettage is a metal fabrication technique in which a pressure vessel such as a fluid end housing is subjected to enormous pressure, causing internal portions of the part to yield plastically, resulting in internal compressive residual stresses once the pressure is released. The goal of autofrettage is to increase the durability of the final product. Inducing residual compressive stresses into materials can also increase their resistance to stress corrosion cracking; that is, non-mechanically-assisted cracking that occurs when a material is placed in a corrosive environment in the presence of tensile stress. The technique is commonly used in manufacturing of high-pressure pump cylinders, warship and tank gun barrels, and fuel injection systems for diesel engines.

[0037] While autofrettage will induce some work hardening, that is not the primary mechanism of strengthening. The tube or housing is subjected to internal pressure past its elastic limit, leaving an inner layer of compressively stressed metal. The tube or housing is subjected to internal pressure of sufficient magnitude to enlarge the bore or bores and in the process the inner layers of the metal are stretched in tension beyond their elastic limit. This means that the inner layers have been stretched to a point where the steel is no longer able to return to its original shape once the internal pressure has been removed. Although the outer layers of the tube or housing are also stretched, the degree of internal pressure applied during the process is such that they are not stretched beyond their elastic limit. The reason why this is possible is that the stress distribution through the walls of the tube is non-uniform. Its maximum value occurs in the metal adjacent to the source of pressure, decreasing markedly towards the outer layers of the tube. The strain is proportional to the stress applied within elastic limit; therefore the expansion at the outer layers is less than at the bore. Because the outer layers remain elastic they attempt to return to their original shape; however, they are prevented from doing so completely by the now permanently stretched inner layers. The effect is that the inner layers of the metal are put under compression by the outer layers. The end result is an inner surface of the tube or housing with a residual compressive stress able to counterbalance the tensile stress that would be induced when the tube or housing is subjected to very high cyclic pressures.

[0038] Autofrettage can produce beneficial compressive stresses to a deeper depth than shot peening and has proven to be very effective with simple cylindrical shapes such a gun barrels. With simple cylindrical shapes the induced compressive stresses are uniformly distributed around the internal surface of the cylinder. However on more complex shapes such as fluid end housings with intersecting internal bores, the beneficial compressive stresses are confined to very small areas where the internal surfaces are stressed sufficiently to induce plasticity in the surface; the remaining internal areas of the housing receive no beneficial induced compressive stresses. Thus if the other areas of housing are subjected to non-pressure loads such as valve impact loads, autofrettage provides no relief from the stresses from these indirect pressure loads.

[0039] Furthermore, autofrettage offers no relief from stress as a result of stress risers in fluid end housings from machining imperfections such as micro tears and sharp bottom grooves in the machined surface. In fact autofrettage will amplify the stresses from such machining imperfections.

[0040] U.S. Pat. No. 4,354,371 discloses a technique in which a pressure chamber is first shot peened and then pressurized in a method similar to autofrettage wherein said "pressure chamber has a fluid pressure applied in the chamber of a magnitude sufficient to deform the said walls defining said chamber beyond the yield strength but not sufficient to cause fracture of said walls." Although this invention does not discuss the additional benefits from shot peening, the peening discussed in this invention clearly reduces stress risers in pressure chambers or fluid end housings from machining imperfections such as micro tears and sharp bottom grooves in the machined surface.

[0041] U.S. Pat. No. 8,747,573, assigned to Durferrit GmbH of Mannheim, Germany, discloses an invention that "relates to a method for producing corrosion-resistant surfaces of nitrated or nitrocarburated steel components, the surfaces having roughness heights (Rz) of $Rz \leq 1.51$ μm." The method comprises the following steps: oxidation of the surfaces of the nitrated or nitrocarburated components in a first oxidation step; carrying out at least a second oxidation of the component surfaces in an immediately subsequent oxidation step; polishing the component surface in a final method step, directly after the final oxidation." The techniques disclosed in U.S. Pat. No. 8,747,573 are trademarked in the US by Durferrit GmbH as TUFFTRIDE® and QPQ®. It is common knowledge in many industries that almost all nitrating or nitrocarburating processing of steel components also produce induced compressive stresses that result in plastic deformation of the surface improve the fatigue life of the effected structure such as the internal cavity of fluid end housing. Thus the TUFFTRIDE® and QPQ® treatments will also impart induced compressive stresses in addition to producing corrosion-resistant surfaces in the internal cavity of fluid end housing.

[0042] If the steel was first shot peened to remove machining stress risers before application of a QPQ® treatment, the 1000° F. temperatures of the typical QPQ® treatments will temper some of the beneficial compressive stresses obtained from shot peening. However the QPQ® treatment temperature is well below the transition temperature of steel, approximately 1700° F. Thus the dislocation generation or grain structure realignment within the crystalline structure of the material will only be minimally effected. QPQ® treatments typically increase the surface hardness of steel, thus if shot peening is solely applied post QPQ® treatment; removing machining stress risers is difficult.

[0043] Additional low intensity shot peening, such as shot peening with glass beads, will improve the surface finish of a conventional shot peened surface.

[0044] Ultrasonic shot peening (Stressonic®) hereafter referred to as USP differs from conventional shot peening by the way the kinetic energy is given to the balls. Instead of using a constant air flow, gravity or a high-speed rotation of a turbine, USP is using the acceleration of a vibrating surface. Frequency of vibration is within the ultrasonic wave range, which explains the name of the technique. A central unit digitally generates a sine wave with an ultrasound frequency (20 kHz). A piezo-electrical emitter converts this signal to a mechanical signal which is then amplified by a series of boosters and a sonotrode. Shot balls gain their energy from the sonotrode vibration, and are thrown to the part to be treated, inside a hermetic chamber. The random displacement of the balls inside the volume of the chamber and the treated part ensures a uniform peening of the part.

The Invention

[0045] The present invention is a post machining treatment for a fluid end housing **12** comprising multi-step cold and hot working processes to provide beneficial compressive stresses to the interior surfaces of the housing **12**. This unique procedure combines preliminary shot peening to reduce stress risers from machining imperfections such as micro tears and grooves in the machined surface of the fluid end housing, followed by a carbonitriding or nitrocarburizing quench-polish-quench process, such as the TUFFTRIDE® and QPQ® quench-polish-quench processes and treatments performed in the United States under the trademarks of Durferrit GmbH, and a final shot peening operation to maximize the cold working of the steel and optimize beneficial compressive stresses. The three step material working process increases yield strength and material fracture toughness of the fluid end housing.

[0046] Step **1**, the first step of the post machining process, includes shot peening most of the pressure exposed surfaces of the interior of fluid end housing **12** as shown in FIG. **9**. Preferably, the shot peening of Step **1** will be performed with a shot size and shot intensity appropriate to the interior surface hardness. Shot having a hardness in the range of 30 to 35 hardness on the Rockwell C scale will typically be of sufficient hardness to be utilized in this first post machining step. Preferably 330# shot at maximum Almen Peening Intensity of 10 A will be utilized for this shot peening Step **1**. The shot peening of Step **1** will be sufficient to induce compressive residual stress values on the interior surfaces of the fluid end housing **12** in the range of about −60,000 pound-force per square inch to about −100,000 pound-force per square inch (about −60 ksi to about −100 ksi) at a surface depth between 0.000 inches to 0.008 inches as shown in the graph of FIG. **10**.

[0047] Step **2**, the second step of the post machining process, includes treatment of the entire fluid end housing **12** utilizing a quench-polish-quench process of nitrocarburizing case hardening such as the carbonitiriding process disclosed in U.S. Pat. No. 8,747,573 which is also known as QPQ® treatment. Ideally the quench-polish-quench process of Step **2** will be at a temperature of at least 1000° F. to add an anticorrosion nitride surface layer of approximately 0.0001 inches depth on the interior surfaces of the fluid end housing. The quench-polish-quench process of this second post machining step at a temperature of at least 1000° F. shall be sufficient to temper some of the compressive stresses on the interior surfaces of the fluid end housing **12** to a lower level from between about −40,000 pound-force per square inch to about −60,000 pound-force per square inch (about −40 to about −60 ksi) at a depth between 0.000 to 0.010 inches as shown in the graph of FIG. **11**. Dislocation generation or grain structure realignment within the crystalline structure of the material comprising fluid end housing **12** will only be minimally effected at the prescribed temperature treatment of Step **2**.

[0048] Step **3**, the third post machining step of the post machining process, includes treatment of the fluid end housing **12** by utilizing additional shot peening to restore the beneficial compressive stresses to the interior surfaces of the housing **12**. Preferably the shot peening in Step **3** will be performed with a shot size and shot intensity appropriate to the interior surface hardness. Shot having a hardness in the range of 50 to 55 hardness on the Rockwell C scale will typically be of sufficient hardness to be utilized in this third post machining step of the process. The shot peening of Step **3** induces compressive residual stress values on the interior surfaces of the fluid end housing **12** from about −80,000 pound-force per square inch to about −100,000 pound-force per square inch (about −80 ksi to about −100 ksi) at a surface depth between 0.000 to 0.010 inches as shown in the graph of FIG. **12**.

[0049] A fluid end housing **12** treated with the three-step process will process greater toughness, cyclic fatigue resistance, and greater fatigue resistance due to the two cold working shot peening steps separated by the tempering of the second step. The steel grain structure at or near the machined surface will be refined by the multi-step process of this invention. The QPQ® treatment increases corrosion resistance to prevent corrosion fatigue. The intervening QPQ® treatment between the shot peening first and third steps serves to increase grain refinement without inducing over peening and fatigue failure.

[0050] The post machining process for treating a fluid end housing may include an optional Step **4** as a final treatment of the interior seal surfaces of the fluid end housing **12**. The optional Step **4** includes low intensity peening of the pressure exposed surfaces of the interior of fluid end housing **12** to improve the interior surface finish of the previous peened surfaces. Low intensity peening of the transition areas with a maximum Almen Peening Intensity of 4 A is thought to be suitable depending on the hardness of the material used for the fluid end housing **12**. Preferably the low intensity peening is performed on the pressure exposed surfaces of the interior of a fluid end housing **12** with GP60 glass beads at a minimum Almen Peening Intensity of 4N.

[0051] The optional Step **4** low intensity peening of the transition areas between the interior surfaces of fluid end housing **12** that were peened in Steps **1** and **3** and of the interior surfaces of fluid end housing **12** that were not peened with glass beads will improve the surface finish where elastomeric seals must seal. The optional Step **4** peening will also facilitate the transition from one fluid end housing interior surface to another and prevent the formation of stress risers at the junction of the interior surfaces that were peened during Steps **1** and **3** and the interior surfaces that were not peened during those process steps.

BRIEF DESCRIPTION OF THE DRAWINGS

[0052] FIG. **1** is a cross-sectional schematic view of a typical plunger pump fluid end housing showing its connection to a power section by stay rods.

[0053] FIG. **2** schematically illustrates a conventional Triplex plunger pump fluid end housing.

[0054] FIG. **3** is a cross-sectional schematic view of suction, plunger, access and discharge bores of a conventional plunger pump fluid end housing intersecting at right angles and showing areas of elevated stress at the intersection of said bores.

[0055] FIG. **4** is a graph illustrating the relationship between fatigue stress and the number of cycles.

[0056] FIG. **5** is a cross-sectional schematic view of suction, plunger, access and discharge bores of a conventional plunger pump fluid end housing showing areas of elevated stress at the suction deck fillet.

[0057] FIG. **6**A is a cross-sectional schematic view of suction, plunger and discharge bores of a Y-block plunger pump fluid end housing intersecting at obtuse angles showing areas of elevated stress.

[0058] FIG. **6**B is a cross-sectional schematic view similar to that in FIG. **6**, including internal plunger pump components of a Y-block fluid end.

[0059] FIG. **7**A schematically illustrates a cross-section of one of the fluid chambers of a right-angular plunger pump fluid end housing having access, suction, discharge, and plunger bores.

[0060] FIG. **7**B schematically illustrates the sectional view labeled B-B in FIG. **7**A.

[0061] FIG. **7**C schematically illustrates the sectional view labeled C-C in FIG. **7**A.

[0062] FIG. **7**D schematically illustrates the sectional view labeled D-D in FIG. **7**A.

[0063] FIG. **7**E schematically illustrates the sectional view labeled E-E in FIG. **7**A.

[0064] FIG. **8** is a graph illustrating the relationship between stress and strain of a work hardened surface.

[0065] FIG. **9** is a cross-sectional schematic view of a typical plunger pump fluid end housing showing the areas subjected to internal working pressure to be shot peened in steps **1** and **3** of the present invention.

[0066] FIG. **10** is a graph illustrating the relationship between induced compressive stresses and surface depth of a shot peened surface of step **1**.

[0067] FIG. **11** is a graph illustrating the relationship between induced compressive stresses and surface depth of a shot peened surface after QPQ® treatment of step **2**.

[0068] FIG. **12** is a graph illustrating the relationship between induced compressive stresses and surface depth of a shot peened surface after QPQ® treatment and final post QPQ® shot peening treatment of step **3**.

[0069] FIG. **13** is the cross-sectional schematic view of a typical plunger pump fluid end housing shown in FIG. **9** showing the transitional areas to be glass peened following steps **1**, **2**, and **3** of the present invention.

[0070] FIG. **14** is a process diagram of the post machining three (3) step cold and hot working processes utilized to add beneficial compressive stresses to the interior surfaces of the fluid end housing.

DESCRIPTION OF THE EMBODIMENTS

[0071] FIG. **9** is a cross-sectional schematic view through one cylinder of a typical embodiment of a high-pressure pump fluid end block or housing **12** to be treated with the processes of the present invention. Housing **12** is the main component of the fluid end assembly **10** that also includes plungers, valves, seats, packing, seals, covers, threaded retainers, and various miscellaneous components. Fluid end housing **12** consist of access bore **9**, suction bore **3**, discharge bore **5**, plunger bore **7**, and inner volume V. Discharge bore **5** contains discharge seat taper **51**, discharge valve chamber **54**, discharge seal area **52**, discharge threaded area **53**, and discharge intersection area **55**. Discharge valve chamber **54** is connected to adjacent discharge valve chambers by discharge manifold **20**. Access bore **9** contains access bore seal area **92**, access bore thread area **93**, and access bore intersection area **95**. Suction bore **3** contains suction seat taper **31**, suction valve chamber **34**, and suction intersection area **35**. Packing bore consists of packing seal area **72**, packing gland nut thread area **73**, and packing bore intersection area **75**.

[0072] Inner volume V in FIG. **9** is defined by the interior surfaces between the four bore intersection areas: discharge bore intersection area **55**, access bore intersection area **95**, suction bore intersection area **35**, and plunger bore intersection area **75**, which each interface between adjacent bores. The interior surfaces comprising inner volume V includes all areas vertically spaced from the top of the suction seat taper **31** to the bottom of the discharge seat taper **51** and all areas horizontally spaced between the inside of the access bore seal area **9** to the inside of the packing seal area **72**.

[0073] The post machining process steps of the present invention are performed on fluid end housing **12** in which the suction bore **3**, discharge bore **5**, plunger bore **7**, and access bore **9** within each fluid chamber of the fluid end housing **12** are treated with a minimum three (3) step cold and hot working processes to add beneficial compressive stresses to the interior surfaces of the housing. The unique post machining process for treating a fluid end housing of the present invention includes steps comprising three post machining cold and hot working processes.

[0074] FIG. **10** illustrates a graph of residual stress versus depth from the surface of a typical steel fluid end housing **12** after final machining of internal surfaces of said housing **12** followed by the initial shot peening of Step **1**. In FIG. **10** the negative stress levels indicate beneficial compressive stresses. Data points obtained after performing the shot peening of Step **1** provide the Step **1** curve represented by the black diamonds. The internal surfaces of the inner volume V of fluid end housing **12** are shot peened in Step **1**.

[0075] FIG. **11** illustrates the graph of residual stress versus depth from the surface of a typical steel fluid end housing **12** shown in FIG. **10** plus additional data obtained after performing QPQ® treatment of Step **2** on the internal surfaces of said housing **12**. Data points obtained after performing the QPQ® treatment of Step **2** provide the Step **2** curve represented by the black circles. The effect of the tempering provided by the QPQ® treatment of Step **2** is shown by the higher values (less compressive stress.) However, compressive stresses still remain on the interior surfaces of the housing **12** indicating that the transformation temperature of the steel was not exceeded by the QPQ® treatment. Preferably, all internal surfaces of the housing **12** are treated by the QPQ® treatment of Step **2**. Optionally, all external surfaces may also be treated by the QPQ® treatment of Step **2**.

[0076] FIG. **12** illustrates the graph of residual stress versus depth from the surface of a typical steel fluid end housing **12** shown in FIG. **11** plus additional data obtained after performing the final shot peening treatment of Step **3**. The data points obtained after performing the additional shot peening of Step **3** provide the Step **3** curve represented by the black triangles. The compressive stresses following the additional shot peening of Step **3** are significantly improved near the surface. The internal surfaces of the inner volume V of fluid end housing **12** are shot peened in Step **3**.

[0077] FIG. **13** is the cross-sectional schematic view of a typical plunger pump fluid end housing shown in FIG. **9**. FIG. **13** shows the transitional areas to be subjected to low intensity shot peening of the optional Step **4** of the present invention. The low intensity shot peening of optional Step **4** is performed after all surfaces of inner volume V of fluid end housing **12** have been shot peened in Steps **1** and **3** and all internal surfaces of the fluid end housing **12** were treated by the QPQ® treatment of Step **2**.

[0078] The optional low intensity shot peening of Step **4**, such as shot peening with glass bead, is performed on the transition areas on the internal surfaces of the housing **12** shown in FIG. **13** and include discharge bore peening transition area **56**, plunger bore peening transition area **76**, suction bore peening transition area **36**, and access bore peening transition area **96**. Discharge bore peening transition area **56** is located at or near the bottom of discharge seat taper **51**. Plunger bore peening transition area **76** is located at or near the inner edge of plunger packing area **72**. Suction bore peening transition area **36** is located at or near the top of suction seat taper **31**. Access bore peening transition area **96** is located at or near the inner edge of the access bore seal area **92**.

[0079] FIG. **14** is a process diagram of the post machining three-step cold and hot working processes utilized to add beneficial compressive stresses to the interior surfaces of the fluid end housing. When performing Steps **1** and **3** of the post machining three-step process, preferably only the surfaces creating inner volume V of fluid end housing **12** shown in FIG. **9** are subjected to the shot peening. All other internal surfaces of the fluid end housing **12** may be masked to prohibit the masked surfaces from being shot peened.

[0080] In Step **2**, the internal surfaces of the fluid end housing **12** are treated with quench-polish-quench process to provide an anticorrosion nitride surface layer to the interior surfaces creating inner volume V. It is thought that a suitable quench-polish-quench process will be a nitrocarburizing case hardening process such as the carbonitiriding process disclosed in U.S. Pat. No. 8,747,573 referenced above which is also known as QPQ® treatment. If desired both the interior and exterior surfaces of the entire fluid end housing **12** may be treated with the quench-polish-quench process of Step **2**.

[0081] If desired the three-step cold and hot working processes of the present invention may be augmented by optional Step **4**. In optional Step **4**, the interior seal surfaces and the interior transition areas of the fluid end housing **12**, including the discharge bore peening transition area **56**, plunger bore peening transition area **76**, suction bore peening transition area **36**, and access bore peening transition area **96**, may be shot peened at a low intensity level such as with glass beads to enhance the transition from the previously peened to the non-peened surfaces. The previously peened interior surfaces of the fluid end housing **12** may also be shot peened at a low intensity level such as with glass beads in this optional Step **4** to improve the interior surface finish of the previously peened surfaces.

[0082] The best results will be obtained when the shot peening of Steps **1** and **3** and optional Step **4** has 100% coverage of the internal surfaces being peened, i.e. where at least 98% of the internal surfaces are dimpled by the shot peening.

[0083] It is thought that the post machining treatment process for a fluid end housing of the present invention present invention and many of its attendant advantages will be understood from the foregoing description; that it will be apparent that various changes may be made in the form, construction and arrangement of the steps of the present invention without departing from the spirit and scope of the invention or sacrificing all of its material advantages; that the form described herein is merely an exemplary embodiment of the invention; and that the invention is limited only by the claims that follows.

What is claimed is:

1. A post machining treatment process for a fluid end housing of a plunger pump with multiple fluid bore chambers having interior surfaces forming an inner volume, comprising the steps of:

(a) a first shot peening of selected areas of said interior surfaces of each said fluid bore chamber;

(b) then treating said interior surfaces of each said fluid bore chamber by a quench-polish-quench process; and

(c) then a second shot peening of said selected interior surfaces of each said fluid bore chamber.

2. The post machining treatment process for a fluid end housing of a plunger pump recited in claim **1** wherein said first shot peening uses shot having a hardness in the range of 30 to 35 hardness on the Rockwell C scale.

3. The post machining treatment process for a fluid end housing of a plunger pump recited in claim **2** wherein second shot peening uses shot having a hardness in the range of 50 to 55 hardness on the Rockwell C scale size.

4. The post machining treatment process for a fluid end housing of a plunger pump recited in claim **3** wherein said step of treating said interior surfaces of each said fluid bore chamber by a quench-polish-quench process includes the step of carbonitiriding or nitrocarburizing.

5. The post machining treatment process for the fluid end housing of a plunger pump recited in claim **4** comprising the additional step of low intensity shot peening said interior chamber surfaces after said second shot peening.

6. The post machining treatment process for the fluid end housing of a plunger pump recited in claim **5** wherein said additional step of low intensity shot peening includes shot peening with glass beads at a minimum Almen Peening Intensity of 4N.

7. A method for cold working and hot working the finish of machined internal surfaces of the fluid end housing of high-pressure plunger pumps comprising the steps of:

(a) providing a plunger pump fluid end housing with a plurality of fluid chambers arranged in a common plane, each said fluid chamber having a machined interior surface;

(b) providing a first shot peening of selected sections of said interior surface of each said fluid chamber;

(c) then utilizing a quench-polish-quench process whereby an anticorrosion nitride surface layer is added to said interior surface of each said fluid chamber; and

(d) then providing a second shot peening of said selected sections of said interior surface of each said fluid chamber.

8. The method recited in claim **7** wherein said step of providing said first shot peening includes shot peening using a shot having a hardness in the range of 30 to 35 hardness on the Rockwell C scale.

9. The method recited in claim **8** wherein said step of providing said second shot peening includes shot peening using a shot having a hardness in the range of 50 to 55 hardness on the Rockwell C scale.

10. The method recited in claim **9** wherein said quench-polish-quench process will be at a temperature of at least 1000° F.

11. The method recited in claim **10** wherein said interior surface of each said fluid chamber has a roughness height $Rz \leq 1.5$ μm.

12. The method recited in claim **11** comprising the additional step of shot peening said interior surface of each said fluid chamber at a maximum Almen Peening Intensity of 4 A after said second shot peening.

13. The method recited in claim **12** comprising the additional step of shot peening said interior surface of each said fluid chamber with glass beads after said second shot peening.

14. The method recited in claim **13** wherein said step of shot peening said interior surface of each said fluid chamber with glass beads includes shot peening at a minimum Almen Peening Intensity of 4N.

15. The method recited in claim **14** comprising the additional step of masking selected sections of said interior surface of each said fluid chamber whereby shot peening is prohibited.

16. The method recited in claim **11** comprising the additional step of masking selected sections of said interior surface of each said fluid chamber whereby shot peening is prohibited.

17. A method for cold working and hot working the finish of machined internal chamber surfaces of steel blocks comprising the steps of:

(a) providing a steel block having a plurality of machined interior chamber surfaces;

(b) providing a first shot peening of selected sections of said interior chamber surfaces using a shot having a hardness in the range of 30 to 35 hardness on the Rockwell C scale;

(c) then utilizing a quench-polish-quench process at a temperature of at least 1000° F. whereby an anticorrosion nitride surface layer is added to said interior chamber surfaces; and

(d) then providing a second shot peening of selected sections of said chamber interior surfaces using a shot having a hardness in the range of 50 to 55 hardness on the Rockwell C scale.

18. The method recited in claim **17** comprising the additional step of shot peening said interior chamber surfaces with glass beads after said second shot peening.

19. The method recited in claim **18** comprising the additional step of masking selected sections of said interior chamber surfaces whereby shot peening is prohibited.

20. The method recited in claim **17** comprising the additional step of low intensity shot peening said interior chamber surfaces after said second shot peening at an Almen Peening Intensity of at least 4N and an Almen Peening Intensity of no more than 4 A.

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