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The Effect of Niobium and Vanadium on the Toughness of High Strength Alloyed Line Pipe Steel Used in Gas & Oil Pipeline

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Abstract

The main objective of this research is to modify the alloy steels of high strength, toughness with good mechanical impact loading resistance properties, which are the general requirements of contractions high pressure, large diameters line pipe used for transporting oil and liquid gases, due to the large demine on these two product .

The use of Niobium (low quantities) with very good controlling on all rolling stages of production plate, which are used in pipe manufacturing (longitudinal or spiral) by dabble submerge welding (outer and inner face) are the main technology used now in pipe manufacturing.

The results of this work shows that the mechanical properties (strength, toughness, and impact resistance) are improved when we used Vanadium with Niobium (controlling quantities), because of their effects on grain size and initiations of precipitation Harding during phase transformations from austenite to ferrite and under full rolling parameters controlling. This leads to have high strength low alloyed line pipes steels (HSLALP) suitable for the longitudinal, spiral pipe mills which satisfy the user requirements in developing the most suitable chemical and mechanical properties line pipe steels.

الخلاصـــــــة

يهدف البحث لتطوير سبائك الفولاذ العالي المقاومة والمتانة والذي يمتلك مواصفات ميكانيكية جيدة لمقاومة الصدمة يُلائم متطلبات إنشاء خطوط الأنابيب ذات الأقطار والضغوط العالية المُستخدمة في نقل المُنتجات النفطية والغاز السائل والتي أصبحت مُلِحة في الفترة الاخيرة بسبب زيادة الطلب على النقل بواسطة الأنابيب بدل الوسائل الأخرى. إن إستخدام عنصر النابيون بنسبة مُحَددة وإضافته مع السيطرة على مراحل الدَرفلة للصفائح المُستَخدَمة في إنتاج الأنابيب بالطريقتين الطولية والحلزونية والتي يُستَخدَم اللحام الغاطِس من الوَجهين (الداخِل والخارج) هو الأسلوب المُعتَمَد حالياً في إنتاج الأنابيب أعلاه. لقد لوحِظ بأن الخواص الميكانيكية من مقاومة ومتانة ومقاومة الصدمة تتحسن بشكل كبير عند إستخدام عُنصري النابيون والفانديوم وبنسب مُحَددة وذلك بسبب تأثيرها على الحجم الحبيبي وأحداث التقسية الترسيبية خلال التحول التطوري من طور الاوستانيت الى الفرايت وتحت السيطرة التامة على العوامل الداخلة في عملية الدرفلة مما أدى الى الحصول على فولاذ عالي الخواص ومناسب لمتطلبات المُستخدم في إنشاء خطوط الأنابيب الطويلة.

1- Introduction

From the early stage of eighties years, energy cost increases prompted high capacity pipe lines designing criteria [1] .High capacity pipe lines mean pipe diameter increases as well as operating pressure are very high, steels having higher tensile properties were required [2] .

In general, American Petroleum Institute (API) 5L specification steels are used in pipelines. Pipeline wall thicknesses are established on the pressure in the line and on the allowable hoop stress levels for the material. The allowable stress levels for gas pipelines vary based on the location of the pipeline and are regulated by the U.S. Department of Transportation (DOT).

Pipelines are pressure tested in addition to nondestructive testing prior to being put into service. Normally, pipelines are hydrostatically stressed to levels above their working pressure and near their specified minimum yield strength. This pressure is held for several hours to ensure that the pipeline does not have defects that may cause failure in use. This proof test of pipelines provides an additional level of confidence that is not found in many other structures.

The productions of plate of high – strength, high toughness wieldable line pipe have a fine – grained polygonal ferrite structure, polygonal – acicular ferrite structure, or mixed are required. A specific reason for choosing acicular ferrite in the low carbon steels is related to the fact that a high toughness level is usually associated with high strength properties and therefore a satisfactory balancing of toughness and strength is obtainable in polygonal ferrite steel [3] .

Steel used for pipe manufacturing is subjected to severe metallurgical controls; deoxidization of liquid steel by micro-alloying elements determines the volume fractioned the morphology of the oxide and sulphide inclusions in the product, in turn, control the impact properties. The volumetric fraction of non – metallic inclusions whose dimensions exceed the critical one and its morphology (elongated, clustered or stringer) greatly influence steel ductility properties. Applied of hot metal desulphurization processes actually allows production of steels with higher impact energy values [4].

To attain a high shelf – energy and a low ductile – to – brittle transitions temperature it is necessary to greatly reduce the steel sulpher content by desulphurization's the hot metal [5] . The former being necessary for improving of brittle and shear fracture propagation [6] .

Present paper deals with the most important stages of production route which play a strong role on obtaining requested materials properties for the final use. The results are the actual feasibility to produce HSLA pipe line steels having high toughness properties and good weldability characteristics.

2. Experimental work

Chemical compositions for pipe steels according to the standard (API SPEC.5L) are shown in the table (1) and the Mechanical properties for these steels are shown in table (2) respectively.

2.1 sample preparation

- Four types of low carbon steel are used as raw materials with 75% scrap of the above pipe steels are mixed and a melting furnace type Fluxotherm [FLUXO-002] is used for melting 5 Kg batch of each sample of the four experimental samples used in this research.
- Niobium elements quantities are calculating as weight percentage required for a concentration between [0.03 to 0.06] .The four batch have the same dosage .Two batch have Vanadium dosage of [0.04 to 0.075] calculated as weight percentage (sample 1 and 4).
- The decreases of sulfur content are obtained with hot metal desulphurization process, performed by addition of CaC_2 (sulfide inclusion shape control is obtained by adding to the steel calcium compound). Reaction of calcium in steel produces sulfide inclusions which remain underformed during rolling stage.
  - Carbon equivalent Formula is taken as [7] ;

$$C + \frac{Mn}{6} + \frac{Mo + V + Cr}{15} + \frac{Cu + Ni}{5} \quad \ldots\ldots\ldots\ldots \quad (1)$$

2.2 Casting

The conditions of solidification control the distribution of non – metallic inclusions and carbon nitride particles. Continuous casting, with its faster cooling rates, is more versatile than ingot casting to the optimization of the size and effectiveness of second phase particles [8] , but because of laboratory equipments limitations' traditional ingot casting process are used to produce the experimental samples.

- The 5 Kg are used to produce 5 slabs of 10 x10 mm square cross section each of 1 Kg weight.
- The total numbers of experimental samples slabs are 20.
- High cooling air rate are used for cooling the slabs to control the distribution of non-metallic inclusions.

2.3 Treatments

- In order to provide homogeneous original microstructure, the slabs are normalized to temperature 850^0C. Heating of specimens was done in muffle furnace type [VEB, 245.3E]. The furnace is automatically controlled.
- The chemical analysis of these steels was done by quanta meter analysis [OPTICAL EMISSION QUATOMETER Type 3400], Table 3 shows the final chemical compositions analysis for experimental samples used during this works.
- Metallographic analyses were done by means of microscope type [NEOPHOT 2 OPTICAL METALLOGRAPHICAL MICROSCOP] with connection with Camera of 35(mm) negative film.(Microstructure was revealed by 2% Nital Etchant).

2.4 Mechanical Properties Measurements

- Tensile tests were performed on rectangular stripe according to the standard set by ASTM. MTS 810 – Material Test System with load frame capacity of [50 kips] are used for these purpose.
- Impact tests in this study were conducted using an instrumented impact testing system [MAT 21 / IT 3 U – Universal Pendulum Impact Tester].

2.5 Control Rolling Technique

- Controlled rolling process is mainly based on the effect of the micro-alloying elements in terms of austenite re-crystallization times after hot deformation, which permits one to optimize the relationships among steel composition, through the proper metallurgical use of the re-crystallization and growth process going on in the hot – deformed austenite.
- Two kinds of controlled rolling process have been tested which differ in ***the reheating slab temperature***, and both have ***low final temperature***.
  - ➢ The First set of experimental work involved high reheating slab temperature and complete solution of alloying element in the austenite.
  - ➢ The second set of test starts from low reheating temperature, in such condition there is not a complete micro – alloying elements dissolution in austenite.
- Rolling Stand is locally manufactured, used to perform the rolling control parameters study.

3- Result and Discussions

3.1 Tensile strength

- A round specimen from inflating sample and a strap specimen from adjacent cold – flattened sample, were tested for yield (σ_y) and ultimate tensile strength (σ_{Uts}).
- The test results summarized in table (5). The results shows that;-
  - No difference in average tensile strength are observed between round and strap specimen [631 Mpa] if the structures are acicular ferrite. But 0.96% incremental in yielding strength for round specimen over that strap one.
  - 0.3% and 0.71% are the differences between tensile and yield strength respectively if the structures are polygonal ferrite.[samples no. 2 and 3].
  - 1.97% and 1.95% are the differences between tensile and yield strength respectively if the structures are mixed (acicular + polygonal ferrite).[sample no. 4].
- The test results indicated that for the considered experimental steel samples, pipes show a yield strength approximately 10 to 50 [Mpa] higher when round specimens are used.
- Strap specimen exhibit continues stress – strain curve without the upper yield point shown on round specimens.
- Unflattened round specimens are more realistically informative.
- The steel yield strength value represents the starting point for permanent deformation behavior. Therefore only a percentage of the specific minimum yield strength is used in pipeline design as hoop stress, which, turns, constitutes a reference value for calculating the maximum allowable operating pressure, and due to bauschinger effect [9], (changes of steel properties during unbending and flattening of the test sample) a drop in yield strength caused by reversing the direction of stressing occurs during sample flattening.

3.2 Notch toughness

- The Chirpy-V Notch energy are measured for different thickness machined from experimental four samples slabs ,which are used to calculate the 2/3 chirpy energy.
- The [2/3] Chirpy-V energy can be calculated as a function of pipe diameter and thickness, backfill depth and the designed hoop stress ,Table (6) shows the results of impact loads experiments .
- The results are summarizes as follows;

- For constant wall thickness, the Charpy V notch toughness energy [J] are increase as the hoop stress [Mpa] increases , 0.863% an increase in toughness for corresponding incremental of 6% in hoop stress at outer diameter of 812[mm] and wall thickness of 8[mm].
- No much difference are found in increasing the wall thickness .For a 125% increasing in wall thickness (from 8 to 17 mm) the toughness is higher by only 0.48%.that means for each working pressures requirements (hoop stress) there are an optimization required for calculating the toughness energy and wall thickness to safe the weight due to extra wall thicknesses.
- For 0.751% increasing in outer diameters (812 to 1422mm), a 0.93% increasing in Charpy V notch toughness energy [J] at constant hoop stress.

- The results show that Toughness is of paramount importance in line pipe material for fracture initiation and fracture propagation control (Fracture control design, which is aimed at minimizing the likelihood of pipe failure, takes into separate consideration the fracture initiation and the fracture propagation control).
- There is a linear relationship between the Chirpy V – notch transition temperature, and shelf energies (which are compatible with some other authorities [10]).
- The variations of toughness are shows in Figures 2 to 7. These results are summarized as follows;
  - Figure 2, shows that the toughness as a relation between wall thickness and hoop stress for 812[mm] outer diameter. For hoop stress of 250 [Mpa] the optimum thickness is 8[mm] and any increases in wall thickness is a lost of money, for 300[Mpa], 350[Mpa] and400 [Mpa] are 11[mm], 14[mm] and 17[mm] respectively. This means that higher toughness required for higher internal working pressures (higher hoop stress level).
  - Similar results are found in Figure 3. As the wall thickness increase with hoop stress incremental due to inner working pressure increase, the toughness also increase, for 250 [Mpa] hoop stress the thickness is 11[mm] and toughness is 27 [J] which is higher than that of 812 [mm] outer diameter by 5[J], and 56 [J] for 400[Mpa] and 17[mm] wall thickness, which is higher than that of 812[mm] by 13 [J].
  - Figures 4 &5 are shows the same differences in the results as before for 1220[mm] &1422[mm].
  - Figures 6 &7 shows all these results mentioned before. its is clear that the toughness is increase as the hoop stress increase for the same wall thickness and as the outer diameter is increased as shown in figure 7.

4- Conclusions

4.1The Effect of Amounts of Niobium

4.1-a) High Reheating Slab Temperature

- It should be pointed out that Niobium is a fundamental element. It influences the other rolling parameters so strongly that one could not conceive at the present optimum controlled rolling process without including Niobium.
- Niobium steels are confirmed to be the most sensitive.
- Niobium precipitates as carbon nitride in austenite during plate rolling, it's re-crystallized between each deformation; that leads to a refinement of the austenite grain and subsequently of the acicular ferrite structure. Figure 1 – c (Steels without Vanadium)
- The steel strength is increased due to precipitation mechanism of fine Niobium carbon nitride in acicular ferrite structures; the start of precipitation in the ferrite coincides with the $\gamma \Rightarrow \alpha$ transformation.

4.1-b) Low Reheating Slab Temperature.

- Lowering the slab reheating temperature has an effect on the size of the austenite grains which are more smaller and the Niobium carbon nitride precipitated at lower temperature ; Resulting in mixed effect on the size and the shape of the acicular ferrite structure . Figure 1 – D

4.2 The Effect of Vanadium

- Vanadium is used as micro alloying element for heavy wall thickness, vanadium bearing steels perform in the same way as Niobium bearing steels, more vanadium than Niobium is required to obtain the same degree of precipitation hardening, the use of vanadium and Niobium additions increases the tensile strength (Table – 4). The incremental in the mechanical properties of materials used in experimental works [1^{st} and 2^{nd}] sample which are 0.4% to 0.66% for tensile strength and between 0.86% to 1.57% for yield strength.
- The results are similar for two type of reheating the slabs during rolling processes. Figure 1 – D (Specimen No.4 – Steel used in experimental works sample No. 2 of chemical compositions given in Table 3- with 0.06 to 0.8% Vanadium).
- The effects of Nb and V elements on the microstructure of low alloy pipe line steels are shown clearly in Figure 1, the comparisons between the strictures of steels grade X60 and X42 given in A & B with that of C&D are shows how the

Nb &V refinement the grain strictures resulting in acicular ferrite, with an improvement in mechanical properties.

4.3 NOTCH TOUGHNESS

- The toughness is a function of many factors as wall thickness, the outer diameter of the pipe line, and hoop stress.
- There are always an optimal wall thickness must be calculated carefully and experimentally approved towards the good parameters optimization of pipe lines.

4.4 The Holding Time For Cooling

- Holding for cooling was done at four times the final plate thickness (total controlled reductions were about 70 – 75 %) , this holding has no effect on toughness , perhaps because of the low reheating temperature used or because of the grain refining action of roughing passes.
- Lowering the slab reheating temperature has the same effect as increasing the total controlled reduction ratio and the same effect as lowering the finish roll temperature (FRT).

Table (1) : Chemical Composition of Steels for Line Pipes According to API Spec. 5L

Grade of Pipes API Spec 5L	*C*	*Mn*	*Si*	*P*	*S*	*Cr*	*Ni*	*Cu*
A25	0.17-0.21	0.35-0.60	0.17-0.37	0.3	0.3	0.3	0.3	0.3
A	0.17-0.22	0.35-0.65	0.17-0.37	0.30	0.30	0.30	0.30	0.30
B, X42	0.17-0.24	0.35-0.65	0.17-0.37	0.30	0.30	0.30	0.30	0.30
X4 , X52 X5 , X60	0.17-0.24	0.60-1.00	0.17-0.37	0.30	0.30	0.30	0.30	0.30
X42 , X52 X56 , X60	0.12-0.19	0.70-0.90	0.20-0.37	0.30	0.30	0.20	0.20	0.30

Table (2) : Mechanical Properties Of Steel For Line Pipe According To API Spec. 5L.

Pipe Grade API Spec. 5L	Designation of Indices		
	Tensile Strength U_{ts} (Mpa)	Yield Strength σ_y (Mpa)	Elongation%
A25	Not		
	310	172	34 – 38.5
A	331	207	32 – 36
B, X42	413	241	26 – 29.5
X46	434	317	25 – 28.5
X52	455	358	24 – 27
X56	489	386	22.5 – 25.5
X60	517	413	21.5 – 24

Table (3) : Compositions of Materials Used For Experimental Work

Sample No.	Elements Fraction Of Total Mass , %											
	C	Mn	Si	P	Al	Nb	S	V	Mo	Cr	Ni	C . E
1	0.06-0.09	1.5-1.7	0.20-0.030	0.020	0.015-0.060	0.035-0.055	0.008	0.045-0.065	------	0.15-.025	------	0.392
2	0.05-0.08	1.5-1.7	0.20-0.030	0.020	0.015-0.050	0.035-0.055	0.008	-------	0.20-0.30	------	0.35	0.605
3	0.12-0.16	1.30-1.65	0.20-0.030	0.020	0.015-0.050	0.035-0.055	0.008	-------	------	------	------	0.385
4	0.10-0.16	1.30-1.65	0.20 -0.030	0.020	0.015-0.050	0.035-0.055	0.008	0.06-0.08	------	------	------	0.403

Table (4) : Mechanical Properties of Materials Used In Experimental Work.

Experimental Sample	*Designation of Indices*		
	Tensile Strength σ_{uts} *(Mpa)*	*Yield Strength* $\sigma_{y,}$ *(Mpa)*	*Elongation* *% (50 mm)*
1	640	550	34
2	635	554	36
3	600	475	32
4	610	510	31

Table (5) : Results of tensile experiment Comparisons of round and strap specimens result.

Sample No.	*No. Of Tested Specimen +type of structure*	*Average Tensile Strength, (Mpa)*		*Average Yield Strength (Mpa)*	
		Round Specimen	*Strap Specimen*	*Round Specimen*	*Strap Specimen*
1	(4) a circular ferrite	631	630	557	508
2	(4) a polygonal; ferrite	635	616	525	490
3	(4) a polygonal; ferrite	600	595	502	460
4	(4), a circular + a polygonal; ferrite	625	522	556	465

Table (6) : Charpy V – Notch Toughness (J) As Function Of Pipe Outside Diameter (mm) , Wall Thickness (mm) , and Hoop Stress (Mpa)

Out Diameter	*812 (mm)*				*1016 (mm)*				*1220 (mm)*				*1422 (mm)*			
Hoop Stress → *Wall Thickness ↓*	250 Mpa	300 Mpa	350 Mpa	400 Mpa	250 Mpa	300 Mpa	350 Mpa	400 Mpa	250 Mpa	300 Mpa	350 Mpa	400 Mpa	250 Mpa	300 Mpa	350 Mpa	400 Mpa
8mm	22	28	34	41												
11mm	21	28	35	42	28	36	45	54								
14mm	20	27	35	42	27	36	45	55	34	45	56	68				
17mm	20	27	35	43	27	36	46	56	34	45	57	70	41	55	68	83
20mm					26	36	47	58	34	46	58	72	42	55	70	86
22mm									34	46	59	73	42	56	71	67
25mm													42	56	73	90

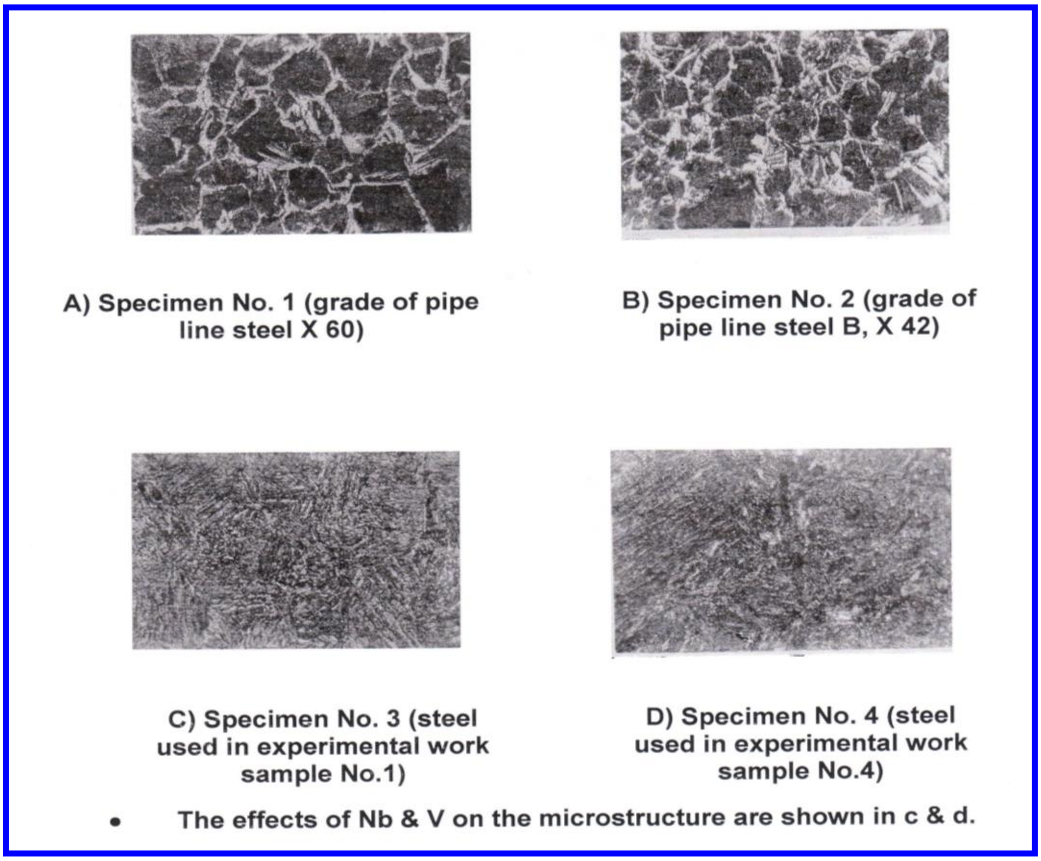
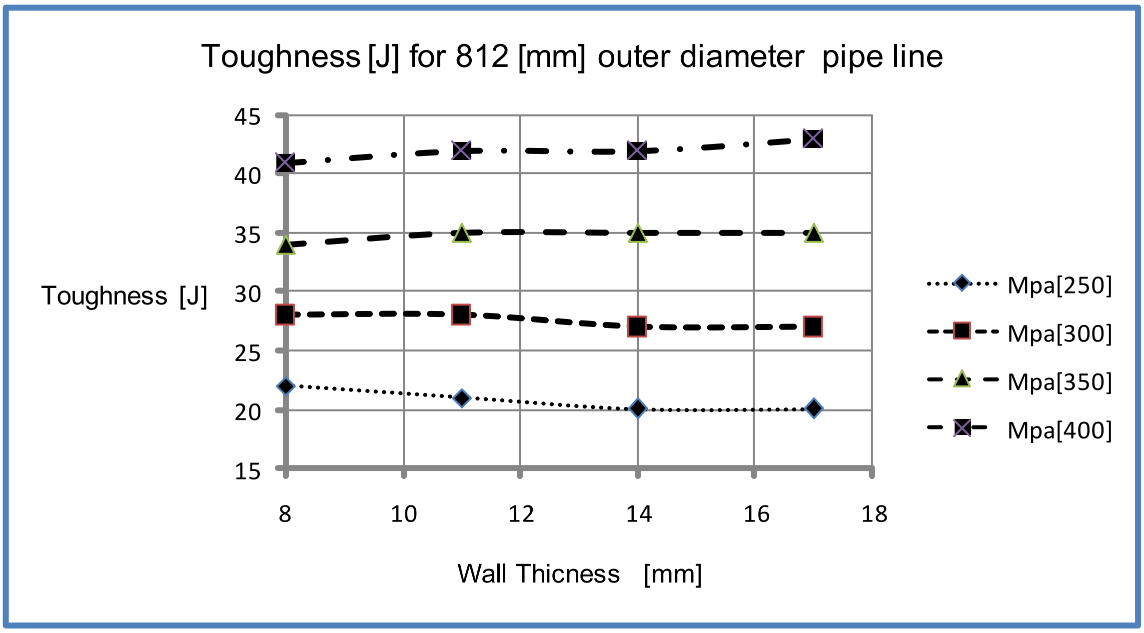


Figure (1) : Microstructure of Samples Used in Experimental Works before and after Nb & V are Used (A&B are tested samples taken from standard



pipe line steels. All 1000X) Used

Figure (2) : Toughness as a relation between wall thickness and hoop stress for [812 mm] outer diamiter of the pipe

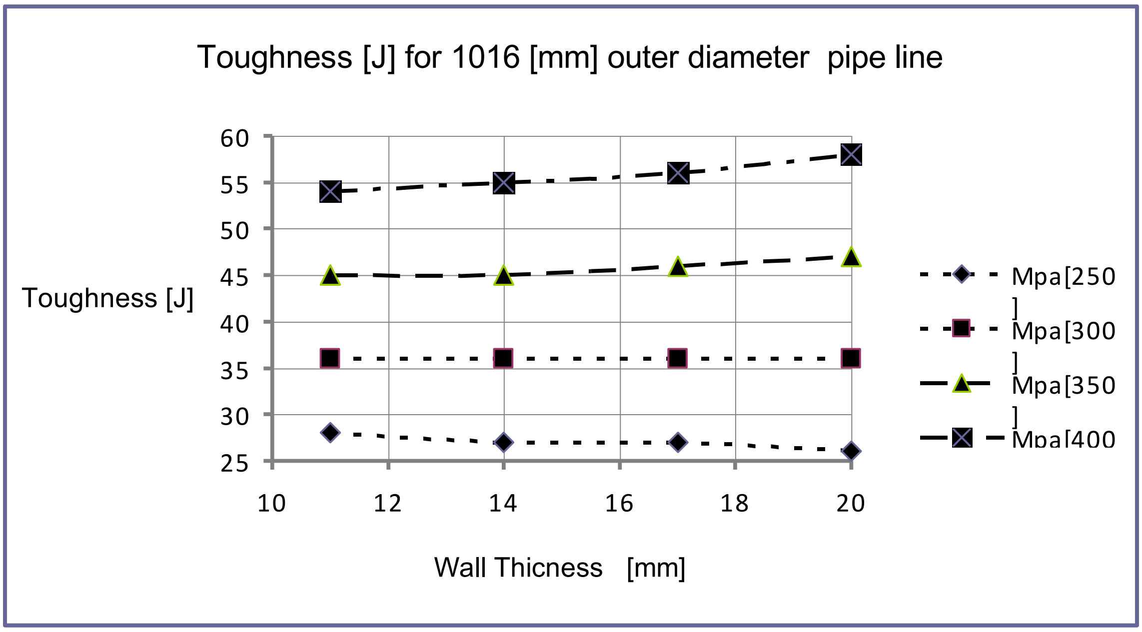


Figure (3) : Toughness as a relation between wall thickness and hoop stress for [1016 mm] outer diamiter of the pipe

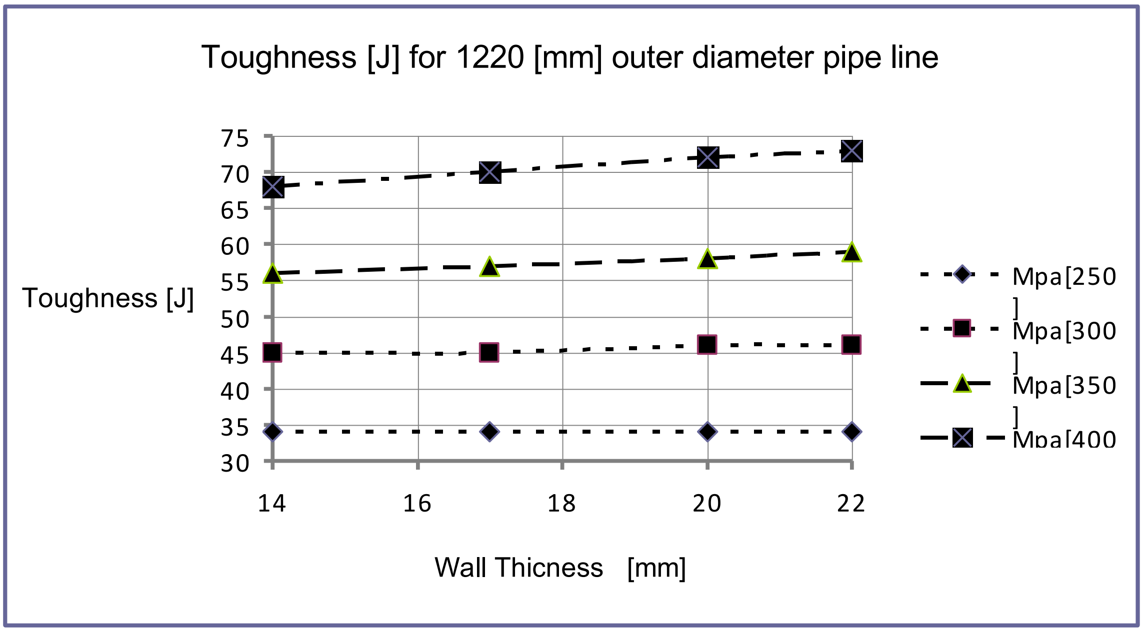


Figure (4) : Toughness as a relation between wall thickness and hoop stress for [1220 mm] outer diamiter of the pipe

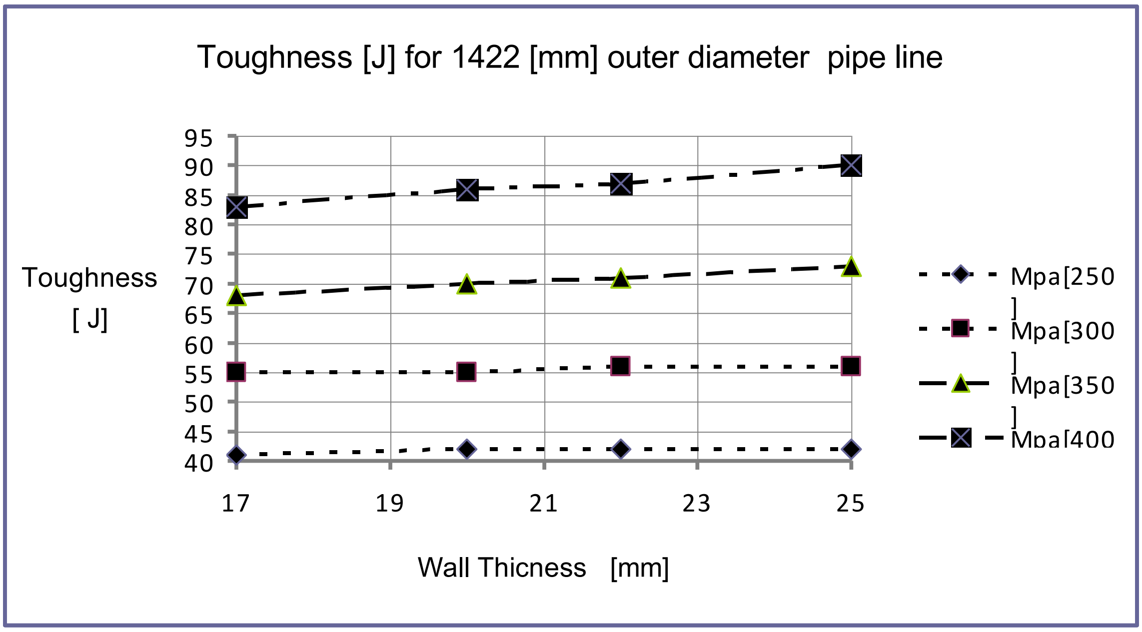


Figure (5) : Toughness as a relation between wall thickness and hoop stress for [1422 mm] outer diamiter of the pipe

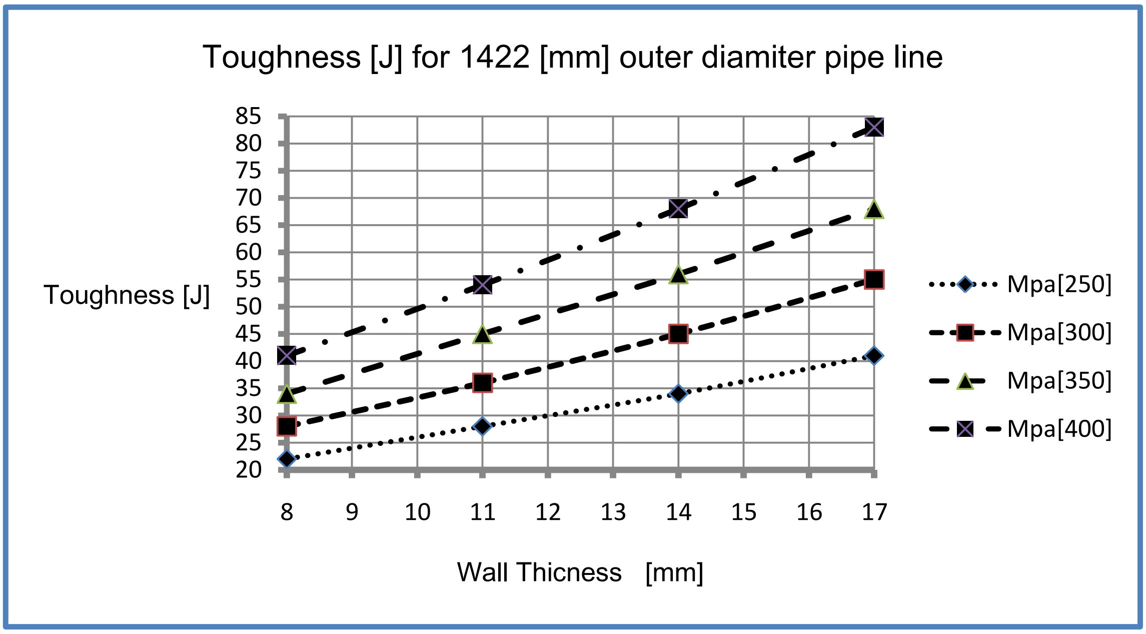


Figure (6) : Toughness as a relation between wall thickness and hoop stress as function of the outer diamiter of the pipe

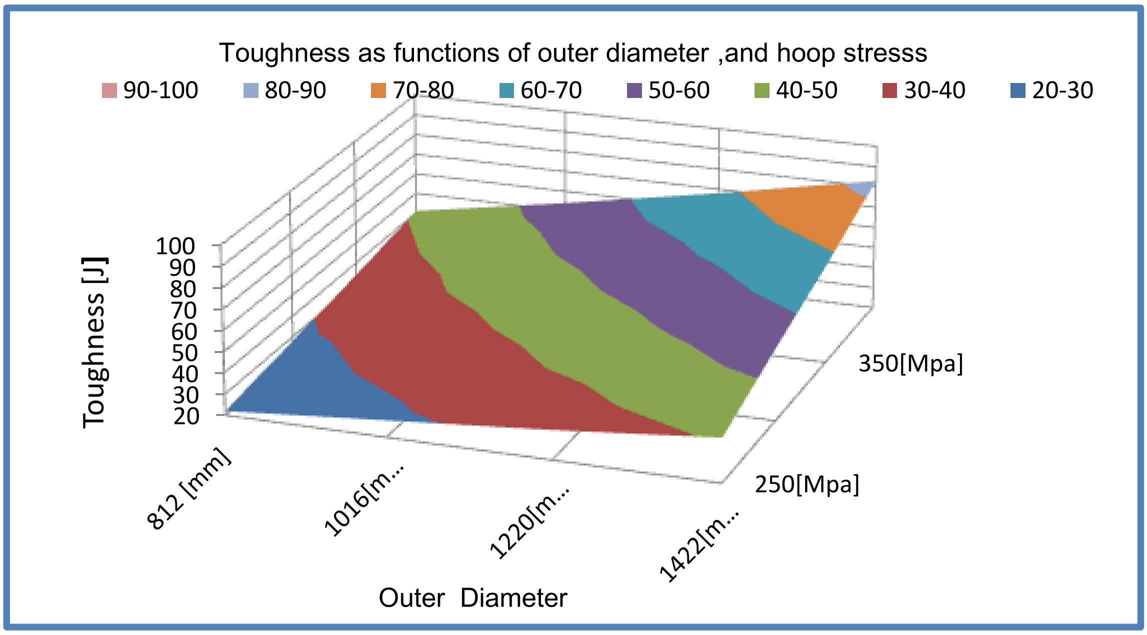


Figure (7) : Toughness as a relation between hoop stress and of the outer diamiter of the pipe

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