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(54) **SEAMLESS STEEL PIPE TO BE USED AS A STEEL CATENARY RISER IN THE TOUCHDOWN ZONE**

(57) The present invention describes an upset SCR of novel low carbon chemical composition and microstructure as well as method of manufacturing the same, which achieves higher improvement in the fatigue life as it is integral with the riser pipe section at the Touch Down Zone. The low carbon upset SCR achieves its desired properties by the thermal treatment which it is subjected to. The novel low carbon chemical composition and microstructure comprises in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35,

chromium 0.40-0.70, molybdenum 0.40- 0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23 and having a yield strength of at least of 65000 psi, the ultimate tensile strength of at least 77000 psi and YS/UTS ratio below 0.89 in material representing the pipe body, the transition zone and the upset end.

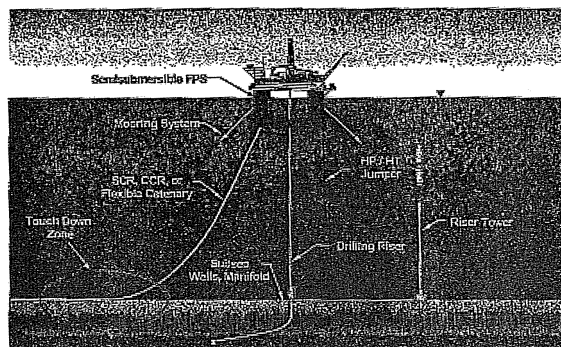


FIG. 1

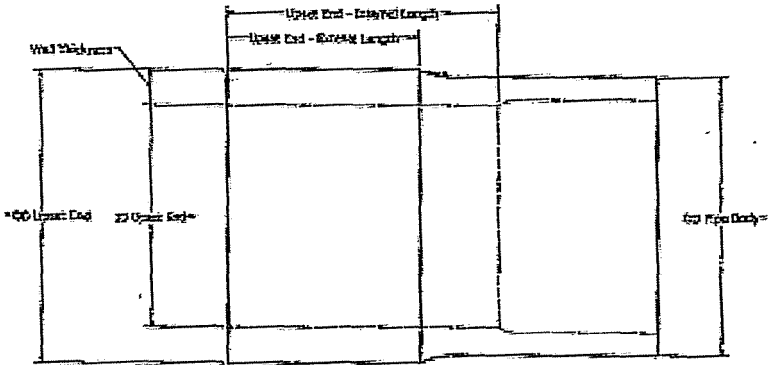


FIG. 2

Description**FIELD OF THE INVENTION**

[0001] This invention relates to seamless steel tubes for use as steel catenary riser.

BACKGROUND OF THE INVENTION

[0002] In recent years, the interest in exploiting deeper water offshore oilfields has increased sensibly. As a consequence, various solutions of marine production systems have been developed. The currently-available solutions are directed generally to semi-floating and floating production systems which are subjected to various movements with respect to seabed, mainly due to marine waves, currents and tides phenomena. The aforementioned systems are complemented by compliant riser systems compatible with mobile surface stations.

[0003] Steel Catenary Risers (SCR) represents one of the most outstanding riser systems to be adopted in these challenging situations. Such component is normally subjected to complex spectra of fatigue loading related to both the mobility of the floating platform and to the very large free span of unconstrained line from the seabed to surface. As a consequence, a big concern in the design of a SCR is related to the fatigue resistance. Since the cyclic loading is predominately in the axial direction, it directly stresses the welded joints between abutting pipes. Such joints generally represent the weakest point with respect to fatigue resistance, and the design life of the whole riser is determined by the capability of this component to resist the fatigue loading.

[0004] Steel Catenary Riser is a proven and economic riser system solution, as a tie-back production riser and as an export riser from Floating Production Systems (FPS) in the development of oil and gas fields in deepwater and ultra-deepwater. The application of SCRs is challenged by, in some cases, the high fatigue damage at the Touch Down Zone (TDZ) from a combination of field specific parameters such as riser size, fluid characteristics, vessel motions, metocean parameters, soil conditions, and water depth.

[0005] The most severe design requirement for SCRs is the fatigue life of the girth welds at the Touch-Down Zone (TDZ) region where the riser touches the seafloor and it connects with the rest of the pipeline, as is illustrated in Figure 1. In this zone, the riser experiences the highest level of cumulative fatigue damage. This is due to the fact that in said zone the highest bending of the catenary line is experienced, contrary to the total absence of bending of the portion of the line lying on the seabed. Due to the various movements of FPS (waves, tides, currents, etc.), the line segment in the TDZ experiences cycles of bending between maximum riser bending and zero bending (straight). The severity of fatigue loading in the TDZ is further complicated by the presence of continuous impacts of the portion of the line when entering in contact with the ground. Moreover, it has to be considered that the same impact of the line could dig a hole just in correspondence of the TDZ, amplifying the amplitude of bending cycle.

[0006] In other words, constant motion by the topside floating vessel results in cyclic pounding for the riser against the seafloor that, if not properly designed, can result in fatigue failure. In addition to the riser motion, other factors that can increase the severity of the TDZ fatigue include large pipe diameter, deep water depth, high currents, and sour service (corrosion degradation).

[0007] Various possible solutions for the improvement of fatigue life at SCR TDZ have been devised and studied. SCRs are utilized as riser systems in ongoing semi-submersible projects.

[0008] Alternative options to obtain an increase in fatigue life at the TDZ in the deepwater field developments have been devised to enable the use of SCR. These solutions include: ID machining for better fit-up and the use of improved welding techniques; the use of thick forged ends welded onshore to ensure better fit-up and to reduce the Stress Concentration Factor (SCF); the periodic movement of the floating vessel to distribute fatigue damage over longer length at the TDZ; and the use of clad steel.

[0009] The upsetting process is commonly used in the industry for casing and riser joints with threaded ends. Steel grades with higher carbon content are normally used for these applications. The upsetting process has not been used so far for weldable pipe of SCR quality. In most of threaded cases, though, the increase in fatigue life has been limited to a factor between 2 to 3. In the case of clad steel applications, a higher increase in fatigue life can be achieved. In addition, alternative catenary riser design has been developed by changing the riser pipe material (composite, titanium) or by hybrid designs (titanium and steel), or by changing the shape near seabed through provision of significant buoyancy (WO97/06341).

[0010] The alternative designs have focused on the improvement of the catenary riser strength near and above the seabed, thus enabling their use in harsher environment and more challenging applications.

[0011] Thus, there is a need to enhance conventional Steel Catenary Risers for Touch Down Zone (SCR TDZ) design for achieving significant increase in fatigue life, particularly, increasing fatigue life in SCR TDZ above 3 under sour and non-sour service environments with a pipe consisting of three regions: pipe body, transition zone and upset end, as is illustrated in Figure 2.

[0012] To accomplish this need, upset pipes to be used in welded joints have been developed. The simple concept for the improved fatigue performance consists, in this case, in locally decreasing the stress experienced by the welding with respect to the stress range generally experienced by the pipe body and, hence, the section of the riser in the TDZ. An upset SCR of novel low carbon chemical composition and microstructure was thus devised to achieve higher improvement in the fatigue life as it is comprised with the riser pipe section.

[0013] The feasibility of manufacturing thick upset end Riser for the Touch Down Zone with improved fatigue resistance varies, nevertheless, with the grade of steel that can be welded for offshore applications. The feasibility to manufacture a thick end Riser for the Touch Down Zone with improved fatigue resistance is the key to ensure that the upset SCR has practical value in application at the TDZ.

[0014] Several Steel Catenary Riser (SCR) solutions have included mild sour service requirements. Sour Service is the performance of the Riser in H₂S environments. Metallurgical properties known to affect performance in H₂S containing environments include: chemical composition, steel cleanliness, method of manufacturing, strength, amount of cold work, heat treatment conditions and microstructure. Since the upset pipe manufacturing process involves additional steps subsequent to the manufacture of the seamless pipe, the end product has to accomplish these requirements.

SUMMARY OF THE INVENTION

[0015] The present invention describes an upset SCR of novel low carbon chemical composition and microstructure which achieves higher improvement in the fatigue life as it is integral with the riser pipe section at the Touch Down Zone. The low carbon upset SCR achieves its desired properties by the thermal treatment which it is subjected to. The novel low carbon chemical composition and microstructure comprises in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40- 0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23 and having a yield strength of at least of 65000 psi, the ultimate tensile strength of at least 77000 psi and YS/UTS ratio below 0.89 in material representing the pipe body, the transition zone and the upset end.

[0016] The present invention also describes a method for manufacturing a seamless steel tube for steel catenary riser with upset ends having a yield strength at least of 65000 psi both in the pipe body, transition and the upset-zone comprising the steps of: (a) providing a steel tube comprising in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40- 0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23; (b) upsetting the tube ends in multiple steps with intermediate heating cycles in between to achieve the required thickness (c) quenching and tempering between 630-710°C; (d) machining the upset ends.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]

Figure 1 shows the Steel Catenary Riser Configuration of a preferred embodiment of the present invention. Figure 2 illustrates an embodiment of the tube with an upset end of a preferred embodiment of the present invention. Figure 3 shows typical macro sections of RP2Z welds for different welding conditions of the tube of a preferred embodiment of the present invention. Figures 4 (a) and (b) show the tensile test results for the longitudinal direction and the transverse direction of a preferred embodiment of the present invention. Figure 5 illustrates the longitudinal and transverse Y/T ratio results of a preferred embodiment of the present invention. Figure 6 shows the Hardness Vickers HV10 of a preferred embodiment of the present invention. Figure 7 illustrates the Transverse Charpy V Notch Impact Test at -30°C of a preferred embodiment of the present invention. Figure 8 shows the Mean curve for specimens 10 3/4" x 0.866" X65 of a preferred embodiment of the present invention. Figures 9 (a) and (b) show the tensile test results for the longitudinal direction and the transverse direction of a preferred embodiment of the present invention. Figure 10 illustrates the longitudinal and transverse Y/T ratio results of a preferred embodiment of the present invention. Figure 11 shows the Hardness Vickers HV10 of a preferred embodiment of the present invention. Figure 12 illustrates the Transverse Charpy V Notch Impact Test at -30°C of a preferred embodiment of the present invention.

Figure 13 shows the Mean curve for specimens 10 3/4" x 1.250" X65 of a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] As illustrated in Figure 1, the present invention describes an upset SCR of novel low carbon chemical composition and microstructure which achieves higher improvement in the fatigue life as it is integral with the riser pipe section at the Touch Down Zone. The low carbon upset SCR achieves its desired properties by the thermal treatment which it is subjected to.

[0019] The steel grade contemplated for use in the upset SCR of the present invention is X-65 (a yield strength of at least 65000 psi in the pipe body and in the upset ends).

[0020] The alloy design consists of a low-C (0.13 max), low-Mn (1.5 max) steel with additions of microalloying elements such as Niobium, Titanium (Nb+Ti 0.1 max), Chromium and Molybdenum (Cr+Mo 1.2 max). The purpose of adding these last two alloying elements is to increase hardenability and promote a martensitic-bainitic transformation on thick upset ends and pipe body achieving high strength. The carbon equivalent (CE) is designed not to exceed 0.43 as requested by API 5L. More preferably, the carbon equivalent is limited to 0.41. The most preferred embodiment of the present invention is not to exceed 0.39.

[0021] Pipes are hot rolled using a recrystallization controlled rolling scheme manufactured from round billets obtained by continuously cast (CC) process. After hot rolling, the pipes are then inspected with non-destructive methods such as electromagnetic inspection, wet magnetic particle inspection and ultrasonic testing with the purpose of finding any longitudinal or transverse defects on internal or external surfaces and to verify wall thickness. The pipes are then upsetted by reheating the pipe ends above the dissolution temperature of Nb (C, N) to provide adequate plastic flow during each upset operation whilst controlling austenite grain size by precipitation of fine TiN particles. The optimum radius at the upset-pipe body transition is modeled thru Finite Element Analysis (FEA), where the Stress Concentration Factor (SCF) resulted 1.135 and 1.12 for Case 1 (273.1 mm OD by 22.0 mm WT Pipe body, 28 mm WT as machined Upset Ends and 35 mm as upset ends, steel grade X65 for non-sour service application, 10.75" x 0.866") and Case 2 (273.1 mm OD by 31.8 mm WT Pipe body, 45 mm WT as machined Upset Ends and 53 mm as upset ends, steel grade X65 for sour service application, 10.75" x 1.250"), respectively. After upsetting both ends of the pipes, a critical quench and temper heat treatment is designed and used to provide the final mechanical properties. Non-destructive testing is again carried out in the pipe body, and the OD and ID surface of the upset ends are machined and then inspected with wet magnetic particle inspection and manual ultrasonic testing. Finally, the pipes are bevel machined for girth welding. Welding and fatigue behavior are thoroughly characterized.

[0022] After the quench and temper heat treatment, the material is then fully characterized. The Yield Strength (YS), the Ultimate Tensile Strength (UTS) and the YS/UTS ratio at room temperature are evaluated using both longitudinal and transverse round specimens taken from the Upset End, Slope Transition and Pipe Body regions in two quadrants, 0° and 180°.

[0023] Hardness Vickers HV10 are measured on the OD (outside diameter), MW (mid-wall) and ID (internal diameter) sections in 4 quadrants are taken from the Upset End, Slope Transition and Pipe Body regions. The hardness readings are taken at 1.5 mm from OD and ID. In addition, transverse Charpy V notch impact testing is carried out at -30°C and -40°C for case 1 and case 2 respectively using 10x10 mm specimens. Sour service resistance is assessed in both pipe body and upset ends by the Hydrogen Induced Cracking (HIC) and Four Point Bend Tests (FPBT).

[0024] The present invention thus describes a seamless steel tube for a steel catenary riser with upset ends comprising in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40-0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, Tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23 and having a yield strength of at least of 65000 psi in material representing the pipe body, the transition zone and the upset end.

[0025] The novel microstructure of the upset SCR which enables the seamless steel tube to achieve a higher improvement in the fatigue life includes the following mechanical properties and corrosion requirements for Upset SCR as shown in Table 1. The minimum requirements are following the API 5L, 43rd edition specification.

Table 1 - Mechanical properties and corrosion requirements for Upset SCR

Requirements	Non Sour Service Case1	Sour Service Case 2
Yield Strength 0.5% EUL	65000 psi (minimum), 80000 psi (maximum)	65000 psi (minimum), 80000 psi (maximum)
Ultimate Tensile Strength 0.5%EUL	77000 psi (minimum)	77000 psi (minimum)

(continued)

Requirements	Non Sour Service Case1	Sour Service Case 2
Yield/Tensile strength ratio	0.89 (maximum)	0.89 (maximum)
Elongation (% in 2 ")	18% (minimum)	18% (minimum)
Hardness Vickers (HV10)	269 (maximum)	250 (maximum)
Absorbed energy value for 3 individual specimens (Joules)	70 minimum Individual, 90 minimum Average at - 30 °C	70 minimum Individual, 90 minimum Average at -40 °C
Crack Tip Opening Displacement L-C direction at -10°C (mm), 3 individual specimens	0.510 minimum Individual,	0.510 minimum Individual,
	0.635 minimum Average	0.635 minimum Average
HIC as per NACE TM0284 using solution "A". Test period 96 hrs.		CTR 3.0% (maximum) CLR 10.0% (maximum) CSR 1.0% (maximum)
FPBT as per ASTM G48, test solution "A" of NACE TM0177. Testing stress 95% of SMYS. Test period 720 hrs.		No cracks after 720 hrs

[0026] Table 2 shows a summary of observed microstructures. All microstructures are homogeneous at midwall, which is the most critical section where mainly bainite, and a mixture of acicular and non-polygonal ferrite is observed independent of the section (pipe body, transition or upset). There is a slight presence of martensite close to the OD and ID sections.

Table 2 - Microstructure of the Upset SCR Seamless Steel Tube

	Pipe Body	Transition	Upset
ID	Bainite, Tempered Martensite and Acicular Ferrite	Bainite, Tempered Martensite and Acicular Ferrite	Bainite and presence of acicular and non-polygonal Ferrite
MW	Bainite and presence of acicular and non-polygonal Ferrite	Bainite, Acicular and non-polygonal Ferrite	Bainite and Acicular and non-polygonal Ferrite
OD	Bainite, Tempered Martensite and Acicular Ferrite	Bainite, Tempered Martensite and Acicular Ferrite	Bainite and presence of acicular and non-polygonal Ferrite

[0027] A specific alloy design is developed and heat treatment parameters are set to obtain the desired microstructural characteristics in both pipe body and heavy wall upset sections. The combination of the above mentioned parameters results in excellent mechanical properties which meet the strength and corrosion objectives.

[0028] The present invention also describes a method for manufacturing a seamless steel tube for steel catenary riser with upset ends having a yield strength at least of 65000 psi both in the pipe body, transition and the upset-zone comprising the steps of: (a) providing a steel tube comprising in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40- 0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, Tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23; (b) quenching and tempering between 630-710°C.

[0029] Multiple steps of upsetting and heating cycles in between each upsetting operation are used to achieve required thickness at the upset ends for each dimension (35 mm wall thickness and 53 mm wall thickness for the case 1 and 2 above mentioned) to obtained final as machined upset ends mentioned above.

[0030] Weldability and full fatigue tests are performed to a large number of pipes to establish fatigue performance. These tests are described as follows:

Welding program

[0031] The properties of the upset pipes subject to different thermal cycles induced by welding operations are evaluated initially by welding on a 35 mm wall thickness pipe with the chemistry as the upset ends.

[0032] The conditions are summarized in Table 3, and have been applied on a welding bevel configuration as recom-

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mended in the standard API RP2Z; Preproduction Qualification for Steel Plates for Offshore Structures [1].

[0033] This specific welding preparation with one of the bevel at 0° enables to quantify the toughness (impact and CTOD testing) of the HAZ in conditions more severe than with the conventional V or U bevel (the fatigue crack is placed in the prescribed coarse-grain HAZ material for at least 15% of the central two thirds of the specimen thickness).

Table 3 - API RP2Z welding conditions

API RP2Z welding conditions on 35mm thick pipe X70			
Heat Input (kJ/mm)	Preheat Temp. (°C)	Interpass Temp. (°C) Fill passes	Interpass Temp. (°C) Cap passes
0.6	100	100	100
0.6	200	200	200
0.8	150	150	150
0.8	200	200	200
0.8	200	200	250
2.0	250	250	250
3.0	250	250	250

[0034] The weldability test requires characterization of the HAZ for two cases subject to different combinations of heat using an API RP2Z bevel: Preproduction Qualification for Steel Plates for Offshore Structures [8]. All tests passes or exceeds the requirements including hardness HV10 below 250 for the sour service case (Case 2).

[0035] The HAZ characterization has been run on both upset pipes with 28 mm and 45 mm thickness at the upset ends, with the welding conditions listed in table 4. The consumables and heat input used are:

- Lincoln STT for the root pass, heat input 0.55-0.75 kJ/mm,
- P-GMAW for fill and cap passes with heat input 0.6 kJ/mm,
- SAW for fill and cap passes with heat input equal or greater than 0.8 kJ/mm.

Table 4 - API RP2Z welding conditions on both upset pipes X65

API RP2Z welding conditions on both upset pipes X65			
Heat Input (kJ/mm)	Preheat Temp. (°C)	Interpass Temp. (°C) Fill passes	Interpass Temp. (°C) Cap passes
0.8	200	200	250
1.5	250	250	250
3.0	250	250	250

[0036] HAZ characterization: testing and results

- Hardness:

[0037] On the 35 mm thick pipe, hardness indentations in HAZ are located in lines parallel to the pipe body, at 1.5 mm from inner and outer diameter of pipe and each 4 mm across the thickness.

[0038] To meet the requirements of 250 Hv10 maximum in HAZ (from root to cap) for sour service application, the welding conditions are:

- a heat input of minimum 0.65 kJ/mm combined with a preheat temperature of 200°C for root pass,
- a heat input of minimum 0.8 kJ/mm combined with an interpass temperature of 200°C for fill passes,
- a heat input of minimum 0.8 kJ/mm combined with an interpass temperature of 250°C for cap passes.

In addition, for the capping, the last bead is not on a side of a bevel but is deposited within the width of the weld preparation so that each cap passing at the edges of the bevel gets the benefit of a tempering effect of the subsequent cap passes. On the upset ends 28 and 45 mm thick, by applying the above mentioned welding conditions, the hardness in HAZ does not exceed 250 HV10.

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The typical macro sections of the API RP2Z welds produced for two heat inputs are shown in Figure 3. These welds are then tested for hardness and toughness (Charpy and CTOD) properties.

- Toughness:

[0039] Impact testing is run at -40°C, from fusion line + 1 mm to fusion line + 3mm, on welds run on 35 mm thick pipe and high heat input (2 and 3 kJ/mm). Absorbed energy obtained is above 200 J for each specimen

[0040] On the upset ends welds, these very high absorbed energy values in HAZ are duplicated, regardless of the wall thickness and the welding conditions: minimum value achieved 200 J, maximum value achieved 450 J.

[0041] In addition, CTOD testing (SENB, Bx2B specimens) in HAZ as per API RP2Z is run at -10°C. With the range of heat input from 0.8 to 1.5 kJ/mm, which is typical of field welding, the achieved CTOD values are from 1.0 to 1.5 mm, which shows an excellent ductility of the HAZ.

Development of the Welding Procedure Specification (WPS)

[0042] In order to force the fatigue crack to initiate away from the weld area and so to better quantify the fatigue resistance of the upset design, a specific welding procedure specification is developed and used for the welds to be full scale fatigue tested: selection of a welding consumable with very high toughness, removal of weld root and reinforcement of cap.

[0043] Full scale testing shows excellent fatigue behavior of upset girth joints. In both cases, the data correspond to failure, or run-outs, well beyond the target mean curve for the sets of tests, demonstrating that both geometries of girth welded upset qualify as top class (B1 in DNV -RP-C203) component for fatigue resistance. Mean curve results can be seen in Figures 8 and 13 for case 1 and case 2 respectively.

Examples

[0044] Heavy Wall Upset seamless steel tubes with the following characteristics are used:

Case 1: 273.1 mm OD by 22.0 mm WT Pipe body, 28 mm WT as machined Upset Ends and 35 mm as upset ends, steel grade X65 for non-sour service application (10.75" x 0.866")

Case 2: 273.1 mm OD by 31.8 mm WT Pipe body, 45 mm WT as machined Upset Ends and 53 mm as upset ends, steel grade X65 for sour service application (10.75" x 1.250").

Case (1) Upset SCR TDZ 10.75"OD x 0.866" WT X65 Non Sour Service

[0045] Figures 4 (a) and (b) and 5 show the Yield Strength (YS), Ultimate Tensile Strength (UTS) and the YS/UTS ratio evaluated at room temperature for quenched and tempered material. Longitudinal and transverse round specimens taken from sections representing the Upset End, Slope Transition and Pipe Body are tested in two quadrants, 0° and 180°. All specimens are standard round except by those from the pipe body in the transverse direction which are sub-size round. Figure 4 (a) and (b) show all the YS and UTS values obtained from the tensile test in the longitudinal and transverse directions, respectively.

[0046] Figure 4 (a) and (b) show that all Yield Strength values obtained are above 65,000 psi minimum and do not exceed the 80,000 psi maximum. All the Ultimate Tensile strength values obtained are above 77,000 psi minimum established.

[0047] Figure 5 shows that, for the YS/UTS ratio, all the values are below 0.89 which is established as maximum YS/UTS specification. The values of YS/UTS ratio are shown in Figure 5 for both the longitudinal and transverse directions.

Hardness test

[0048] For the material in the "as quenched and tempered condition", Hardness Vickers HV10 (3 readings per row) are measured on the OD, MW and ID sections in 4 quadrants taken from the Upset End, Slope Transition and Pipe Body regions. The hardness readings are taken at 1.5 mm from outer diameter (OD) and inner diameter (ID). As quenched and tempered material HV10 test results are shown in Figure 6.

[0049] Even as the material from case 1 is not initially considered for sour service application, as shown in Figure 6, all hardness readings are below 250HV10 (22 HRC) complying with NACE requirement for material to be used in sour environments.

Toughness test

[0050] The fracture mechanics characteristic is evaluated using the Transverse Charpy V Notch Impact Test. The test temperature is -30°C. Sets of three full II size specimens (10x10mm) are taken from upset end, slope transition and pipe body regions in two quadrants, 0° and 180°, for each sample of quenched and tempered material.

[0051] Figure 7 shows that all the individual values of Absorbed Energy are above 70 Joules which is established as minimum target and 90 Joules as minimum average of 3 specimens. The transition temperature obtained in the transverse direction using Charpy V-notch 10x10 specimens in material representing pipe body and upset end are below -60°C as is shown in Tables 5 (a) and (b).

Table 5 - Transition Temperature Curve. (a) Pipe body and (b) Upset End											
Transverse Charpy V-Notch test results (Joules), 10x10 mm specimen											
Sample	Pipe/End	Location	Test Temperature °C	1	% Sh.A	2	% Sh.A	3	% Sh.A	Average Absorbed Energy (J)	Average Shear Area (%)
64283	Pipe 10 North End	Pipe body	-30	439	100	419	100	443	100	434	100
			-40	440	100	408	100	415	100	421	100
			-50	435	100	355	100	437	100	409	100
			-60	357	100	451	100	280	100	363	100
(a)											
64286	Pipe 15 South End	Upset End	-30	425	100	428	100	431	100	428	100
			-40	388	100	374	100	435	100	399	100
			-50	424	100	422	100	435	100	427	100
			-60	344	100	384	100	394	100	374	100
(b)											

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[0052] CTOD results representing the pipe body and upset end, as shown in Table 6, show exceptional results above 0.6 mm at - 30°C.

Table 6 - CTOD Results Representing (a) Pipe Body (b) Upset End

PIPE BODY - CTOD TEST RESULTS LONGITUDINAL ORIENTATION RECTANGULAR BX2B SPECIMEN								
Sample	Pipe	End	Test Temperature °C	Delta (mm)			Average CTOD Delta Value (mm)	Minimum CTOD Delta Value (mm)
				1	2	3		
64283	10	North	-10	1.54	1.51	1.49	1.51	1.49
64286	915	South	-30	1.49	1.52	1.39	1.47	1.39
Minimum Specification							0.635	0.510
(a)								
UPSET END - CTOD TESTS RESULTS LONGITUDINAL ORIENTATION COMPACT BX2B SPECIMEN								
Sample	Pipe	End	Test Temperature °C	Delta (mm)			Average CTOD Delta Value (mm)	Minimum CTOD Delta Value (mm)
				1	2	3		
64283	10	North	-10	1.13	1.11	1.10	1.11	1.10
64286	15	South	-30	1.15	1.11	1.13	1.13	1.11
Minimum Specification							0.635	0.510
(b)								

Microstructural analysis

[0053] Samples from as-quenched and as-quenched and tempered material are prepared for microstructural analysis. The transverse face to the rolling axis is metallographically prepared by sanding down to 600 sand paper and polished to a mirror-like appearance with diamond paste and etched with Nital at 2% to carry out microstructural observations by optical microscope.

[0054] Microstructures are observed on OD, MW and ID sections of pipe body, slope transition and upset end regions. Two quadrants, 0° and 180°, photomicrographs at 500X representing the microstructure from OD, MW and ID are obtained.

[0055] In this case, the observed microstructure in the pipe body after quenching consists of a mixture of predominantly bainite and acicular ferrite through the wall thickness and a slight presence of martensite close to the outer and inner surface. Similarly, bainite and acicular ferrite and some regions of non-polygonal ferrite are observed through the wall thickness at the upset section.

[0056] The prior austenitic grain size (PAGS) are measured using image analysis on as-quenched material etched with saturated aqueous picric acid on samples from the pipe body and the upset end at 0° and 180° Quadrants, resulting in an average size of 9/10 ASTM.

[0057] The microstructure after the tempering treatment consists of predominantly bainite and acicular ferrite are observed through the wall thickness on material representing pipe body, slope transition and upset end.

Fatigue Test Results

[0058] The fatigue test results are shown in Figure 8. The test results show very high fatigue performance at upset ends, transition and pipe body.

Case (2) Upset SCR TDZ 10 ¾"OD x 1.250"WT X65 Sour Service

[0059] For case (2), in addition to all the destructive testing including tensile, hardness toughness performed in case (1), the Sour Service Hydrogen Induced Cracking Test as per NACE TM0284 and Sulphide Stress Cracking by using the Four Point Bend Test is performed. Figure 9 shows the tensile results where it can be seen that Yield Strength values obtained are above 65,000 psi and do not exceed the maximum value of 80,000 psi. All the Ultimate tensile strength values obtained are above 77,000 psi which is established as the minimum specified.

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[0060] All the YS/UTS ratio values are below 0.89 as shown in Figure 10 for both longitudinal and transverse direction.

[0061] As shown in Figure 11, all the hardness readings are below 250 HV10 (22 HRc) complying with NACE MR0175 requirements for materials to be used in sour environments.

[0062] For this case (2), the Charpy test temperature is -40°C. Sets of three full size specimens (10x10mm) are taken from midwall of upset end, slope transition and pipe body regions in two quadrants 0° y 180°, from quenched and tempered material. As shown in Figure 12, all results are above the expected minimum absorbed energy values of 70 Joules minimum individual and 90 Joules as minimum average of 3 specimens.

[0063] Transverse Charpy V-Notch impact transition curves are obtained from 2 samples, one representing upset end and another one representing pipe body from quenched and tempered material for each case.

[0064] The transition temperature obtained in the transverse direction using Charpy V-notch 10x10 specimens is between - 50°C and -60°C for the material representing the upset end and below -70°C for material representing pipe body as shown in Table 9.

[0065] As shown in Figure 12, all results were above the expected minimum values of 70 Joules minimum individual and 90 Joules as minimum average of 3 specimens.

[0066] Transverse Charpy V-Notch impact transition curves are obtained from 2 samples representing upset end and another representing pipe body of quenched and tempered material for each case.

[0067] The transition temperature obtained in the transverse direction using Charpy V-notch 10x10 specimens is between - 50°C and -60°C for the material representing the upset end and below -70°C for material representing pipe body as shown in Table 7.

55 50 45 40 35 30 25 20 15 10 5

Table 7 - Transition Temperature Curve. (a) Pipe body and (b) Upset End

Transverse Charpy V-Notch test results (Joules), 10x10 mm specimen											
Sample	Pipe/End	Location	Test Temperature °C	1	% Sh.A	2	% Sh.A	3	% Sh.A	Average Absorbed Energy (J)	Average Shear Area (%)
64521	Pipe 10 North End	Pipe body	-20	436	100	450	100	439	100	442	100
			-30	432	100	440	100	422	100	431	100
			-40	434	100	442	100	446	100	441	100
			-50	446	100	436	100	449	100	444	100
			-60	384	100	440	100	439	100	421	100
			-70	398	100	424	100	435	100	419	100
(a)											
64518	Pipe 6 North End	Upset End	-20	422	100	447	100	409	100	426	100
			-30	430	100	430	100	452	100	437	100
			-40	429	100	428	100	424	100	427	100
			-50	443	100	449	100	405	100	432	100
			-60	9	0	439	100	432	100	294	67
			-70	6	0	415	100	444	100	288	67
(b)											

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[0068] CTOD results from material representing pipe body and upset end are above 0.6 mm at -10°C as shown in Table 8.

Table 8 - CTOD Results Representing (a) Pipe Body (b) Upset End

PIPE BODY - CTOD TEST RESULTS LONGITUDINAL ORIENTATION BX2B SPECIMEN								
Sample	Pipe	End	Test Temperature °C	Delta (mm)			Average CTOD Delta Value (mm)	Minimum CTOD Delta Value (mm)
				1	2	3		
64577	9	North	-10	1.50	1.55	1.54	1.53	1.50
64578	9	South	-10	1.61	1.56	1.57	1.58	1.56
Minimum Specification							0.635	0.510
(a)								
UPSET END - CTOD TESTS RESULTS LONGITUDINAL ORIENTATION COMPACT SPECIMEN								
Sample	Pipe	End	Test Temperature °C	Delta (mm)			Average CTOD Delta Value (mm)	Minimum CTOD Delta Value (mm)
				1	2	3		
64577	9	North	-10	1.13	1.14	1.07	1.11	1.07
64578	9	South	-10	1.14	1.15	1.17	1.15	1.14
Minimum Specification							0.635	0.510
(b)								

Corrosion test only case (2)

Hydrogen Induced Cracking

[0069] HIC test is performed on 1 sample representing upset end and another representing pipe body for Case 2. Each set of 3 specimens (3 quadrants, 0°, 120° and 240°) representing pipe body and another set representing upset end is tested as per NACE TM0284 using Solution "A", test period was 96 hours. The results are shown in Tables 9 and 10.

Table 9 - Hydrogen Induce Cracking Test Results - Pipe Body

HYDROGEN INDUCE CRACKING TEST RESULTS-PIPE BODY SOLUTION A: NACE TM 0284																
Specimen	Section	Crack		Blisters	Section Average Cracking			Coupon Average Cracking								
		Length (mm)	Width (mm)		% CSR	% CLR	% CTR	% CSR	% CLR	% CTR						
1	A1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00						
		0.00	0.00													
		0.00	0.00													
	A2	0.00	0.00		0.00	0.00	0.00				0.00	0.00	0.00			
		0.00	0.00													
		0.00	0.00													
	A3	0.00	0.00		0.00	0.00	0.00							0.00	0.00	0.00
		0.00	0.00													
		0.00	0.00													

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(continued)

HYDROGEN INDUCE CRACKING TEST RESULTS-PIPE BODY SOLUTION A: NACE TM 0284										
Specimen	Section	Crack		Blisters	Section Average Cracking			Coupon Average Cracking		
		Length (mm)	Width (mm)		% CSR	% CLR	% CTR	% CSR	% CLR	% CTR
2	B1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00							
		0.00	0.00							
	B2	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
	B3	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
3	C1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00							
		0.00	0.00							
	C2	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
	C3	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							

Table 10 - Hydrogen Induce Cracking Test Results - Upset End

HYDROGEN INDUCE CRACKING TEST RESULTS -UPSET END SOLUTION A: NACE TM 0284										
Specimen	Section	Crack		Blisters	Section Average Cracking			Coupon Average Cracking		
		Length (mm)	Width (mm)		% CSR	% CLR	% CTR	% CSR	% CLR	% CTR
1	A1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00							
		0.00	0.00							
	A2	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
	A3	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							

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(continued)

HYDROGEN INDUCE CRACKING TEST RESULTS -UPSET END SOLUTION A: NACE TM 0284										
Specimen	Section	Crack		Blisters	Section Average Cracking			Coupon Average Cracking		
		Length (mm)	Width (mm)		% CSR	% CLR	% CTR	% CSR	% CLR	% CTR
2	B1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00							
		0.00	0.00							
	B2	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
	B3	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
3	C1	0.00	0.00	None	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00							
		0.00	0.00							
	C2	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							
	C3	0.00	0.00		0.00	0.00	0.00			
		0.00	0.00							
		0.00	0.00							

[0070] These tables show that neither cracks nor blisters are found after test period showing that all the requirements for the Hydrogen Induced Cracking test are met.

Sulfide Stress Cracking

[0071] SSC Four Point Bend Test is performed on 1 sample representing upset end and another representing pipe body. Each set of 3 specimens (3 quadrants, 0°, 120° and 240°) representing pipe body and another set representing upset end is tested as per ASTM G48. Test solution "A" of NACE TM0177 is considered. Testing stress is 95% of Specified Minimum Yield Strength (SMYS) and two test periods of 96 hours and 720 hours. The results are shown in Tables 11 and 12.

**Table 11 - SSC Four Point Bend Test Results Representing Material From Pipe Body (a) After 96 Hrs. Exposure
(b) After 720 Hrs. Exposure**

SULFIDE STRESS CRACKING - FOUR POINT BEND TEST SOLUTION "A" NACE 0177-96- TEST DURATION: 96 HRS. PIPE BODY						
Specimen No.	Initial Values		Final Values		Stress Applied %SMYS	Result
	SATi	PHi	SATf	pHf		
1	2418.32	2.72	2503.61	3.57	95	Not failed
2	2418.32	2.72	2503.61	3.57	95	Not failed
3	2418.32	2.72	2503.61	3.57	95	Not failed
(a)						

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(continued)

SULFIDE STRESS CRACKING - FOUR POINT BEND TEST SOLUTION "A" NACE 0177-96- TEST DURATION: 720 HRS. PIPE BODY						
Specimen No.	Initial Values		Final Values		Stress Applied %SMYS	Result
	SATi	PHi	SATf	pHf		
1	2809.95	2.70	2980.25	3.62	95	Not failed
2	2809.95	2.70	2980.25	3.62	95	Not failed
3	2809.95	2.70	2980.25	3.62	95	Not failed
(b)						

Table 12 - SSC Four Point Bend Test Results From Upset End (a) After 96 Hrs. Exposure (b) After 720 Hrs Exposure

SULFIDE STRESS CRACKING - FOUR POINT BEND TEST SOLUTION "A" NACE 0177-96- TEST DURATION: 96 HRS. UPSET END						
Specimen No.	Initial Values		Final Values		Stress Applied %SMYS	Result
	SATi	PHi	SATf	pHf		
1	2418.32	2.72	2503.61	3.57	95	Not failed
2	2418.32	2.72	2503.61	3.57	95	Not failed
3	2418.32	2.72	2503.61	3.57	95	Not failed
(a)						
SULFIDE STRESS CRACKING - FOUR POINT BEND TEST SOLUTION "A" NACE 0177-96- TEST DURATION: 720HRS. UPSET END						
Specimen No.	Initial Values		Final Values		Stress Applied %SMYS	Result
	SATi	PHi	SATf	pHf		
1	2809.95	2.70	2980.25	3.62	95	Not failed
2	2809.95	2.70	2980.25	3.62	95	Not failed
3	2809.95	2.70	2980.25	3.62	95	Not failed
(b)						

[0072] Tables 11 and 12 show that all Four Point Bend specimens passed successfully the SSC test after the test period, stressed at 95%SMYS, no cracks are observed after 96 hours and even after 720 hours.

Microstructural Characterization

[0073] Optical Microscopy and Scanning Electron Microscopy is used for material characterization. Microstructural analysis is performed on OD, MW and ID sections of pipe body, slope transition and upset end regions in two quadrants 0° and 180° for samples in the as-quenched condition and quench and tempered condition.

[0074] The pipe body as-quenched microstructure consists of predominantly bainite and acicular ferrite at midwall and, close to the outer and inner surface, a slight presence of martensite is observed.

[0075] The upset as-quenched microstructure consists of predominantly bainite and acicular ferrite through the wall thickness.

[0076] The PAGS is measured using image analysis on as-quenched material etched with saturated aqueous picric acid on samples from pipe body and upset end. An average PAGS size of 7/8 ASTM is obtained for both pipe body and upset end respectively.

[0077] The microstructure at mid-wall after tempering consists of predominantly bainite and acicular ferrite at the pipe body and slope transition; and bainite, acicular ferrite, and non-polygonal ferrite at the upset ends.

Fatigue results

[0078] The fatigue test results are plotted in Figure 13. The test results show very high fatigue performance at upset ends, transition and pipe body.

[0079] The invention has been fully described and experimental fatigue results obtained shows that the fatigue performance for these two Upset Solutions described above in case (1 and 2) has been increased with a factor ranged between 3 and 15.

Claims

1. A seamless steel pipe for a steel catenary riser with upset ends comprising in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40- 0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max, tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23 and having a yield strength of at least of 65000 psi, the ultimate tensile strength of at least 77000 psi and YS/UTS ratio below 0.89 in material representing the pipe body, the transition zone and the upset end.
2. The seamless steel pipe according to claim 1, in which the microstructure of as-quench and temper material is homogeneous at midwall which is the most critical section and it is mainly bainite and a mixture of acicular and non polygonal ferrite independently of the section: pipe body, transition or upset zones.
3. The seamless steel pipe according to claim 1, in which the prior austenitic grain size has an average size is at least 7 ASTM both in pipe body and in the upset pipe ends.
4. The seamless steel pipe according to claim 1, which the material in the as quenched and tempered condition has a Hardness Vickers HV10 value below 250 both in the pipe body and the upset ends.
5. The seamless steel pipe according to claim 1, in which the materials from pipe body and upset ends have an individual value of absorbed energy above 70 Joules, and 90 Joules average of three specimens and the transition temperature in the transverse direction was below -50°C.
6. The seamless steel pipe according to claim 1, in which the materials from pipe body and upset ends exceed in at least 2 times the minimum individual value of 0.51 mm required of crack tip opening displacement test (CTOD test).
7. The seamless steel pipe according to claim 1, which is weldable at the upset ends in a heat input range between 0.8KJ/mm and 1.5 KJ/mm, where CTOD testing using SENB, Bx2B specimens undertaken from the heat affected zone run at -10°C as per API RP22Z, gave CTOD values above 0.6 mm.
8. The seamless steel pipe according to claim 7, which is weldable at the upset ends in a heat input between 0.8KJ/mm and 3.0 KJ/mm and the hardness in the heat affected zone is less than 250 HV10.
9. The seamless steel pipe according to claim 7, which is weldable at the upset ends in a heat input between 0.8KJ/mm and 3.0 KJ/mm and the absorbed energy values evaluated at fusion line + 1 mm in the heat affected zone are above 100 Joules.
10. The seamless steel pipe according to claim 1, which is weldable at the upset ends in a heat input range between 0.8KJ/mm and 1.5 KJ/mm, where CTOD testing using SENB, Bx2B specimens undertaken from the axis of the weld metal run at - 10°C gave CTOD values above 0.6 mm
11. A method for manufacturing a seamless steel tube for steel catenary riser with upset ends having a yield strength at least of 65000 psi both in the pipe body, transition and the upset-zone comprising the steps of: (a) providing a steel tube comprising in weight per cent, carbon 0.04-0.10, manganese 0.40-0.70, silicon 0.15-0.35, chromium 0.40-0.70, molybdenum 0.40-0.70, nickel 0.10-0.40, nitrogen 0.008 max, aluminum 0.010-0.045, sulfur 0.005 max, phosphorus 0.020 max, titanium 0.003-0.020, niobium 0.020-0.035, vanadium no more than 0.10, copper 0.20 max,

tin 0.020 max, and carbon equivalent 0.43 max and PCM no more than 0.23; (b) upsetting the tube ends in multiple steps with intermediate heating cycles in between to achieve the required thickness (c) quenching and tempering between 630-710°C; (d) machining the upset ends.

- 5 **12.** The method for manufacturing a seamless steel pipe according to claim 11 wherein pipes were hot rolled using a recrystallization controlled rolling scheme, manufactured from round billets obtained by continuously cast (CC) process.
- 10 **13.** The method for manufacturing a seamless steel pipe according to claim 11 wherein the pipes were upsetted by reheating the pipe ends above the dissolution temperature of Nb (C, N) to provide adequate plastic flow during each upset operation whilst controlling austenite grain size by precipitation of fine TiN particles.
- 15 **14.** A pipe string for use as steel catenary riser for non-sour service environment using the pipes according to claim 1, wherein pipes are welded on the upset ends.
- 20 **15.** A pipe string for use as steel catenary riser for sour service environment using pipes according to claim 1, wherein pipes are welded on the upset ends.
- 25
- 30
- 35
- 40
- 45
- 50
- 55

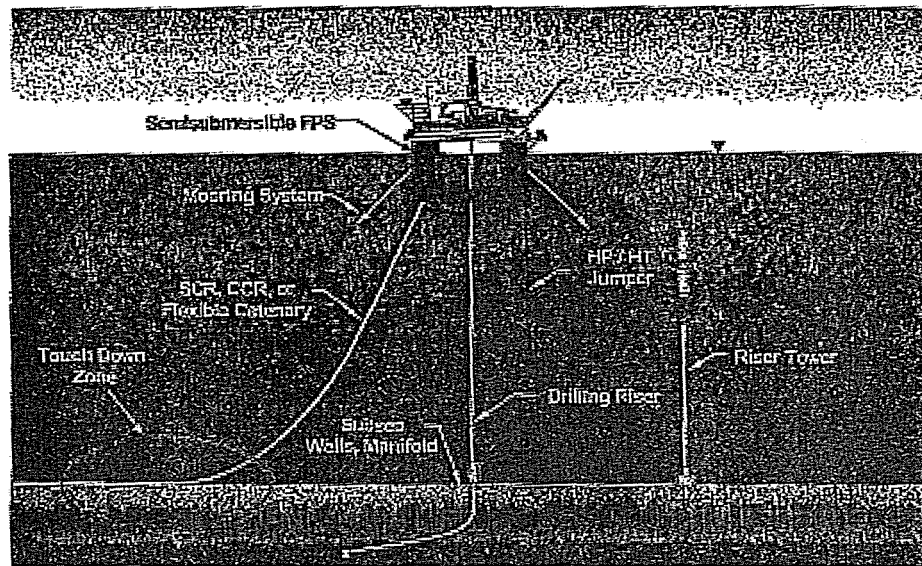


FIG. 1

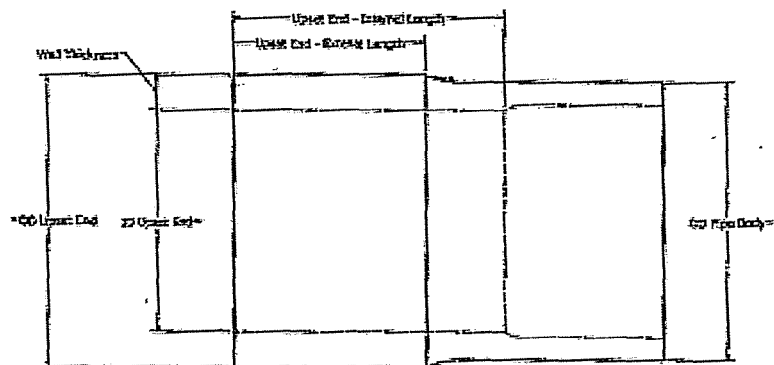
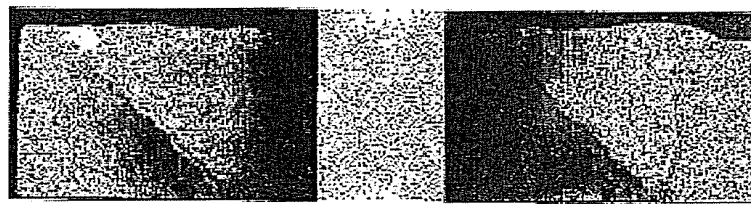


FIG. 2

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(a) 0.8 kJ/mm 200°C

(b) 3 kJ/mm 250°C

FIG. 3

LONGITUDINAL TENSILE TEST

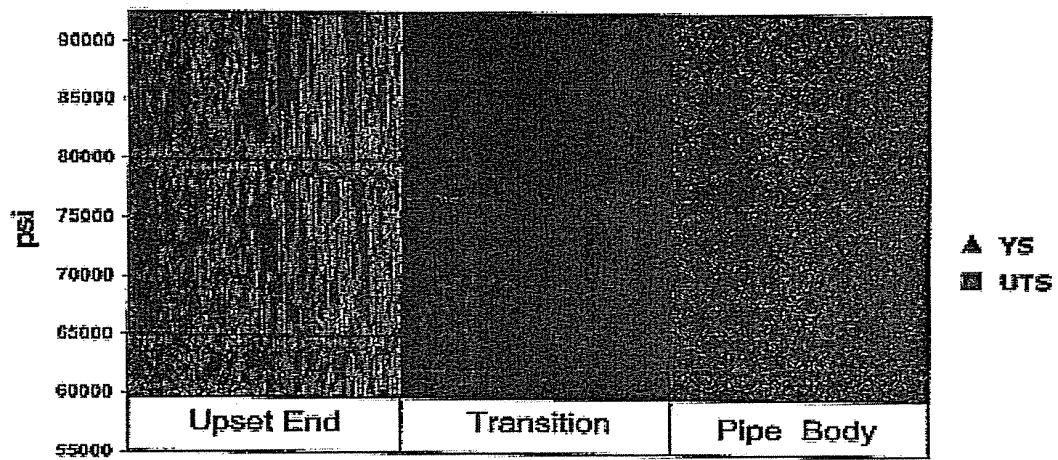


FIG. 4a

TRANSVERSE TENSILE TEST

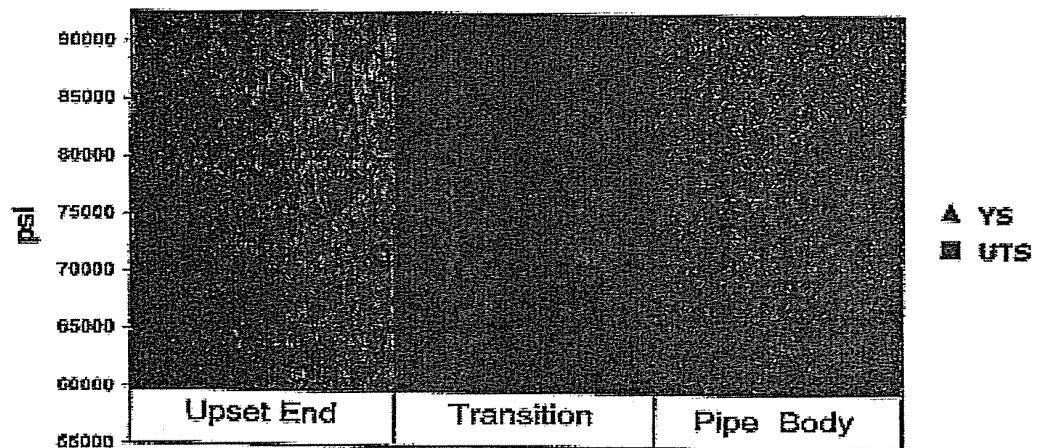


FIG. 4b

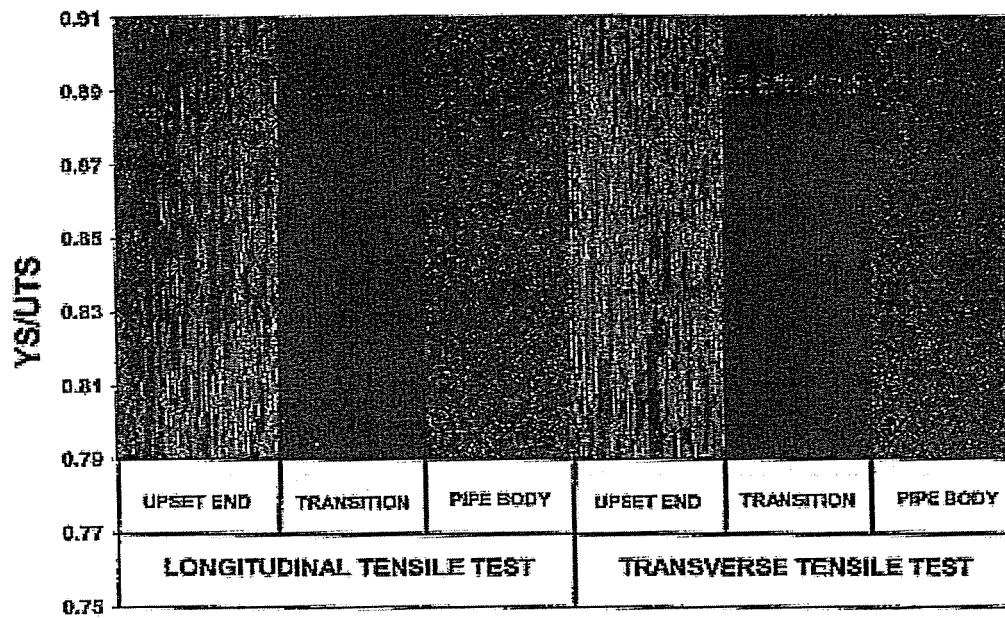


Fig. 5

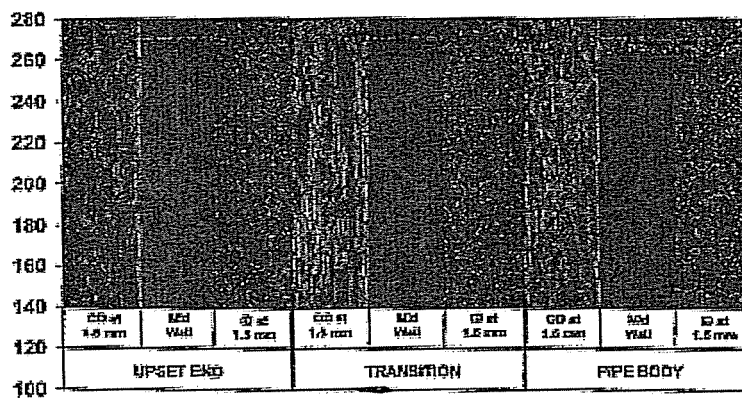


Fig. 6

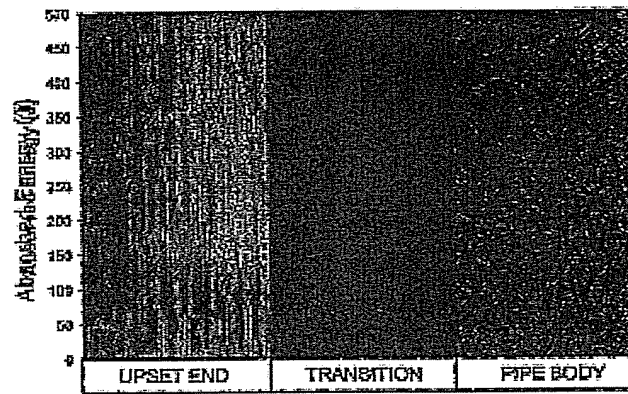


Fig. 7

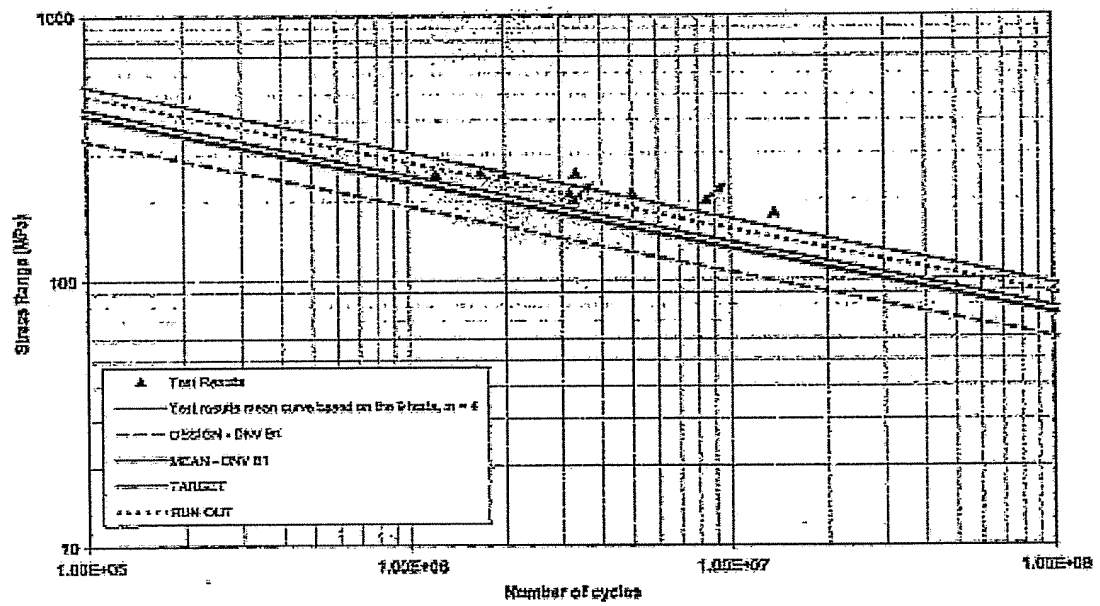


Fig. 8

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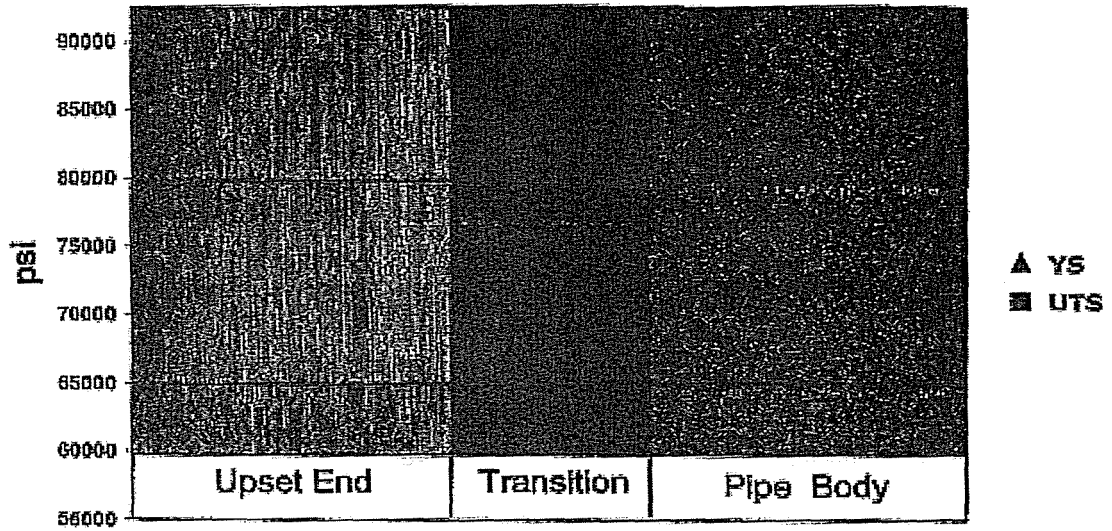


Fig. 9a

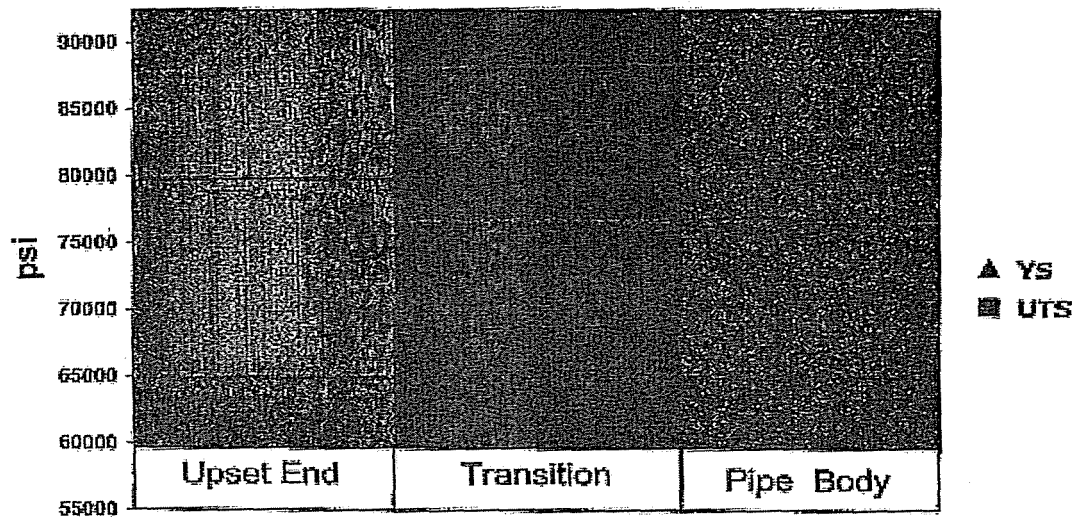


Fig. 9b

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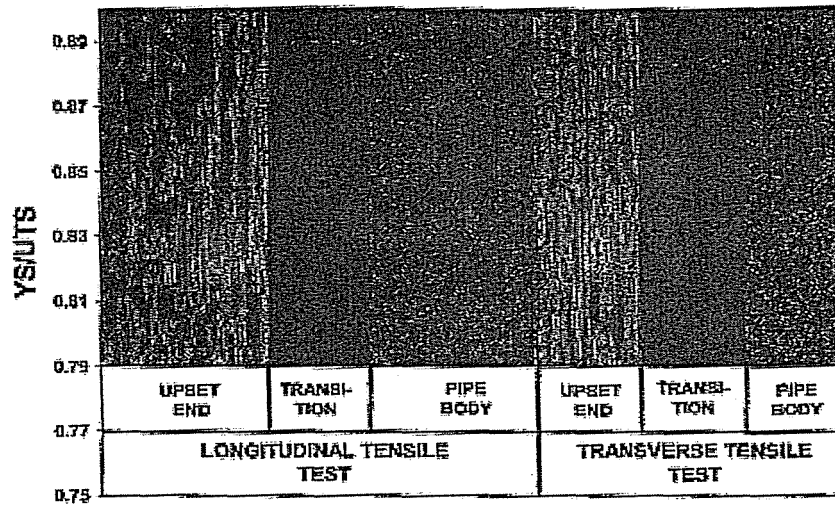


Fig. 10

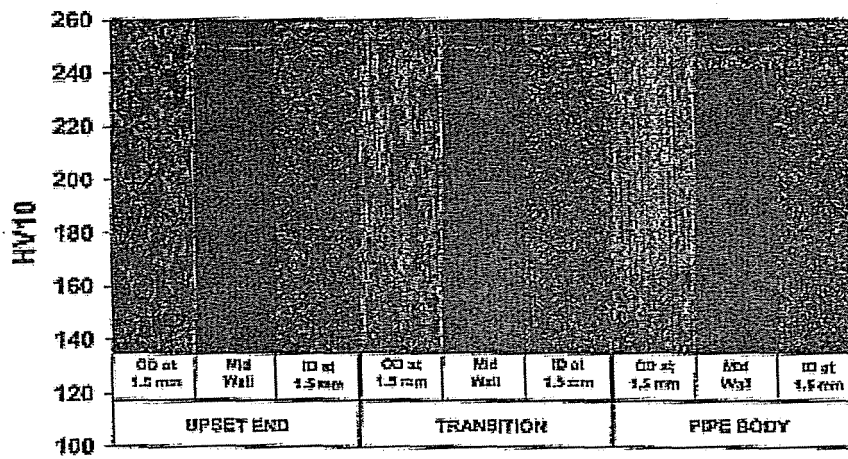


Fig. 11

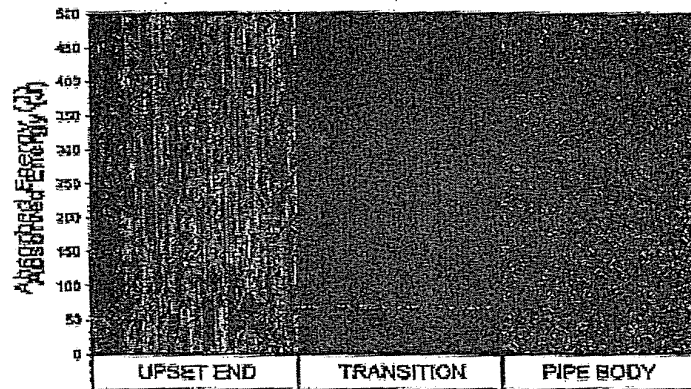


Fig. 12

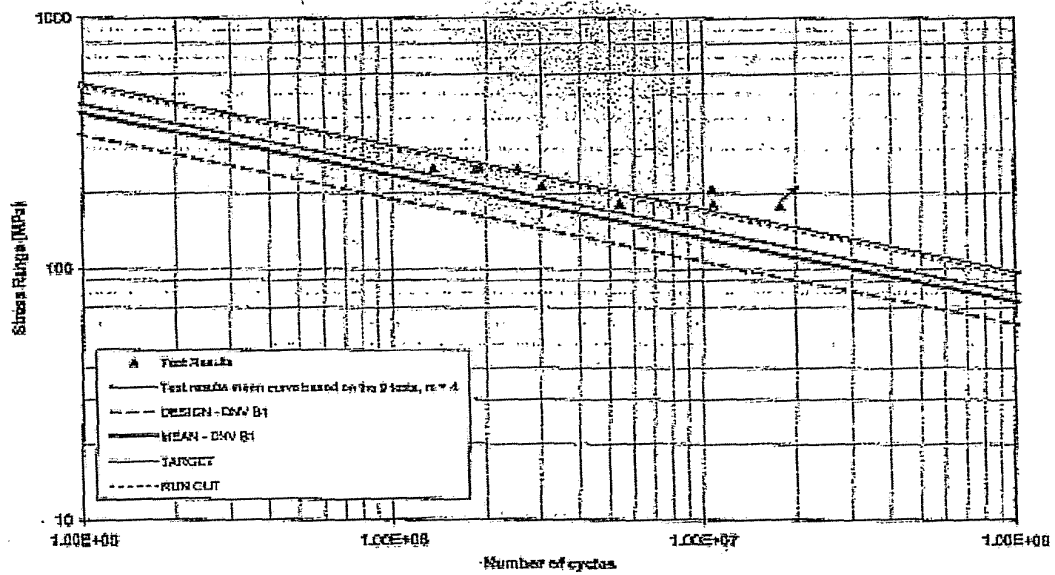


Fig. 13

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- WO 9706341 A [0009]