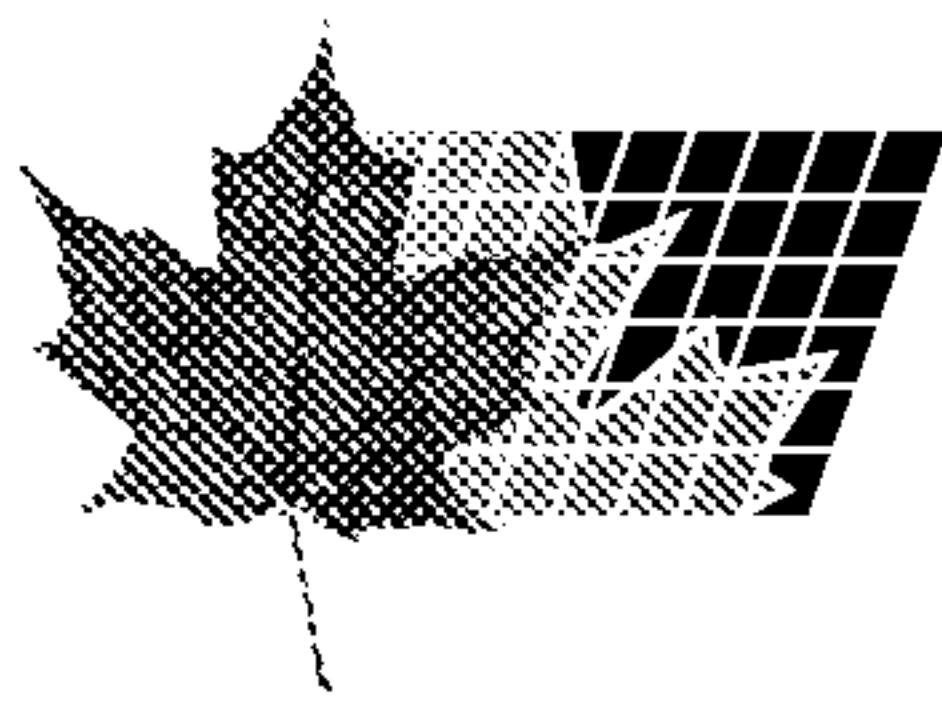
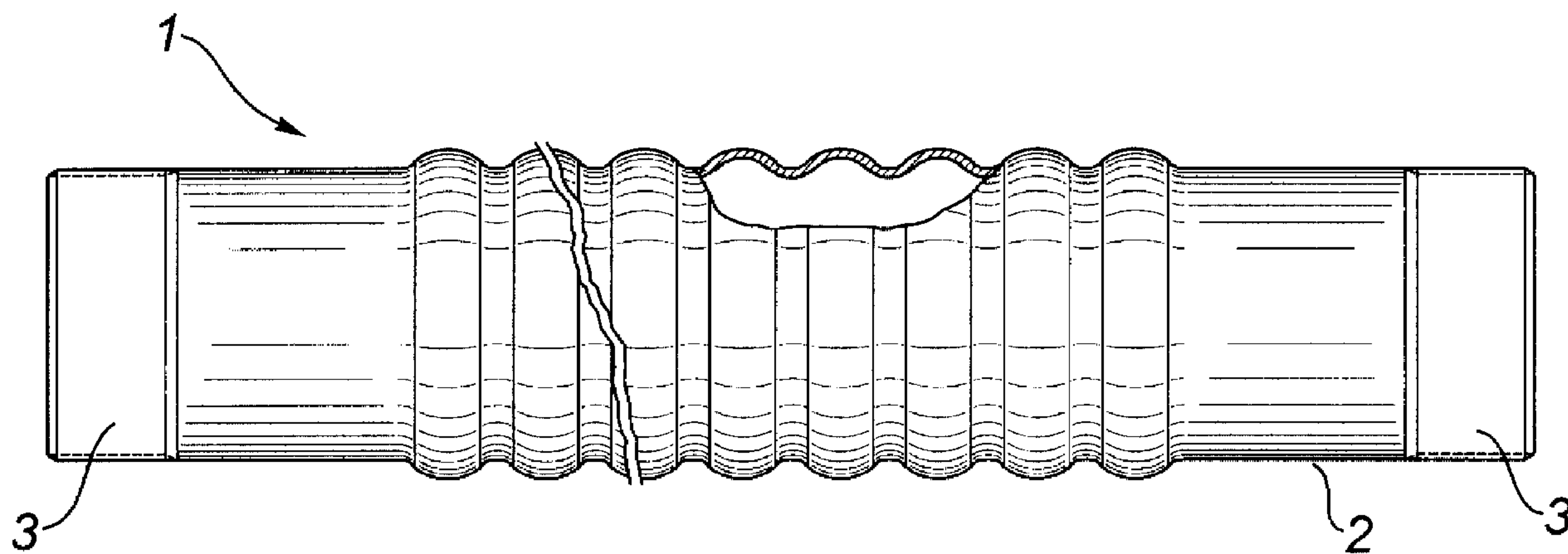




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(54) **TUYAU A PAROI EPAISSE ONDULEE POUR PUITS DE
FORAGE**
(54) **CORRUGATED THICK-WALLED PIPE FOR USE IN
WELLBORES**



(57) Thick-walled steel pipe is corrugated for the purpose of managing axial load when the pipe is used in an earth-restrained application. For example, the pipe may be used as casing in a cyclic steam stimulation well, where the axial loads are induced as the casing is heated and cooled.

1 **ABSTRACT OF THE DISCLOSURE**

2 Thick-walled steel pipe is corrugated for the purpose of managing axial
3 load when the pipe is used in an earth-restrained application. For example,
4 the pipe may be used as casing in a cyclic steam stimulation well, where the
5 axial loads are induced as the casing is heated and cooled.

1 **"CORRUGATED THICK-WALLED PIPE**
2 **FOR USE IN WELLBORES"**

3 **FIELD OF THE INVENTION**

4 The present invention relates to corrugated pipe and its use in tubular
5 strings conveying fluid through earth material, for example as part of a buried
6 pipeline or casing in a well.

7
8 **BACKGROUND OF THE INVENTION**

9 The invention was initially developed as a means to reduce thermally
10 induced axial load in the production casing string of a well undergoing cyclic
11 steam stimulation. The production casing strings in such wells are normally
12 cemented in place and are therefore largely constrained from expanding or
13 contracting axially during heating and cooling cycles. This constrained
14 thermal strain is manifested as axial load which becomes more compressive
15 during heating and more tensile during cooling. Depending on the thermo-
16 mechanical material properties of the casing and the magnitude of
17 temperature cycling, the axial stress may exceed the axial yield strength of
18 the pipe in compression during heating and may exceed the axial yield
19 strength in tension during cooling. Among other consequences, the high
20 stresses place severe demands on the structural and sealing capacity of the
21 tubular connections between casing joints and significantly reduce the ability
22 of the pipe body to withstand collapse, bending and shear loads which may
23 arise from various hydraulic and geomechanical factors. The incidence of
24 leakage, fracture and access impairment 'failures' is therefore relatively high in
25 connection with the casing of thermal process wells.

1 Approaches taken by the industry to address this problem have
2 typically included improving the strength and leakage resistance of the
3 connections by utilizing more complex designs, for example substituting
4 premium connections for the standard 8-round or buttress threadform
5 connections, or increasing the grade of steel used. These approaches, while
6 potentially providing significantly better seepage control and modest
7 incremental structural performance, tend to increase cost and do not
8 substantially reduce the risk of fracture or deformation induced failure.

9 Therefore there remains a need to address the primary confounding
10 variable, namely the high axial stress induced by confined thermal expansion
11 and contraction.

12 While thermal well design has been the primary motivator for the
13 present invention, it is not to be limited to this application. The invention finds
14 use in situations where there is interaction of loads between tubulars,
15 surrounding earth material and contained or excluded pressure fluids, and
16 where it would be desirable to increase axial or flexural compliance, decrease
17 effective axial yield load and increase collapse resistance. One such situation
18 involves buried pipelines. Here axial and flexural strain due to tubular-soil
19 interaction must be absorbed without loss of pressure integrity. It would be
20 desirable to provide tubulars of reduced axial and therefore flexural stiffness
21 because these properties result in lower axial and bending loads than straight
22 pipe for the same temperature variations and deformation magnitude.

SUMMARY OF THE INVENTION

1
2 The phrase "string of joints" as used herein is intended to encompass a
3 plurality of joints of metal pipe, usually steel, connected end to end either by
4 welding or threaded connections and to further encompass a sand exclusion
5 liner if such is part of the string. The phrase "thick-walled pipe" is intended to
6 mean high pressure pipe useful as oil country tubulars, such as casing and in
7 high pressure pipelines, said pipe having a diameter to wall thickness ratio
8 ("D/t") less than 100, preferably less than 50.

9 The present invention applies a well known mechanical design
10 concept, corrugations, to thick-walled metal pipe which is to be used in earth-
11 restrained applications, such as in a string of joints used as casing in a well or
12 as part of a pipeline. The corrugations are incorporated for the purpose of
13 managing changes in axial load subsequent to installation.

14 More specifically, the invention involves forming thick-walled pipe to
15 convert at least part of its straight side wall into a corrugated configuration.
16 The corrugations are formed so as to have a corrugation radius of curvature
17 to thickness ratio ("R/t") less than 10, preferably less than 5. Preferably the
18 corrugation webs have a maximum angle equal to or greater than 20° with
19 respect to the pipe axis. More preferably the corrugations have thinned webs
20 and flattened peaks. Preferably, the pipe is hydroformed, without
21 substantially changing its original length, to create the corrugations. By
22 selecting the geometry defined by these limitations we have balanced axial
23 compliance (i.e. reduced axial stiffness) with diametral limitations arising from
24 the cost of increasing annular space consumed in a wellbore and material
25 strain capacity.

1 Broadly stated then, in one embodiment the invention is concerned
2 with a string of joints of thick-walled pipe extending through and being
3 restrained by earth material, the string being subject to a change in axial load
4 subsequent to installation, the side wall of at least one such joint having been
5 formed into corrugations along at least part of its length, the corrugations
6 having an R/t ratio less than 10. Preferably, one or more of the following
7 conditions apply:

- 8 • the string is used in a well and is subject to changes in axial load
9 arising from thermal expansion or contraction (for example where
10 the well is involved in cyclic steam stimulation) or from earth
11 movement;
- 12 • the string forms part of a buried pipeline;
- 13 • the R/t ratio is less than 5;
- 14 • a plurality of corrugated joints are distributed in spaced apart
15 alignment along the string;
- 16 • the corrugation webs have a maximum angle equal to or greater
17 than 20° relative to the pipe axis;
- 18 • the wall thickness of the webs of the corrugations are thinner than
19 the peaks;
- 20 • the corrugations having been formed by hydroforming, more
21 preferably without substantially changing its original length.

1 In another embodiment, the invention is concerned with a thick-walled
2 steel pipe having threaded ends, the body of the pipe between the ends
3 having been hydroformed to produce corrugations along at least part of its
4 length, the corrugations having an R/t ratio less than 10. Any of the
5 previously mentioned preferred conditions also may be incorporated.

6

7 DESCRIPTION OF THE DRAWINGS

8 Figure 1 is a partially cut-away side view of a corrugated casing joint
9 having threaded ends;

10 Figure 2 is a side view showing casing joints in accordance with the
11 invention incorporated into two casing strings in a thermal horizontal well;

12 Figure 3 is a side view showing an alternative arrangement of
13 corrugated joints;

14 Figure 4 is a partially sectional side view of a joint of straight-walled
15 pipe installed in tri-axial plane strain hydroforming apparatus, prior to
16 application of forming pressure;

17 Figure 5 is similar to Figure 2 after the joint has been formed to provide
18 corrugations;

19 Figure 6 is a longitudinal sectional side view of the corrugated joint as
20 formed under plane strain conditions, showing thickness variations; and

21 Figure 7 is a side view of part of Figure 6, showing corrugation and
22 pipe geometry parameters.

DESCRIPTION OF THE PREFERRED EMBODIMENT

1 While recognizing the likely benefits of corrugated earth restrained
2 tubulars used for pipeline and well bore casing applications, the present
3 invention also required a means to place corrugations in the metal tubular
4 materials typically employed for these purposes. It was therefore desirable to
5 devise a manufacturing or forming process capable of creating suitably
6 shaped corrugations in the wall of standard casing and high pressure pipeline
7 materials of more or less full standard joint length. Such tubulars have a D/t
8 ratio less than 100, preferably less than 50. It was particularly desirable to
9 discover a process suited to casing tubulars for use in well bores in a manner
10 providing a geometry yielding suitable stress and strain behaviour under
11 installation and operational loads within the allowable annular space.
12

13 Machining and forming are two techniques well known as means
14 capable of producing corrugation geometries in metal tubulars. Machining
15 provides a means to produce corrugation geometries of almost any desired
16 shape, but it is difficult to implement on the internal surfaces of casing
17 intervals beyond a few diameters of the tube ends. This technical difficulty,
18 combined with the relatively high cost of machining compared to forming,
19 makes forming or forming combined with only external machining the
20 preferred alternative.

21 Existing methods for forming corrugated pipe or bellows from straight
22 tube may generally be divided into rolling and hydroforming or hydrofolding
23 processes. Rolling methods are used on thin-walled material having smaller
24 diameter than that employed for casing or high pressure pipeline tubulars.
25 While other variations of rolling are applicable to larger thicknesses, where for

1 example an internal spiral grooved mandrel is placed on the inside of the pipe
2 and external rollers are used to deform the pipe into the mandrel grooves,
3 such localized forming methods do not enjoy the simplicity of the global
4 forming accomplished with hydroforming.

5 It should be pointed out that forming corrugations in spiral welded pipe
6 by placing corrugations in the strip prior to or during the welding process
7 offers another realistic forming process for larger diameter high pressure
8 pipeline tubulars. Of course this method cannot be applied to tubes and is not
9 suitable for smaller diameter pipeline and casing sizes.

10 The manufacture of corrugated pipe or bellows for applications such as
11 pipeline expansion joints, by hydroforming or hydrofolding, is a technique well
12 known in the art. As described in US patent 4,193,280, "In a process of this
13 kind, the operation starts with a sheet-metal sleeve of a length greater than
14 that of the bellows to be obtained, the said length being, in fact, equal to the
15 developed length of the cylindrical ends of the said bellows and of the
16 deformable corrugations therebetween. A series of suitably spaced rings is
17 applied to the outer wall of the sleeve, which is preferably provided with end-
18 flanges, and it is then placed upon the fixed platen of a press. The interior of
19 the sleeve is filled with a liquid which escapes at a controlled rate and the
20 press is operated in such a manner that the mobile platen is applied to one
21 end of the assembly. The partially confined liquid inside the sleeve develops
22 an internal pressure and, assisted by the axial load, causes the metal to
23 deform outwardly between the forming rings, so that the bellows is eventually
24 shaped."

1 As described, this technique does not contemplate application to
2 casing and high pressure pipeline tubulars which have relatively smaller
3 diameter to thickness (D/t) ratios than the pipe materials to which it is usually
4 applied, described as a "sheet metal sleeve". Further, this description shows
5 that the method as presently practiced does not contemplate changing the arc
6 length of the shaped pipe, in that "the developed length" is expected to be the
7 same as the initial "sheet metal sleeve" length. While the method does
8 provide for direct control of corrugation period through selection of ring
9 spacing and amount of axial compression, these parameters simultaneously
10 control amplitude to a large extent. Little additional control of corrugation
11 shape is possible beyond contouring of the confining rings and the natural
12 unrestrained toroidal bulge formed between the rings. Control of wall
13 thickness distribution is not considered as indicated for example by the use of
14 the term "hydrofolding" and by the expectation that "the developed length"
15 remains unchanged which can not in general be the case if thickness is to be
16 varied. However for application to casing and high pressure pipeline tubular
17 corrugation, it is desirable to obtain corrugations without dramatic changes in
18 original tubular length, to more independently control period and amplitude
19 and to control aspects of the local corrugation geometry variables such as
20 shape and thickness.

21 Before considering how the modified hydroforming process of the
22 present invention may be used to overcome these difficulties and limitations
23 and provide other advantages, it is desirable to consider the relationship
24 between these corrugation geometry variables and corrugated casing
25 performance. It is thus also desirable to consider how the corrugations to be

1 introduced into casing materials differ from the accepted understanding of
2 corrugation geometry.

3 As a term well accepted in the art, a pipe corrugation is generally
4 meant to describe a wrinkle or wave in the wall of otherwise cylindrical tubes.
5 Such corrugations commonly go from peak to valley to peak to valley etc.
6 along all or some portion of the pipe length and, even when helical, are largely
7 circumferential in orientation. This understanding also carries the assumption
8 that the material thickness does not vary substantially along the wave and that
9 these pipes may be treated as shells for stress analysis purposes. Such
10 corrugations or bellows may be treated as shells, and design characteristics
11 such as stress and displacement response to load obtained using standard
12 treatments, such as given, for example, by W.C. Young, "Roark's Formulas
13 for Stress and Strain", Sixth Edition, McGraw Hill Inc., 1989, pg 570. However
14 such treatments break down where the ratio of corrugation radius of curvature
15 to thickness becomes small. In the given reference, this occurs for R/t ratios
16 less than 10.

17 While the term corrugation is applied herein to convey the general
18 sense of the modified casing wall geometry intended to provide the benefits of
19 the present invention, the peculiar requirements of the well bore casing
20 application require corrugation geometries substantially outside the
21 understandings of corrugations usual to the art. To provide corrugations with a
22 significant reduction in axial compliance and yield load as needed for the
23 intended applications, it is generally desirable to create corrugations with a
24 maximum web angle greater than about 20° with respect to the pipe axis. To
25 stay within reasonable amplitudes, and to further optimize the stress and

1 strain distributions by varying the wall thickness over the corrugation interval
2 or wavelength, this implies a radius of curvature to thickness ratio
3 substantially less than 10, preferably less than 5, is needed. It is therefore
4 necessary to consider the corrugations to be placed in casing or pipeline
5 tubular walls as *thickwall* corrugations and to obtain estimates of performance
6 determining stress and strain variables accordingly.

7 As will be evident to one skilled in the art, the corrugation amplitude is
8 constrained to occur within the annular clearances allowable by both outer
9 and inner confining surfaces, typically the well bore wall and production tubing
10 respectively, plus additional running and cementing clearances. Within this
11 constraint, the corrugation geometry produced to obtain the desired reduction
12 in axial stiffness must still provide for sufficient strength to run the tubular, and
13 perhaps react pressure end load. While meeting these basic requirements it is
14 further desirable to obtain a geometry which will produce an axial load
15 significantly lower than occurs with cylindrical pipe when heated, but not at the
16 expense of high cyclic plastic strain, a parameter that strongly controls the
17 corrosion fatigue failure response. To obtain significant stiffness reduction, the
18 angle of the pipe wall portion falling between the peaks and valleys of the
19 corrugation, referred to here as the corrugation web, should be increased
20 substantially, typically above 45° with respect to the axis. This necessitates
21 relatively sharp curvatures in the peak and valley regions to prevent
22 amplitudes exceeding the available annular space. For casing and high
23 pressure pipeline tubulars these curvatures result in R/t ratios nearer 1 than
24 10, placing such corrugations well beyond the limits of standard membrane
25 stress analysis treatments. Particularly at the peak locations, this tends to

1 result in severe flexural stress or strain concentrations under axial loading if
2 typical toroidal geometries are employed. It is therefore beneficial to provide a
3 geometry where the peaks are somewhat flattened to distribute the flexural
4 strain over a longer interval. It is further beneficial to provide a geometry
5 where the web portions of the wall are somewhat thinner, providing a further
6 improvement of stress distribution and lower axial stiffness within the same
7 annular space constraint. Because the flexural wall stiffness is a very strong
8 function of thickness (proportional to the third power of thickness for elastic
9 deformations) apparently small variations in thickness appear to have a
10 disproportionately large effect on stress distribution.

11 Control of such geometry considerations, arising as they do from the
12 thick wall nature of casing corrugations, are not generally contemplated in
13 existing hydroforming processes. As already discussed, the corrugations to be
14 formed by these existing processes are largely constant thickness, toroidal at
15 peaks and valleys and thin wall in nature. The term '*triaxial hydroforming*' has
16 therefore been adopted herein to describe the more specialized process
17 needed to produce casing containing thick wall corrugations better suited to
18 earth-restrained tubular design requirements. This process typically requires
19 higher pressures, greater control of the axial load and is more sensitive to
20 friction behaviour between the tubular and confining mold than hydrofolding
21 where compressive load is primarily used to cause internally pressured pipe
22 to buckle between confining rings.

1 It has been found that triaxial hydroforming conducted under global
2 plane strain conditions, where the corrugations are formed by application of
3 high internal fluid pressure while the overall pipe length is kept constant,
4 produces a corrugation geometry well suited to thermal strain absorption. In
5 this case the axial force is in fact tensile during forming, and the resulting
6 plastic material flow which is further controlled by contact and friction induced
7 stress between the pipe and form, produce an advantageous thinning in the
8 web region of the corrugation during forming of the corrugation 'bulge' under
9 pressure.

10 But this is just one combination of axial load or displacement and
11 pressure or fluid volume control. Other combinations are possible as for
12 example would occur if no axial load were applied (plane stress) and forming
13 was completely accomplished by the application of internal pressure causing
14 bulges to form between rings as commonly used for hydroforming. Such
15 variants of the pressure axial load relationship may be manipulated to
16 produce geometries having characteristics suitable for particular applications
17 and to simultaneously control the change in overall tubular length caused by
18 the forming process.

19 The simplicity of the triaxial plane strain forming process used to
20 produce this corrugation geometry of the preferred embodiment, lends itself
21 particularly well to modest manufacturing cost and small annular space
22 requirements. The resulting tubular architecture is well suited for use in wells
23 using the cyclic steam stimulation production method, as well as other
24 applications benefiting from tubulars with reduced axial load or greater strain
25 absorption to prevent the instabilities associated with global plastic

1 deformation. The plane strain condition enjoys the further advantage of
2 maintaining the original joint length which facilitates interchangeability
3 between corrugated and straight tubulars.

4 From the foregoing, it should be apparent to one skilled in the art, that
5 the fundamental triaxial process variables of confining mold shape, axial load
6 or strain, internal pressure and contact friction, enables a pipe corrugation to
7 be configured with significant control over both the corrugation amplitude as a
8 function of axial length and its thickness distribution to help control stress and
9 strain response to meet a large spectrum of design requirements for earth
10 restrained tubular systems. However corrugation shape obtained by plane
11 strain hydroforming provides a particularly well conditioned corrugation shape
12 for application to cyclic steam stimulation well completion applications as
13 anticipated in the preferred embodiment.

14 The placement of suitable corrugations in the tubular wall is supported
15 through provision of a specialized hydroforming process providing a means of
16 creating axially compliant corrugation geometries without substantial internal
17 machining which process employs control of axial length during hydroforming
18 and is therefore capable of controlling the change in the length of the tubular
19 being formed. The hydroforming process comprises the steps of:

- 20 • placing a length of cylindrical tube inside a confining surface comprised
21 of elements spaced and shaped to control the joint geometry to
22 generally have corrugations in the mid-section and cylindrical end
23 sections and contained within a confining tube supporting or guiding
24 the elements creating the confining surface;

1 • applying sufficient internal pressure to force the tubular wall radially
2 outward against the confining surface while simultaneously controlling
3 the axial length of the tubular during and after application of internal
4 pressure and thus plastically form the tubular article where such axial
5 length control is preferably such that the original tubular length is
6 substantially preserved or unchanged;

7 • removing the formed corrugated tubular joint from the forming
8 apparatus which removal may be facilitated by the application of
9 external pressure sufficient to free the article from the confining
10 surface; and

11 • additionally finishing the formed joint, if required, by external machining
12 of the corrugations to further control the final geometry or machining of
13 the cylindrical ends to provide for joining by threaded connections,
14 welding or other joining method.

15 In its preferred embodiment, joints 1 of corrugated tubular are provided.
16 The joint has cylindrical ends 2 to facilitate joining, using industry standard
17 methods such as welding for pipelines or threaded connections for well bore
18 casing. Such a joint of corrugated casing is shown in Figure 1 with threaded
19 pin ends 3. The diameter and wall thickness of the cylindrical ends 2 are
20 chosen to ensure compatibility with industry sizing standards. The cylindrical
21 end length would typically be chosen to allow for gripping with standard
22 connection make up and handling equipment. In certain cases other
23 operational or completion requirements such as packer setting locations may
24 dictate longer cylindrical intervals at the ends or additional cylindrical sections
25 elsewhere along the joint length. Also, as shown in Figure 1, the corrugation

1 valleys are arranged to coincide with the nominal pipe internal diameter so
2 that the corrugation amplitude has the effect of increasing the effective pipe
3 body diameter. While it is expected this configuration will be desirable for
4 most applications, a corrugation valley diameter less than the nominal pipe
5 diameter may also be provided.

6 The triaxial plane strain hydroforming process preferred to provide such an
7 article of corrugated casing requires an apparatus 4 such as shown in Figure
8 2. In this apparatus 4, a confining tube 5 is provided with sealing annular end
9 closures 6 and a contoured form 7. The form 7 comprises elements providing
10 cylindrical end sections 8 and a centre corrugating section 9 closely fitting
11 inside said confining tube 5. The tube 5, end closures 6 and contoured form 7
12 together comprise a forming vessel 30. A forming fluid access port 10 is
13 provided in one annular end closure 6. A mandrel 11 with external end seals
14 12 and a forming fluid access port 13 is also provided.

15 The centre corrugating section 9 is constructed of various axisymmetric
16 ring and sleeve elements 14, 15 as shown in Figures 2 and 3. To facilitate
17 removal after forming, some or all of these elements 14, 15 are split. Element
18 shapes comprising the forming profile are selected to provide a distribution of
19 void space into which the tubular material is caused to flow under the
20 application of internal pressure. Friction forces activated by contact stress
21 between the confining surface and casing joint 16 also contribute to
22 controlling plastic flow during forming. For a given tubular, the final
23 corrugation shape is thus controlled by void space distribution, lubrication or
24 friction coefficient in the interfacial region between the casing joint 16 and
25 form 7 and forming pressure.

1 The cylindrical end sections 8 have an internal diameter only slightly larger
2 than the outside diameter of the casing joint 16 to be formed to provide casing
3 joint end sections 2 of standard dimensions suitable for threading and
4 handling. The end sections 8 need not be split to allow removal. If desired, the
5 ring and sleeve elements 14, 15 of the centre corrugating section 9, and
6 indeed the cylindrical end sections 8 as well, may all be provided as a single
7 split half form. This configuration of the form or mold permits more rapid
8 assembly and disassembly where repeated forming is required.

9 As shown in Figure 2, the casing joint 16 is placed inside the forming
10 vessel 30 and the mandrel 11 is placed inside the casing joint. The mandrel
11 11 provided with seals 31 for sealing against the inside surface 31 of the
12 casing joint 16 at two locations, typically near the joint ends. The seals 32 are
13 spaced to provide an interval of the casing joint, inside the forming vessel 30,
14 that may be internally fluid loaded to a pressure causing the casing material to
15 plastically expand outward. Similarly the annular end closures are provided
16 with seals 33 to seal between the casing joint exterior and confining tube end
17 closures 6 at nearly the same axial position as the mandrel seals 32, so that
18 the casing joint may be externally pressured over the same interval.

19 Thus arranged, the apparatus 1 is used to form the casing joint 16 by first
20 applying internal pressure, beyond the pipe body yield, to expand the casing
21 material outward against the inside surface 38 of the corrugating section 9.
22 The inner contoured form of the forming vessel 30 is provided to control the
23 shape of the external expansion of the casing material so that as internal
24 pressure is increased the casing material will be progressively forced into
25 contact with the profiled surface 38 as shown in Figure 3.

1 As shown in Figure 3, the casing joint length is not substantially reduced
2 by this process as in typical hydroforming or hydrofolding processes used to
3 provide corrugated pipe. It will be clear that the plane strain forming condition
4 requires the development of axial tensile stress as the corrugations 34 are
5 formed. The apparatus 1 reacts the resulting force through friction forces
6 developed along the cylindrical end sleeves. The friction forces are enabled
7 by contact stress between the internally pressured casing material and the
8 confining form end sections 8 as pressure is initially increased beyond that
9 required to initiate yield and close the relatively small installation gap provided
10 between the casing joint and form end sections 8. Further increases of
11 pressure are used to cause flow into the corrugation voids to the extent
12 required to form corrugation geometries providing substantial reductions in
13 tubular axial compliance, where the pressure required to cause such
14 deformation magnitudes will typically exceed the casing material yield
15 pressure by several times.

16 Following forming under these high pressures, the residual contact stress
17 between the casing joint 16 and contoured form surface 38 tends to preclude
18 straightforward removal of the casing joint 16 from the forming vessel 30.
19 Therefore the forming process is completed by applying sufficient external
20 pressure through port 10 to plastically yield the casing joint and cause inward
21 radial deformation to form a gap between the joint and contoured form surface
22 38 and thus substantially eliminate the residual contact stress inhibiting
23 removal. The pressure and sealing capacity of the annular end closures 6 and
24 seals 33 need only provide sufficient containment to cause global pipe body
25 yield.

1 Following application and removal of external pressure, the mandrel and at
2 least one end cap are removed. The casing and contoured form are then
3 removed and finally the elements of the form removed from the casing. The
4 process may be repeated to form additional joints of formed pipe.

5 In certain applications, the utility of the corrugated pipe formed by this
6 process may be further enhanced by heat treatment, such as annealing for
7 steel, after forming. This may be needed because the amount of plastic
8 deformation imposed by the forming process may affect performance
9 properties such as corrosion sensitivity, fatigue life or simply remaining plastic
10 capacity.

11 A typical thickwall corrugation geometry of the casing joint shown in Figure
12 1, and formed by the plane strain tri-axial hydroforming process, is shown in
13 Figure 4. This figure shows a cross section through several corrugations 34.
14 The relatively subtle variations in thickness obtained using the triaxial forming
15 process are evident. Stress analysis of this geometry using the finite element
16 method was used to calculate a reduction in axial stiffness of approximately 5
17 times that of the original non-corrugated straight pipe.

18 Example

19 To illustrate the utility of the present invention in reducing thermally
20 induced axial load, consider a well where cylindrical steel casing with yield
21 strength of 550 MPa is cemented at 20° C with negligible axial load and is
22 subsequently heated to 250° C. Typical properties for the thermal expansion
23 coefficient and elastic modulus of casing steel are 12 $\mu\text{e}/\text{C}$ and 200 GPa

1 respectively. For such a material, provided its elastic limit is not exceeded, the
2 axial stress increase upon heating is calculated from the relation,

3 Axial stress = temperature change X expansion coefficient X elastic
4 modulus = 552 Mpa.

5 The casing will thus be just at its yield load with consequent deleterious
6 impact on connection and pipe body resistance to failure. However in this
7 same application, casing with corrugations such as shown in Figure 4 over
8 most of its length would reduce this load by a factor of nearly 5, reducing the
9 axial stress to 110 MPa, placing the casing and connections in a much more
10 favorable load operating regime.

11 As an alternative to hydroforming by application of internal pressure to
12 expand a tubular against an external form as described in the preferred
13 embodiment, this process may be inverted to apply external pressure to the
14 tubular and providing a form internal to the tubular. In this case the form would
15 typically be configured to provide spiral corrugations to facilitate removal.

16 In another aspect, we believe the properties of corrugations provided
17 by the tri-axial hydroforming process may be further improved for certain
18 applications through selectively removing material by external machining
19 either before or after hydroforming. For example such machining can be used
20 to further thin the web thickness and extend the range of available elastic
21 deformation.

1 In another aspect, a cylindrical liner with a first and second end is
2 provided on the interior of a corrugated tubular joint with first and second ends
3 where the first end of the liner is joined/fastened to the first end of the
4 corrugated tubular joint and said liner extends to cover all or a portion of the
5 corrugated interval. This configuration permits telescopic sliding of the straight
6 liner relative to the corrugated tubular to provide a system retaining the axial
7 compliance of the corrugated tubular but having increased flexural stiffness
8 and therefore buckling stability, reduced flow losses, simpler cleaning with
9 pigs or wiper plugs and a smooth surface for sealing of devices such as
10 packers. In a further aspect of such a corrugated tubular with internal liner the
11 second end of the liner and second end of the tubular may be provided with
12 interlocking stop rings or similar devices permitting the telescopic relative axial
13 movement only over a certain range where this range can be arranged to limit
14 the stretch or compression of the corrugated tubular to prevent excess strain.

15 In another aspect, a cylindrical liner with a first and second end is
16 provided on the exterior of a corrugated tubular joint with first and second
17 ends where the first end of the liner is joined/fastened to the first end of the
18 corrugated tubular joint and said liner extends to cover all or a portion of the
19 corrugated interval. This configuration permits telescopic sliding of the straight
20 liner relative to the corrugated tubular to provide a system retaining the axial
21 compliance of the corrugated tubular but having increased flexural stiffness
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23 tubular with external liner the second end of the liner and second end of the
24 tubular may be provided with interlocking stop rings or similar devices
25 permitting the telescopic relative axial movement only over a certain range

1 where this range can be arranged to limit the stretch or compression of the
2 corrugated tubular to prevent excess strain.

3 In another aspect, the end sections of the forms may be configured to
4 form expanded tubular intervals suitable for internal threading and thus
5 simultaneously form a tubular article with corrugations and an integral box
6 connection on one or both ends.

7 In another aspect, the forming vessel may be arranged as a split form.

8 In another aspect, the forming elements may be arranged to provide
9 helical corrugations.

10 As an alternative embodiment, we believe an axially compliant tubular
11 may be formed by providing forming elements arranged to create a double
12 helix corrugation using left and right helixes. Such a geometry is similar to that
13 occurring in diamond wall buckling of thin cylinders.

14 As an alternative embodiment, we believe the corrugation geometry
15 may be further controlled by application of axial load subsequent to
16 hydroforming where such load would typically be compressive.

17 As a further alternative embodiment to control corrugation geometry,
18 we believe the forming process may be conducted with independent control of
19 axial displacement as a function of forming fluid pressure or volume control.
20 This embodiment requires the form to be arranged with the corrugating
21 section having floating restraint rings confining the profiled split rings and at
22 one of the end cylindrical sections arranged to telescope within the confining
23 tube and on the mandrel. Control of the axial displacement of this telescoping
24 end section with respect to the confining tube by means of a hydraulic ram or

1 other suitable load application device then permits the desired independence
2 of axial and pressure loads or displacements.

3 In another aspect, material may be placed in the space between some
4 or all of the corrugations, either on the outside or inside, as a means to control
5 or limit the compressive load displacement response of individual
6 corrugations. Materials suitable for this purpose include plastic, cement, split
7 sleeves, rings or springs which may be used separately or in combination with
8 each other.

9 In another aspect, the corrugation amplitude at the ends of a
10 corrugated interval may be ramped down over the last few corrugations to
11 provide a more gradual axial stiffness contrast between cylindrical and
12 corrugated tubular wall intervals.

1 THE EMBODIMENTS OF THE INVENTION IN WHICH AN
2 EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS
3 FOLLOWS:

4 1. In a string of joints of metal pipe extending through and being
5 restrained by earth material, the string being subject to change in axial load
6 subsequent to installation, each such joint comprising a tubular body having a
7 side wall, the improvement comprising:

8 the body side wall of at least one such joint being formed into
9 corrugations along at least part of its length;

10 the side wall having a diameter/thickness ratio less than 100;

11 the corrugations having a corrugation radius of curvature to thickness
12 ratio less than 10.

13

14 2. The improvement as set forth in claim 1 wherein:

15 a plurality of such corrugated joints are spaced apart along the string.

16

17 3. The improvement as set forth in claim 1 wherein:

18 all of the joints of a section of the string are corrugated.

19

20 4. The improvement as set forth in claim 1 wherein:

21 the corrugations have a corrugation radius of curvature to thickness
22 ratio less than 5.

1 5. The improvement as set forth in claim 1, 2, 3 or 4 wherein:
2 the corrugations of each corrugated joint have webs and peaks and the
3 webs have a maximum angle of at least 20° with respect to the axis of the
4 corrugated joint; and
5 the wall thicknesses of the webs of the corrugations are thinner than
6 the peaks.

7
8 6. The improvement as set forth in claim 1, 2, 3 or 4 wherein:
9 the corrugations of each corrugated joint have webs and peaks and the
10 webs have a maximum angle of at least 20° with respect to the axis of the
11 corrugated joint;
12 the wall thicknesses of the webs of the corrugations are thinner than
13 the peaks; and
14 the corrugated joint has been hydroformed while maintaining its original
15 length.

16
17 7 The improvement as set forth in claim 1 comprising an outer sleeve
18 containing the corrugations.

19
20 8 The improvement as set forth in claim 1 comprising:
21 a sleeve, internal of the corrugated joint, supporting the corrugations.

22
23 9 The improvement as set forth in claim 1 comprising:
24 rings positioned between the corrugations to limit compression.

1 10 In a string of joints of steel pipe positioned in a wellbore and
2 extending through and being restrained by earth material, the string being
3 subject to change in axial load arising from thermal expansion or contraction,
4 each such joint comprising a tubular body having a side wall and threaded
5 ends, the improvement comprising:

6 the body side wall of at least one such joint being formed into
7 corrugations along at least part of its length;

8 the side wall having a diameter/thickness ratio less than 100;

9 the corrugations having a corrugation radius of curvature to thickness
10 ratio less than 10.

11

12 11 The improvement as set forth in claim 10 wherein:

13 the corrugated joint has been hydroformed while maintaining its original
14 length.

15

16 12. The improvement as set forth in claim 10 wherein:

17 a plurality of such corrugated joints are spaced apart along the string.

18

19 13. The improvement as set forth in claim 10 wherein:

20 all of the joints of a section of the string are corrugated.

21

22 14. The improvement as set forth in claim 10 wherein:

23 the corrugations have a corrugation radius of curvature to thickness
24 ratio less than 5.

1 15. The improvement as set forth in claim 10, 11, 12, 13 or 14
2 wherein:

3 the corrugations of each corrugated joint have webs and peaks and the
4 webs have a maximum angle of at least 20° with respect to the axis of the
5 corrugated joint.

6

7 16. The improvement as set forth in claim 10 comprising an outer
8 sleeve containing the corrugations.

9

10 17. The improvement as set forth in claim 10 comprising:
11 a sleeve, internal of the corrugated joint, supporting the corrugations.

12

13 18. The improvement as set forth in claim 10 comprising:
14 rings positioned between the corrugations to limit compression.

15

16 19. The improvement as set forth in claim 10, 11, 12, 13 or 14
17 wherein:

18 the string is used in connection with a wellbore used in a thermal
19 process;

20 the corrugations of each corrugated joint have webs and peaks and the
21 webs have a maximum angle of at least 20° with respect to the axis of the
22 corrugated joint; and

23 the wall thicknesses of the webs of the corrugations are thinner than
24 the peaks.

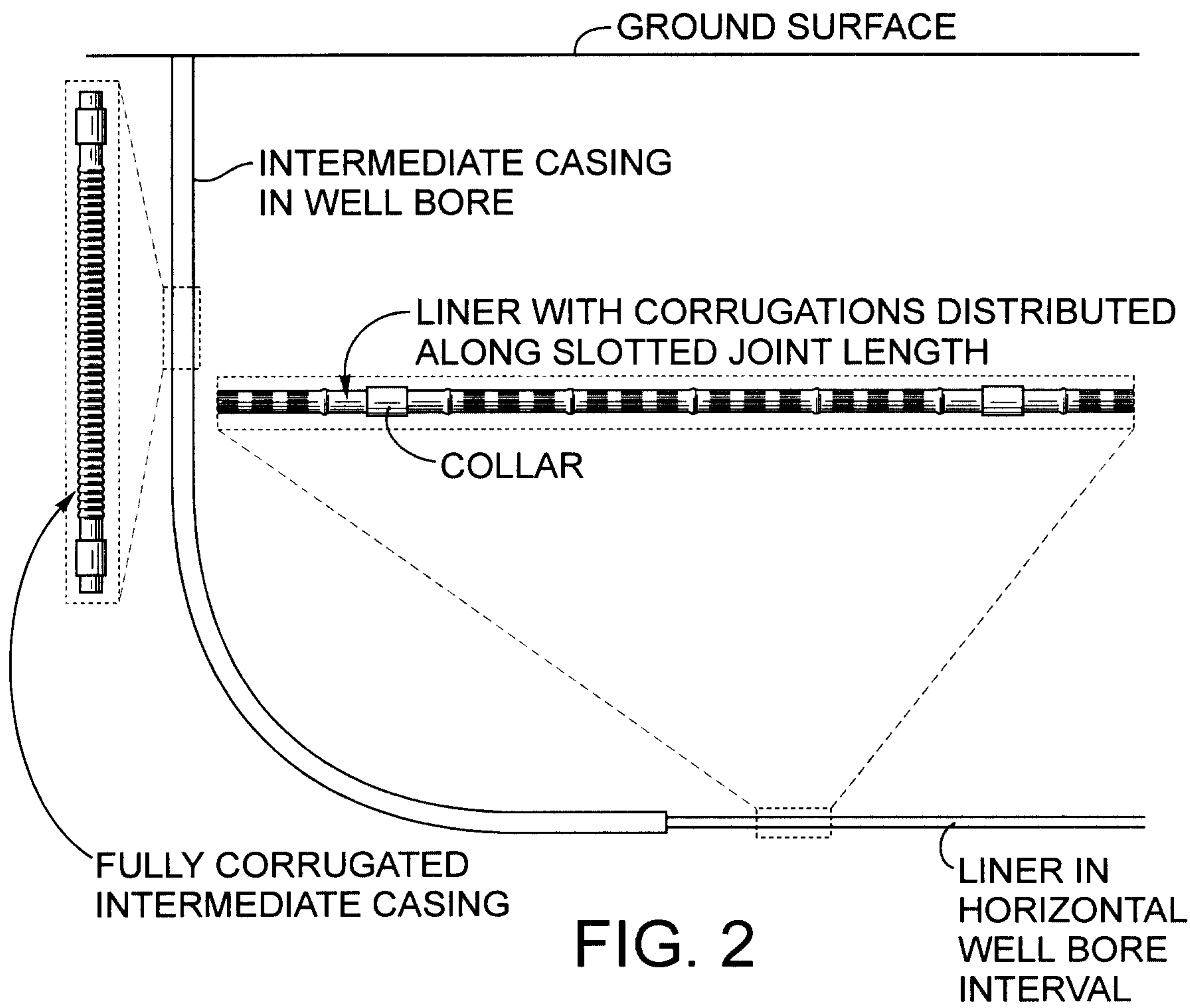
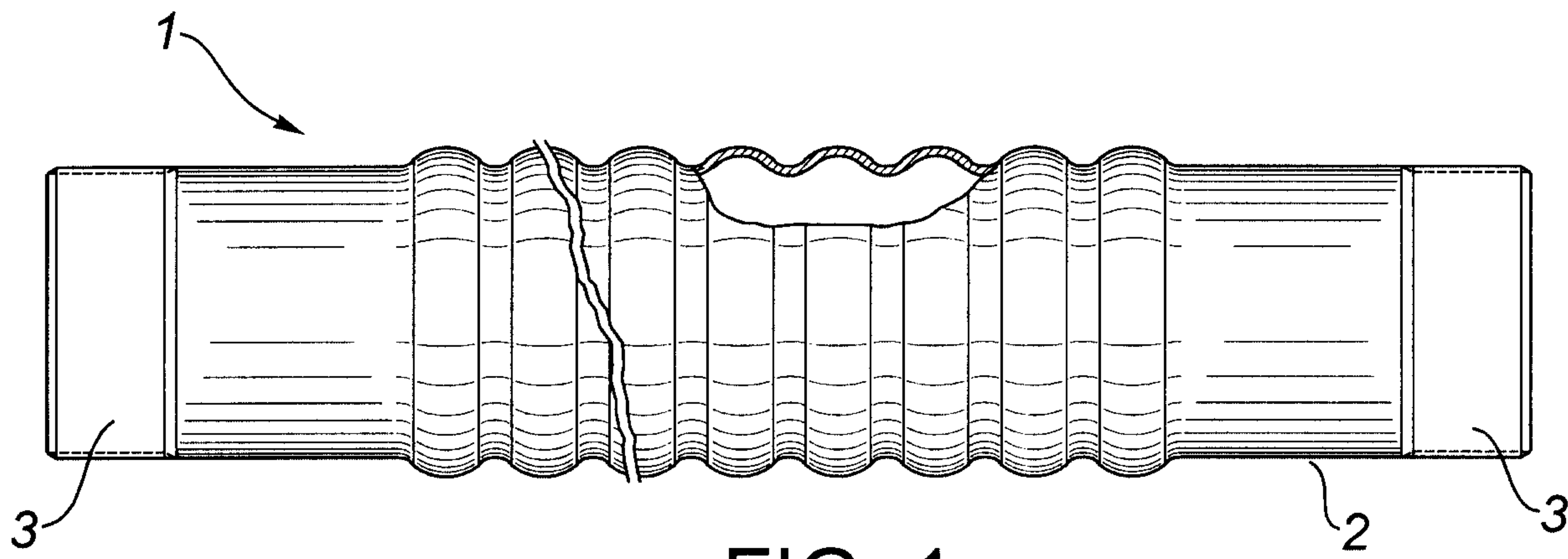
1 20. A joint of steel pipe comprising:
2 a tubular body having a side wall and threaded ends;
3 part of the body side wall between the ends having been hydroformed
4 into corrugations while maintaining its original length;
5 the side wall having a diameter/thickness ratio less than 100;
6 the corrugations having a corrugation radius of curvature to thickness
7 ratio less than 10.

8
9 21. The joint as set forth in claim 20 wherein:
10 the corrugations have a corrugation radius of curvature to thickness
11 ratio less than 5.

12
13 22. The joint as set forth in claim 21 wherein:
14 the corrugations have webs and peaks and the webs have a maximum
15 angle of at least 20° with respect to the axis of the joint.

16
17 23. The joint as set forth in claim 21 or 22 wherein:
18 the wall thicknesses of the webs of the corrugations are thinner than
19 the peaks.

1/3



2/3

FIG. 3

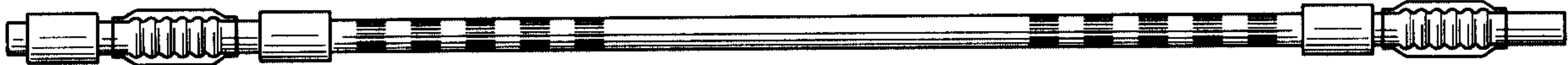


FIG. 4

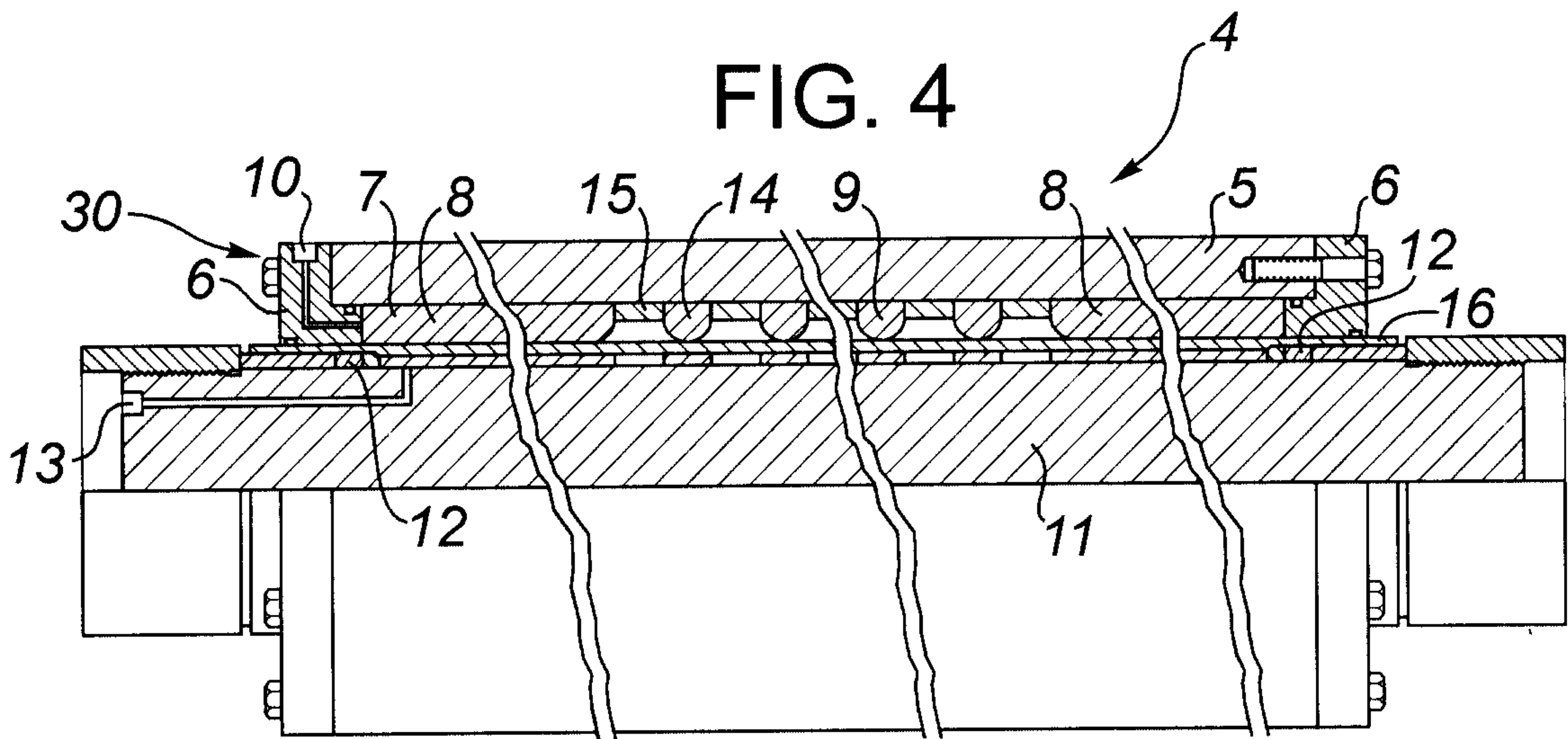
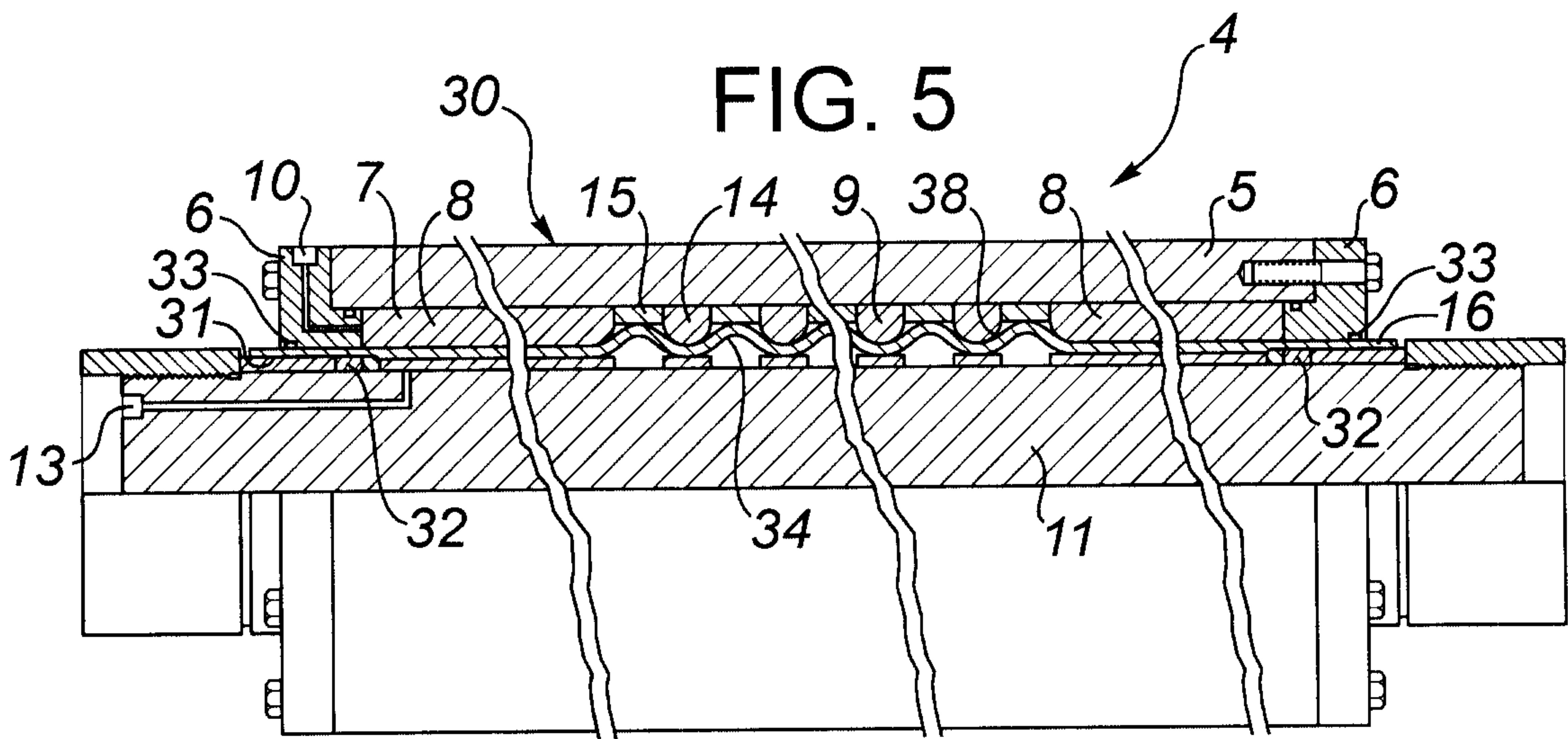


FIG. 5



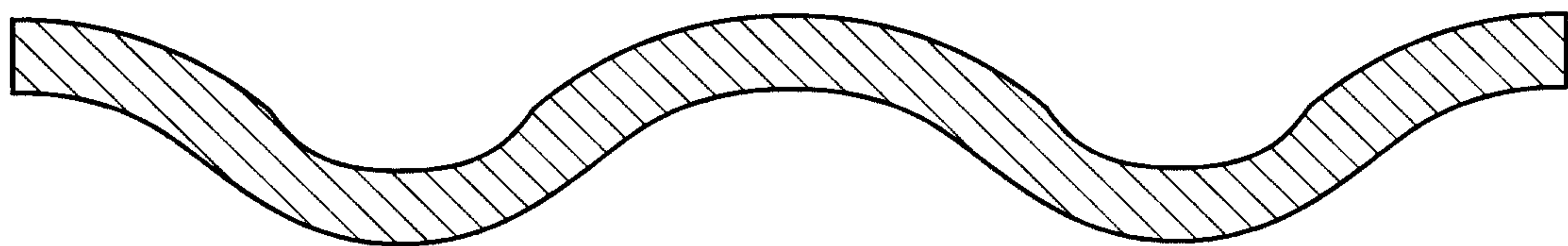


FIG. 6

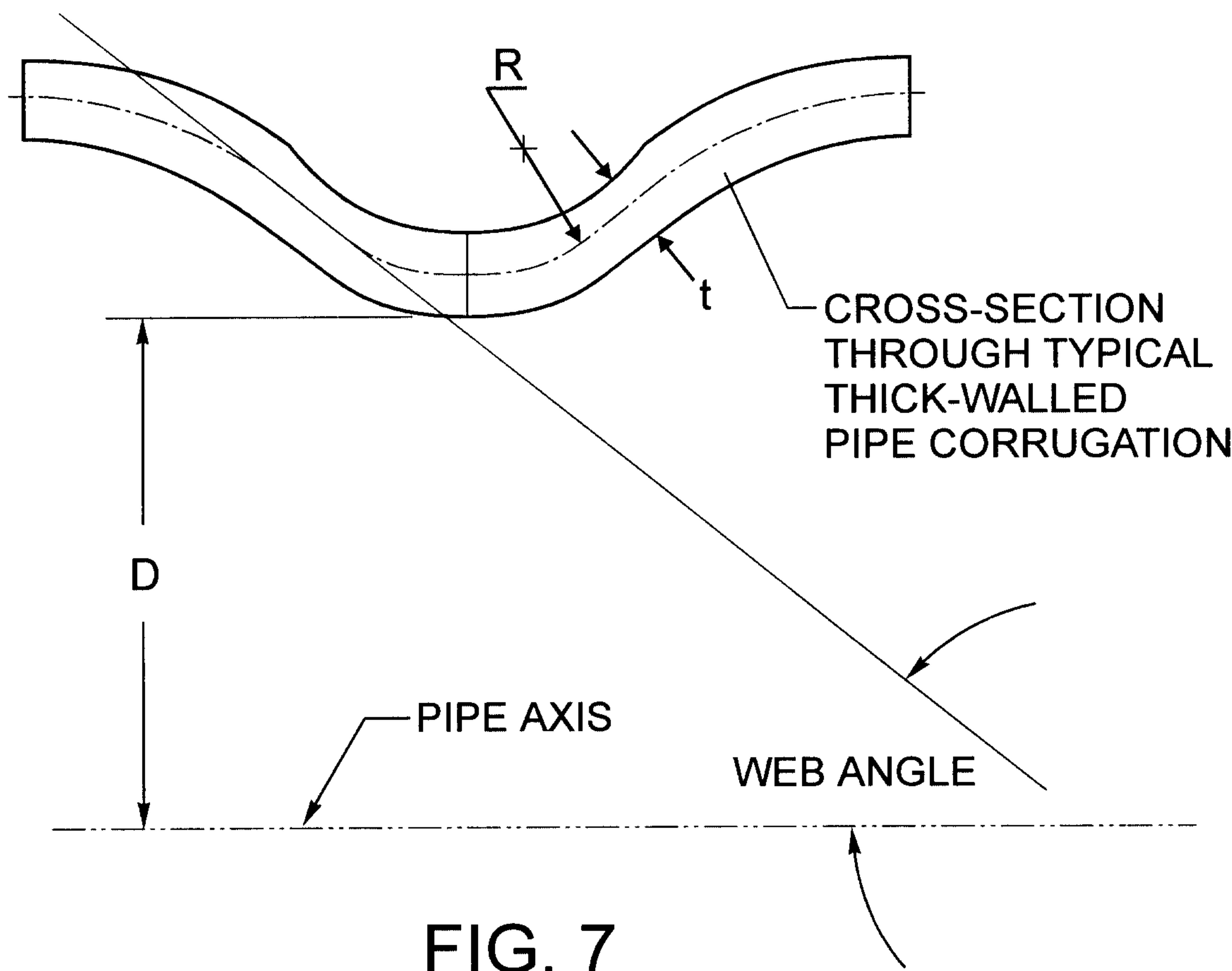


FIG. 7

