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Galle et al.

(54) DAMAGE TOLERANT CASING HANGER SEAL

(76) Inventors: **Gary L. Galle**, Houston, TX (US); **Rick C. Hunter**, Friendswood, TX (US)

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USPC **277/314**; 277/322; 277/323

(57) **ABSTRACT**

A seal assembly is inserted within an annulus between inner and outer coaxially disposed annular members having a common axis. The seal assembly includes a seal stack having a compliant element sandwiched between two anti-extrusion elements that contain the flow of the compliant element. The seal assembly also includes a sealing ring and a locking ring coupled to the sealing ring. The seal assembly also includes an energizing ring configured to be moved axially in a first direction by a ring tool to apply an axial force to the locking ring, which in turn acts on the sealing ring to radially deform the sealing ring into sealing engagement with the annular members. Continued axial movement of the locking ring in the first direction radially deforms the locking ring into locking engagement with the annular members.

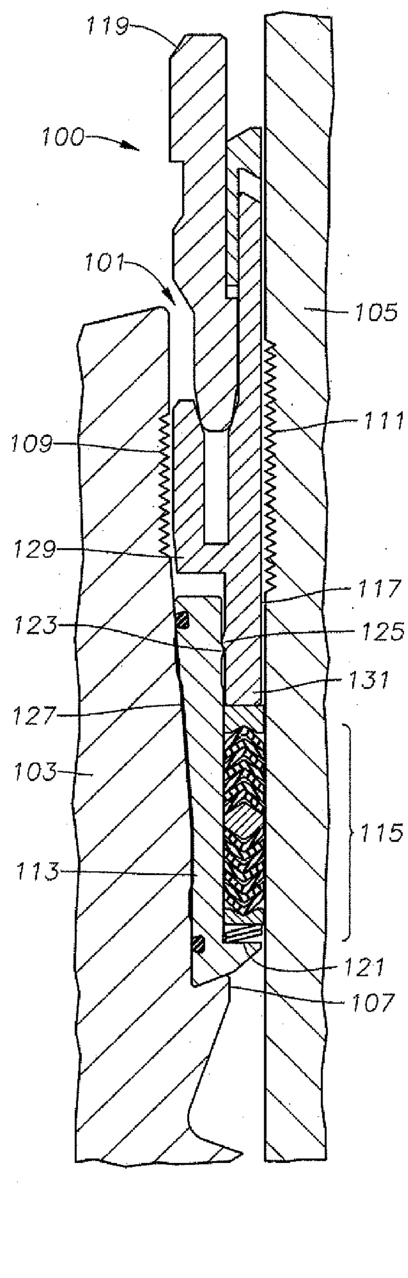
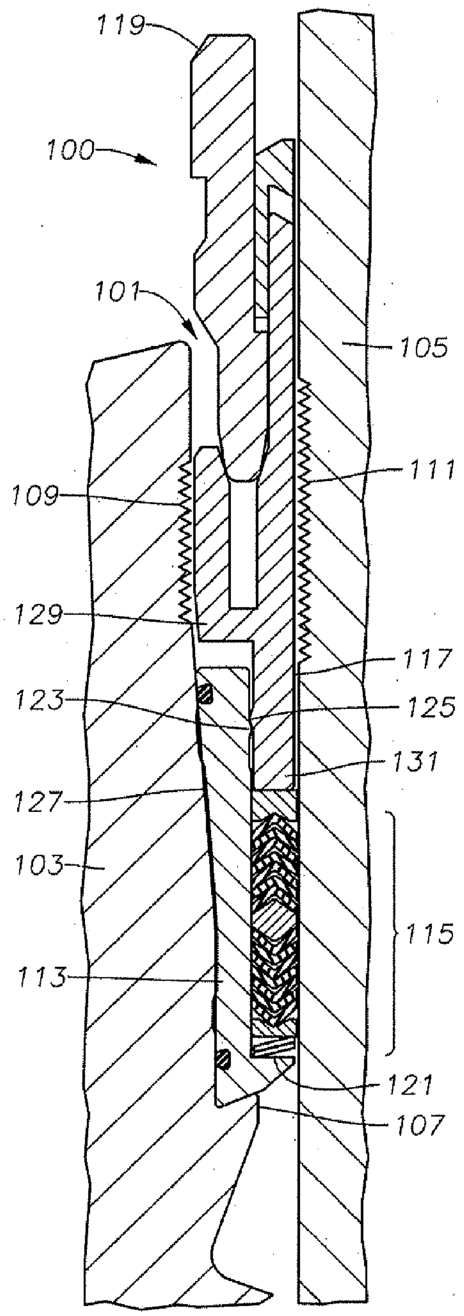


Fig. 1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111
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129
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125
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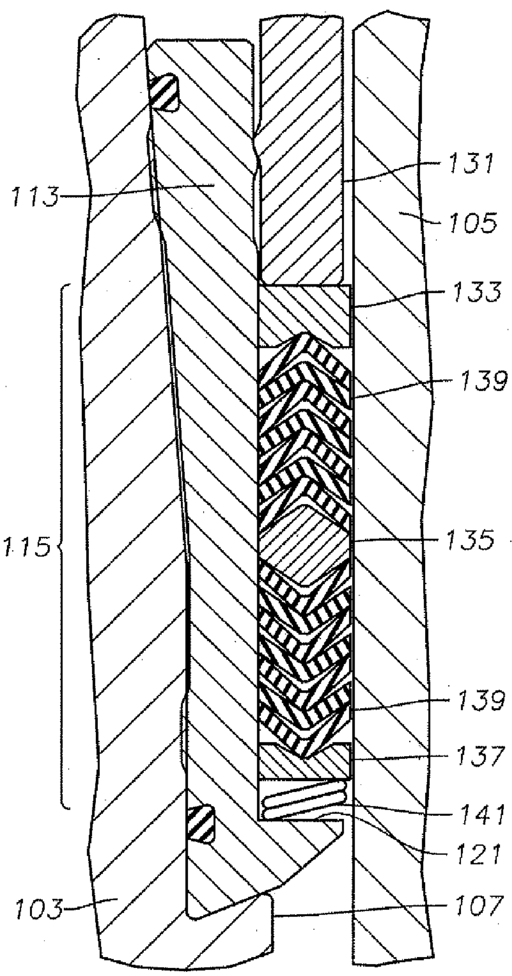
127
103
115
113
121
107

Fig. 2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115
135
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137
141
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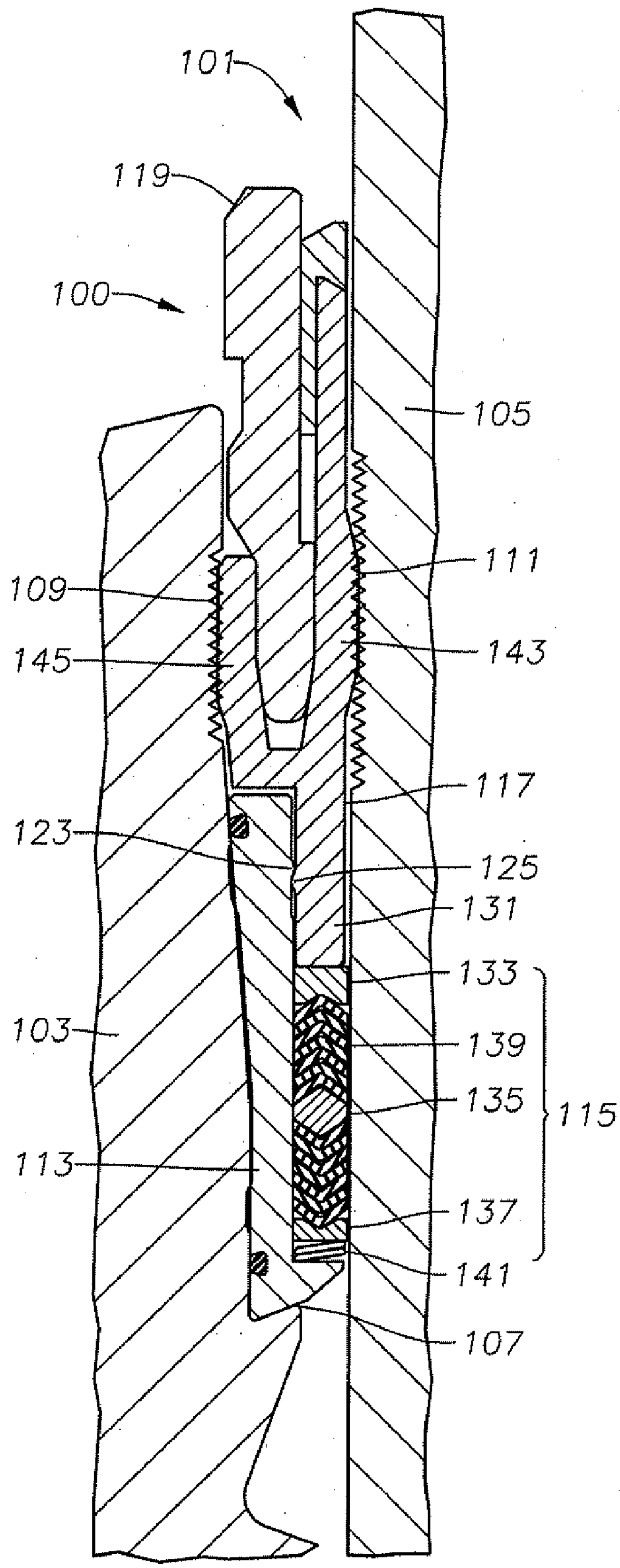
Fig. 3


101
119
100
105
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107

Fig. 4A

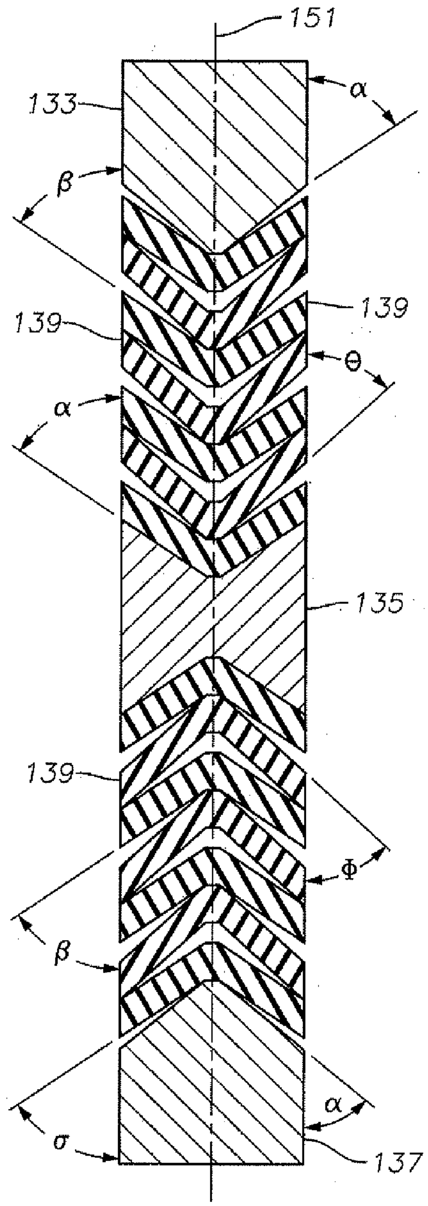

151
133
α
β
139
139
θ
α
135
139
Φ
β
σ
α
137

Fig. 4B

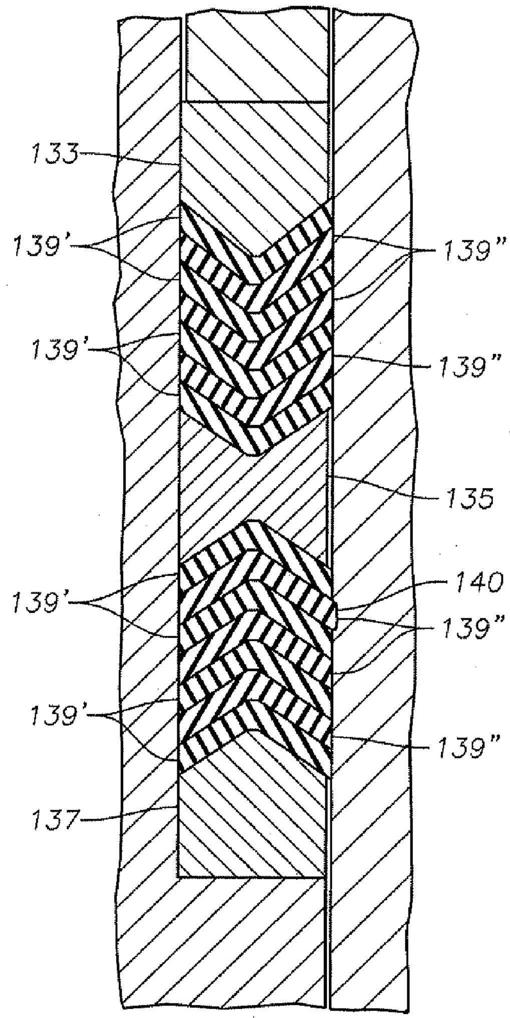
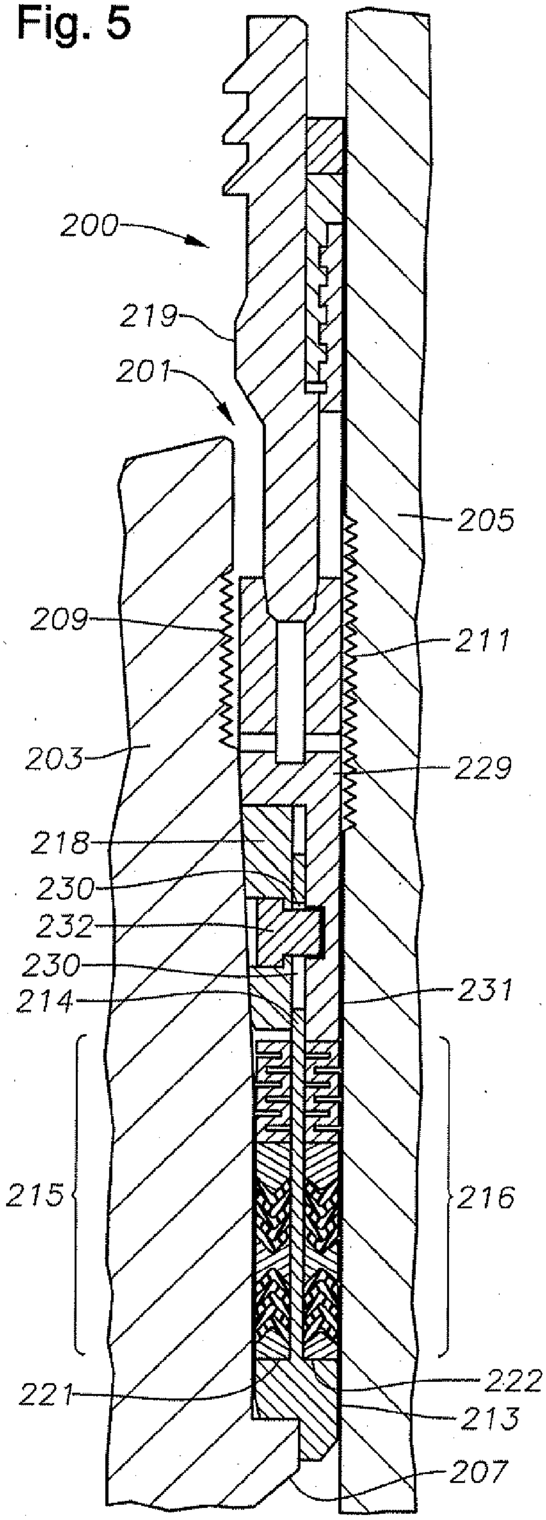

133
139'
139"
139'
139"
135
139'
140
139"
139'
139"
137

Fig. 5


200
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207

Fig. 6

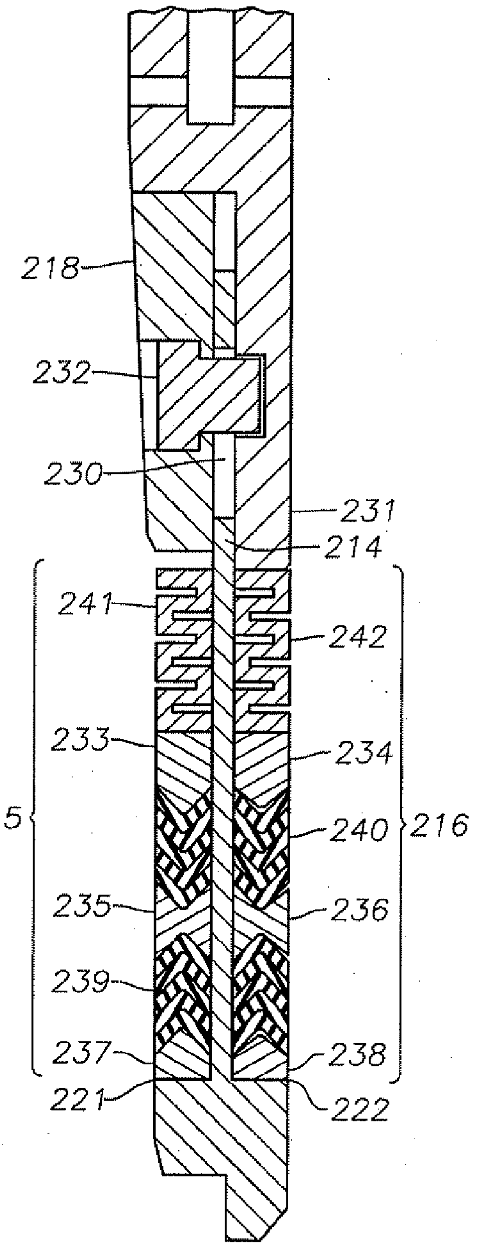
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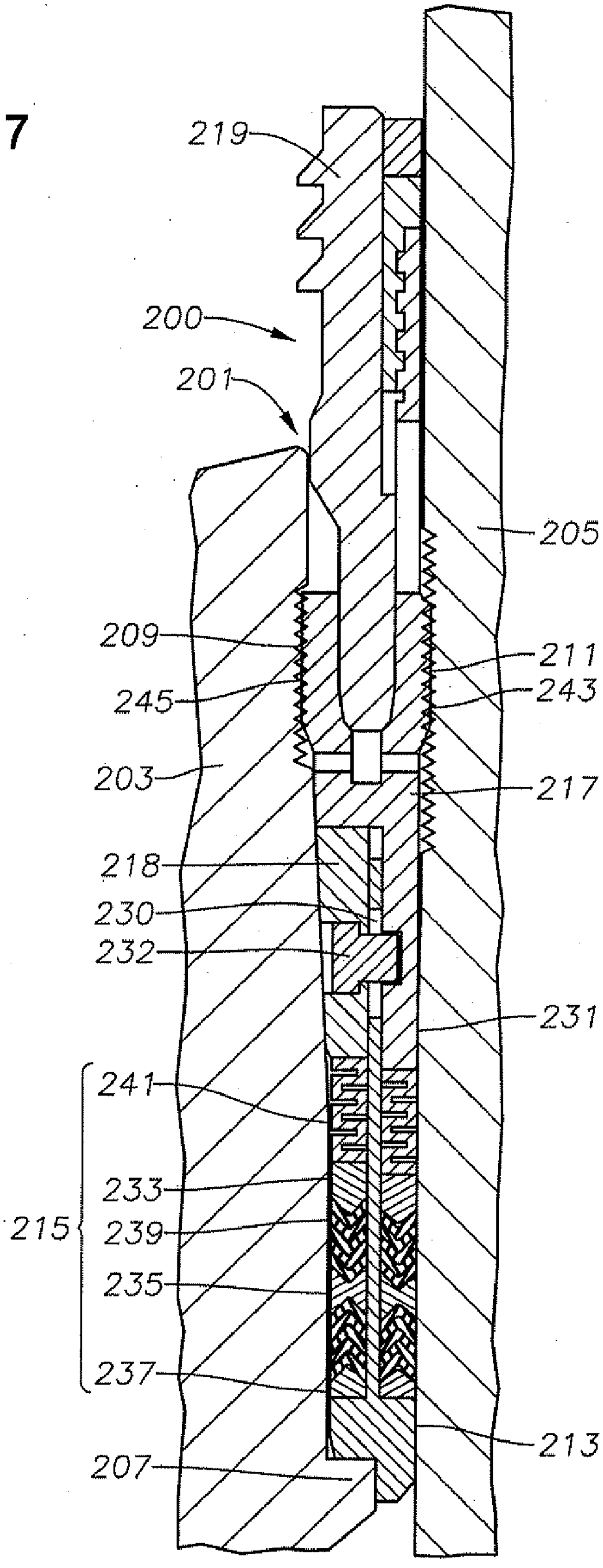
Fig. 7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201
205
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211
245
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213
207

Fig. 8A

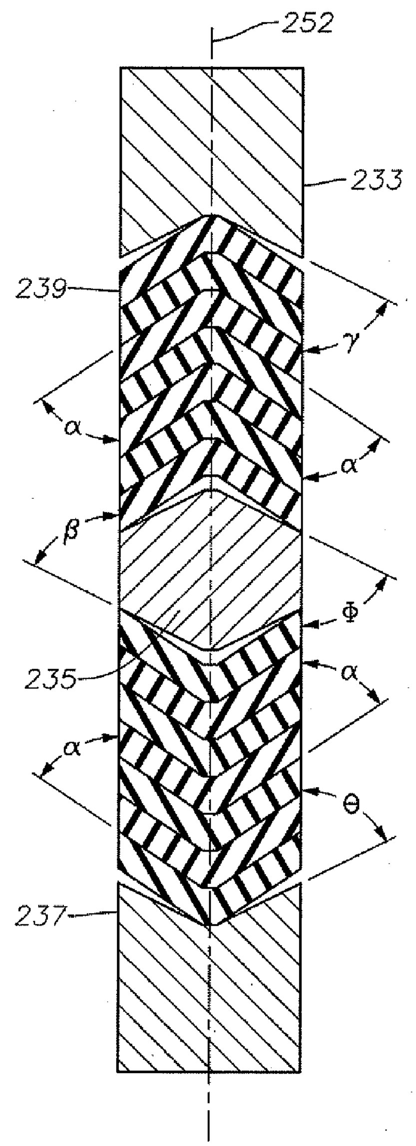
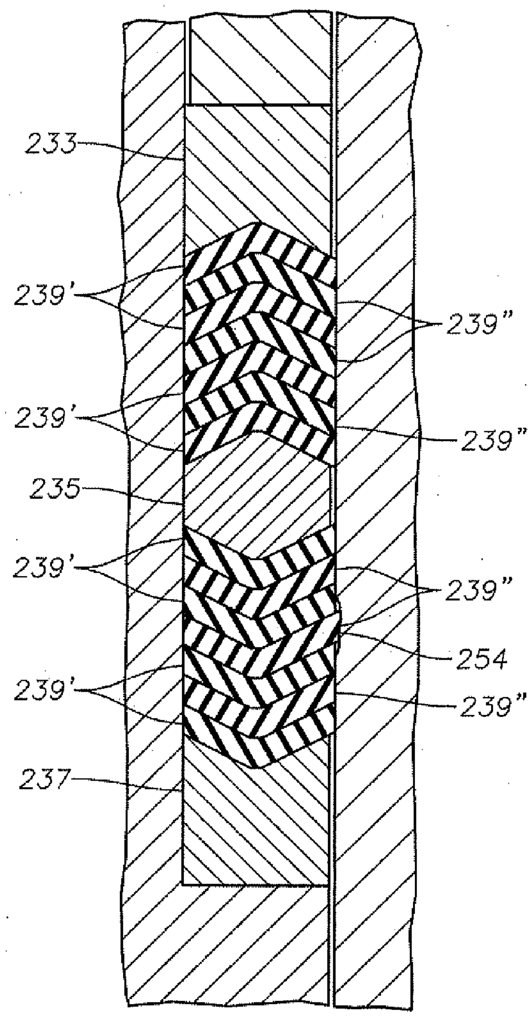

252
233
239
γ
α
α
β
Φ
235
α
α
θ
237

Fig. 8B


233
239'
239"
239'
239"
235
239'
239"
254
239'
239"
237

DAMAGE TOLERANT CASING HANGER SEAL

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates in general to wellhead seals and, in particular, to a damage tolerant casing hanger seal.

[0003] 2. Brief Description of Related Art

[0004] During creation of a wellhead, drilling operations often cause damage to casing elements of the well inserted into the wellbore prior to the switch from drilling to production. In particular, casing hangers and high pressure wellhead housing can be damaged with scratches and gouges that range from minor scratches, such as a few thousandths deep, to major scratches, as much 0.1" deep. In order to seal the wellbore, seals must be constructed of compliant material that can extrude and fill the scratches and gouges. Currently, seals consisting of elastomer seal elements are used to seal the wellbore annulus between the casing elements.

[0005] Unfortunately, elastomer seal elements do not meet the current needs of well drilling and production. For example, many seals are used in conditions where the seal is subjected to extreme cold, extreme heat, and/or cycles between the two extremes. In these situations, the elastomer seals fatigue and fail prior to the end of the seal's desired field life. Current industry standards allow for a ninety day seal field life. However, industry desires a seal that can last the expected life of the well, approximately twenty years. In addition, the life cycle of the well may include start up and shut down of the well, pressure testing of well elements, and the like. These life cycle activities increase the number of extreme stress and temperature cycles to which elastomer seals are exposed. The life cycle activities cause elastomer seals to fatigue and fail well before the twenty year desired field life requirement of wellhead seal systems. Therefore, there is a need for wellhead seals that can withstand extreme temperatures, extreme temperature cycling, and varying life cycle operations of the well up to an expected life cycle of twenty years.

[0006] In addition, elastomer seal elements may experience explosive decompression. Explosive decompression occurs when high pressures surrounding an eleastomer sealing element force the elastomer seal to absorb gases from the surrounding environment. When pressures surrounding the eastomer seal element drop, the gases absorbed into the elastomer seal element at higher pressures rapidly escape the elastomer seal element. The rapid escape of gases causes tearing and destruction of the elastomer seal element. Therefore, there is a need for wellhead seals that are not subject to failure by explosive decompression during high pressure loading and unloading cycles.

[0007] Many wellhead seals use elements that seal the annulus between wellhead members by means of an interference seal. Interference seals use sealing members with a slightly larger width than the annular space to be sealed. Interference seals force the sealing members into the sealing area to prevent passage of fluid or other materials. Because these interference seals are larger than the annular space to be sealed, use of an interference seal often causes damage to the annular space to be sealed and the interference seal itself. This hinders drilling and operation of the well and leads to early failure of the seal. Therefore, there is a need for wellhead seals that will not damage the wellhead casing elements during insertion and energizing.

[0008] Many wellhead seal assemblies used to seal an annulus between wellhead casing elements are not retrievable. Once put in place and energized, the seal cannot be removed. It is in the wellhead until the seal fails. This can hinder drilling and operation of the well where the seal may interfere with running tools and the like. In addition, during emergency situations, standard seals cannot be retrieved; thus, once a seal is used in an emergency situation, it must remain in the wellbore. This prevents use of subsequent better seals or the passage of other equipment or tools through the space. Therefore, there is a need for wellhead seals that are retrievable.

SUMMARY OF THE INVENTION

[0009] These and other problems are generally solved or circumvented, and technical advantages are generally achieved, by preferred embodiments of the present invention that provide a seal assembly, and a method for using the same.

[0010] In accordance with an embodiment of the present invention, a seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis comprises a first anti-extrusion sealing ring having a chevron shaped geometry, and a second anti-extrusion sealing ring having a chevron shaped geometry. The second anti-extrusion sealing ring is coaxial with and axially below the first anti-extrusion sealing ring. The seal assembly also comprises a first compliant sealing ring having a chevron shaped geometry. The first compliant sealing ring is coaxial with and interposed between the first anti-extrusion sealing ring and the second anti-extrusion sealing ring. At least one of the first and second anti-extrusion sealing rings is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force. The first compliant sealing ring is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force.

[0011] In accordance with another embodiment of the present invention, a seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis comprises a seal stack, and an upper activation ring. The upper activation ring is coaxial with and axially above the seal stack. The upper activation ring has a lower mating surface forming an angle to the axis different from the adjacent surface of the seal stack. The seal assembly also comprises a lower activation ring coaxial with and axially below the seal stack. The lower activation ring has an upper mating surface Miming an angle to the axis different from the adjacent surface of the seal stack. Mating surfaces between elements of the seal stack are at equivalent angles to the axis. This the elements to contact the along the length of the mating surfaces. Under axial load contact between the upper and lower activation ring mating surfaces with adjacent seal stack mating surfaces causes radial expansion of the seal stack.

[0012] In accordance with yet another embodiment of the present invention, a seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis comprises a first seal stack having an inner diameter. The first seal stack has compliant sealing elements that, when energized, seal to a damaged surface of the outer annular member. The seal assembly also comprises a second seal stack coaxial with the first seal stack. The second seal stack has an outer diameter smaller than the inner diameter of the first seal stack. In addition, the second seal stack has compliant sealing elements that, when energized, seal to a damaged surface of the inner annular member.

[0013] In yet another embodiment of the present invention, a method for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis comprises providing a sealing ring, and coupling a locking ring to the sealing ring. The method continues by axially moving an energizing ring in a first direction with a ring tool to apply an axial force to the locking ring, which in turn acts on the sealing ring to radially deform the sealing ring into sealing engagement with the annular members. The method concludes by continuing axial movement of the locking ring in the first direction to radially deform the locking ring into locking engagement with the annular members.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] So that the manner in which the features, advantages and objects of the invention, as well as others which will become apparent, are attained and can be understood in more detail, more particular description of the invention briefly summarized above may be had by reference to the embodiment thereof which is illustrated in the appended drawings, which drawings form a part of this specification. It is to be noted, however, that the drawings illustrate only a preferred embodiment of the invention and is therefore not to be considered limiting of its scope as the invention may admit to other equally effective embodiments.

[0015] FIG. **1** is a sectional view of a sealing assembly in accordance with an embodiment of the present invention.

[0016] FIG. **2** is a detail view of the sealing assembly of FIG. **1**.

[0017] FIG. **3** is a sectional view of an energized sealing assembly of FIG. **1**.

[0018] FIG. **4**A is a detail view of exemplary sealing rings of FIG. **1**.

[0019] FIG. **4**B is a detail view of energized exemplary sealing rings of FIG. **1**.

[0020] FIG. **5** is a sectional view of a sealing assembly in accordance with an embodiment of the present invention.

[0021] FIG. **6** is a detail view of the sealing assembly of FIG. **5**.

[0022] FIG. **7** is a sectional view of an energized sealing assembly of FIG. **5**.

[0023] FIG. **8**A is a detail view of exemplary sealing rings of FIG. **5**.

[0024] FIG. **8**B is a detail view of energized exemplary sealing rings of FIG. **5**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0025] The present invention will now be described more fully hereinafter with reference to the accompanying drawings that illustrate embodiments of the invention. This invention may be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and the prime notation, if used, indicates similar elements in alternative embodiments.

[0026] In the following discussion, numerous specific details are set forth to provide a thorough understanding of the present invention. However, it will be obvious to those skilled in the art that the present invention may be practiced without such specific details. Additionally, for the most part, details concerning drilling unit operation, materials, and the like have been omitted inasmuch as such details are not considered necessary to obtain a complete understanding of the present invention, and are considered to be within the skills of persons skilled in the relevant art.

[0027] Referring to FIG. **1**, an un-energized casing hanger seal **100** is shown positioned within an annulus **101** between a casing hanger **103** and a high pressure wellhead housing **105** having a common axis. Casing hanger **103** is that portion of a wellhead assembly that provides support for subsequent casing strings lowered into the wellbore. Casing hanger **103** has a shoulder **107** at a lower end of casing hanger **103**, and wickers **109** proximate to an upper end of casing hanger **103**. Similarly, wellhead housing **105** has wickers **111** proximate to wickers **109** across annulus **101** such that, absent casing hanger seal **100**, wickers **109** and wickers **111** approximately face each other across annulus **101**.

[0028] Casing hanger seal **100** comprises a seal retainer ring **113**, sealing ring assembly **115**, locking ring **117**, and energizing ring **119**. Sealing ring assembly **115** mounts to seal retainer ring **113** on a shoulder **121** of seal retainer ring **113**. Locking ring **117** movably couples to seal retainer ring **113** such that locking ring **117** applies an axial force to sealing ring assembly **115** when casing hanger seal **100** is energized (see FIG. **3**). In the illustrated embodiment, seal retainer ring **113** defines an annular protrusion **123**, and locking ring **117** defines a corresponding protrusion **125** such that when energized (shown in FIG. **3**) protrusion **125** will move past protrusion **123** in an interference fit securing locking ring **117** to seal retainer ring **113** in the energized state. This interference fit may occur by force of the weight of locking ring **117** or by exertion of an axial force on locking ring **117**, such as by energizing ring **119**. A person skilled in the art will understand that locking ring **117** and seal retainer ring **113** may be coupled by means of shear bolts or the like.

[0029] Locking ring **117** comprises an annular member having an approximately U-shaped cross section **129** with locking ring legs **143**, **145** and a lower leg **131**. Lower leg **131** extends past an upper end of seal retainer ring **113** and contacts a top of sealing ring assembly **115**. Energizing ring **119** comprises a ring having an axially lower end slightly larger than the U-shaped slot defined by locking ring **117**. As described in more detail below, a running tool will apply an axial force to energizing ring **119**, forcing energizing ring **119** axially into locking ring **117**, providing an interference fit that will press locking ring legs **143**, **145** of locking ring **117** into adjacent wickers **109** and **111**. A person skilled in the art will understand that the energizing ring **119** may be energized by a running tool or the like.

[0030] Referring now to FIG. **2**, there is shown casing hanger **103**, shoulder **107** of casing hanger **103**, seal retainer ring **113**, lower leg **131** of locking ring **119**, and sealing ring assembly **115** of FIG. **1**. As illustrated in FIG. **2**, sealing ring assembly **115** comprises an upper base ring **133**, a center ring **135**, and a lower base ring **137**. Preferably, upper base ring **133**, center ring **135**, and lower base ring **137** are formed of a high strength steel or the like. In addition, sealing ring assembly **115** comprises a plurality of sealing rings **139**, and a spring element **141**. Spring element **141** mounts to seal retainer ring **113** at shoulder **121** of seal retainer ring **113**. Preferably, spring element **141** is preloaded such that spring element **141** exerts an axial force on sealing ring assembly **115** after casing hanger seal **100** is energized. Preferably, spring element **141** is formed of a high strength low yield material. In the illustrated embodiment, spring element **141** comprises Bellville washers, although a person of skill in the art will understand that other spring elements may be used.

[0031] Lower base ring **137** mounts to seal retainer ring **113** proximate to, and axially above spring element **141** such that an axial force preloaded into spring element **141** during manufacture of casing hanger seal **100** will transfer through lower base ring **137**. Upper base ring **133** mounts to seal retainer ring **113** axially above sealing rings **139** and proximate to lower leg **131** of locking ring **117**. Upper base ring **133** provides an upper base for the transfer of axial energy from locking ring **117** to sealing rings **139**.

[0032] Sealing rings **139** comprise a series of axially stacked chevron rings creating a seal stack. In cross-section, each sealing ring **139** has a V-shape and is preferably of constant thickness. Before being set, the radial width of each sealing ring **139** from its inner diameter to its outer diameter is less than the radial width of the seal pocket. Beginning at lower base ring **137**, sealing rings **139**, are stacked such that an apex of a sealing ring **139** is adjacent to or contacts lower base ring **137**. Sealing rings **139** are then stacked axially above lower base ring **137** in alternating layers of materials such that the apex of the subsequent ring inserts into a concave portion of the prior ring. In the illustrated embodiment, the sealing ring **139** adjacent to lower base ring **137** comprises a metal such as carbon steel or the like. The next sealing ring **139** comprises a thermoplastic material, such as Teflon or the like. Following the thermoplastic sealing ring **139** another metal sealing ring **139** is stacked axially over the prior thermoplastic sealing ring **139**. This continues until the number of sealing rings **139** needed for the particular application is reached. In the illustrated embodiment, seven sealing rings **139** are used between lower base ring **137** and center ring **135**. A person skilled in the art will understand that any desired number of sealing rings **139** may be used. For example, embodiments may include use of three, five, or nine sealing rings **139**.

[0033] Center ring **135** mounts to seal retainer ring **113** axially interposed between adjacent but oppositely facing sealing rings **139**. A lower annular surface of center ring **135** approximately conforms to a concave portion of the sealing ring **139** axially below center ring **135**. Similarly, an upper annular surface of center ring **135** approximately conforms to a concave portion of the sealing ring **139** axially above center ring **135**. Sealing rings **139** are then stacked axially above center ring **135** in alternating layers of materials such that an apex of the prior ring inserts into a concave portion of the subsequent ring. In the illustrated embodiment, the sealing ring **139** adjacent to center ring **135** comprises a metal such as carbon steel or the like. The next sealing ring **139** comprises a thermoplastic material, such as Teflon or the like. Following the thermoplastic sealing ring **139** another metal sealing ring **139** is stacked axially over the prior thermoplastic sealing ring **139**. This continues until the number of sealing rings **139** needed for the particular application is reached. In the illustrated embodiment, seven sealing rings **139** are used between center ring **135** and upper base ring **133**. A person skilled in the art will understand that any desired number of sealing rings **139** may be used. For example, embodiments may include use of three, five, or nine sealing rings **139**. Similarly, a different number of sealing rings **139** may be used above and below center ring **135**. For example, embodiments may include use of three sealing rings **139** above center ring **135** and five sealing rings **139** below center ring **135**. Conversely, embodiments may include use of five sealing rings **139** above center ring **135** and three sealing rings **139** below center ring **135**.

[0034] A lower annular surface of upper base ring **133** approximately conforms and abuts the apex of the sealing ring **139** adjacent to upper base ring **133**. In this manner, sealing rings **139** are bound by upper base ring **133**, center ring **135**, and lower base ring **137**. When energized, described in more detail below, axial forces exerted on upper and lower base rings **133**, **137** will cause sealing rings **139** to flair radially inward and outward coming into tight sealing contact with seal retainer ring **113** and high pressure housing **105**. The outer diameter edge seals against high pressure housing **105**. The inner diameter edge seals against retainer ring **113**.

[0035] In this manner two separate stacks of sealing rings **139** are used, one in which the apex of sealing rings **139** is axially up, and one in which the apex of sealing rings **139** is axially down. This allows casing hanger seal **100** to effectively seal bi-directionally. Annulus **101** will be sealed regardless of whether pressure is applied above or below casing hanger seal **100**.

[0036] Sealing ring **139** materials are selected based on the varying properties of the thermoplastic and metal rings. Preferably, both the thermoplastic rings and the metal rings must flare radially when energized. In addition, the thermoplastic rings should not extrude too quickly. Ideally, the metal sealing rings will flare radially prior to extrusion of thermoplastic rings, thereby containing the flow of the thermoplastic rings. Following flare of metal sealing rings, thermoplastic sealing rings will extrude into any abrasions or scratches in high pressure housing **105**. A preferred embodiment uses 15% carbon filled PTFE for the thermoplastic sealing rings, and carbon steel metal sealing rings having a yield strength of 40 ksi or less. Alternative embodiments of thermoplastic sealing rings may use PEEK or include varying amounts of carbon fiber, nanotubes, graphite particles and the like. In still other embodiments, thermoplastic sealing rings may be replaced with soft metal rings comprised of brass, tin, brass tin alloys, and the like. These materials provide an effective working temperature range of casing hanger seal **100** from −20 degrees Fahrenheit to 350 degrees Fahrenheit. Appropriate materials of sealing rings **139** gives casing hanger seal **100** an effective life of 20 years through any manner of pressure or temperature cycling caused by operation of the well.

[0037] Referring now to FIG. **3**, energizing ring **119** has energized casing hanger seal **100**. Here, a casing hanger running tool (not shown) has forced the energizing ring **119** into the slot defined by locking ring **117**. Initially, an axial force applied to energizing ring **119** by the casing hanger running tool forces energizing ring **119** against locking ring **117**. In response, protrusion **125** of locking ring **117** pushes past protrusion **123** of seal retainer ring **113**. The axial force also forces lower leg **131** of locking ring **117** to against upper base ring **133** compressing sealing ring assembly **115**.

[0038] In the illustrated embodiment, the compression of sealing ring assembly **115** causes sealing rings **139** to flare radially. As shown in FIG. **4**A, this occurs due to the differing angle of each sealing ring arm **139** relative to the adjacent sealing ring arm **139**. In FIG. **4**A, surfaces of upper base ring **133**, center ring **135**, and lower base ring **137** adjacent to a sealing ring **139** all form angles of α with a vertical axis **151**. Adjacent surfaces of the arms of sealing rings **139** instead form varying angles of β, θ, ϕ, and σ with vertical axis **151**. When sealing assembly **115** is compressed, the varying angles flare the arms of sealing rings **139** outward radially rather than toward vertical axis **151**. The angle of each sealing ring **139** is determined through use of Finite Element Analysis in order to generate the desired contact with the sealed members based on the particular geometry of sealed members and the materials used in the individual sealing rings. In some instances a may be greater than β, θ, ϕ, and σ, and in others a may be both greater than or less than the angles of the β, θ, ϕ, and σ group. In alternative embodiments, each arm of each sealing ring **139** does not have a different angle from the arm of the adjacent sealing ring **139**. In these instances, upper base ring **133**, center ring **135**, and lower base ring **137** have a differential angle at the point of contact with the adjacent sealing ring **139** as described in more detail below with respect to FIG. **8**. Under compression, it is the differential angle of upper base ring, center ring, and lower base ring **133**, **135**, **139** that causes flaring of sealing rings **139**. A person skilled in the art will understand that the angle of each sealing ring **139** may be selected so that the sealing effect of the individual sealing ring **139** increases as fluid or gas pressure within annulus **101** increases.

[0039] As described above, seal assembly **115** includes a seal stack of sealing rings **139**. The seal stack has an anti-extrusion sealing ring **139'**, preferably comprised of a metal, axially above and below a compliant sealing ring **139"**, preferably comprised of a thermoplastic material. As shown in FIG. **4**B, when energized, sealing rings **139** flare radially. Flared anti-extrusion sealing rings **139'** engage high pressure housing **105** and seal retainer ring **113**, creating a trapped volume between the upper anti-extrusion sealing ring **139'** and the lower anti-extrusion sealing ring **139'**. The trapped volume constrains any deformation of compliant sealing ring **139"**. The axial pressure on sealing ring assembly **115** deforms compliant sealing ring **139"**, causing compliant sealing ring **139"** to flow into sealing engagement with high pressure housing **105** and seal retainer ring **113**. In this manner, compliant sealing rings **139"** will fill any damaged areas **140** of high pressure housing **105** in the area to be sealed by casing hanger seal **100**. In some embodiments, at least one of the anti-extrusion sealing rings **139'** above and below compliant sealing ring **139"** will seal to high pressure housing **105** and seal retainer ring **113**. In these embodiments, each sealing ring **139** may be selected for a specific purpose. For example, a first anti-extrusion sealing ring **139'** may seal to high pressure housing **105** and seal retainer ring **113**, a compliant sealing ring **139"** may fill damaged areas **140** of high pressure housing **105**, and a second anti-extrusion sealing ring **139'** may not seal to high pressure housing **105** or seal retainer ring **113** while still constraining deformation of complaint sealing ring **139"**.

[0040] Continued application of an axial force to energizing ring **119** following compression and flaring of sealing ring assembly **115** forces energizing ring **119** into the slot defined by locking ring **117**. As shown in FIG. **3**, this forces locking ring legs **143**, **145** radially into wickers **109**, **111** of casing hanger **103** and high pressure housing **105**. Locking ring legs **143**, **145** then deform into wickers **109**, **111**, limiting axial movement of locking ring **117**. The limitation of axial movement of locking ring **117** maintains compression of sealing ring assembly **115**, helping to maintain the flare of sealing rings **139** and an effective seal of annulus **101**.

[0041] In the illustrated embodiment, spring element **141** is preloaded such that spring element **141** exerts an axial force on sealing ring assembly **115**. During operational use of casing hanger seal **100**, casing hanger seal **100** will experience thermal expansion and contraction. The thermal expansion and contraction of casing hanger seal **100** will cause axial slippage of locking ring **117** lessening the axial force on seal assembly **115**. Preloaded spring element **141** will exert an axial force on seal assembly **115** to maintain the flare of sealing rings **139** during events of axial slippage of locking ring **117**. In this manner, casing hanger seal **100** maintains an effective seal of annulus **101**.

[0042] Axial pressure from energizing ring **119** also forces seal retainer ring **113** into an interference fit with casing hanger **103**. When energized, seal retainer ring **113** engages casing hanger **103** in an interference fit along inner diameter surface **127**. In some embodiments, the metal to metal seal created between seal retainer ring **113** and casing hanger **103** is enhanced by coating inner diameter surface **127** with a soft metal such as silver that will deform into any abrasions or scratches in the surface of casing hanger **103**. In other embodiments, inner diameter surface **127** is coated with a dispersion coating having an extremely low coefficient of friction, approaching 0.007, allowing for a tighter interference fit during placement and energizing of casing hanger seal **100**.

[0043] In instances where casing hanger seal **100** must be removed, a running tool secures to energizing ring **119** and applies an upward axial force. This upward axial force withdraws energizing ring **119** from the slot defined by locking ring **117**. In response, locking ring legs **143**, **145** withdraw from their deformed positions on wickers **109**, **111**, thus unlocking locking ring **117**. Once locking ring **117** is removed from its locked position, an axial force no longer maintains compression of seal assembly **115** releasing the seal maintained by sealing rings, **139** unsealing annulus **101**. A running tool may then retrieve casing hanger seal **100** from the annulus **101** without causing damage to casing hanger **103** or high pressure housing **105**.

[0044] Referring now to FIG. **5**, an un-energized casing hanger seal **200** is shown positioned within an annulus **201** between a casing hanger **203** and a high pressure wellhead housing **205**. Casing hanger **203** is that portion of a wellhead assembly that provides support for subsequent casing strings lowered into the wellbore. Casing hanger **203** has a shoulder **207** at a lower end of casing hanger **203**, and wickers **209** proximate to an upper end of casing hanger **203**. Similarly, wellhead housing **205** has wickers **211** proximate to wickers **209** across annulus **201** such that, absent casing hanger seal **200**, wickers **209** and wickers **211** approximately face each other across annulus **201**.

[0045] Casing hanger seal **200** comprises a seal retainer ring **213**, inner sealing ring assembly **215**, outer sealing ring assembly **216**, locking ring **217**, coupling ring **218**, and energizing ring **219**. Seal retainer ring **213** defines an inner shoulder **221** and an outer shoulder **222** separated by a cylindrical member **214**. Inner sealing ring assembly **215** mounts to seal retainer ring **213** on a shoulder **221** of seal retainer ring **213**. Outer sealing ring assembly **216** mounts to seal retainer ring

213 on shoulder **222** of seal retainer ring **213**. Locking ring **217** movably couples to seal retainer ring **213** such that locking ring **217** applies an axial force to inner and outer sealing ring assemblies **215**, **216** when casing hanger seal **200** is energized (see FIG. **7**).

[0046] Locking ring **217** comprises an annular member having an approximately U-shaped cross section **229** with locking ring legs **243**, **245** and a lower leg **231** extending past an upper end of cylindrical member **214** of seal retainer ring **213** and contacting a top of outer sealing ring assembly **216**. Coupling ring **218** comprises a ring having an diameter less than the diameter of lower leg **231**. In the illustrated embodiment, an outer diameter surface of coupling ring **218** abuts an inner diameter of cylindrical member **214** proximate to a plurality of bolt slots **230** and axially above inner seal assembly **215**. Coupling ring **218** couples to lower leg **231** of locking ring **217** by a plurality of bolts **232**. Bolt slots **230** comprise a plurality of slots in cylindrical member **214** proximate to an upper end of cylindrical member **214**. Bolt slots **230** are of a size and shape such that locking ring **217** and coupling ring **218** may move axially with respect to cylindrical member **214**, thereby compressing inner and outer seal assemblies **215**, **216**.

[0047] Energizing ring **219** comprises a ring having an axially lower end slightly larger than the slot defined by locking ring **217**. As described in more detail below, a running tool will apply an axial force to energizing ring **219** forcing energizing ring **219** axially into locking ring **217** providing an interference fit that will press locking ring legs **243**, **245** of locking ring **217** into adjacent wickers **209** and **211**. A person skilled in the art will understand that the energizing ring **219** may be energized by a running tool or the like.

[0048] Referring now to FIG. **6**, there is shown seal retainer ring **213**, lower leg **231** of locking ring **217**, coupling ring **218**, bolt slot **230**, bolt **232** and inner and outer sealing ring assemblies **215**, **216** of FIG. **5**. As illustrated in FIG. **6**, inner sealing ring assembly **215** comprises an upper base ring **233**, a center ring **235**, and a lower base ring **237**. In addition, inner sealing ring assembly **215** comprises a plurality of sealing rings **239**, and a spring element **241**. Similarly, outer sealing ring assembly **216** comprises an upper base ring **234**, a center ring **236**, a lower base ring **238**, a plurality of sealing rings **240**, and a spring element **242**. Preferably, inner and outer upper base rings **233**, **234**, inner and outer center rings **235**, **236**, and inner and outer lower base rings **237**, **238** are formed of a high strength steel or the like. In addition, inner and outer spring elements **241**, **242** are preferably formed of a high strength material having low yield.

[0049] Inner and outer lower base rings **237**, **238** mount to seal retainer ring **213** at shoulders **221**, **222**. Inner and outer upper base rings **233**, **234** mount to seal retainer ring **113** axially above inner and outer sealing rings **239**, **240** proximate to and axially below inner and outer spring elements **241**, **242** such that an axial force preloaded into inner and outer spring elements **241**, **242** during manufacture of casing hanger seal **200** will transfer through inner and outer upper base rings **233**, **234**. Inner and outer spring elements **241**, **242** are proximate to lower leg **231** of locking ring **217**. In the illustrated embodiment, spring elements **241**, **242** comprise axial spring rings, although a person of skill in the art will understand that other spring elements may be used. Inner and outer upper base rings **233**, **234** provide an upper base for the transfer of axial energy from locking ring **217** and inner and outer spring elements **241**, **242** to inner and outer sealing rings **239**, **240**.

[0050] Inner and outer sealing rings **239**, **240** comprise a series of axially stacked chevron rings. In cross-section, each inner and outer sealing ring **239**, **240** has a v-shape and is preferably of constant thickness. Before being set, the radial width of each inner and outer sealing ring **239**, **240** from its inner diameter to its outer diameter is less than the radial width of the seal pocket. Beginning at inner and outer lower base rings **237**, **238**, inner and outer sealing rings **239**, **240** are stacked such that a concave portion of the inner and outer sealing ring **239**, **240** is adjacent to or contacts inner and outer lower base ring **237**, **238**. Inner and outer sealing rings **239**, **240** are then stacked axially above inner and outer lower base rings **237**, **238** in alternating layers of materials such that an apex of the prior inner and outer sealing ring **239**, **240** inserts into a concave portion of the subsequent inner and outer sealing ring **239**, **240**.

[0051] In the illustrated embodiment, the inner and outer sealing ring **239**, **240** adjacent to inner and outer lower base ring **237**, **238** comprises a metal such as carbon steel or the like. The next inner and outer sealing ring **239**, **240** comprises a thermoplastic material, such as Teflon or the like. Following the thermoplastic inner and outer sealing ring **239**, **240** another metal inner and outer sealing ring **239**, **240** is stacked axially over the prior thermoplastic inner and outer sealing ring **239**, **240**. This continues until the number of inner and outer sealing rings **239**, **240** needed for the particular application is reached. In the illustrated embodiment, five inner and outer sealing rings **239**, **240** are used between inner and outer lower base ring **237**, **238** and inner and outer center ring **235**, **236**. A person skilled in the art will understand that any desired number of inner and outer sealing rings **239**, **240** may be used. For example, embodiments may include use of three, five, or nine inner and outer sealing rings **239**, **240**.

[0052] Inner and outer center ring **235**, **236** mounts to seal retainer ring axially interposed between adjacent but oppositely facing inner and outer sealing rings **239**, **240**. A lower annular surface of inner and outer center ring **235**, **236** approximately conforms to the apex of the inner and outer sealing ring **239**, **240** axially below inner and outer center ring **235**, **236**. Similarly, an upper annular surface of inner and outer center ring **235**, **236** approximately conforms to an apex of the inner and outer sealing ring **239**, **240** axially above inner and outer center ring **235**, **236**. Timer and outer sealing rings **239**, **240** are then stacked axially above inner and outer center ring **235**, **236** in alternating layers of materials such that a concave portion of the prior inner and outer sealing ring **239**, **240** receives an apex of the subsequent inner and outer sealing ring **239**, **240**.

[0053] In the illustrated embodiment, the inner and outer sealing ring **239**, **240** adjacent to inner and outer center ring **235**, **236** comprises a metal such as carbon steel or the like. The next inner and outer sealing ring **239**, **240** comprises a thermoplastic material, such as Teflon or the like. Following the thermoplastic inner and outer sealing ring **239**, **240** another metal inner and outer sealing ring **239**, **240** is stacked axially over the prior thermoplastic inner and outer sealing ring **239**, **240**. This continues until the number of inner and outer sealing rings **239**, **240** needed for the particular application is reached. In the illustrated embodiment, five inner and outer sealing rings **239**, **240** are used between inner and outer center ring **235**, **236** and inner and outer upper base ring

233, **234**. A person skilled in the art will understand that any desired number of inner and outer sealing rings **239**, **240** may be used and that differing numbers of inner and outer sealing rings **239**, **240** may be used. For example, embodiments may include use of three, five, or nine inner and outer sealing rings **239**, **240**. Similarly, a different number of inner and outer sealing rings **239**, **240** may be used above and below inner and outer center ring **235**, **236**. For example, embodiments may include use of three inner and outer sealing rings **239**, **240** above inner and outer center ring **235**, **236** and five inner and outer sealing rings **239**, **240** below inner and outer center ring **235**, **236**. Conversely, embodiments may include use of five inner and outer sealing rings **239**, **240** above inner and outer center ring **235**, **236** and three inner and outer sealing rings **239**, **240** below inner and outer center ring **235**, **236**. Similarly, the number of inner sealing rings **239** may differ from the number or outer sealing rings **240** used.

[0054] A lower annular surface of inner and outer upper base ring **233**, **234** approximately conforms and abuts the concave portion of the inner and outer sealing ring **239**, **240** adjacent to inner and outer upper base ring **233**, **240**. In this manner, inner and outer sealing rings **239**, **240** are bound by inner and outer upper base ring **233**, **234**, inner and outer center ring **235**, **236**, and inner and outer lower base ring **237**, **238**. When energized, described in more detail below, axial forces exerted on inner and outer upper base rings **233**, **234**, and inner and outer lower base rings **237**, **238** will cause inner and outer sealing rings **239**, **240** to flair radially inward and outward coming into tight sealing contact with cylindrical member **214** of seal retainer ring **213**, high pressure housing **205**, and casing hanger **203**.

[0055] In this manner two separate stacks of inner and outer sealing rings **239**, **240** are used, one in which the apex of inner and outer sealing rings **239**, **240** is axially up, and one in which the apex of inner and outer sealing rings **239**, **240** is axially down. This allows casing hanger seal **200** to effectively seal bi-directionally. Annulus **201** will be sealed regardless of whether pressure is applied above or below casing hanger seal **200**.

[0056] Inner and outer sealing ring **239**, **240** materials are selected based on the varying properties of the thermoplastic and metal rings. Preferably, both the thermoplastic rings and the metal rings must flare radially when energized. In addition, the thermoplastic rings should not extrude too quickly. Ideally, the metal sealing rings will flare radially prior to extrusion of thermoplastic rings. Following flare of metal rings, thermoplastic rings extrude into any abrasions or scratches in casing hanger **203** or high pressure housing **205**. A preferred embodiment uses 15% carbon filled PTFE for the thermoplastic sealing rings, and carbon steel metal sealing rings having a yield strength of 40 ksi or less. Alternative embodiments of thermoplastic sealing rings may use PEEK or include varying amounts of carbon fiber, nanotubes, graphite particles and the like. In still other embodiments, thermoplastic sealing rings may be replaced with soft metal rings comprised of brass, tin, brass tin alloys, and the like. These materials provide an effective working temperature range of casing hanger seal **200** from −20 degrees Fahrenheit to 350 degrees Fahrenheit. Appropriate selection of inner and outer sealing ring **239**, **240** materials gives casing hanger seal **200** an effective life of 20 years through any manner of pressure or temperature cycling caused by operation of the well.

[0057] Referring now to FIG. **7**, energizing ring **219** has energized casing hanger seal **200**. Here, a casing hanger running tool (not shown) has forced the energizing ring **219** into the slot defined by locking ring **217**. Initially, an axial force applied to energizing ring **219** compresses inner and outer sealing ring assembly **215**, **216** by applying a downward axial force to locking ring **217** through energizing ring **219**. The downward axial force applied to locking ring **217** also causes coupling ring **218** to move axially downward to the limit allowed by the movement of bolt **232** in bolt slot **230** of cylindrical member **214**. In this manner, locking ring **217** compresses outer seal assembly **216**, and coupling ring **218** compresses inner seal assembly **215**. In the illustrated embodiment, the compression of inner and outer sealing ring assembly **215**, **216** causes inner and outer sealing rings **239**, **240** to flare radially.

[0058] As exemplified in FIG. **8**A with respect to inner seal assembly **215**, but applicable to inner and outer seal assemblies **215**, **216**, a surface of inner upper base ring **233** adjacent to inner sealing rings **239** form an angle of with a vertical axis **252**. The surfaces of the arm of inner sealing ring **239** adjacent to inner upper base ring **233** forms an angle of α with vertical axis **252**. Similarly, inner center ring **235** forms an angle of ϕ with vertical axis **252** that differs from inner sealing ring **239** angle α. Inner center ring **235** forms an angle of β with vertical axis **252** that differs from inner sealing ring **239** arm angle α. Finally, inner lower base ring **237** forms an angle of θ that differs from inner sealing ring **239** arm angle α. Under compression, it is the differential angles of inner upper base ring **233**, inner center ring **235**, and inner lower base ring **237** that causes flaring of inner sealing rings **239**. The angle of upper base ring **233**, ϕ and β of inner center ring **235**, and θ of lower base ring **237** is determined through use of Finite Element Analysis in order to generate the desired contact with the sealed members based on the particular geometry of sealed members and the materials used in the individual sealing rings. In some instances the angle α of sealing rings **239** may be greater than β, θ, ϕ, and γ, and in others α may be both greater than or less than the angles of the β, θ, ϕ, and γ group. In alternative embodiments, this occurs due to the differing angle of each inner and outer sealing ring arm **239**, **240** relative to the adjacent inner and outer sealing ring arm **239**, **240** as described above with respect to FIG. **4**. A person skilled in the art will understand that the angle of each inner and outer sealing ring **239**, **240** may be selected so that the sealing effect of the individual inner and outer sealing ring **239**, **240** increases as fluid or gas pressure within annulus **201** increases.

[0059] As described above, seal assemblies **215**, **216** include seal stacks comprised of sealing rings **239**, **240**. Each seal stack has an anti-extrusion sealing ring **239'**, preferably comprised of a metal, axially above and below a compliant sealing ring **239"**, preferably comprised of a thermoplastic material. As shown in FIG. **8**B, when energized, sealing rings **239** flare radially. Flared anti-extrusion sealing rings **239'** engage high pressure housing **205** and casing hanger **203**, creating a trapped volume between the upper anti-extrusion sealing ring **239'** and the lower anti-extrusion sealing ring **239'**. The trapped volume constrains any deformation of compliant sealing ring **239"**. The axial pressure on sealing ring assembly **215** deforms compliant sealing ring **239"**, causing compliant sealing ring **239"** to flow into sealing engagement with casing hanger **203**. In this manner, compliant sealing rings **239"** will fill any damaged areas **254** of casing hanger **203** in the area to be sealed by casing hanger seal **200**. Similarly, compliant sealing rings **240'** will fill any damaged areas of high pressure housing **205** in the area to be sealed by casing hanger seal **200**.

[0060] In some embodiments, at least one of the anti-extrusion sealing rings **239'** above and below compliant sealing ring **239"** will seal to casing hanger **203**. In these embodiments, each sealing ring **239** may be selected for a specific purpose. For example, a first anti-extrusion sealing ring **239'** may seal to casing hanger **203**, a compliant sealing ring **239"** may fill damaged areas **254** of casing hanger **203**, and a second anti-extrusion sealing ring **239'** may not seal to casing hanger **203** while still constraining deformation of complaint sealing ring **239"**.

[0061] As illustrated in FIG. **7**, continued application of an axial force to energizing ring **219** following compression and flaring of inner and outer sealing ring assembly **215**, **216** forces energizing ring **219** into the slot defined by locking ring **217** forcing locking ring legs **243**, **245** radially into wickers **209**, **211** of casing hanger **203** and high pressure housing **205**. Further application of axial force to energizing ring **219** causes locking ring legs **243**, **245** to deform into wickers **209**, **211**, limiting axial movement of locking ring **217**. The limitation of axial movement of locking ring **217** causes continual compression of inner and outer sealing ring assembly **215**, **216**, helping to maintain the flare of inner and outer sealing rings **239**, **240** and an effective seal of annulus **201**.

[0062] In the illustrated embodiment, inner and outer spring elements **241**, **242** are preloaded such that inner and outer spring element **241**, **242** exerts an axial force on inner and outer sealing ring assembly **215**, **216**. During operational use of casing hanger seal **200**, casing hanger seal **200** will experience thermal expansion and contraction. The thermal expansion and contraction of casing hanger seal **200** will cause axial slippage of locking ring **217** lessening the axial force on inner and outer seal assemblies **215**, **216**. Preloaded inner and outer spring element **241**, **242** will exert an axial force on inner and outer seal assemblies **215**, **216** to maintain the flare of inner and outer sealing rings **239**, **240** during events of axial slippage of locking ring **217**. In this manner, casing hanger seal **200** maintains an effective seal of annulus **201**.

[0063] In instances where casing hanger seal **200** must be removed, a running tool secures to energizing ring **219** and applies an upward axial force. This upward axial force withdraws energizing ring **219** from the slot defined by locking ring **217**. In response, locking ring legs **243**, **245** withdraw from their deformed positions on wickers **209**, **211**, thus unlocking locking ring **217**. Once locking ring **217** is removed from its locked position, an axial force no longer maintains compression of inner and outer seal assemblies **215**, **216** releasing the seal maintained by inner and outer sealing rings **239**, **240**, unsealing annulus **201**. A running tool may then retrieve casing hanger seal **200** from the annulus **201** without causing damage to casing hanger **203** or high pressure housing **205**.

[0064] Accordingly, the disclosed embodiments provide numerous advantages over other casing hanger seals. For example, the embodiments disclosed herein provide a casing hanger seal that seals damaged casing hangers and high pressure wellhead housings without using elastomer seal elements. In addition, the disclosed embodiments provide a seal with an expected life of twenty years that can withstand extreme temperature ranges from −20 degrees Fahrenheit to 350 degrees Fahrenheit. Furthermore, the disclosed embodiments do not require an interference fit, instead maintaining the seal within a smaller area than the sealed annulus until the casing hanger seal is energized, thus preventing additional damage to wellbore casing and the casing hanger seal. Finally, the disclosed embodiments provide a casing hanger seal that is retrievable and replaceable.

[0065] While the invention has been shown or described in only some of its forms, it should be apparent to those skilled in the art that it is not so limited, but is susceptible to various changes without departing from the scope of the invention.

What is claimed is:

1. A seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis, the seal assembly comprising:

a first anti-extrusion sealing ring having a chevron shaped geometry;

a second anti-extrusion sealing ring having a chevron shaped geometry, the second anti-extrusion sealing ring coaxial with and axially below the first anti-extrusion sealing ring;

a first compliant sealing ring having a chevron shaped geometry, the first compliant sealing ring coaxial with and interposed between the first anti-extrusion sealing ring and the second anti-extrusion sealing ring;

wherein at least one of the first and second anti-extrusion sealing rings is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force; and

the first compliant sealing ring is configured to radially engage at least one of the inne and outer coaxially disposed annular members when subjected to an axial force.

2. The seal assembly of claim **1**, further comprising:

a spring axially aligned with the first and second anti-extrusion sealing rings and the compliant sealing ring; and

wherein the spring maintains an axial force on the first and second anti-extrusion sealing ring and the first complaint sealing ring, thereby maintaining a radial force between the sealing rings and the inner and outer annular members.

3. The seal assembly of claim **1**, further comprising:

a third anti-extrusion sealing ring having a chevron shaped geometry, the third anti-extrusion sealing ring coaxial with the first and second anti-extrusion sealing rings;

a fourth anti-extrusion sealing ring having a chevron shaped geometry, the fourth anti-extrusion sealing ring coaxial with the first, second, and third anti-extrusion sealing rings;

a second compliant sealing ring having a chevron shaped geometry, the second compliant sealing ring coaxial with and interposed between the third anti-extrusion sealing ring and the fourth anti-extrusion sealing ring; and

wherein the first and second anti-extrusion sealing rings face in a first axial direction, and the third and fourth anti-extrusion sealing rings face in a second axial direction, opposite the first axial direction, thereby forming a bi-directional seal when energized.

4. The seal assembly of claim **1**, wherein the first compliant sealing ring comprises a material having a modulus of elasticity no greater than half of the modulus of elasticity of the first and second anti-extrusion rings.

5. The seal assembly of claim **1**, wherein:

the first and second anti-extrusion sealing rings are formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof; and

the first compliant sealing ring is formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof.

6. The seal assembly of claim **1**, further comprising:

an upper activation ring coaxial with and axially above the first anti-extrusion ring, the upper activation ring having a lower mating surface forming an angle to the axis different from the adjacent surface of the first anti-extrusion ring;

a lower activation ring coaxial with and axially below the second anti-extrusion ring, the lower activation ring having an upper mating surface forming an angle to the axis different from the adjacent surface of the second anti-extrusion ring;

wherein mating surfaces between the first anti-extrusion ring and the first compliant ring are at equivalent angles to the axis, allowing the first anti-extrusion ring and the first compliant ring to contact along the length of the mating surfaces;

wherein mating surfaces between the second anti-extrusion ring and the first compliant ring are at equivalent angles to the axis, allowing the second anti-extrusion ring and the first compliant ring to contact along the length of the mating surfaces; and

wherein under axial load, contact between the upper and lower activation ring mating surfaces with adjacent anti-extrusion sealing ring mating surfaces causes radial expansion of the first and second anti-extrusion sealing rings and the compliant sealing ring.

7. The seal assembly of claim **6**, wherein the angles of the mating surfaces between the first anti-extrusion sealing ring, the second anti-extrusion ring, and the compliant ring cause an increase in sealing pressure in response to increased pressure within the annulus.

8. The seal assembly of claim **1**, further comprising:

the first anti-extrusion sealing ring having a lower mating surface forming an angle to the axis that is different than an angle formed by a mating surface of the adjacent compliant sealing ring to the axis;

the second anti-extrusion sealing ring having an upper mating surface forming an angle to the axis that is different than an angle formed by a mating surface of the adjacent compliant sealing ring to the axis; and

wherein under axial load, contact between the mating surfaces causes radial expansion of the first and second anti-extrusion sealing rings and the compliant sealing ring.

9. The seal assembly of claim **8**, wherein at least one of the angles of the first anti-extrusion sealing ring mating surface and the second anti-extrusion ring surface causes an increase in sealing pressure in response to increased pressure within the annulus.

10. The seal assembly of claim **1**, further comprising:

a third anti-extrusion sealing ring having a chevron shaped geometry, the third anti-extrusion sealing ring coaxial with the first and second anti-extrusion sealing rings;

a fourth anti-extrusion sealing ring having a chevron shaped geometry, the fourth anti-extrusion sealing ring coaxial with the first, second, and third anti-extrusion sealing rings, and axially below the third anti-extrusion sealing ring;

a second compliant sealing ring having a chevron shaped geometry, the compliant sealing ring coaxial with and interposed between the third anti-extrusion sealing ring and the fourth anti-extrusion sealing ring;

wherein the third and fourth anti-extrusion sealing rings have an outer diameter smaller than an inner diameter of the first and second anti-extrusion sealing rings;

wherein outer diameter surfaces of at least one of the first and second anti-extrusion sealing rings seal to the outer annular member when energized;

wherein outer diameter surfaces of the first compliant sealing ring seal to the outer annular member when energized;

wherein inner diameter surfaces of at least one of the third and fourth anti-extrusion sealing rings seal to the inner annular member when energized; and

wherein inner diameter surfaces of the second compliant sealing ring seal to the inner annular member when energized.

11. The seal assembly of claim **10**, the seal assembly further comprising:

a seal retainer ring comprising an annular member defining inner and outer annular upward facing shoulders separated by a cylindrical member coaxial with the axis;

wherein the seal retainer ring removably couples to a running tool for insertion of and removal of the seal assembly;

wherein the first and second anti-extrusion sealing rings and the first compliant sealing ring mount to the outer upward facing shoulder of the seal retainer ring; and

wherein the third and fourth anti-extrusion sealing rings and the second compliant ring mount to the inner upward facing shoulder of the seal retainer ring.

12. A seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis, the seal assembly comprising:

a seal stack;

an upper activation ring coaxial with and axially above the seal stack, the upper activation ring having a lower mating surface forming an angle to the axis different from the adjacent surface of the seal stack;

a lower activation ring coaxial with and axially below the seal stack, the lower activation ring having an upper mating surface forming an angle to the axis different from the adjacent surface of the seal stack;

wherein mating surfaces between elements of the seal stack are at equivalent angles to the axis, allowing the elements to contact the along the length of the mating surfaces; and

wherein under axial load contact between the upper and lower activation ring mating surfaces with adjacent seal stack mating surfaces causes radial expansion of the seal stack.

13. The seal assembly of claim **12**, further comprising:

a spring axially aligned with the seal stack; and

wherein the spring maintains an axial force on the seal stack, thereby maintaining a radial force between the seal stack and the inner and outer annular members.

14. The seal assembly of claim **12**, wherein the seal stack comprises:

a first anti-extrusion sealing ring having a chevron shaped geometry;

a second anti-extrusion sealing ring having a chevron shaped geometry, the second anti-extrusion sealing ring coaxial with and axially below the first anti-extrusion sealing ring;

a first compliant sealing ring having a chevron shaped geometry, the first compliant sealing ring coaxial with and interposed between the first anti-extrusion sealing ring and the second anti-extrusion sealing ring;

wherein at least one of the first and second anti-extrusion sealing rings is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force; and

the first compliant sealing ring is configured to radially engage at least one of the inner and outer coaxially disposed annular, members when subjected to an axial force.

15. The seal assembly of claim **14**, wherein the seal stack further comprises:

a third anti-extrusion sealing ring having a chevron shaped geometry, the third anti-extrusion sealing ring coaxial with the first and second anti-extrusion sealing rings;

a fourth anti-extrusion sealing ring having a chevron shaped geometry, the fourth anti-extrusion sealing ring coaxial with the first, second, and third anti-extrusion sealing rings, and axially below the third anti-extrusion sealing ring;

a second compliant sealing ring having a chevron shaped geometry, the second compliant sealing ring coaxial with and interposed between the third anti-extrusion sealing ring and the fourth anti-extrusion sealing ring; and

wherein the first and second anti-extrusion sealing rings face in a first axial direction, and the third and fourth anti-extrusion sealing rings face in a second axial direction, opposite the first axial direction, thereby forming a bi-directional seal when energized.

16. The seal assembly of claim **14**, wherein the first compliant sealing ring comprises a material having a modulus of elasticity no greater than half of the modulus of elasticity of the first and second anti-extrusion rings.

17. The seal assembly of claim **14**, wherein:

the first and second anti-extrusion sealing rings are formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof; and

the first compliant sealing ring is formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof.

18. The seal assembly of claim **14**, further comprising:

a third anti-extrusion sealing ring having a chevron shaped geometry, the third anti-extrusion sealing ring coaxial with the first and second anti-extrusion sealing rings;

a fourth anti-extrusion sealing ring having a chevron shaped geometry, the fourth anti-extrusion sealing ring coaxial with the first, second, and third anti-extrusion sealing rings, and axially below the third anti-extrusion sealing ring;

a second compliant sealing ring having a chevron shaped geometry, the second compliant sealing ring coaxial with and interposed between the third anti-extrusion sealing ring and the fourth anti-extrusion sealing ring;

wherein the third and fourth anti-extrusion sealing rings have an outer diameter smaller than an inner diameter of the first and second anti-extrusion sealing rings;

wherein outer diameter surfaces of at least one of the first and second anti-extrusion sealing rings seal to the outer annular member when energized;

wherein outer diameter surfaces of the first compliant sealing ring seal to the outer annular member when energized;

wherein inner diameter surfaces of at least one of the third and fourth anti-extrusion sealing rings seal to the inner annular member when energized; and

wherein inner diameter surfaces of the second compliant sealing ring seal to the inner annular member when energized.

19. The seal assembly of claim **18**, the seal assembly further comprising:

a seal retainer ring comprising an annular member defining inner and outer annular upward facing shoulders separated by a cylindrical member coaxial with the axis;

wherein the seal retainer ring removably couples to, a running tool for insertion of and removal of the seal assembly;

wherein the first and second anti-extrusion sealing rings and the first compliant sealing ring mount to the outer upward facing shoulder of the seal retainer ring; and

wherein the third and fourth anti-extrusion sealing rings and the second compliant ring mount to the inner upward facing shoulder of the seal retainer ring.

20. A seal assembly for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis, the seal assembly comprising:

a first seal stack having an inner diameter;

the first seal stack having compliant sealing elements that, when energized, seal to a damaged surface of the outer annular member;

a second seal stack coaxial with the first seal stack, the second seal stack having an outer diameter smaller than the inner diameter of the first seal stack; and

the second seal stack having compliant sealing elements that, when energized, seal to a damaged surface of the inner annular member.

21. The seal assembly of claim **20**, the seal assembly further comprising:

a seal retainer ring comprising an annular member defining inner and outer annular upward facing shoulders separated by a cylindrical member coaxial with the axis;

wherein the seal retainer ring removably couples to a running tool for insertion and removal of the first and second seal stack;

wherein the first seal stack mounts to the outer upward facing shoulder of the seal retainer ring; and

wherein second seal stack mounts to the inner upward facing shoulder of the seal retainer ring.

22. The seal assembly of claim **20**, wherein the first and second seal stacks each comprise:

a first anti-extrusion sealing ring having a chevron shaped geometry;

a second anti-extrusion sealing ring having a chevron shaped geometry, the second anti-extrusion sealing ring coaxial with and axially below the first anti-extrusion sealing ring;

a first compliant sealing ring having a chevron shaped geometry, the first compliant sealing ring coaxial with and interposed between the first anti-extrusion sealing ring and the second anti-extrusion sealing ring;

wherein at least one of the first and second anti-extrusion sealing rings is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force; and

the first compliant sealing ring is configured to radially engage at least one of the inner and outer coaxially disposed annular members when subjected to an axial force.

23. The seal assembly of claim **22**, wherein the compliant sealing ring comprises a material having a modulus of elasticity no greater than half of the modulus of elasticity of the first and second anti-extrusion rings.

24. The seal assembly of claim **22**, wherein:

the first and second anti-extrusion sealing rings are formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof; and

the compliant sealing ring is formed from materials selected from the group consisting of metals, polymers, elastomers, ceramics, and composites thereof.

25. The seal assembly of claim **22**, wherein the first and second seal stacks each further comprise:

a third anti-extrusion sealing ring having a chevron shaped geometry, the third anti-extrusion sealing ring coaxial with the first and second anti-extrusion sealing rings;

a fourth anti-extrusion sealing ring having a chevron shaped geometry, the fourth anti-extrusion sealing ring coaxial with the first, second, and third anti-extrusion sealing rings;

a second compliant sealing ring having a chevron shaped geometry, the second compliant sealing ring coaxial with and interposed between the third anti-extrusion sealing ring and the fourth anti-extrusion sealing ring; and

wherein the first and second anti-extrusion sealing rings face in a first axial direction, and the third and fourth anti-extrusion sealing rings face in a second axial direction, opposite the first axial direction, thereby forming a bi-directional seal when energized.

26. The seal assembly of claim **20**, further comprising:

a spring axially aligned with the first and second seal stacks; and

wherein the spring maintains an axial force on the first and second seal stacks, thereby maintaining a radial force between the first and second seal stacks and the inner and outer annular members.

27. A method for sealing within an annulus between inner and outer coaxially disposed annular members having a common axis, the method comprising:

(a) providing a sealing ring;

(b) coupling a locking ring to the sealing ring;

(c) axially moving an energizing ring in a first direction with a setting tool to apply an axial force to the locking ring, which in turn acts on the sealing ring to radially deform the sealing ring into sealing engagement with the annular members; and

(d) continuing axial movement of the locking ring in the first direction to radially deform the locking ring into locking engagement with the annular members.

28. The method of claim **27**, wherein step (b) comprises applying an axial force to the sealing ring.

29. The method of claim **27**, wherein step (b) comprises placing the sealing ring on an upward facing surface in a seal pocket between the inner and outer members after the locking ring is coupled to the sealing ring and before step (c).

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