Multi-criteria material selection for casing pipe in shale gas wells application.

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Multi-criteria material selection for casing pipe in shale gas wells application

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Abstract

The conventional method of casing selection is based on availability and/or order placement to manufacturers based on certain design specifications to meet the anticipated downhole conditions. This traditional approach is very much dependent on experience as well as constructing oil and gas wells at minimum budget. However, this material selection approach is very limited in meeting the requirement of shale gas wells. This study utilises the material performance indices and ANSYS Granta database to examine three different casing pipe buckling scenarios including the buckling with corrosion potentials and buckling with impact and long-term service temperature conditions. Consequently, numerical evaluations of the response of the selected casing materials established the stress, deformations, and safety factor for the first scenario (shale gas well with buckling tendencies). The significance of this new method is added advantage in terms of integrating materials' physicochemical, thermal and mechanical properties and the casing functional performance to establish ideal selection within the design space or requirements. Results obtained in this study show that there are optional materials that outperform the most common casing grades (P110 and Q125) utilised in shale gas development in terms of both safety and cost. This study established a procedure for evaluating optimum performance between cost, safety, performance indices and materials' physical and mechanical properties for a typical well design scenario. This procedure will assist the design engineer to justify the selection of a particular material(s) safely and technically for a given shale well casing application in future. In all the 10 materials investigated, even though the P110 (API casing grade) meets the buckling design scenario and widely used in shale gas well development, there are many alternative viable material candidate options that outperform P110 Grade with the best material candidate studied in this work being BS 145.

Introduction

The development of shale gas wells through multi-stage hydraulic fracturing mainly focuses on getting the maximum possible production from such fractures. However, a new challenge of casing deformation failure usually occurs during such a process. This challenge is identified to be a function of many factors such as geomechanics, material selection and design, and operational practice. Consequently, there is increasing evidence of casing failure due to buckling deformations. Globally, approximately 26,600 wells out of 380,000 wells have at least one form of integrity failure costing hundreds of million-dollar investment losses (Davies et al. 2014).

The performance of tubular hardware (tubing and casing) depends on tubes properties, existing and applied

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stresses, and the environment in which the tube is operating, as pointed out by Hausler et al. (2017). Selecting safe and economical materials for unconventional wells is challenging. Pipes' materials that could withstand the harsh downhole condition are generally of higher strength capacity and thicker geometries, but more expensive compared to lower strength capacity materials. Besides, Kaldal et al. (2015) indicated that substantial temperature changes pose many design challenges in a diverse range of structures including casing in oil and gas wells. For example, Yang et al. (2018) noted that the yield strength of N80 and P110 casing grades decreases with the increase in temperature. Specifically, both N80 and P110 meet the API requirement on yielding strength below 350 °C conditions. However, when the temperature is above 350 °C, neither N80 nor P110 casing strengths' meets the API specification (Yang et al. 2018). In addition, this extreme temperature is not commonly encountered in oil and gas wells, however, geothermal wells exhibit elevated bottom hole temperature ranging from (232–399 °C) or 450–750 °F (Smithson 2016). In a separate study, however, Wang et al. (2020) established that increasing casing thickness can effectively reduce stress under load.

The literature shows that of 34% out of 101 wells drilled in Weiyuan shale play had casing failures during shale gas development (Xi et al. 2018). Meanwhile, forty-eight (48) casing collapsed in Asmari formation—Iran, owing to reservoir compaction, geo-mechanical effects according to Salehi et al. (2009). Also, there were 45% tubular failures out of 14,297 wells in the US Gulf of Mexico during 1980s, and a recent data statistic shows that 25% of eighty wells had casing deformation from Cleveland Sandstone, Granite Wash and Marmaton formations in the Western Anadarko Basin of the North Texas (Noshi et al. 2018). This trend is presently increasing globally especially in shale gas provinces.

Although the API standards guidelines such as API Spec 5CT, API Spec 5C2 and 5C3 have proved to be adequate reference materials for casing materials in conventional oil and gas wells but inadequate for unconventional wells such as shale gas wells (Hay and Belczewski 2003). The challenges however posed by unconventional wells are numerous and entirely different from conventional wells (Casero and Rylance 2020; Mohammed et al. 2020). The study of Gouveia et al. (2020) on the current search for oil and gas shows that the casing is being increasingly exposed to unconventional reservoirs, i.e. reservoirs characterised with higher depths, extreme pressure, and temperatures in (HPHT), deep-water, shale gas and tight oil and gas reservoirs. In addition, these wells have long been identified to pose different kinds of challenges raging from material selection, design, drilling and completion to abandonment (Liang et al. 2017; Lihong et al. 2013; Wang et al. 2014; Mohammed et al. 2019; Pan 2018). Depending on the well type and the circumstance, striking a balance between cost and

safety is an essential consideration for casing grades selection, design, installation and subsequent operations in oil and gas wells. The selection and design of casing for shale gas application are essential aspect of the well construction process in order to ensure well integrity and safeguard the environment during such process.

The standard practice in the industry is to select and design these casings using either API or proprietary grades (non-API approved) and apply safety margin based on anticipated downhole condition. The standard approach involves selecting these casings from available grades or place an order to manufacturers with certain specifications in order to meet the anticipated downhole conditions. This procedure is adequate for conventional wells that do not endanger the integrity of the casing pipes. On the other hand, for unconventional wells—such as shale gas—this procedure may not be adequate. The reason being that of induced stresses and displacement resulting from hydraulic fracturing which are not accounted during casing selection and design.

As such, this traditional approach is very much dependent on experience as well as constructing oil wells at minimum budget. However, due to increase in complexity experienced in development of unconventional wells (such as high pressure/high temperature (HPHT) wells that are associated with significant amount of acid gases), Sumitomo alloys selection chart was developed to cope with the selection challenge (Hill and Perez 2017). This chart is based on calculating the partial pressures and the chloride content on a limited casing grade. Additionally, Millet et al. (2020) developed a simplified selection chart for super martensitic stainless steel solution for high acid gases (hydrogen sulphide (H_2S) and carbon dioxide (CO_2) environment based on partial pressures and temperature).

As it can be seen on Fig. 1, the selection is limited to few steel alloys and partial pressures of hydrogen sulphide
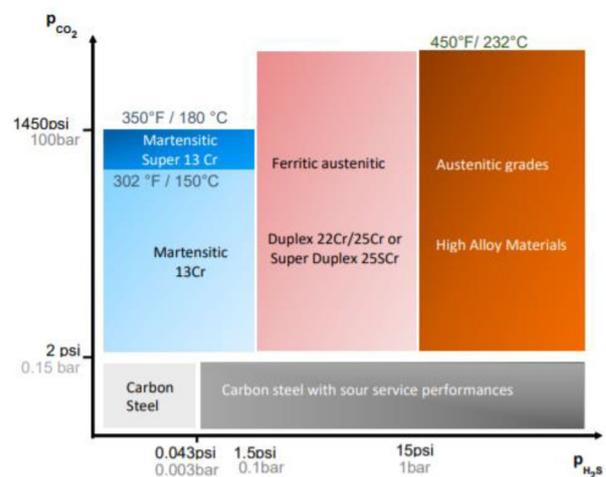

Fig. 1 Simplified material selection chart (Millet et al. 2020)

and carbon dioxide and cannot be applied in wide range of scenarios like shale gas wells and deep-water wells. Also, in situations where there is inter-relationship and dependencies between the attributes to a particular objective, both Sumitomo and the simplified material selection chart cannot give the desired result/outcome. Further, Marbun et al. (2020) established that production casing of well HCE29 failed in Dieng Field, Indonesia, after the well was drilled and completed. The well which is an unconventional is characterised by a water-dominated geothermal system with temperature of up to 330 °C and pressure of up to 19.4 MPa. In a separate study on pitting corrosion, Yan et al. (2019) found out that two pits in circumferential direction in the casing are more likely to cause failure than the double pits located along the axial direction on the casing. Also, the study of Correa et al. (2020) suggests the use of the failure assessment diagram (FAD) tool to prove the structural integrity of riser pipes is essential for the evaluation of crack and determining the critical crack size and its likely failure method for application in deep-water.

There is an emerging urgent need to address casing failures that demands a more methodical approach to unconventional wells. However, casing materials (grades) selection using ANSYS Granta Selector (Cambridge Engineering Selector—CES) is essential but is still a gap in the literature. Materials selected using this method for casing application can further be evaluated using finite element modelling to predict its structural response in a shale gas well scenario. Similar strategy of predicting defects and materials response to applied loads and/or stress were reported by (Ferro and Bonollo 2019; Fazekas and Goda 2020; Liu et al. 2016; Feng et al. 2019).

Therefore, using ANSYS Granta database, this study examines multiple criteria for casing selection and application in oil and gas wells for the first time in the literature to the best of the authors knowledge. This study focuses on shale gas wells with buckling tendencies, corrosion and impact potentials resulting from rock shear as well as long-term service temperature constraints. The factors examined are Young's modulus, yield strength, density, cost, elongation, buckling load, corrosion, service temperature and suitability to application in sour oil and gas wells. The significance of this work is to study and compare the performance of both currently API grades and propriety material grades along with other commercially available alternative materials to establish a balance between cost and safety levels to be reached in a typical well scenario. By doing so, this study aims to assist the designer (Engineer) to justify the selection of casing safely and technically for unconventional shale gas wells.

Multi-criteria decision-making for materials selection: an overview

The driving force for material selection is generally performance improvement and cost minimisation. However, criteria such as critical loads and weight reduction are also strong motivations for proper material selection. For example, in the aerospace industries, weight reduction is one of the foremost targets for design enhancements. Conversely, in oil and gas wells, strength and stiffness may be the main objectives in selecting casing and tubing pipes to ensure well integrity.

Kumar and Ray (2014) pointed out that inappropriate material selection may lead to requirement of customers and manufacturers not being satisfied. Poor selection of materials can cause premature failure of an assembly and reduction in product performance. Thus, efficiency and profitability can be affected adversely and organisation reputation damaged (Allwood et al. 2011; Kabir et al. 2014). To solve the problem of material selection, different techniques have been applied in the literature and one of the popular methods that have been applied is the multi-criteria decision-making (MCDM) method. Some of the popular MCDM tools that have been applied in the literature for material analysis are ANSYS Granta selector (Yavuz 2019; Ferro and Bonollo 2019), Analytical Hierarchy Process (AHP) (Chen et al. 2013), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Li et al. 2020a, b), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Rahim et al. 2018).

As established above, there are many multi-criteria decision-making processes for material selection. However, this study examines the Ashby chart to select alternative material for casing based on key pertinent parameters for the first time in the literature. The basis for the comparison of these methods involves both material properties and anticipated loading on casing during shale gas well stimulation.

The MCDM methods are applied in selecting an optimum decision in circumstance that has to do with multiple alternatives having multi-conflicting and non-commensurable decision criteria. The MCDM is a recognised tool for solving complex engineering problems due to their inherent ability to judge diverse alternatives with reference to various decision criteria in order to choose to best alternative (Emovon and Oghenenyerovwho 2020). Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR, Analytic Hierarchy Process (AHP) (Chen et al. 2013), Preference Ranking Organisational Method for Enriched Evaluation (PROMETHEE) (Çalışkan et al. 2013), Weighted Sum Model (WSM) and Weighted product model (WPM) (Pematangsiantar 2017), ELECTRE, and Multi-Attribute Utility Analysis (MAUA) are amongst the popular MCDM

techniques that are commonly utilised for solving decision problem (Emovon and Oghenenyerovwho 2020).

The Ashby method is based on the work of M. F. Ashby who in 1992 invented the technique based on ratio to develop a means of assessing the performance of alternative materials between material properties (Emovon and Oghenenyerovwho 2020). This ratio translates to bubble diagram for initial screening of the available materials based on their properties. The best candidate (material) is the one with the highest performance index. This approach is very effective for the initial screening process of materials based on the performance index developed to suit a particular requirement. It also demands the advantage of robust database from which the screening is made, as well as the relative comparison with other potential candidates.

The materials and processes data-tables lie at the heart of the set. The first contains records for the properties of structural, functional, and biological materials (Fig. 2). The second gives access to records for shaping, joining, and finishing processes, with schematics and images of processes. The elements data contain records for the basic properties of the elements of the periodic table; they are linked, where appropriate, to records in the other material dataset hence providing a one-click access to relevant fundamental atomic properties. The phase diagrams data contain the most-used phase diagrams and an interactive tool to illustrate how to interpret them. The Process-Property profiles data set allows the effect of processing on properties to be explored and the associated structure and mechanisms to give insight into structural changes that manipulate properties. This makes the CES a preferred choice for material science and engineering across many fields of study since it establishes
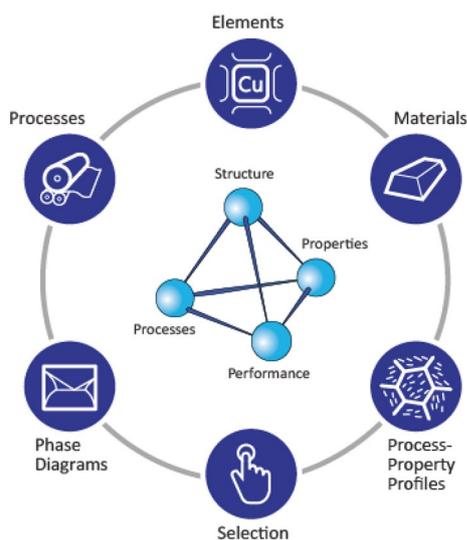
relationship between processing, structure, proper ties, and performance as shown in Fig. 2 (Ashby et al. 2018).

Methodology

Using advanced level 3 aerospace database in ANSYS Granta selector (CES), Ashby plot (bubble diagram) is employed for casing material selection with emphasis given to shale gas wells casing performance indices. Figure 3 presents high-level overview of the selection process as implemented in this study. As it can be seen on Fig. 3, the preparatory stage involves defining the main objectives followed by distinguishing the key factors or requirement to meet a particular design. As soon as the driving parameters are identified, the performance indices are derived using relevant equations.

The selection process involves plotting the performance indices on an XY plot using the advanced plotting techniques in CES. This is followed by applying constraints and limits to further refine the initial selection. Depending on the situation, an alternative material or best material choice is obtained at the end of this stage. If there is need for further screening or evaluation then, further screening is carried out using either
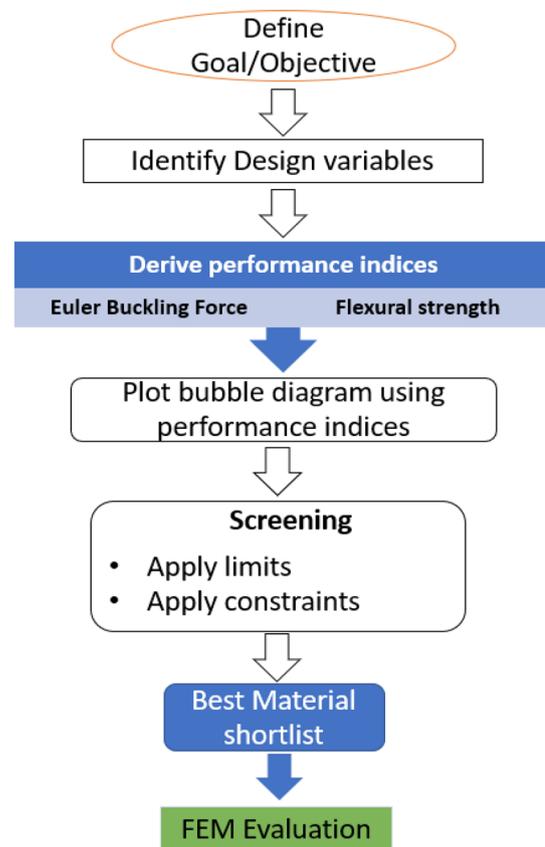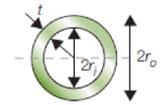

Fig. 2 Data-structure of the CES for Material Science and Engineering database (Ashby et al. 2018)

Fig. 3 Casing material selection process for shale gas wells

Table 1 cross section of a hollow cylinder (pipe) with corresponding moments

Section shape	Area A (m^2)	Moment I (m^4)	Moment K (m^4)	Moment Z (m^3)	Moment Z_p (m^3)
	$\pi(r_o^2 - r_i^2)$ $\approx 2\pi r t$	$\frac{\pi}{4}(r_o^4 - r_i^4)$ $\approx \pi r^3 t$	$\frac{\pi}{2}(r_o^4 - r_i^4)$ $\approx 2\pi r^3 t$	$\frac{\pi}{4 r_o}(r_o^4 - r_i^4)$ $\approx \pi r^2 t$	$\frac{\pi}{3}(r_o^3 - r_i^3)$ $\approx \pi r^2 t$

The second moment of area I, measures the resistance of the section to bending about a horizontal axis

TOPSIS, AHP and/or finite element analysis (FEA) using ANSYS workpackage. The finite element model (FEM) is employed to make the final decision/selection as shown in Fig. 6. Consequently, using advanced ANSYS Granta Level 3 aerospace CES Edupack database (physical, chemical, and mechanical properties) with the capability of manipulating materials' performance indices numerical evaluations can resolve the challenge of material selection for unconventional wells as shown in Fig. 3 flowchart.

Performance indices

Using the Ashby method, the performance indices were developed and used for the selection of relevant material from the CES – EDUPACK database. For the casing that experience bending stress (external load) because of induce stress during shale gas well stimulation, Eq. (1) is utilised to derive the performance index assuming the flexural load on the casing to act as in simply supported beam.

$$\sigma_f = \frac{MY}{I} \tag{1}$$

where σ_f = "flexural strength," Y = "displacement measure from the neutral axis of the beam," I = "Moment of area of the hollow pipe," M = "internal bending moment about the pipe neutral axis."

The moment, K, measures the resistance of the section to twisting, and Z is the section modulus—which determines how strong a beam of a given cross section is. The moment of inertia for a hollow pipe is $I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right)$ as shown in Table 1. However, $r_o^4 - r_i^4 = t^4$ represents the thickness of the casing pipe, which implies $t = \left(\frac{4I}{\pi}\right)^{1/4}$. Again, the cross-sectional area of a hollow pipe $A = \pi\left(r_o^2 - r_i^2\right)$ is as shown in Table 1. For a minimum mass that will give the optimum flexural strength of certain cross-sectional area—the mass can be expressed in terms of area, length and density. Mass, $m = A \cdot l \cdot \rho$ substituting for A, I and t and simplifying leads to expression for optimum mass obtained with the index term as shown in Eq. (2).
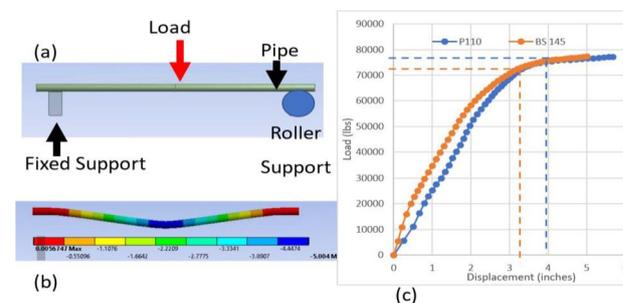

Fig. 4 3-point bending load dispalcement curve for P110 and BS 145. **a** Physical model, **b** deform numerical model, **c** load versus displacement for P110 and BS145

$$M = \left(4\pi MYL^2\right)^{1/2}\left(\frac{\rho}{\sigma_f^{1/2}}\right) \tag{2}$$

Taking the reciprocal of the index term results in

$$\left(\frac{\sigma_f^{1/2}}{\rho}\right) = \mathbf{M1} \tag{3}$$

The flexural strength strictly only applies to brittle materials. For ductile materials, the flexural strength is the "effective" yield strength measured from the load at which a beam, loaded in bending, first becomes fully plastic, as in Fig. 4c (dash lines). As such, in this study, the assumption is that the flexural strength of all the materials is equal to material yield strength (elastic limit) for the derivation of the performance index and hence Eq. (3) applies (Table 2).

Table 2 The material data properties for the P110 and BS 145

Material	Young's modulus (MPa)	Poisson's ratio	Inner diameter (inches)	Outer diameter (inches)
P110	210,000	0.3	4.5	5.5
BS 145	206,000	0.295	4.5	5.5

The boundary condition is applied as in Fig. 4a. Both ends are fixed, and a 5 inches displacement is gradually applied as shown in Fig. 4a. Another assumption is based on Euler buckling equation, i.e. using this Eq. (4); the performance index is derived to determine ratio from CES database which will avoid critical buckling of the casing under load at minimum thickness.

$$F = \frac{\pi^2 EI}{KL^2} \tag{4}$$

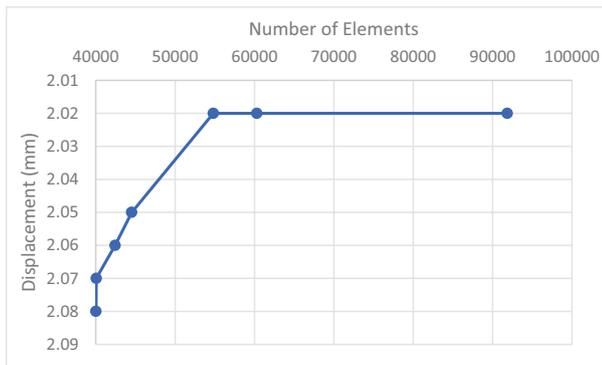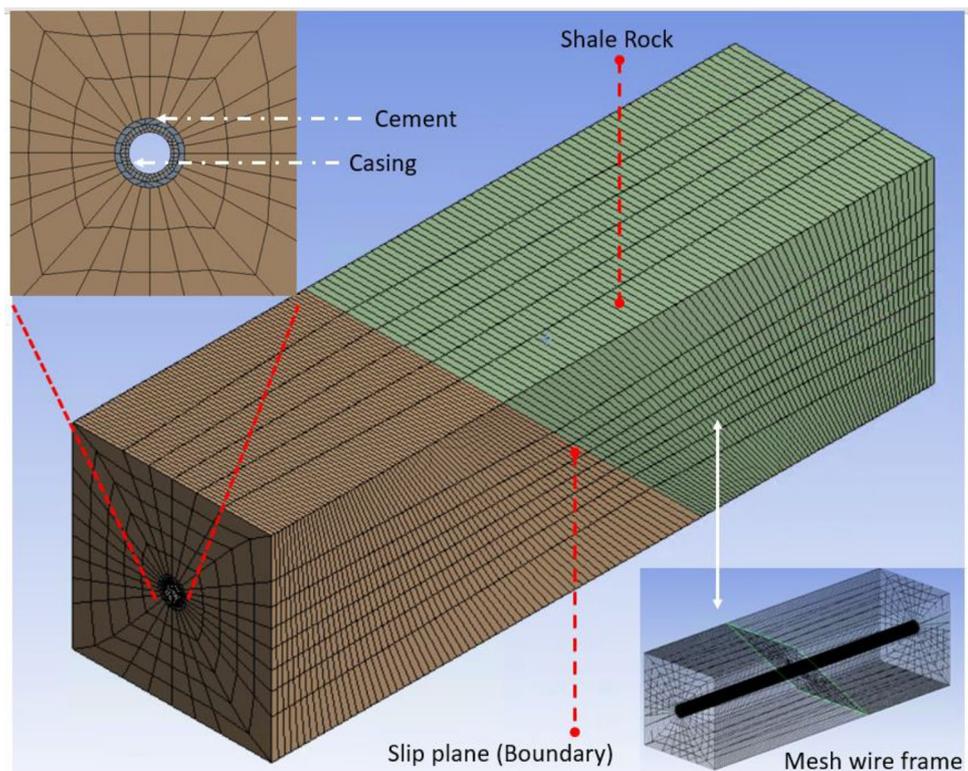Flexural strength is calculated from the load F at which beam fractures (brittle materials) or becomes fully plastic for ductile materials as shown in Fig. 4c. This plot reveals the flexural load of P110 and BS 145 to be 75750lbs and 73098lbs, respectively.

The moment of inertia for a hollow pipe is $I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right)$ as shown in Fig. 5. However, $r_o^4 - r_i^4 = t^4$ represents the thickness of the casing pipe which implies $t = \left(\frac{4I}{\pi}\right)^{1/4}$. Again, the cross-sectional area of a hollow pipe $A = \pi\left(r_o^2 - r_i^2\right)$ is shown in Fig. 5. Now substituting for A, I and t and simplifying, to obtain the material with minimum thickness and mass that will avoid the buckling of the casing at minimum mass m is, we get

$$m = 2r(\pi F)^{1/4} \cdot L^{3/2}\left(\frac{\rho}{E^{1/4}}\right) \tag{5}$$

The index term is $\left(\frac{\rho}{E^{1/4}}\right)$.

And the reciprocal gives : $\quad \left(\frac{E^{1/4}}{\rho}\right) = \mathbf{M2}. \tag{6}$

Finite element modelling

The shortlisted materials from ANSYS Granta selector are further studied using finite element analysis to determine the structural response of the casing in shale gas well. The aim is to determine the von Mises stress, transverse displacement

Fig. 5 Mesh sensitivity study to ensure simulation result accuracy

Fig. 6 Finite element model (54,816 elements and 286,352 nodes) showing casing, cement, rock and slip plane

and safety factor for each potential material candidate and then further compare with the P110 casing grade that is commonly applied in shale gas well development.

The 3D finite element model was developed and consisted of casing, cement and the shale rock as shown in Fig. 6 and built using 3D type 'SOLID186' elements. Mesh convergence study consisting of 54,816 elements is shown in Fig. 5 justifying result accuracy. Each element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal *X*, *Y*, and *Z* directions. The element has plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilities. This model enabled the prediction of casing structural response under a particular scenario in shale gas well. The material properties for casing cement and shale rock are listed in Table 3. The shale rock is a square cross section with dimension measuring 47.24×47.24 inches to avoid boundary effect on stress. As can be seen in Fig. 6, the scenario examined the casing structural response based on applied slip displacement assuming bonded relationship between, the casing, cement and shale rock (composites). Using this approach, the shortlisted materials' performance is evaluated through numerical simulation. Consequently, the materials are compared with P110 casing grade performance primarily based on the safety factor, stress and displacement.

It is difficult to replicate the downhole hole condition involving casing cement and formation rock in the laboratory. However, in order to ensure result accuracy, a mesh sensitivity convergence study was carried out in order to ensure the reliability of numerical simulation. Therefore, as a good FEA practice, Fig. 5 shows that 54,816 elements are enough to ensure result verification and validation.

This analysis enables the prediction of casing response to slip displacement during hydraulic fracturing. The boundary condition is applied in such a way to replicate fracture slip traversing the well at an angle of 45° as established in the study of Yin et al. (2018). As such, a slip displacement of 3 mm is applied on the green surface of the shale rock while the brown surface is fixed in all degree of freedom.

Although the best material candidates are identified from ANSYS Granta selector, performance evaluation

through finite element modelling further evaluates the safety of these materials in a typical scenario. The shortlisted materials from CES are exported to ANSYS for structural analysis. The material properties are taken from the database while for the API and the non-API casings, material properties are determined from American Petroleum Institute (API specification 5CT 2006) and manufacturers catalogues, respectively (Steel 2013).

Results and discussion

Material selection for shale gas well

The initial selection begins with the advanced plotting features for all the materials in the ANSYS Granta selector database. The material family (Ferrous) and based material (Iron) limiting constraints are applied to the initial selection in order to search for materials that will meet the casing material requirements. Material family ferrous with iron as based material is selected because of their high strength, low cost and ductility. Furthermore, a 195GPa is applied as the minimum threshold for materials Young's Modulus to get most stiff materials from this family. However, using API 5CT, and other mechanical properties from the casing manufacturers, user-defined materials records are created in the selection at this stage for comparison with other materials in the ANSYS Granta selector tool. It should be noted that both API and non-API steel grades are considered. However, for the non-API steel grades, only V150 and SM125 are included owing to their applicability in harsh gas wells high pressure, high temperature, and high hydrogen sulphide as pointed by Wang et al. (2019).

Also, based on study conducted by Jacobs (2020) and Mohammed et al. (2020) established the casing to buckle at very low shear rates, hence a minimum shear strength of 13 MPa was applied to modify the selection. As a result, Fig. 7a is developed from CES database. Figure 7a shows the bubble diagram of the materials that meet selection criteria and show their corresponding performance. Based on Fig. 6b, the design engineer can select and justify the selection for a particular well application. Furthermore, materials on the lower left are of low performance and cheaper and lighter. In contrast, materials on top right are of higher performance but more expensive and heavier. Under this circumstance, the trade-off has to be made. Figure 7b shows that the API casing performs very well with P110 casing grades being the highest, while SM 125 being the best for the non-API material grades. Furthermore, high strength low alloy (YS460 hot rolled) from the metal and alloys family are shown to be the best performing material from the ANSYS Granta Database relevant to casing application.

Table 3 Material properties of casing, cement and shale rock

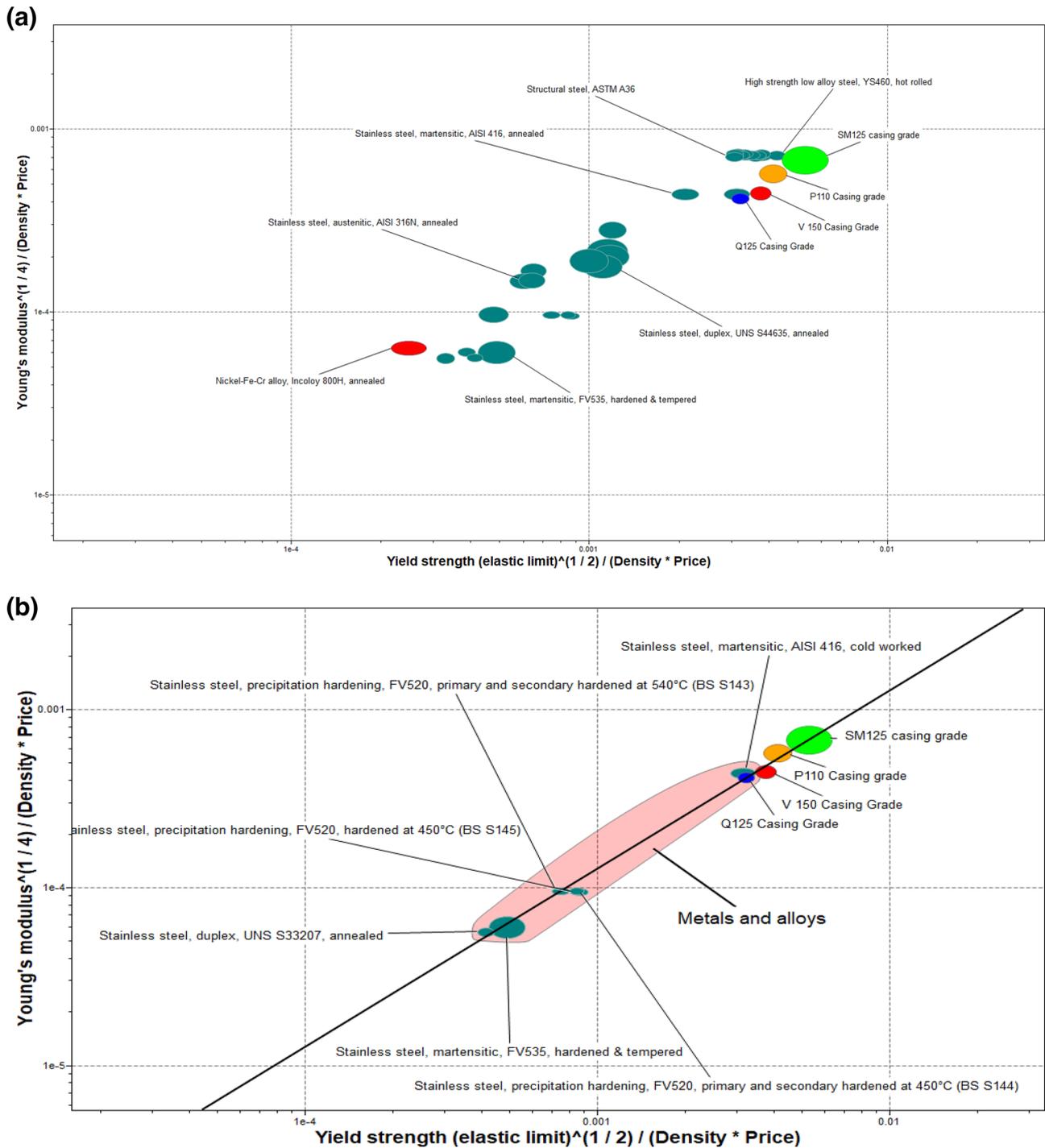| Material	Young's modulus (MPa)	Poisson's ratio (μ)	Yield strength (MPa)	OD (inches)
Casing P110	210,000	0.3	758	5.5
Cement	7000	023	–	6.625
Shale Rock	20,900	0.18	–	–

Fig. 7 **a** The shortlisted candidates for shale gas well casing. **b** Top ten (10) materials after further optimisation

Further refinement is achieved as shown in Fig. 7b reducing the number of materials to 10. The "active constraints" method can be applied to further optimised the selection—a process which allows the selection of a specific material that optimally meets two or more constraints.

As it can be seen based on the performance indices, SM125, P110 and V150 appear to be the best in terms of performance but more expensive and heavier than stainless steels (BS143, BS144, BS145) and FV535 stainless steel.

Table 4 lists the top ten materials that meet the selection criteria for shale gas well and their pertinent material

Table 4 Top ten (10) materials selected for shale wells with induced stresses

Material description	YM (GPa)	YS (MPa)	Density (kg/m³)	% Elong	Price (£/kg)	Service temperature (°C)	Buckling load (lbf)
Stainless Steel Duplex UNS S33207	205	816	7740	16.5	9.05	365	73,330
Stainless Steel (BS S145)	206	1280	7830	15	5.24	427	73,688
Stainless steel martensitic FV535	216	1030	7830	22	9.28	550	77,265
Stainless steel Precipitation (BS143)	216	955	7830	22	5.24	427	77,265
Stainless steel Precipitation FV520	216	1200	7830	18	5.24	427	77,265
Stainless Steel AISI 416	210	820	7880	18	1.17	750	75,119
Q125 Casing grade	216	862	7800	18	1.25[a]	250	77,265
P110 Casing Grade	210	758	7800	15	0.929[a]	250	75,119
V150 Casing Grade	220	1034	8150	18	1.16[a]	250	78,696
SM 125	202	862	7790	18	0.85[a]	250	72,257

YM Young's modulus, *YS* yield strength

[a]Denotes average cost online

properties for this study obtained using ANSYS Granta selector. The buckling load is calculated using Eq. (4). On the other hand, the service temperature for API casing materials was taken as 250 °C because most oil and gas reservoir temperatures are below 260 °C. These shortlisted materials are each studied through numerical modelling to determine their structural responses for stress, displacement and safety factor.

Selection based on induced stress and corrosion

Again, using the same material indices as in the previous section and different selection criteria, another shortlist of materials is obtained from the database. In similar manner, the entire database was used in order not to discriminate unsuitable materials. Further, Marbun et al. (2020) observed that the material selection for the production casing and production liner in the Dieng Field, Indonesia was estimated according to corrosion equations established by Ekasari and Marbun (2015). Using this equation, the chromium equivalent (Creq value) is calculated. Next, based on the temperature, pH data of the fluid in the field and the corrosion rate target (0.1 mm/year), the Creq diagram for production casing and production liner was plotted. However, this methodology is limited to geothermal wells in the Dieng Field and cannot be in shale gas wells casing wells selection. The main reason being the characteristics of geothermal and shale gas wells are different. Also, the composition of fluids and downhole conditions (pressure and temperature) and rock matrix (lithology) are different.

For instance, the pitting resistant equivalent number (PREN) for metals and alloys ranges from 0 to 56.4 and proprietary austenitic stainless steels for directional drilling (PREN between ~ 20 to ~ 45 (Marya 2020). Based on this, 15 to 30

PREN was applied as the minimum and maximum, respectively. Moreover, the resistance of the materials to sour oil and gas, i.e. that which contains high levels of hydrogen sulphide, was considered. This qualitative attribute is categorised as either; Excellent, Good, Moderate, Restricted, and Poor. Therefore, excellent, good and moderate materials are chosen to further optimise the selection. This selection results are shown in Fig. 8b with the material family envelop of metals and alloys. More specifically, Fig. 8b presents stainless steel and nickel alloys material families. Both nickel and stainless steel have good corrosion resistance as established in the studies of (Craig and Smith 2011; Carrasco et al. 2019; Liu et al. 2020; Qi et al. 2020). Similarly, materials on the top right-hand corner demonstrate good performance but are relatively expensive and heavy compared to those on the bottom left-hand corner. These materials such as nickel alloys are lighter, cheaper but of low performance. This is expected considering the limiting criteria. However, none of the API steel grades meets these criteria as such not shown in bubble diagram in Fig. 8a, b.

The second scenario for the selection of potential materials for the casing investigates different limiting criteria. The Young's modulus was selected ranging from 160 to 200 GPa for a typical casing grade (SM125). Another constraint imposed was the strain (≥ 14%) to get the stiffest materials from the database based on this equality constraint. At this stage, out of 4169 potential materials, 569 materials meet the criteria. Those materials that do not meet these criteria are shown in grey and subsequently removed (Fig. 7a). The resulting selection is further limited with yield strength of 758 MPa (P110 casing grade). This yield strength is applied as limiting constraints considering the deformation of P110 casing grade reported in the literature (Mohammed et al. 2019; Yin et al 2018; Wang et al. 2019). In addition,
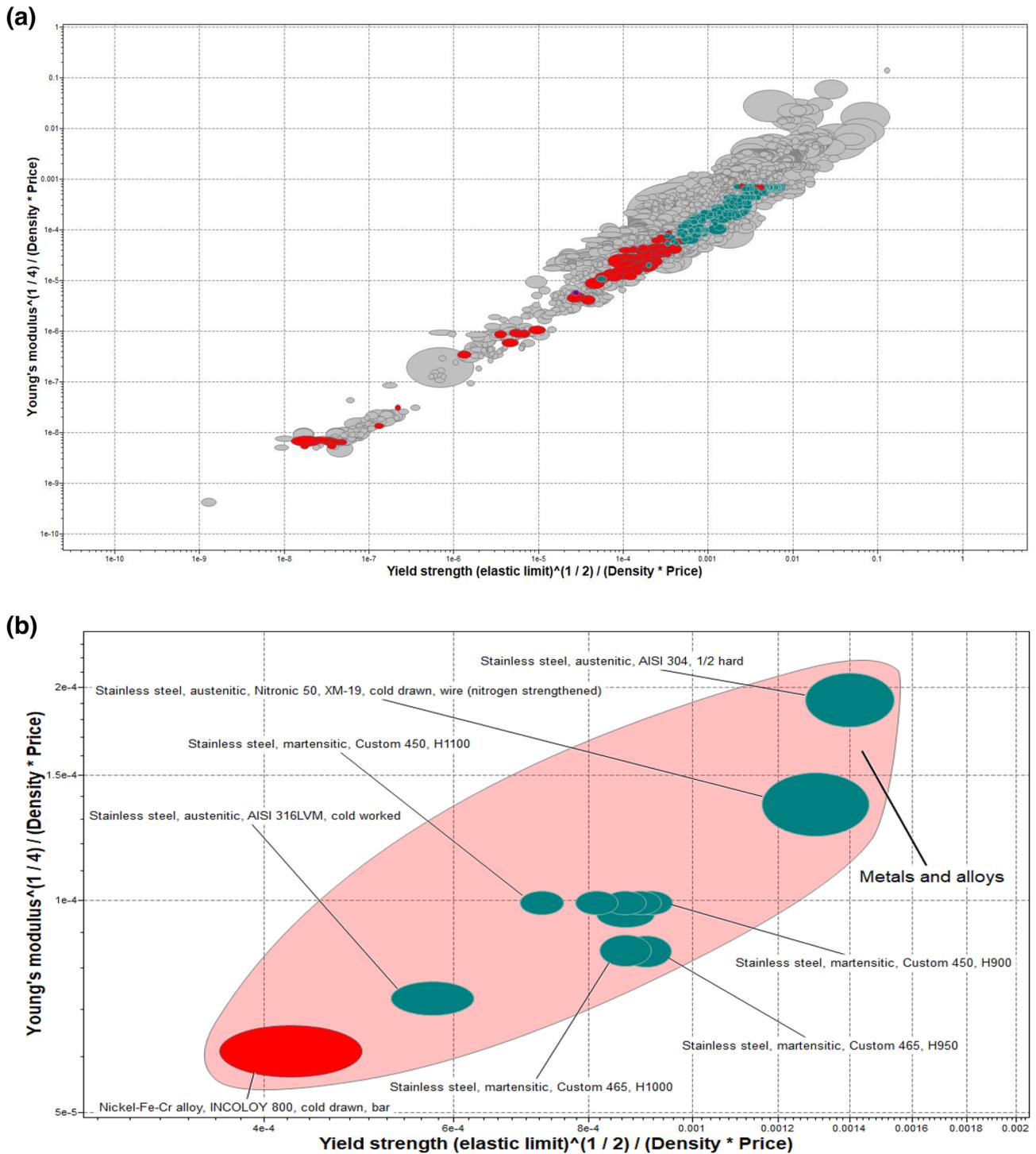
(a)

(b)

Fig. 8 **a** The initial screening for the second scenario—induced stress and corrosion. **b** Shortlisted materials for high sour oil and gas wells

assuming a high pressure, high temperature, high H_2S gas well, the corrosion potential for this class of wells is severe. The bubble diagram in Fig. 8b presents successful materials that meets these selection criteria.

Selection based on induced stress, service temperature and external load (impact)

There are circumstances in which the casing is installed in an environment where thermal loads are present apart from

the localised stress due to fracturing pressure. Moreover, shale development is often associated with impact resulting from shearing of the rock during fracturing process (Bokor et al. 2020). Significant fracture toughness in materials is essential factor for performance under this situation. The study by Correa et al. (2020) computed the fracture toughness of API 5CT P110 steel using crack tip opening displacement (CTOD) through FEA in order to determine the acceptability of the cracks in rigid risers. Risers can be rigid, flexible or hybrid. However, rigid risers (Pipes) are susceptible to external threats such as accidental impacts and environmental factors such as the high corrosion potential during operations (Correa et al. 2020).

As such, it is therefore essential to select material using these indices but can withstand significant amount of impact energy. A recent study by Zhu et al. (2020) on experimental studies on dynamic behaviour of pipes under repeated impact loadings show that the pipe mainly experienced local dent close to the upper side, while the global bending was very small. This phenomenon is similar to casing deformation commonly encountered during shale gas wells stimulation. However, materials with high impact energy absorption (KJ/m^2) absorb high impact energy before deformation while materials with low toughness absorb little impact energy, and as a result, permanent deformation of the casing may be the result.

The P110 casing grade did not meet selection criteria as its ranges between 15 and 30ft-lbs (0.020–0.04 kJ/m^2) which is well below the minimum threshold of 30 kJ/m^2 for fracture toughness. As such, it does not appear in the selection made for this scenario. The current practice in selection and design of casing for oil and gas wells is largely based on downhole conditions (pressure, temperature, and fluids properties) but fails to capture couple effects. For example, the study of Karlsdottir et al. (2015) and Marbun et al. (2020) pointed the danger of the combined influence of high temperature and pressure on casing strength degradation and casing thickness reduction and eventual failure of the casing. Therefore, meticulous selection using CES database and performance indices for casing materials would be more robust and effective method in preventing corrosion and prolonging the lifetime of the well than the conventional approach. Similarly, all those materials that do not meet the selection criteria are eliminated/screened out which reduce the materials to 568 from initial 4164 in ANSYS Granta level 3 database. Figure 9a presents the resulting materials bubble plots based on these constraints. The resulting selection is shown in Fig. 9b with a tangent line delineating optimum selection.

This selection is further expanded to aid in visualisation with a tangent line connecting the optimum candidates for this selection so as to further reduce the list to the most qualified materials (pareto optimal solution) as shown in Fig. 10a. Having applied the additional limiting criterion

such as ferrous and nonferrous metals, base materials, and service temperature $\geq$ 120 °C, and pareto optimal selection; the selection reduces to 10 materials from the previous 568 shortlisted. As it can be seen, the final list is mostly stainless steel family (80%) and titanium and nickel alloys account for 20% as shown in Fig. 9b.

The final shortlist comprises nickel and titanium alloys as well as the carbon steel alloys in Fig. 10b. This optimised selection revealed that carbon steel (AISI 1025 annealed) is the overall best material for impact loads and service temperature based on this scenario. This perhaps is associated with low cost per kilograms; thereby making it to outperform the other materials. This, however, means that if the reservoir temperature is in the neighbourhood of 120 °C, then, carbon steel AISI 1025 is a preferred choice as shown. Moreover, these materials all belong to the metals and alloys group as shown in Fig. 10b material family envelop.

Additionally, having determine the best materials in terms of performance, a quick stress analysis enables the determination of equivalent von Mises stress, total deformation and the safety factor for the top ten (10) selected materials to be evaluated. This is crucial in keeping the total deformation and stress below elastic limit to avoid permanent deformation of the casing during installation and operations.

Performance comparison for various materials

The alternative materials that outperform the popular P110 casing grade are identified using the FEA study. For example, stainless steel (BS145) demonstrated superior performance than P110 in terms of safety factor. Under the same condition of geometry and boundary condition, stainless steel (BS145) gives a safety factor of 2.4, while P110 gives approximately 1.4. See Fig. 11a, d for this comparison. Additionally, it is observed that the total displacement in both stainless steel and P110 is relatively the same: 2.700 mm for stainless steel Fig. 11b, while 2.79 mm for P110 casing Fig. 11e. This difference suggests that the stainless steel (BS145) is stiffer than the P110.

As expected, relatively lower von Mises stress values are associated with stainless steel (BS145). Although the von Mises stresses obtained are lower than yield strengths of both BS145 and P110 materials, the stainless steel (BS145) is emerging preferential in reducing the buckling tendencies in shale gas wells than the popular casing grades. The von Mises stress for stainless steel (BS145) is 610 MPa as shown in Fig. 11c while for P110 is approximately 634 MPa as shown in Fig. 11f.

Safety Factor is defined as the ratio between the strength of the material and the maximum stress in the material. If the ratio is less than 1—it means the material will fail. If, on other hand, the safety factor is more than
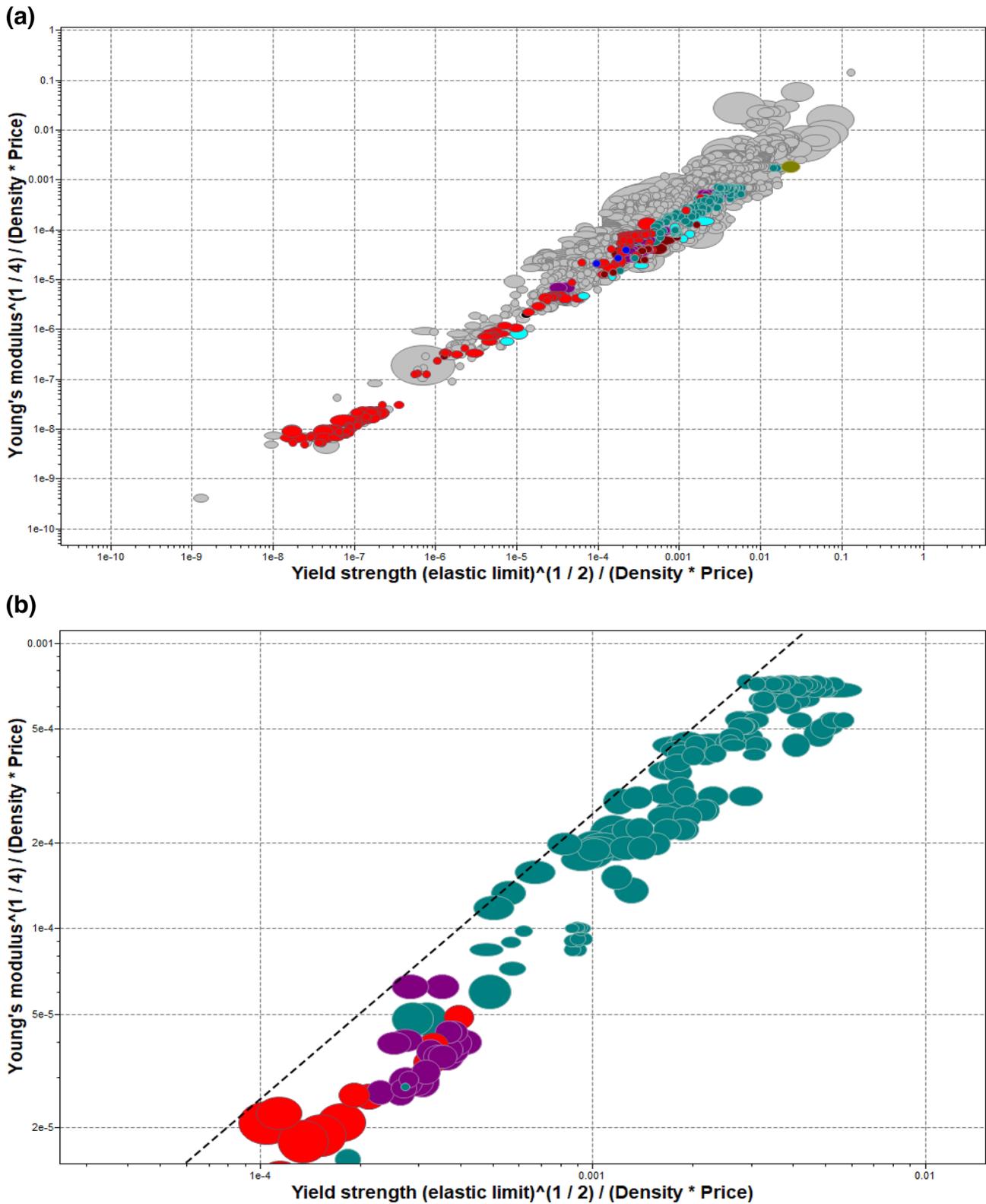
(a)

(b)

Fig. 9 **a** The shortlisted materials for shale gas wells with high impact energy and temperature. **b** Optimum selection using tangent line for pareto solution
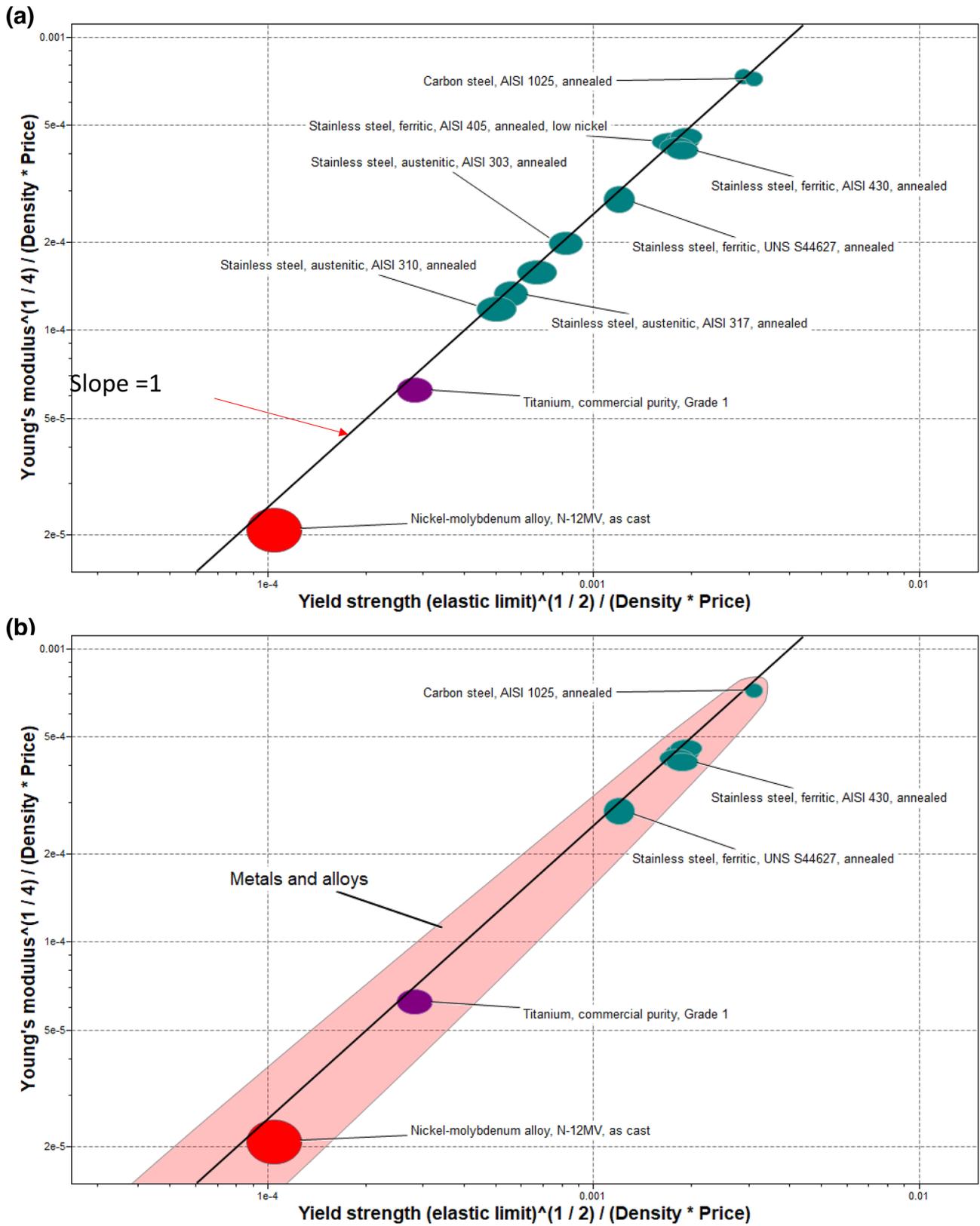
(a)

(b)

Fig. 10 **a** The shortlisted materials for shale gas wells with high impact potentials and service temperature. **b** The family envelope of the short-listed material brittleness for high impact shales
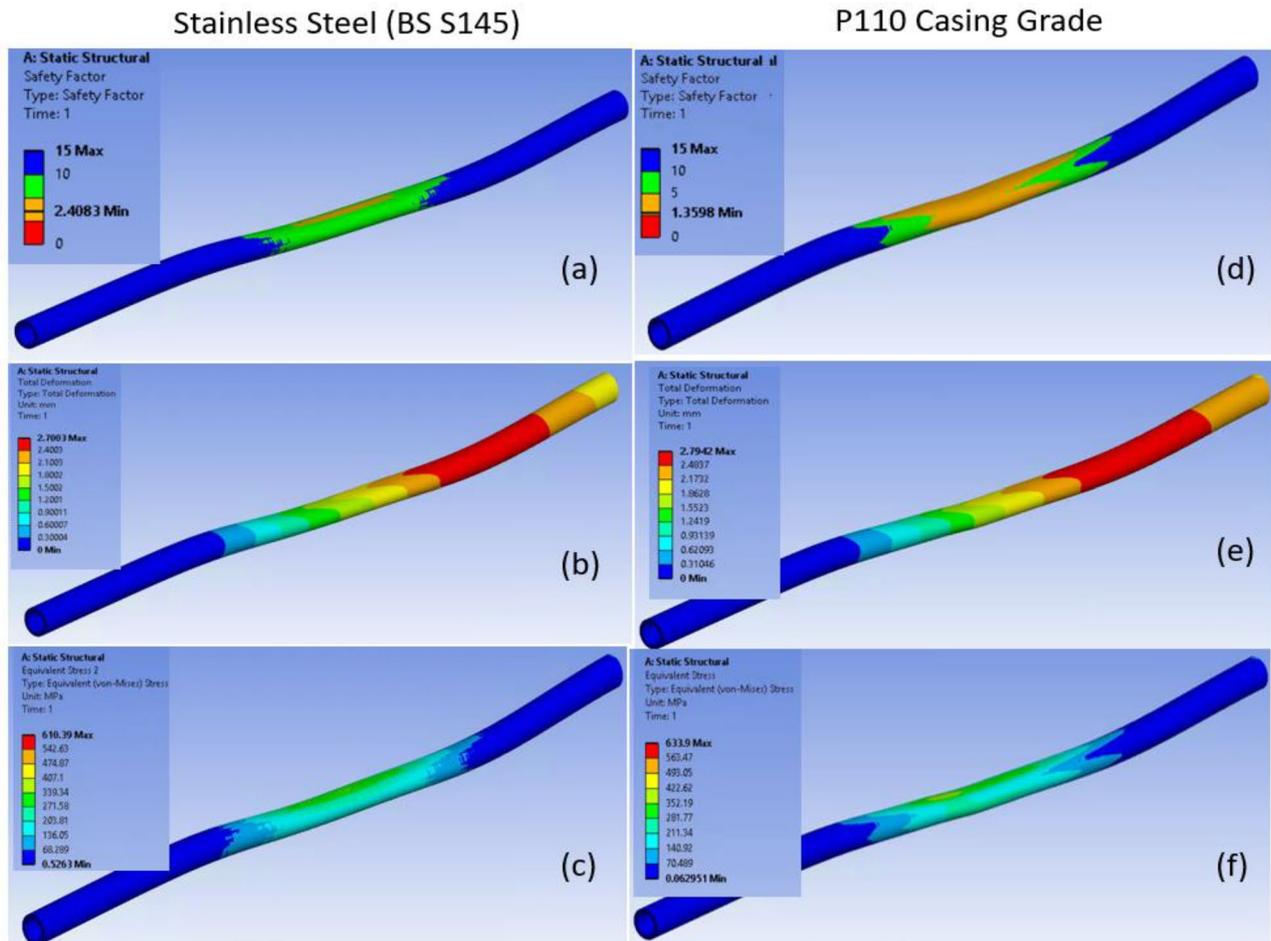
Fig. 11 Comparison between stainless steel (BS145) with P110 Casing grade showing **a** safety factor for—BS145, **b** Total Displacement—BS145, **c** von Mises stress—BS145, **d** safety factor—P110, **e** displacement—P110 and **f** von Mises stress

1, it is expected that the material will not fail. Therefore, the Safety Factor is chosen as a yardstick because it is essential to ensure the structural designs do not fail unexpectedly due to applied load, deformation or defect. The smaller the Factor of Safety, the higher chances were there for the design to be a failure, resulting in an uneconomical and non-functional design. Further comparison on the safety factor shows that there are alternative materials that can be used to replace the P110 or Q125 casing for shale gas well development using ANSYS Granta database. As it can be seen in Fig. 12, (green bar) represents the stainless steel with 2.4 safety factor while the reference material P110 (red bar) is only 1.4.

In the context of this work, the main requirement for the casing is to ensure well integrity throughout the well producing life. However, in unconventional wells such as shale gas wells where hydraulic fractures induce casing buckling and deformations during stimulation, stiffness and strength become a major requirement in the selection and design of the casing. In addition, high buckling load, low cost, and

low-density material will be identified amongst key design variables to meet this requirement.

Based on these variables, the performance indices are derived using flexural strength and Euler buckling equation. The constant terms are separated from the indices in each case. Using the CES database, the entire material family is plotted and subsequent screening—that involves applying limits and constraints—is accomplished to obtain the best performing candidates. The three scenarios investigated using this database are the shale gas with buckling tendencies, applied stress and corrosion, and induce stress, service temperature and impact resistance.

A quick comparison on simulation studies that adopt the conventional method of casing selection for shale gas wells revealed higher stresses and poor safety factor. For example, the safety coefficient was only 0.76 for the Q125 (862 MPa) grade casing and 0.85 for the TP140 (965 MPa) grade casing, which was not able to meet the safety requirements (Yan et al. 2017). Also, the study of Mohammed et al. (2021) on casing deformation based on conventional casing selection

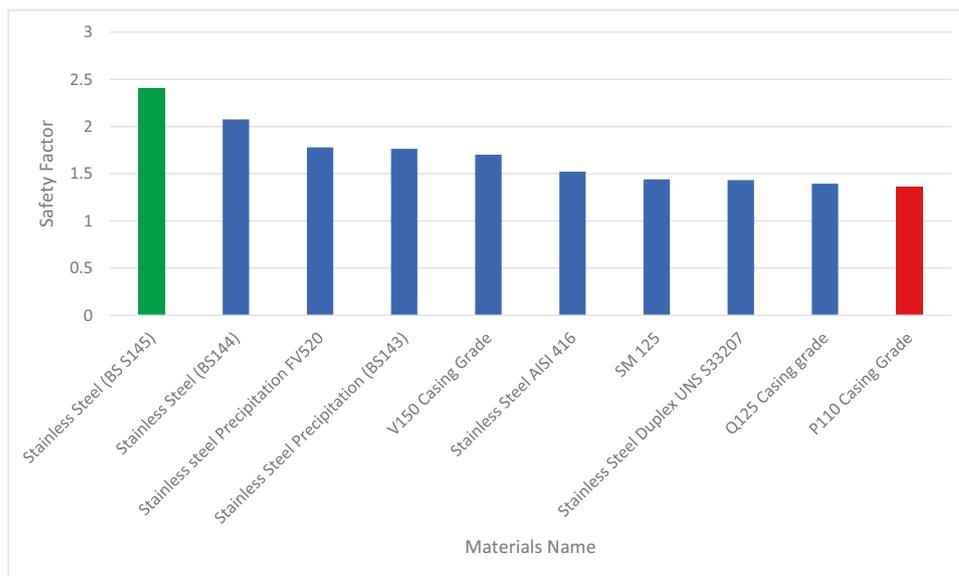**Fig. 12** Safety factor for the 10 shortlisted materials as evaluated from FEM for each material

Table 5 comparison between other studies and the present for stress and safety factor

References	Von Mises stress (MPa)	Safety factor (margin)
Yan et al. (2017)	1134	0.76
Mohammed et al. (2021)	932.46	0.8
Li et al. (2020a, b)	816.42	0.93
Present study	634	1.4

reveals casing failure with a safety factor less than unity. In a different study investigating the impact of shale swelling on API casing that do not consider MCDM in the selection process indicated stress increases up to 816.42 MPa from 672.94 MPa, which exceeds the yield strength for the P110 grade casing; as a result, Q125 grade casing is needed to avoid the casing deformation under such a circumstance (Li et al. 2020a, b).

However, in comparison with the research accomplished in this paper, it is obvious that the new method for casing material selection and design gives the advantage of other material options and improved safety factor—which results in lower stresses as shown in Table 5. This shows that the new method increases design safety margin which means optimum material choice and avoiding casing deformation in shale gas wells during development.

Conclusions

The material selection of steel casing was carried out for shale gas wells considering scenarios such as buckling tendencies, long-term corrosion, impact and service temperature of such wells using CES and numerical evaluation using ANSYS Workbench. It is shown that the casing material selection for shale gas wells requires an additional step compared to the conventional selection approach to address the unusual multiple yet conflicting challenges. This additional step to a large extent depends on the specific scenario for a particular shale gas well conditions with different scenarios leading to variation in options in sets of materials available to the designer as demonstrated in this study. The shortlisted materials using this new procedure are much more reliable in terms of performance compared to the current industrial practices.

The proposed approach offers enhanced assurance with regards to establishing appropriate operational boundaries based on materials properties as per performance requirements. This is especially important as there have been cases of failures of casing materials in gas wells despite the meticulous steps taken using the conventional selection methods. While the conventional approach overlooks many selection considerations and the inter-relationship between design variables—this limitation of the conventional method may have been key factor contributing to the failures of the casing. The proposed procedure for casing material selection and analysis for downhole tubulars (pipes) performance evaluation for gas well applications is justified as presented in this paper. In all, although the P110 (API casing grade) meets the first scenario and widely used in the oil and gas sector, there are alternative

viable material candidate options that outperform P110 Grade with the best material candidate being BS S145.

Declarations

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