

Ministry of Higher Education and Scientific Research

Hassiba Benbouali University of Chlef

Faculty of Technology

Department of Mechanical Engineering



# THESIS

to the fulfilment of the requirements for a

## DOCTORATE

Field: Mechanical engineering

Specialty: Energetic

By:

**MESSAOUD Zahi**

Title:

**Investigate of pipelines repair by composite materials and natural fibers, considering the influence of the chemical properties of hydrocarbons on their structures**

Defended on 27-02-2025, before a jury composed of:

ZAHOUH Hamou	Professor	Hassiba Benbouali University of Chlef	President
MAAZOUZI Reda	Professor	Djilali Bounaama of University Khemis Miliana	Examiner
BOUZIDANE Ahmed	Professor	Ibn Khaldoun University of Tiaret	Examiner
TOUAIBI Rabeh	Professor	Djilali Bounaama of University Khemis Miliana	Examiner
MENDAS Mohammed	Professor	Hassiba Benbouali University of Chlef	Examiner
MERIEH Benziane Madjid	Professor	Hassiba Benbouali University of Chlef	Supervisor

---

# Acknowledgement

I thank ALLAH the Almighty for giving me the courage, will and patience to complete this present work.

I would like first to warmly thank my thesis director, Mr. **Madjid Meriem Benziane** Professor at the University Hassiba Benbouali University of Chlef for his valuable advice and help as well as the attention with which he surrounded me throughout the duration of this work. May he be assured of my deep appreciation, gratitude and sympathy.

Secondly, I would like to thank Professor **Hamou Zahoul**, Director of the Laboratory of **Rheology and Mechanics** (LRM), **Hassiba Ben Bouali-Chlef**, who did me the honor of being the president of the thesis jury. May he find here my gratitude and recognition for the interest he has shown in this work.

I am grateful to the entire team of the **ALTUMET-Raghia** company laboratory (in Algeria) and the **ORSIM-Oued Rhiou** company laboratory (in Algeria) for their knowledge support and expertise assistance in the field of mechanical testing while throughout the internship.

Additionally, I thank Professor **MAAZOUZI Reda** of the **University Djilali Bounaama Khemis Miliana**, who gave me the honor of being a thesis examiner. May he find here the expression of my deep gratitude and my sincere appreciation.

I thank Professor **Rabeh TOUAIBI** of the **University Djilali Bounaama Khemis Miliana** who gave me the honor of being a thesis examiner. May he find here the expression of my deep gratitude and my sincere appreciation.

I thank Professor **Ahmed BOUZIDANE** of the **University Ibn Khaldoun of Tiarte**, who gave me the honor of being a thesis examiner. May he find here the expression of my deep gratitude and my sincere appreciation.

I thank Professor **Mohammed MENDAS** of the **University Hassiba Benbouali of Chlef**, who gave me the honor of being a thesis examiner. May he find here the expression of my deep gratitude and my sincere appreciation.

## ***Dedication***

*I dedicate this modest work*

*To the memory of my late brother Hacem and to my dear father Salah.*

*To my mother who was always by my side*

*To my wife Assia*

*To my children: Fatima, Nour El Houda, Miliza and Ibrahim*

*To my brothers and sisters*

*To all my families*

*To my work colleagues*

*To all my friends.*

## ملخص:

يهدف هذا المشروع إلى دراسة تأثير العيب شبه الإهليجي تجريبياً على فولاذ خط الأنابيب API X52 وإصلاحه باللحام وبرقعة من المركبات الهجينة المصنوعة من الألياف الطبيعية والمواد الاصطناعية. تم إجراء اختبارات الشد على عينات فولاذ API X52، مع وبدون عيوب شبه إهليجية من خلال تغيير نسب  $a/t$  و  $a/c$ ، ثم تم اختبار العينات التي تم إصلاحها باللحام والرقع المركبة ومقارنتها بنتائج عينات المواد الأصلية. تشير النتائج التجريبية للخصائص الميكانيكية إلى تأثير العيوب على سلامة خط أنابيب نقل الطاقة من خلال النسب المختلفة لـ  $a/c$  و  $a/t$ . لوحظ أن عيوب نسبة  $a/t$  أكثر خطورة من نسبة  $a/c$  خاصة عندما تكون نسبة  $a/t$  أعلى من 0.5. من الواضح أنه يمكن اعتبار كل من طرق إصلاح اللحام والرقع المركبة حلاً للحفاظ على سلامة أنظمة الأنابيب.

**الكلمات الرئيسية:** التآكل، الفولاذ API X52، العيوب شبه الإهليجية، خطوط الأنابيب، الإصلاح، اللحام، التصحيح، الألياف الطبيعية، المواد المركبة الهجينة.

**Abstract:**

The aim of this project is to experimentally study the effect of semi-elliptical defects on API X52 pipeline steel and its repair by welding and by patching with hybrid composites made of natural fibers and synthetic materials. Tensile tests were performed on API X52 steel samples, with and without semi-elliptical defects through the variation of  $a/c$  and  $a/t$  ratios, and then the samples repaired by welding and composite patches were tested and compared with the results of origin material samples. The experimental results of mechanical properties indicate the effect of defects on the integrity of the pipeline of energy transport through the different ratios of  $a/c$  and  $a/t$ . It was observed that  $a/t$  ratio defects are more dangerous than the ratio  $a/c$ , especially when the ratio  $a/t$  is higher than 0.5. It is clear that both welding repair and composite patch methods can be considered as a solution for maintaining the integrity of the piping systems.

**Keywords:** Corrosion, API X52 steel, Defects Semi-elliptical, Pipeline, Repairing, Welding, patch, Natural fiber, Hybrid composite materials.

**Résumé :**

L'objectif de ce projet est d'étudier expérimentalement l'effet du défaut semi-elliptiques sur l'acier de canalisation API X52 et sa réparation par soudage ou par patch de composites hybrides en fibres naturelles et matériaux synthétiques. Des essais de traction ont été réalisés sur des échantillons d'acier API X52, avec et sans défauts semi-elliptiques à travers la variation des rapports  $a/c$  et  $a/t$ , puis les échantillons réparés par soudage et patchs composites ont été testés et comparés aux résultats des échantillons de matériaux de base sans défaut. Les résultats expérimentaux des propriétés mécaniques indiquent l'effet des défauts sur l'intégrité de la canalisation de transport d'énergie à travers les différents rapports  $a/c$  et  $a/t$ . Il a été observé que les défauts de rapport  $a/t$  sont plus dangereux que le rapport  $a/c$  surtout lorsque le rapport  $a/t$  est supérieur à 0,5. Il est clair que les méthodes de réparation par soudage et par patch composite peuvent être considérées comme une solution pour maintenir l'intégrité des systèmes de transport.

**Mosts clés :** Corrosion, acier API X52, défauts semi-elliptiques, pipeline, réparation, soudage, patch, fibre naturelle, matériaux composites hybrides.

## Contents

Abstracts: Arabic, English, French	I
Figures list	x
Tables list	xvi
List of Abbreviations	xv
General introduction	1
<b>Chapter 1: Review of Steel, Fiber natural with its derivations and using in piping systems</b>	
1.1 Introduction.....	4
1.2 Pipelines.....	4
1.3 High grade steels for pipeline.....	5
1.4 Pipeline manufacturing process.....	5
1.4.1 Welded piping systems in a spiral form.....	7
1.4.2 Forming and welding of the strip.....	7
1.4.3 Pipe testing and control conformity of norms.....	8
1.4.4 Internal and external pipe coating.....	8
1.4.5 Final inspection and storage.....	9
1.5 Steel manufacturing process .....	10
1.5.1 Pipelines material norms.....	11
1.5.2 High grade wires for pipelines.....	14
1.5.3 Physical characteristics of the thermo-mechanical control process (TMCP)....	16
1.6 Syntheses bibliography .....	17
1.6.1 Interaction between pipeline and hydrocarbons.....	18
1.6.2 Welding process.....	21
1.6.3 Composite materials.....	21
1.6.4 Natural Fibers.....	22
1.6.5 Application of Natural fiber in building.....	22
1.6.6 Industrial fibers (Carbon and glass fibers).....	24
1.6.7 Hybridization of natural fibers with synthetic fibers.....	24
1.6.8 Application of Natural fiber in automobile.....	25
1.6.9 Piping systems corrosion.....	26
1.7 Conclusion.....	27

## **Chapter 2: Corrosion and repair by patches**

2.1 Introduction.....	29
2.2 Corrosion .....	30
2.3 External corrosion of hydrocarbon pipelines.....	30
2.3.1 Corrosion of different cells.....	31
2.3.2 Galvanic corrosion .....	31
2.3.3 Uniform Corrosion .....	32
2.3.4 Pitting corrosion.....	32
2.3.5 Caving corrosion.....	32
2.3.6 Under deposits corrosion.....	32
2.4 Corrosion interne of pipeline.....	34
2.4.1 Under Deposit Corrosion (UDC).....	35
2.4.2 Defects of corrosion in the piping systems.....	35
2.5 Method of calculating corrosion defects.....	36
2.5.1 Corrosion defect evaluation.....	36
2.5.2 Evaluate depending the time.....	37
2.5.3 Data pressure evaluation.....	38
2.6 Maintenance of piping systems.....	39
2.6.1 Uses of inhibitors.....	39
2.6.2 Repairing by Patch.....	40
2.6.3 Repairing with welding.....	41
2.6.4 Pipeline Repair by FRP.....	42
2.6.5 Pipeline Repair by composite hybrid.....	45
2.7 Conclusion.....	48

## **Chapter 3: Experimental study of specimens with/without defect and repaired by welding**

3.1 Introduction.....	50
3.2 Modeling the corrosion defects of pipeline .....	52
3.3 Piping System Welding .....	53
3.4 Choice to proceed with the assembly of the tubes.....	53
3.4.1 Manuelwelding .....	53
3.4.2Automated welding.....	54
3.5 Material and experimental methods.....	54

3.5.1 Material.....	54
3.5.2 Test specimen and experiment.....	55
3.5.2.1 Tensile test specimens.....	55
3.5.2.2 Experimental method.....	57
3.5.3 Test results and Analysis.....	58
3.5.3.1 Experimental method.....	58
3.5.3.2 Tensile test of different specimens.....	60
3.5.3.3 Tensile test of specimen with defect through ratio $0 < a/c \leq 1$ .....	61
3.5.3.4 Tensile test of specimen with defect ratio $0 < a/t \leq 0.8$ .....	63
3.6 Automatically and manually welding operations.....	65
3.6.1 Results of repaired pipes and compared.....	65
3.7 Discussions of results.....	67
3.7.1 Results of Ultimate strength.....	67
3.7.2 Results of Ultimate strength, Ratio of $0 < a/t \leq 0.8$ .....	68
3.7.3 Elongation test tensile of base metal, defect metal and repaired metal.....	68
3.7.4 Toughness test tensile of base metal, defect metal and repaired metal.....	70
3.7.5 Toughness results for Ratios $0 < a/c \leq 1$ and $0 < a/t \leq 0.8$ .....	72
3.8 Conclusion.....	73
<b>Chapter 4: Experimental study of specimens with/without defect and repaired by patches composites hybrid</b>	
4.1 Introduction.....	75
4.2 Industrial of natural fiber composite and hybrid.....	78
4.3 Uses of Composite Patch in Repair.....	79
4.4 Pipeline repair with natural fiber.....	79
4.4.1 Materials.....	79
4.4.2 Composite materials.....	79
4.4.3 Jute fiber.....	79
4.4.4 Glass Fibers.....	80
4.4.5 Metal wires.....	81
4.4.6 Polyester resin.....	81
4.4.7 Mass Fraction of composite.....	83
4.4.8 Pipeline material.....	84
4.5 Manufacturing method of composite materials.....	84
4.6 Experimental specimens.....	85

4.6.1 Composite specimens.....	85
4.6.2 Specimens API X52 pipeline steel.....	86
4.7 Experimental tests.....	88
4.7.1 Mechanical tests.....	88
4.7.2 Tensile testing.....	88
4.7.3 Flexural testing.....	90
4.8 Result and desiccation.....	92
4.8.1 Tensile test.....	92
4.8.2 Toughness composites.....	95
4.8.3 Flexural test.....	96
4.9 Repairs with patches and calculated Efficiency.....	98
4.9.1 Repair with patch.....	98
4.9.2 Calculate patch efficiency.....	101
4.10 Fractography analysis of samples .....	104
4.11 Conclusion.....	105

## Figures List

### Chapter 1: Review of Steel, Fiber natural with its derivations and using in piping systems

Fig.1.1 Project of the trans-Saharan gas pipeline region through Niger and to the town of Hassi R'Mel in Algeria – is to connect regional African and European .....	5
Fig.1.2 Process Seamless Pipes [3, 4].....	6
Fig.1.3 Process welded pipes in longitudinal form [4,5].....	6
Fig.1.4 Process welded pipes in spiral form [6,7].....	6
Fig.1.5 Technique for shaping the welded pipeline into the spiral.....	7
Fig.1.6 Manufacturing pipe machine in content (forming and welding).....	8
Fig.1.7 Outer pipe stripping.....	8
Fig.1.8 Cladding of pipes a) exterior and b) interior.....	9
Fig.1.9 Marking of pipes a) exterior and b) interior.....	9
Fig.1.10 Steel manufacturing process through to final product [9].....	10
Fig.1.11 The percentage of carbon depending on the grade API X42-X120 [11, 12].....	11
Fig.1.12 Développement de grade de l'acier des pipelines dans le temps, [11,19].....	15
Fig.1.13 Développement des pipelines (composition, procédé TMCP, microstructure, API grade) [ 18,20].....	15
Fig.1.14 Traitement thermomécanique lors de la mise en forme de la tôle [23].....	16
Fig.1.15 Evolution des propriétés mécaniques des plaques selon les grades [24].....	17
Fig.1.16 Damage of accident pipeline cause interaction steel-flow [30], a) broken pipe b)morphology insides the rupture fluid [31] and c)fracture due to the SCC, plastic deformation - the local bulging [29].....	18
Fig.1.17 Schematic diagram illustrating the electrochemical reactions, interaction X80 steel containing red, sol environment[33].....	19
Fig.1.18 Conventional welded and composite repair [54].....	20
Fig.1.19 a) Coconut fibers, b) Hemp fibers,c) Kenaf fibers,d) Jute fibers, e) Sisal fibers , f) Cotton fibers[72].....	23
Fig.1.20 a) Banana fibers) Bamboo fibers) Sugarcane bagasse fibers,d) Abaca fibers [72].....	23
Fig.1.21 House made with hemp concrete. [81, 82].....	24
Fig.1.22 50 components of Mercedes Benz E class was produced from natural fibers [80,106].....	25
Fig.1.23 The sketch corroded pipeline repaired by hybrid composites (natural fiber and synthetic fiber)[122].....	27

## Chapter 2: Corrosion and Repair by patches

Fig.2.1 External corrosion-induced failure mechanisms of oil and gas pipelines acting on the exterior of the pipe due to corrosive soil [30].....;	33
Fig.2.2 Représentation schématique en coupe transversale de toutes les formes caractéristiques présentées de corrosion externe[30].....	33
Fig.2.3 Représentation schématique de plusieurs formes de corrosion externe [30].....	34
Fig.2.4 Schematic of the numerical model with corrosion defects [42].....	37
Fig.2.5 Loading scheme of the pipe with an external crack under soil environment action[40].....	38
Fig.2.6 Corrosion as an electrochemical process (HyperPhysics) [155].....	40
Fig.2.7 Corrosion mechanism on the surface of the DMW [156].....	40
Fig.2.8 Schematic diagram of type-B sleeve repair method for a corroded pipeline [109].....	41
Fig.2. 9 Pipeline repair via type B Sleeve [110].....	42
Fig.2.10 composite structure of corroded pipeline repaired by sleeve [170].....	42
Fig.2.11 Specimen repair preparation of defect for hydrostatic testing [112].....	43
Fig.2.12 Application of composite wrap on the defective pipe [113].....	44
Fig.2.13 Comparison of strains in the defective and repaired pipes [113].....	44
Fig.2.14 Pipe test vessels with machined flaws with a depth of 50% wall thickness for (a) and (b) Pipe repair process filling defect with putty [114].....	45
Fig.2.15 Wrapping epoxy wetted carbon fabric around the defecting and b Example of a ruptured vessel with an axisymmetric defect [114].....	45
Fig.2.16 The three main hybrid configuration (a) interlayer or layer by layer,(b)interlayer or yarn-by-yarn, and (c) interlayer or fiber by fiber [ 172_174].....	46
Fig.2.17 Repairing in water with hybrid glass/carbon layers [175].....	46
Fig.2.18 Test after combined axial compression [175].....	47
Fig.2.19 A composite pipe in three point bending [176].....	47
<b>Chapter 3:Experimental study of specimens with/without defect and repaired by welding</b>	
Fig.3.1 Pipeline corrosion morphology [168].....	53
Fig.3.2 X52 steel pipes by arc welding a) Manuel welding,b)Automated welding.....	54
Fig.3.3 Location of tensile specimens in API 5L X52 pipe.....	56
Fig.3.4 a) Geometry standards of semi-elliptical defects b) Dimension of the test specimen.....	57
Fig.3.5 Forms of defect geometry used in the test tensile.....	57
Fig.3.6 a) Zwick-Roell brand universal testing machine, b) Specimen with defect and withoutdefect.....	58

Fig.3.7 Specimen with defect, without defect. And reared by weld.....	59
Fig.3.8 Stress-Strain curve for API X 52 pipeline steel when tested with specimen automatic weld and without weld.....	61
Fig.3.9 Stress-Strain curve for API X 52 pipeline steel when tested with the various defects tensile specimen of $0 < a/c \leq 1$ .....	62
Fig.3.10 Stress-Strain curve for API X 52 pipeline steel when tested with the repaired welding tensile specimens of $0 < a/c \leq 1$ .....	62
Fig.3.11 Stress-Strain curve for API X 52 pipeline steel when tested with the various defects tensile specimen of $0 < a/t \leq 0.8$ .....	63
Fig.3.12 Stress-Strain curve for API X 52 pipeline steel when tested with the repaired welding tensile specimen of $0 < a/t \leq 0.8$ .....	64
Fig.3.13 Stress-Strain curve for the compared to different with repaired specimen of $a/c = 1$ and with specimen automatic weld.....	66
Fig.3.14 Results of ultimate strength when tested with the defect specimens $0 < a/c \leq 1$ .....	67
Fig.3.15 Results of ultimate strength when tested with the repaired welding specimens $0 < a/c \leq 1$ .....	67
Fig.3.16 Results of Ultimate strength when tested with the defect specimens $0 < a/t \leq 0.8$ .....	68
Fig.3.17 Results of Ultimate strength when tested with the repaired welding specimens $0 < a/t \leq 0.8$ .....	68
Fig.3.18 Results of elongation in tensile specimen of base metal and with defect specimens of $0 < a/c \leq 1$ .....	69
Fig.3.19 Results of elongation in tensile specimen of base metal and repaired welding specimens of $0 < a/c \leq 1$ .....	69
Fig.3.20 Results of elongation in tensile specimen of base metal and with defect specimens of $0 < a/t \leq 0.8$ .....	69
Fig.3.21 Results of elongation in tensile specimen of base metal and repaired welding specimens $0 < a/t \leq 0.8$ .....	69
Fig.3.22 Toughness is by calculating the areas under the stress-strain curves.....	71
Fig.3.23 Experimental set up (a) Before Failure, (b) After Failure.....	71
Fig.3.24 Results of toughness in tensile specimen of base metal and with the defect specimens of $0 < a/c \leq 1$ .....	72
Fig.3.25 Results of toughness in tensile specimen of base metal, weld metal specimen and repaired welding specimens of $0 < a/c \leq 1$ .....	72
Fig.3.26 Results of toughness in tensile specimen of base metal and with the defect specimens of $0 < a/t \leq 0.8$ .....	72
Fig.3.27 Results of toughness in tensile specimen of base metal, weld metal sp. and repaired welding specimens of $0 < a/t \leq 0.8$ .....	

## Chapter 4: Experimental study of specimens with/without defect and repaired by patches composites hybrid

Fig.4.1 The sketch corroded pipeline repaired by hybrid composites (natural fiber and synthetic fiber).....	77
Fig.4.2 Optical images of characteristic locations. a) To d) SEM images of characteristic locations.....	80
Fig.4.3 Images obtained during Scanning Electron Microscopy (SEM) [c9].....	80
Fig.4.4 The photo of the Jute, Glass, Steel wire and layer jute by hand lay-up method.....	82
Fig.4.5 Device for measuring the weight of components (jute, glass, steel wire).....	83
Fig.4.6 Manufacturing processes of five plates of composite by hand lay-up method.....	85
Fig.4.7 Specimens dimension of test traction and flexion for two methods a) ASTM-D 3039 and ASTM-D790,b) see left of specimens.....	86
Fig.4.8 Location of bending specimen in API 5L X52 pipe with/without defect.....	86
Fig.4.9 a) Geometry standard of semi-elliptical defects b) Dimension of the test specimen.....	87
Fig.4.10 a) Geometry standard of semi-elliptical defects b) Dimension of the test specimen.....	87
Fig. 4.11 Test of the composite specimen (S5) on a universal machine capacity of 50kN	89
Fig. 4.12 Equipment of flexural Testing and defect specimen with patch.....	91
Fig.4.13 Tensile test stress–strain curve of different composite hybrid Jute –Steel wire.....	92
Fig.4.14 Comparison of the Ultimate strength between of composite glass hybrid and composite Jute hybrid.....	93
Fig.4.15 Tensile test load-length curve of different composites.....	94
Fig.4.16 Comparison ultimate load of different composites.....	94
Fig.4.17 Results of toughness in tensile specimen of composite laminates.....	96
Fig.4.18 Test flexural load-displacement curve of the composite laminates.....	97
Fig.4.19 Comparison of flexural strength of the composite laminates.....	98
Fig.4.20 Load–displacement curve for API X 52 pipeline defected for various ratios of $a/t(0 < a/t \leq 0,8)$ .....	99
Fig.4.21 Load–displacement curve for API X 52 pipeline steel repaired using the patch composite natural.....	100
Fig.4.22 Specimen API X 52 pipeline steel test with and without repaired using the patch composite natural.....	101

Fig.4.23 Highlights on the comparison of the loads results of the bending test for the specimens with/without defects where the API X52 pipeline specimens with defects were repaired through jute fiber reinforced with steel wires.....	102
Fig.4.24 Comparison of ultimate load of API X52 pipeline steel between specimen without defect and specimens with defect for different ratios ( a/t ) which were repaired using composite of natural hybrid (S5).....	103
Fig.4.25 Failure analysis fractography, a) and b) Sample of natural fiber composite J(1,5ST)J(1,5ST)J(1,5ST)J(S5),(c) and (d)Sample of hybrid composite JGJG (S2).....	104

### List of Abbreviations

API: American Petroleum Institute

ASME: American Society of Mechanical Engineers

TM: Thermo mechanical

TMCP: Thermo Mechanical Controlled Processing

UDC: Under Deposit Corrosion

SMAW: submerged metal arc welding

FAD: Failure Assessment Diagram

SEDER:National Steel Company

SONTRACH: National Company for research, production, transport, transformation, and marketing of hydrocarbons

SONELGAZ:National Electricity and Gas Company

NFC: natural fiber composite

SFC: Synthetic fiber composite

FRP: Fiber reinforce polymer

a: Depth of semi-elliptical defect

c:Length of semi-elliptical defect

t:wall thickness

a/c: Ratio of the semi-elliptical shape of the defect based on the variation of length (c) and fixed depth (a)

a/t: Ratio of the semi-elliptical shape of the defect based on the variation of depth (a) and fixed length (c)

## Tables list

### **Chapter 1: Review of Steel, Fiber natural with its derivations and using in piping systems**

Table 1.1 API grade steel pipelines [14, 13].....	12
Table 1.2 API grade steel pipelines [16,17].....	12
Table 1.3 Progressive evolution of pipeline properties and scientific discovery As explained by Gray [18].....	13

### **Chapter 3: Experimental study of specimens with/without defect and repaired by welding**

Table 3.1 Chemical composition and mechanical characteristics of API X52[14].....	55
Table 3.2 Results of tensile test for forms of specimens with/without defects.....	56
Table 3.3 Tensile mechanical properties of processed specimens.....	60

### **Chapter 4: Experimental study of specimens with/without defect and repaired by patches composites hybrid**

Table 4.1 Characteristics of Jute and Glass fibers [203].....	81
Table 4.2 Physical properties of Steel Wire [207].....	81
Table 4.3 Properties of polyester resin [87] .....	82
Table 4.4 Composites Fabricated and weight fraction.....	84
Table 4.5 Designation of different composites.....	89
Table 4.6 Tensile and flexural properties of different composite specimen (Average of five samples).....	90
Table 4.7 Tensile properties of different specimen in API 5L X52 (Average of three samples).....	91

---

## General introduction

Hydrocarbons, such as oil and gas, transported through pipelines play a crucial role in global energy security. However, corrosion threatens the sustainability of existing networks. Indeed, corrosion defects, such as pitting, stress cracking, and other types of degradation, can seriously compromise the integrity of pipelines, leading to material, economic, and environmental losses.

In this context, semi-elliptical corrosion defects are a major issue addressed in this work. They alter pipeline materials due to chemical reactions between the pipeline walls and their environment, especially near the soil. This phenomenon weakens structures and can cause failures under pressure, particularly when small cracks or defects extend to critical zones.

The aim of this work is to analyze the experimental results to study the influence of semi-elliptical corrosion defects, characterized by  $a/c$  and  $a/t$  ratios, on the mechanical properties of API X52 steel. The first type of semi-elliptical geometry is defined by the ratio  $a/c$ , which is based on the variation of the length ( $c$ ) while the depth ( $a$ ) remains fixed. The second type is characterized by the ratio  $a/t$ , based on the variation of the depth ( $a$ ) with a constant length ( $c$ ). Furthermore, this study aims to propose solutions to mitigate semi-elliptical corrosion defects in piping systems. To achieve this, two repair approaches are considered:

The first solution is based on the welding process using API A710 standard specimens, which are examined through mechanical tensile tests.

The second solution is to repair damage defects using natural and synthetic fiber composite (hybrid) patches to maintain the safety of the integrity of pipeline transportation systems. This project has focused on two techniques: welding and using a hybrid patch to repair the defects of corroded pipelines, where this study is divided into four chapters and a general conclusion.

The **first chapter** presents the evolution of pipeline manufacturing and the different grades of high-grade API 5PL steels developed to meet the technical and economic requirements through articles on the problems of pipeline corrosion, in particular the use of welding techniques and natural fiber composites as suitable solutions.

The **second chapter** is divided into two parts. The first part was reserved for the presentation of the internal and external corrosion interaction of hydrocarbon pipelines. The second part was reserved for the different repairs of corroded pipelines.

The **third chapter** presents the comparison between the experimental results of tensile tests for specimens with defects and without defects as well as the specimens repaired by welding.

The **fourth chapter** deals with the preparation process of natural and synthetic fiber composites, taking into account the numbers of layers and additive compounds, where five samples were tested through tensile and bending tests, focusing on the patch to repair the corrosion defect, and finally a general conclusion was presented.

## **Chapter 1: Review of Steel, Fiber natural with its derivations and using in piping systems**

## **1.1 Introduction**

Energy is considered as the heart of Global trade where it is based on the Hydrocarbons (Oil and gas ) which have been sought the most companies to improve all means of transport for long distances between extraction field and operating stations using elbows, valves and pipelines which have been become the great challenge to increase the transport safety and security of energy taking into account the operating conditions including the temperature, the pressure and nature of pipeline materials.

Depending on international norms of piping systems industry , many solutions proposed to avoid the serious problems including using of the composite material with their different types such as the natural fibers, industrial fibers and hybrid fibers due to their high efficiency , low costs and recyclable.

In this chapter, we discuss the general aspects of pipelines, the steel used in their manufacture, the process of pipe production,as well as the various repairs or intervention required to maintain and repair pipelines, we also provided an overview of the techniques and process used in pipeline repairs. Finally, we addressed the growing use of natural fibers in the industry or in the building. These materials, being more eco-friendly and sustainable, are finding various applications in industry, of fering interesting alternatives to traditional materials.

## **1.2 Pipelines**

According to the history of the mechanical industry, the pipeline origin name is a word of English from Greek. Due to the excellent features to transport fluids, liquid or gas, over long distances, it has been used as an important tool in the energy field over time. Using the pipelines to transport hydrocarbons from extraction sources to the stations of the refinery is a challenge faced by most companies, whether in liquid or gas form. The piping systems are made from steel pipes welded and painted externally and internally to protect from corrosion. The transporting by piping system is one of the safest tool safety and security to arrive at the energy worldwide. Moreover, other tools have been used, such as trucks, trains, or oil tankers, which are less safe than the piping systems.

Depending on the operating conditions, the liquids transported, the materials nature of piping systems, the maintenance of the hydrocarbon transport system, and the flow safety during all stages of transport and storage are very important.



Fig.1.1 Project of the trans-Saharan gas pipeline region through Nigeria, Niger and to the town of Hassi R'Mel in Algeria – is to connect regional African and European (4,128-km of the pipelines).

### 1.3 Pipeline for high-grade steels

Research on high-grade steels has been started since 1978 to date. X70, X80, X90, X100, and X120 steels; there are many progressive technological developments such as HY, HSLA, and TMCP steels (Table and Fig .1.I3)[11,12].HSLA (High Strength Low Alloy) steels include various types of standard designs used to provide specific mechanical properties such as resistance with the addition of a quantity of copper (Cu), hardness, and corrosion resistance. These kinds of products are not considered to be alloy steels, although their suitable properties are used with small additions of alloys. However, they are classified as a category of separate steel, which is similar to laminated carbon steel, with reinforced mechanical properties reached by additions of alloys and special process techniques such as controlled rolling [13].

### 1.4 Pipeline manufacturing process

The design of a pipeline network begins with studies and exams on the choices of diameters and thicknesses, as well as their techniques for manufacturing the pipes. However, the hydrocarbons transport network is made up of three of the types of pipes, namely:

Pipes welded in spiral form, welded pipes in longitudinal form, and seamless pipes [3-7]

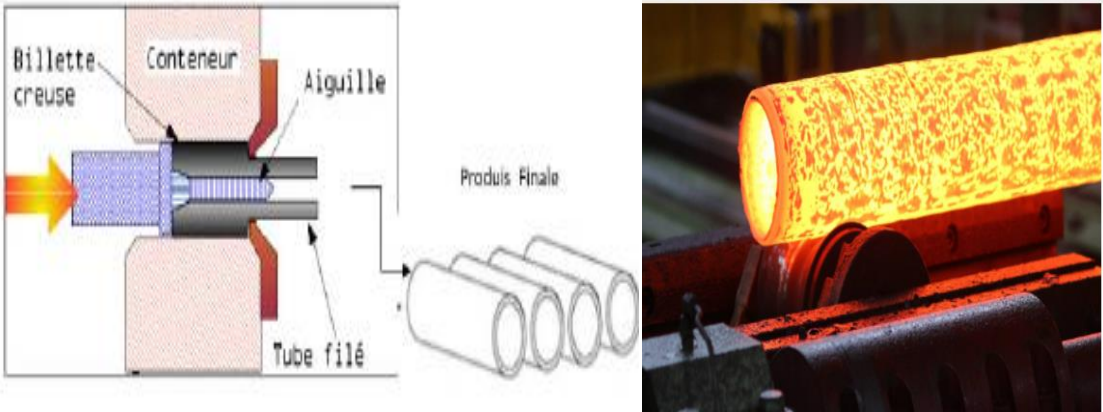


Fig.1.2 Process Seamless Pipes [3,4].

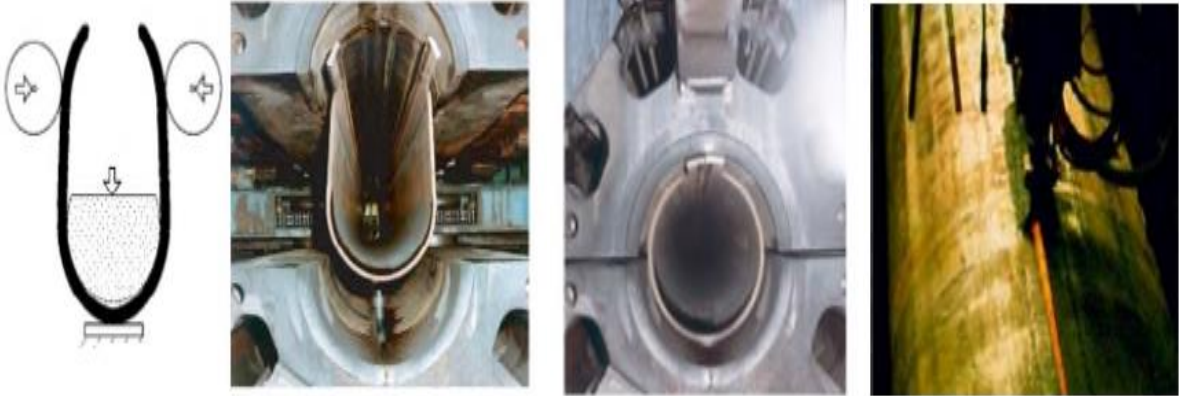


Fig.1.3 Process welded pipes in longitudinal form [4,5].

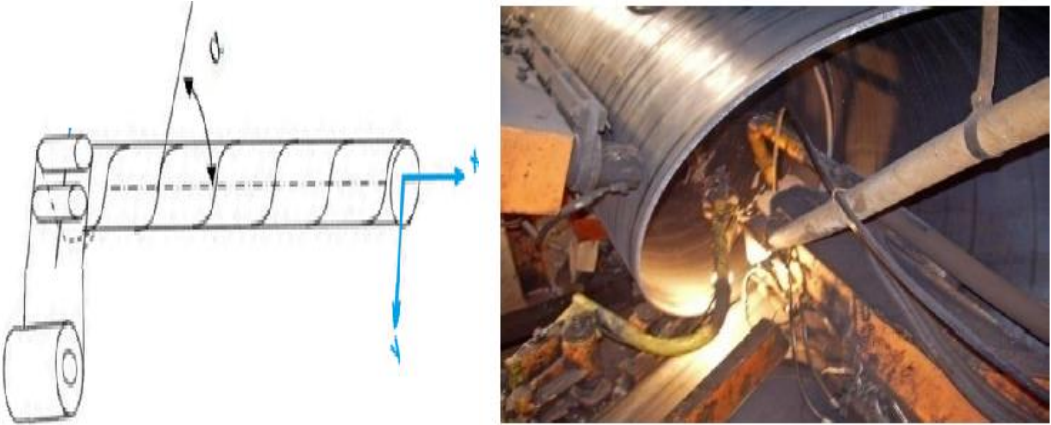


Fig.1.4 Process welded pipes inspiral form [6,7].

### 1.4.1 Welded piping systems in a spiral form

In the framework industry of piping systems in energy fields, most companies selected the kind of welded piping systems in a spiral form due to the recommendation of most of the oil and gas laboratories. Many manufacturers worldwide have used the welded spiral pipes that are installed in different regions by national companies, where they have been used by SONTRACH and SONEGGAZ.



Fig.1.5  
Technique for shaping the welded pipeline into the spiral.

The manufacturing of spiral pipes can be divided into five main subsequent processes:

- 1) Pipe forming and welding,
- 2) Pipe testing and control,
- 3) Product conformity of norms,
- 4) Internal and external pipe coating,
- 5) Final control, reception and storage.

### 1.4.2 Forming and welding of the strip

The laminate is moved the plate of metal by two cylinders, it subjects to carrying out by guide manner drive the strip and introduce it into the forming step consisting of many sets of rollers and tools that are adjusted according to the diameter of the pipe to be produced. The strip is formed into a spiral and welded internally and externally.

The process used is automatic submerged arc welding (SMAW)[7]. The pipe comes out of the semi-finished machine and is cut to length controlled by an oxy-cutting carriage.



Fig.1.6 Manufacturing pipe machine in content (forming and welding).

### **1.4.3 Pipe testing and control conformity of norms**

It has been observed during pipe manufacturing that visual checks are carried out by machine operators (self-checking), as well as specific devices for checking defects such as hydrostatic proof tests, ultrasonic checks, and magnetic particle inspections. These are non-destructive tests. Furthermore, before marketing the finished products, there are other destructive controls that consolidate the product quality by standard standards. These controls are mechanical and chemical tests carried out in the company's laboratories in compliance with API 5L and ASTM standards.

### **1.4.4 Internal and external pipe coating**

Stripping: Stripping the pipe after forming and control tests is carried out to eliminate oxide particles on the pipe surface as well as surface cleaning for a better coating [8].



Fig.1.7 Outer pipe stripping

**Pipe coating:** Pipelines buried or laid on the surface sometimes emerged in fresh or salt water for this reason, the coating is made up of three layers: the first is epoxy resin applied by electrostatic spraying 50 to 80 microns thick, the second layer is a copolymer intended to ensure polyethylene adhesion, and the last layer is extruded polyethylene. The advantages of exterior polyethylene coating are characterized by excellent adhesion of coating to steel, and high resistance to soil aggressiveness is determined by analyzing the pH, chlorides and sulfate. The interior coating is made of epoxy resin meeting the requirements of the API RP 5L Standard[32].

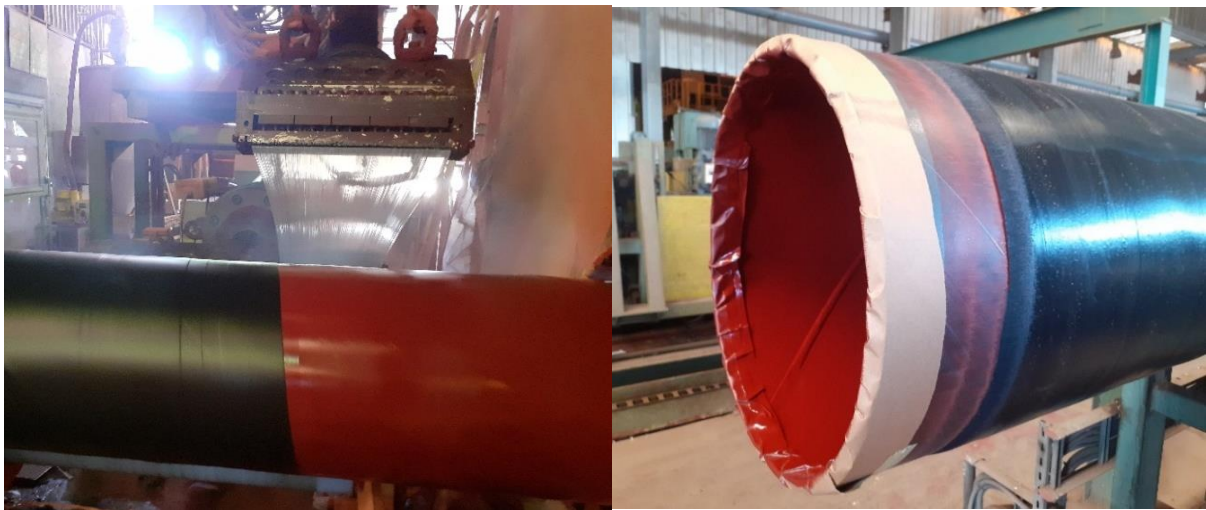


Fig.1.8 Cladding of pipes a) exterior and b) interior.

#### 1.4.5 Final inspection and storage

Before proceeding with storage, a final visual and dimensional checker, which consists of controlling the quality status of each pipe by checking the information mentioned on the pipe-tracking sheet for receipt or declassification under a sequential number, is finally a marking of conformities on the pipes carried out according to the procedure in force.



Fig.1.9 Marking of pipes a) exterior and b) interior.

### 1.5 Steel manufacturing process

Many factories that produce iron and steel by several steps, where existing procedures have been carried out through the use of recycled iron, for example, the use of Torsalli located in Oran(Algeria), or through mining, such as the SEDER El Hadjar complex located in Anaba(Algeria). The metal transformation complex of iron through a high-quality process is performed in three major steps as follow s:

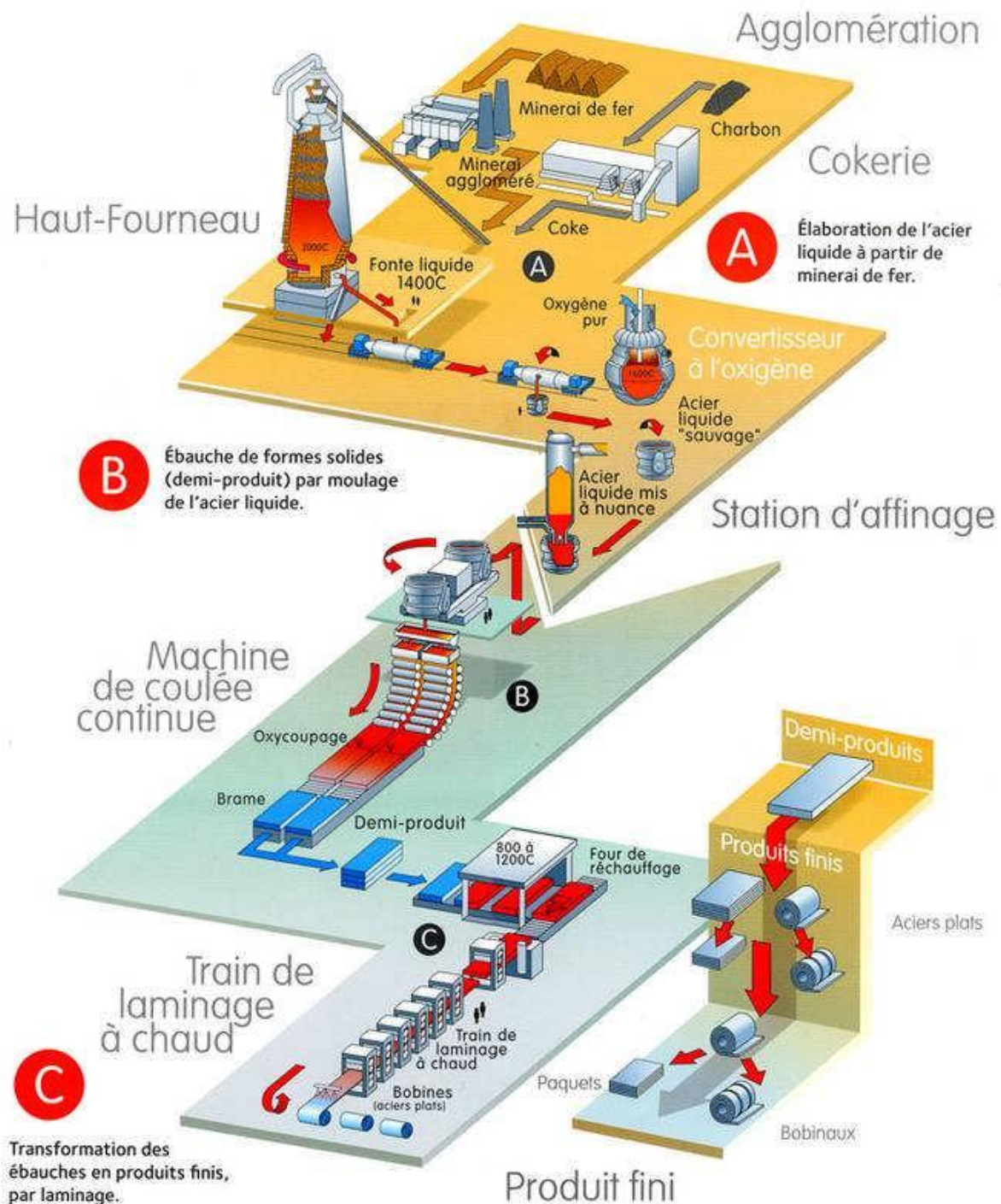


Fig.5.10 Steel manufacturing process through to final product [9].

### 1.5.1 Pipelines material norms

The API standards are among the norms that define the presence of carbon content to classify the grade of steel (Fig1.11) on the one hand, and on the other hand, they are many kinds of pipeline that are designed by different types including iron with carbon, iron with copper and iron with aluminum as well as it possible to use carbon fiber, natural fiber and hybrid fiber. The pipelines have been used depending on the percentage of carbons and other additives as follows X42-X52, X60, X65, and X70-X120 [10-13].

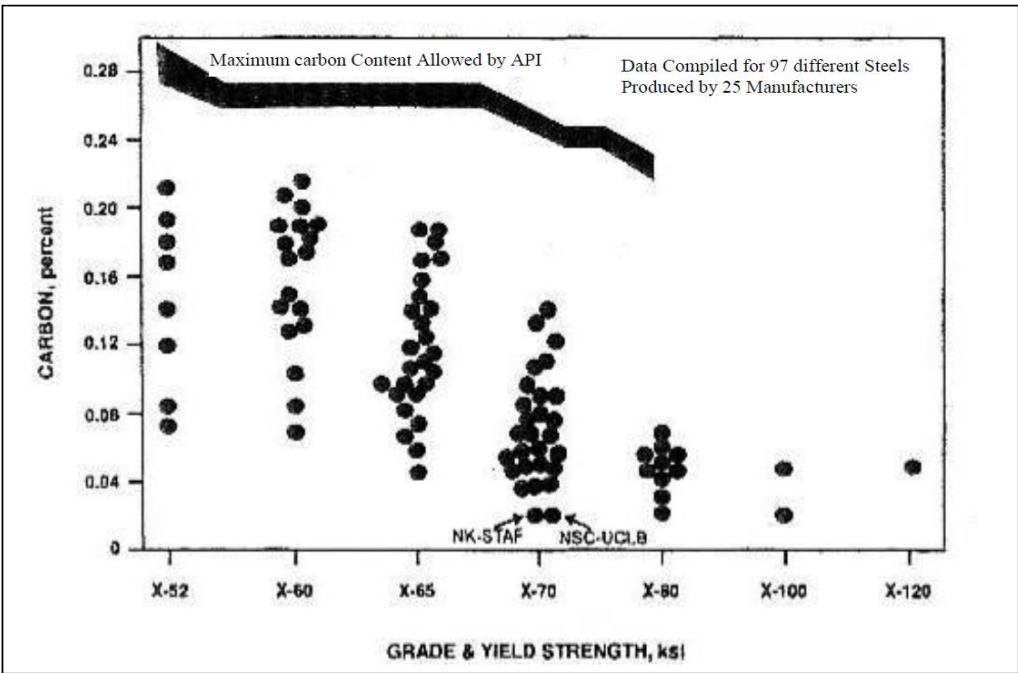


Fig.1.11The percentage of carbon depending on the grade API fromX42-X120[11, 12].

The international standards American Petroleum Institute API 5L [14] and American Society of Mechanical Engineers ASME B31G [15] have been used by many industrial company to design and industry of piping systems according to the suitable operating conditions to keep the mechanical characteristics for the long time.

Table1.1 NAPI grade steel pipelines [14, 13].

<b>Grade API 5L</b>	<b>Ultimate strength (MPa)</b>	<b>Yield Strength (MPa)</b>
<b>X42</b>	414	290
<b>X52</b>	455	359
<b>X60</b>	517	414
<b>X65</b>	531	448
<b>X70</b>	565	483

According to the American Petroleum Institute (API) standard, the tensile strength exceeds 530 MPa to reach 1024 MPa, keeping the elongation, thus the ductility property, of 25% for grade X120 steel; see Table I .5 [16,17].

Table1.2 API grade steel pipelines [16, 17].

<b>Grade API 5L</b>	<b>YieldStrength(MPa)</b>	<b>Ultimate Strength(MPa)</b>	<b>Elongation (%)</b>
API 5L- X65	448	530	24
API 5L- X70	483	566	23
API 5L- X80	551	620	22
API 5L- X100	690	770	25
API 5L – X120	951	1024	26,5

The pipelines are made of standard grade materials, less than X70 grade steels, a now the grade X70 and X80 are used for long-distance pipelines, and from grades X90 to X120 are being evaluated [17-19].

Table 1.3 Progressive evolution of pipeline properties and scientific discovery as explained by Gray [18].

Dates	Events	Industry reactions
1943	Observation of ductile-brittle transition in carbon steels for ships	Introduction of minimum fracture energy of 20J into specifications for ship plates
1954	Ductile-brittle transition considered relevant for pipelines	TUV introduces required energy of 34.3J/cm <sup>2</sup> for pipelines
1960	Brittle fracture over 13 km in an NPS30 gas pipeline	Development of the Batelle test (BDWTT)
1968	Propagation by ductile fracture in a non-brittle material assumed to be crack-resistant	Introduction of minimum Charpy energy from different fracture models
1970	Proposal to build the Alaska / Canada Gas Pipeline (CAGSL)	Development focused frantically on X80 steel (551 MPa) and required toughness at -69°C
1972	Hydrogen-induced cracking in X65-BP pipeline at Umm Shaif (UAE)	Introduction of BP test (NACE TM -02-84) [Solution B]
1974	Unexpected crack arrest in full-scale test attributed to rich gases at separations, high circumferential stresses and erroneous models.	Introduction of crack arrestors, improved crack arrest modelling and revised rolling ideas for high-strength pipelines
1978	Stress corrosion cracking failure in newly installed pipelines in Canada and Australia.	Improved metallurgical control (hardness) and improved external coatings. Improved implementation protocols
1978	Molybdenum shortage and price increase.	Molybdenum-free X70, added Nb-Cr +TMCP
1988-1989	Vanadium price increase to \$50 per kilo	Vanadium-free steels, substituted with Mo, Cr+TMCP
1990	1Development of deep-water oil and gas reserves and new pipelines: Oman to India and the Black Sea	Heavy gauge DSAW (roll welded) pipelines resistant to pressure buckling, developed in conjunction with 80 ksi (552 MPa) seamless high-grade steel pipelines
1997	Need for high-pressure systems for Arctic development	Ultra-high-strength steels (UTS of 135 ksi = 931.4 MPa) and steel reinforcementconventional
2010	Need for higher-performance characteristics	High-grade steels X100 X120

### **1.5.2 High grade wires for pipelines.**

High-grade steels include a large number of standard grades and are designed to provide specific combinations of properties such as strength, toughness, formability, weldability, and resistance to atmospheric corrosion. These steels are not considered alloy steels, although their desired properties are accomplished by the use of small additions of alloys. Instead, they are classified as a separate category of steel, which is similar to rolled mild carbon steel, with enhanced mechanical properties achieved by judicious alloy additions and special processing techniques such as controlled rolling [17-19].

The development of steels with high elastic limits is achieved thanks to the mastery of special processing techniques such as thermo mechanical rolling (TM) replacing thermomechanical hot rolling with accelerated cooling (TM+ACC) to produce high grade steels that are equivalent to X70 and X80 without increasing the content of carbon and microalloyed with niobium and vanadium. In recent years, the refinement of the microstructure has been the subject of development in the metallurgy of ferritic grain size structures with the use of thermo-mechanical temperature-controlled rolling processing procedures TMCP (Thermo Mechanical Controlled Processing). This development makes it possible to significantly reduce the grain size of ferrite-pearlitic steels, while high levels of resistance have been obtained while maintaining good toughness and elongation of the steel; the evolution towards ferrite-bainitic structures is obtained. fat with increasing speed and final cooling temperature [12,13].

The accelerated cooling process (Figs. 1. 13, 14) is adopted during slab rolling in order to achieve a homogeneous, fine-grained microstructure to obtain better mechanical properties. The resistance of material (steel) reaches 700 MPa in the standard norms, taking into account the dimensions as well as the effect of the temperature. Depending on the recent studies, it has been proven that the efficiency of the structure of the complex chemical composition of the carbon fiber with the addition of Ni and Ti, is able to reach the fabrication of the pipes and gasoline pipes with a diameter of 1420 mm with a 20-inch. These pipes have excellent features such as high density to the end rupture and the limits of resistance to the rupture, as shown Fig.1.12 [17-20].

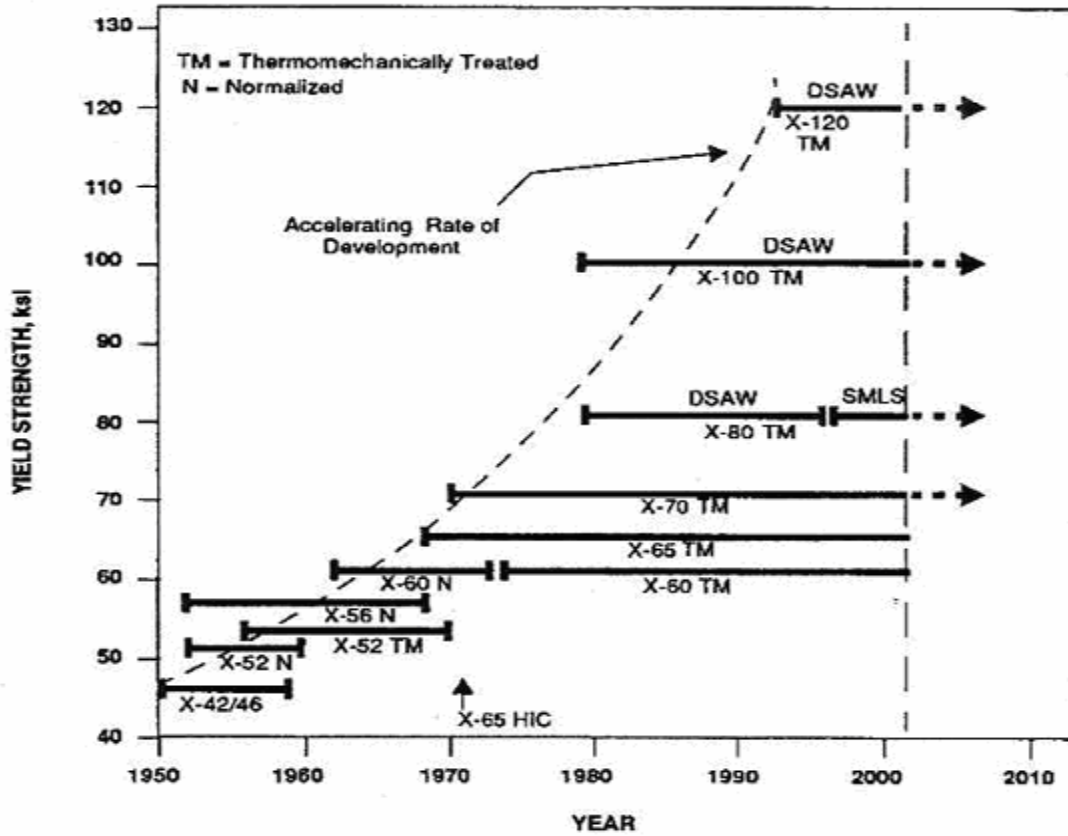


Fig.1.12 Pipeline steel grade development over time [11,19].

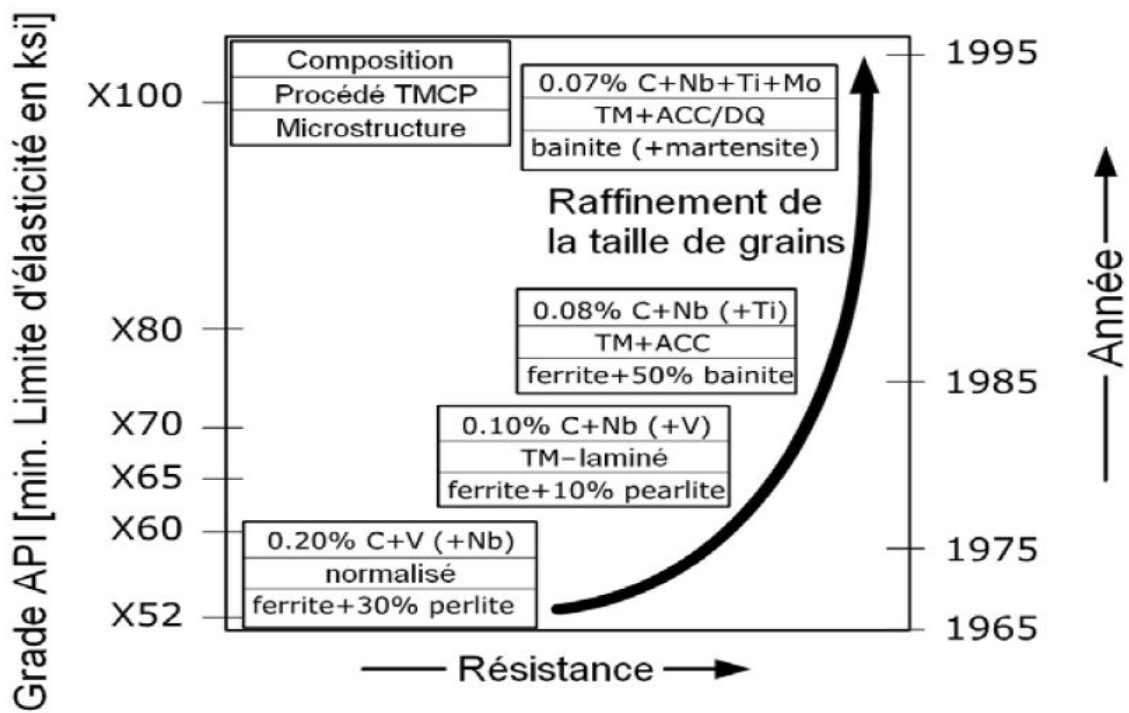


Fig.1.13 Pipeline development (composition, TMCP process, microstructure, API grade) [18,20].

### 1.5.3 Physical characteristics of the thermo-mechanical control process (TMCP)

In the case of low alloy steels, the final microstructure depends on the cooling rate and the final cooling temperature [13-14]. The cooling method (see Figs.1.13 and 1.14) is used while the sheet is rolling to perform homogeneously for better mechanical characteristics and excellent corrosion resistance (HIC), close to steels made by conventional thermo-mechanical lamination [21,22]. The TRC diagram (see Fig.1.14) helps full the microstructures as a model of the cooling rate.

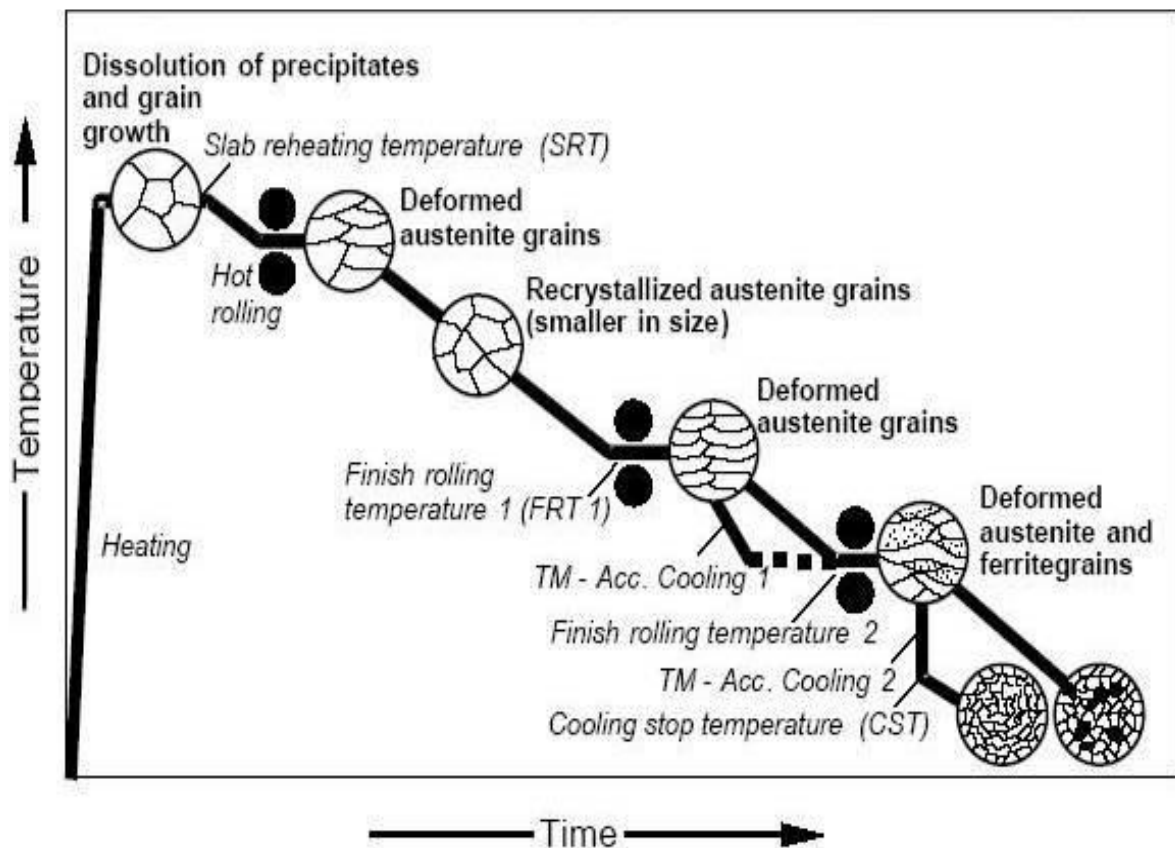


Fig.1.14 Thermo mechanical treatment during sheet metal forming [23].

Depending on the process of treatment of material, the chemical composition and thermo-mechanical treatment effect on the microstructure of materials through many factors, such as the nature of the material and its compounds, as follows, chemical composition and heat treatment influence microstructure, which governs mechanical properties(Figs.1.14 and 1.15).

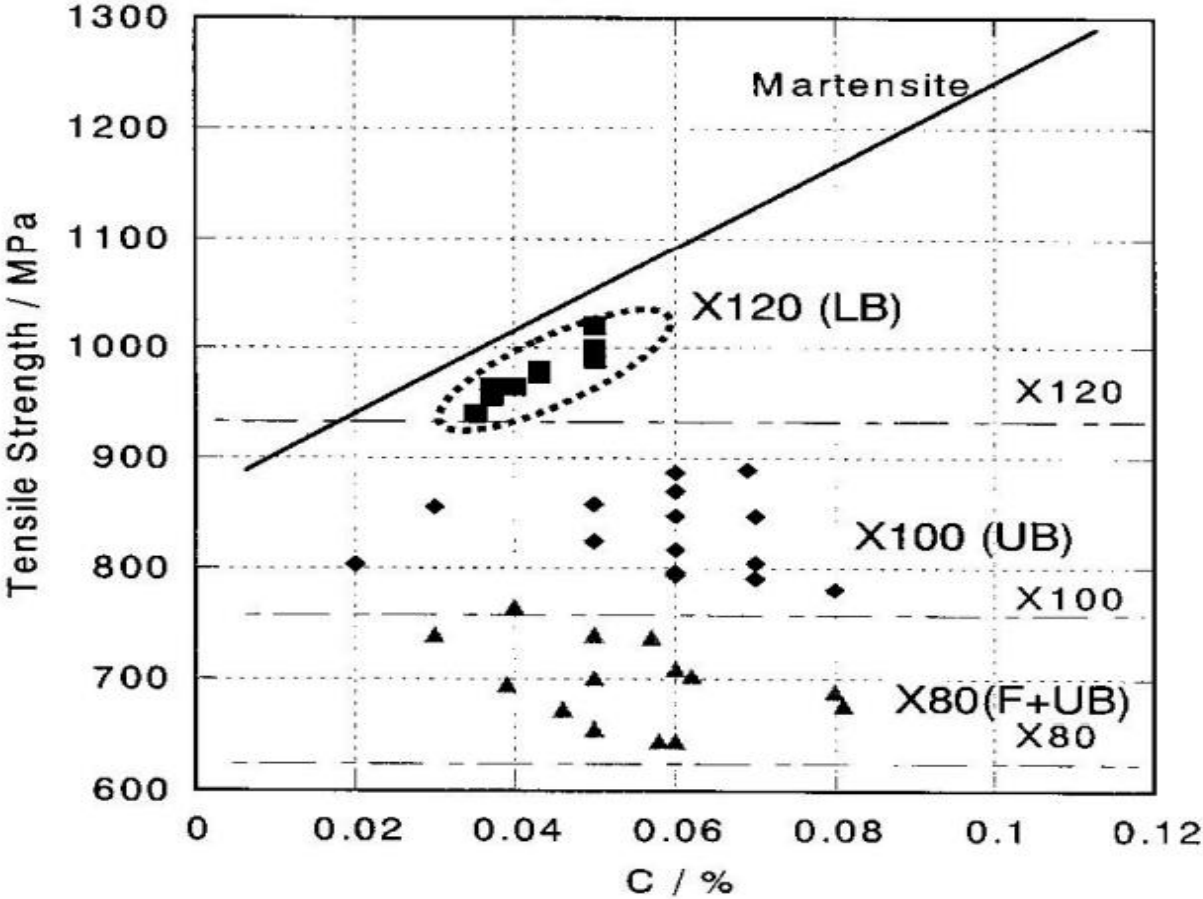


Fig.1.15 Evolution of the mechanical properties of the plates according to the grades [24].

**1.6 Bibliography Synthesis**

Depending on hydrocarbons transport, there are various factors influenced on the safety of piping systems taking into account high temperatures and pressures, and small cracks or defect of corrosion along distance from fields to refinery stations. These defects are usually caused through many reasons such as impurities, small cracks and bad welding and bad linked of control valves [25]. During last decades, there have been studying various studies about the safety of piping systems, where the control of all types of cracks including small crack which cannot be seen by macroscopic on the external or internal wall of piping systems.

High pressures, temperatures, nature of used material and nature of transported fluids are among reasons of corrosion, which is occurred as result of complex chemical reactions. Depending on these conditions, the corrosion issue has become a great challenge for many companies energy. In additions, many techniques which used in the extraction crude oils, based on moderns features linked with depth of wells, nature of extracted fluids ( simple or

complex ) taking into account the dimensions , thickness of wall, positions of welding, as well as the presence of elbows and valves, Whether underground or above ground or on bridges and off shore [25-27].

### 1.6.1 Interaction between pipeline and hydrocarbons

During the transport of hydrocarbons, several cracks occurred at critical positions due to many reasons such as vibrations and load. According to the major reasons for the corrosion phenomenon, which generates through appearing small cracks at critical zones such as around welding positions, valves, and elbows to change the pipeline direction on the one hand, on the other hand, the cracks can take several forms including semi-elliptical forms with depth or superficial, There is a lower pipeline rupture pressure for the localized corrosion reaction type of defect; the rupture pressure depends on the interaction that occurs between internal hydrocarbon-steel defects and the external steel-soil environment associated with stresses of higher temperatures see (Fig 1.16 [25-29]).



Fig.1.16 Damage of accident pipeline cause interaction steel-flow [30], a) broken pipe, b) morphology insides the rupturefluid [31] and c) fracture due to the SCC, plastic deformation - the local bulging [29].

According to the increase in the demand for energy worldwide especially, in Asia (China, India, Japan), the safety of the piping systems to transport the crude oil and gas, which are very significant to assure the international norms ( API) quantity and quality on the one hand and to keep the operating process on the other hand [27]. In order to continue transport operations, maintenance costs and control the piping system's safety, the corrosion problem can be avoided, where the process of design is usually based on the internal coating made of epoxy resin on the wall in order to stop the chemical reactions on the one hand, and, on the other hand, on the external coating made of polyethylene to protect from the strong conditions, including high temperature and humidity, interaction, and the steel-sol

environment (see Fig1.17 [32,33]). These conditions help to keep the safety of the piping systems from the corrosion phenomenon through humidity [30], contamination by bacteria [33], naphthanic acid corrosion [31], as well as the friction wear and cracks due to the high pressure and temperature [60].

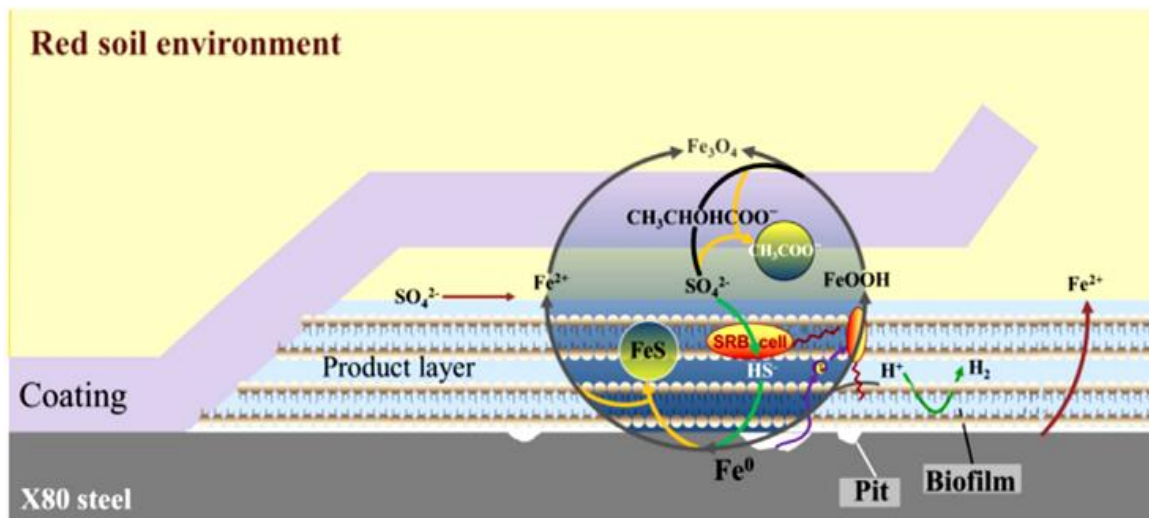


Fig.1.17 Schematic diagram illustrating the electrochemical reactions, interaction X80 steel containing red, soil environment [33].

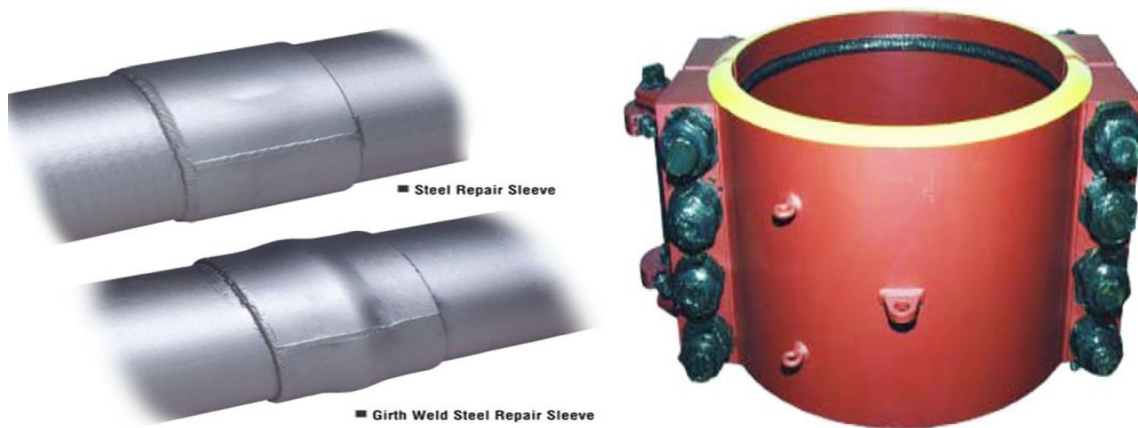
During the transport of hydrocarbons via the piping systems, the phenomenon of corrosion can make the challenge faced by many companies, such as hydrocarbons. According to these causes, many methods were applied to investigate the issues of cracks in order to keep the safety of piping systems. The analysis and examination during the transport of fluid were used fully using protective devices on the one hand [35], and on the other hand, the failure can propagate along the pipeline network [36,37].

The corrosion issue is considered as an one of among advanced dangerous phenomena which lead to failure of the structures of piping systems and deteriorated under strong operating conditions such as high pressures and temperatures [38,39], these problems concentrated at critical zones including the welding zones and elbows through propagation of small cracks along pipelines [39-40]. According to transport, hydrocarbons, many complex chemical reactions that lead losing the external (interaction steel-environment) or internal (interaction flow-environment) layers represented by the brown layer, where these problems allow decreasing the thickness of wall and increasing the maintenance costs. The corrosion problem may take pits in the forms as semi-elliptical shapes depending on the nature of fluids transported and piping systems material and operating conditions [40-42]. Through the

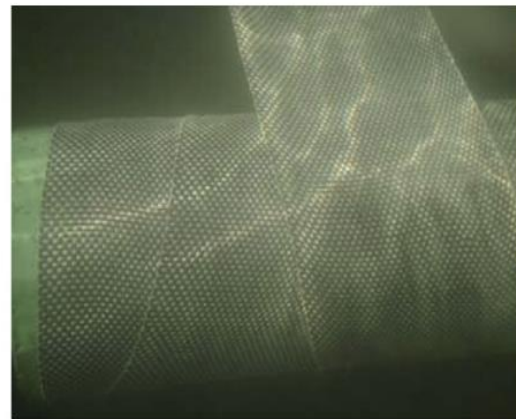
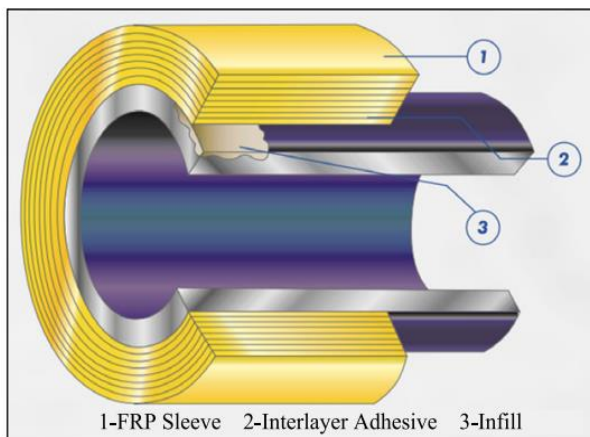
suitable conditions of corrosion, complex conditions have been leading to weak states at in the critical zones along the piping systems, such as elbows and valves [42-44]. In the framework of searching for solutions, many studies were carried out to analyze the effect of corrosion on the unsafely of piping systems, including the internal structures, which leads to a decrease in the mechanical properties.

The most solutions are based on the repairing by welding technique on the one hand [43-46] and material composites on the other hand; see Fig.1.18[46-49].

Due to the complex phenomenon, there are many approach studies, which treat the corrosion problem through a three-dimensional finite element method.



a) Steel repair sleeves [50]. b) Sleeve repair clamp [51].



c) Clock Spring repair [52].

d) Flexible wrap system for underwater [53].

Fig.1.18 Conventional welded and composite repair [54].

I.S. Raju and J.C. Newman [55, 56] performed the study about the cracks of piping systems, which based on the semi-elliptical shapes along of piping systems through superficial or depth defects.

Through the approach study, there are many factors used to analyze the cracks such as stress intensity factors, which allows taking into account form of cracks and its size [57, 58].

The development of piping systems is an important step to protect stations of hydrocarbons transport from any problem has relationship with corrosion issue at weak positions along of piping systems.

Although many results, L. Xu [61] carried out project based on the finite element method to investigate the effect of the small cracks on the continuity of power transportation, where this study showed the effect of cracks on the safety of piping systems through crack depth ratios of shape semi-elliptical and their sizes [60-64].

In addition, the Failure Assessment Diagram (FAD) is used to analyze the safety of piping systems, which are affected by cracks where this technique allows classifying the degree of resistance of wall cracks and surface cracks through three zones as follows : safety, security, and failure [64-66]. Basing on the experimental and numerical methods is one of the better steps to analyze and control of the defects behavior of weak positions (small cracks and pits) such as welding positions, elbows, and valve zones on the walls of pipelines [67-68].

### **1.6.2 Welding process**

During this decade, the welding technique is one of the better techniques to repair the cracks on the one hand and, on the other hand, to avoid the failure at critical zones, where the welding process is represented as a solution to link between two parts of the pipeline taking into account the thickness of the piping system's wall and the used material's nature [35, 65, 69, 70].

### **1.6.3 Composite materials**

Due to the greasing of corrosion problems, the composite materials become important such as natural fibers and synthetic fibers, which are used in energy fields [71, 72]. Using of Glass fiber, carbon fiber or Jute with addition of resin as hybrid composite is considered as the great challenge steps in the modern industries through a material with better mechanical properties features [73] using the original materials despite of the variation of their chemical and physical characteristics.

### **1.6.4 Natural Fibers**

By considering the natural fibers as an excellent solution due to many advantages, including the low costs, recyclability, and availability in the worldwide market, they have been utilized

as a plate for a patch to repair the defects instead of fiber carbon or fiberglass or carbon-glass fibers due to low density, corrosion resistance, and high mechanical resistance [74-75].

Throughout the ages, the natural fibers from various origins have used in many domains such as sheep wool, papyrus and various plants for writing, shoes and clothes of war as well as the roofs of houses, horse carriages, bridges, sailing ships, etc.[76-79].

Egyptian and Greek civilizations had been characterized by using wool, wood, papyrus fiber in their in their daily lives such as mummifying, pyramids and sailing ships [76-79].

### **1.6.5 Application of Natural fiber in building**

Using the natural fibers become as better solution in many fields where this industry is based on the various plants such as basalt, coconut, banana, sugarcane bagasse, hemp, kenaf, bamboo, jute, sisal, abaca and cotton to reinforce any material such as steel, iron, others composites as well as cement. Natural fibers have excellent features including eco-friendly instead with conventional fibers [72,80]. In fact, many recently studies have provided the better solutions and techniques to develop the mechanical features through available in the worldwide, low costs and high resistance.

Nowadays, most manufactories have focused on the natural fibers as the principal material used in the mechanical products due to more properties such as coconut fibers or banana fibers as shown in Fig.1.19 and 20, [72, 80]. Depending on the more studies, especially banana fibers, which are able to increase the mechanical properties, compared with other plants taking into account the kind of used field [72].

In addition, the sugarcane fibers have been used to reinforce the cement with high efficiency especially in the building construction and mechanical industries due to their several features [82]. Due to the advantages of natural fibers which have been become a necessary to develop of global economy by their available in the markets where it can use in other fields such as houses, roofs, piping systems, furniture, cars and bikes [72-82].

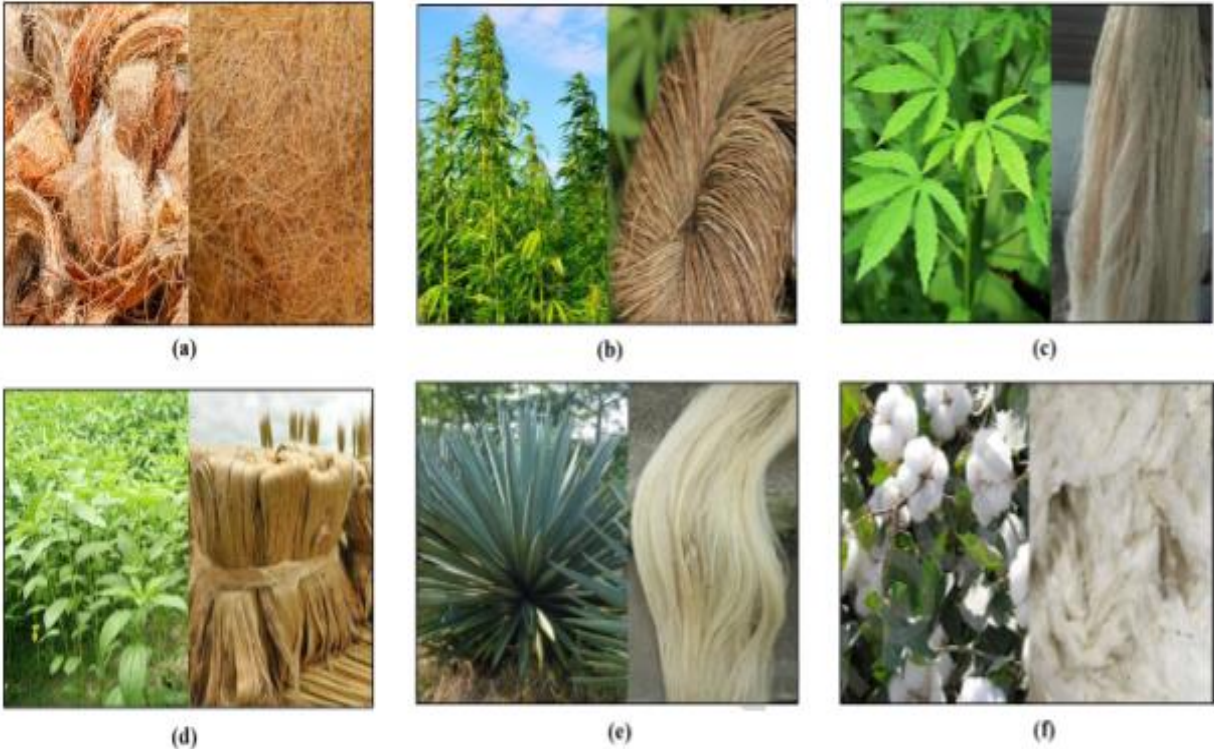


Fig.1.19 a) Coconut fibers, b) Hemp fibers,c) Kenaf fibers,d) Jute fibers, e) Sisalfibers, f) Cotton fibers [72].

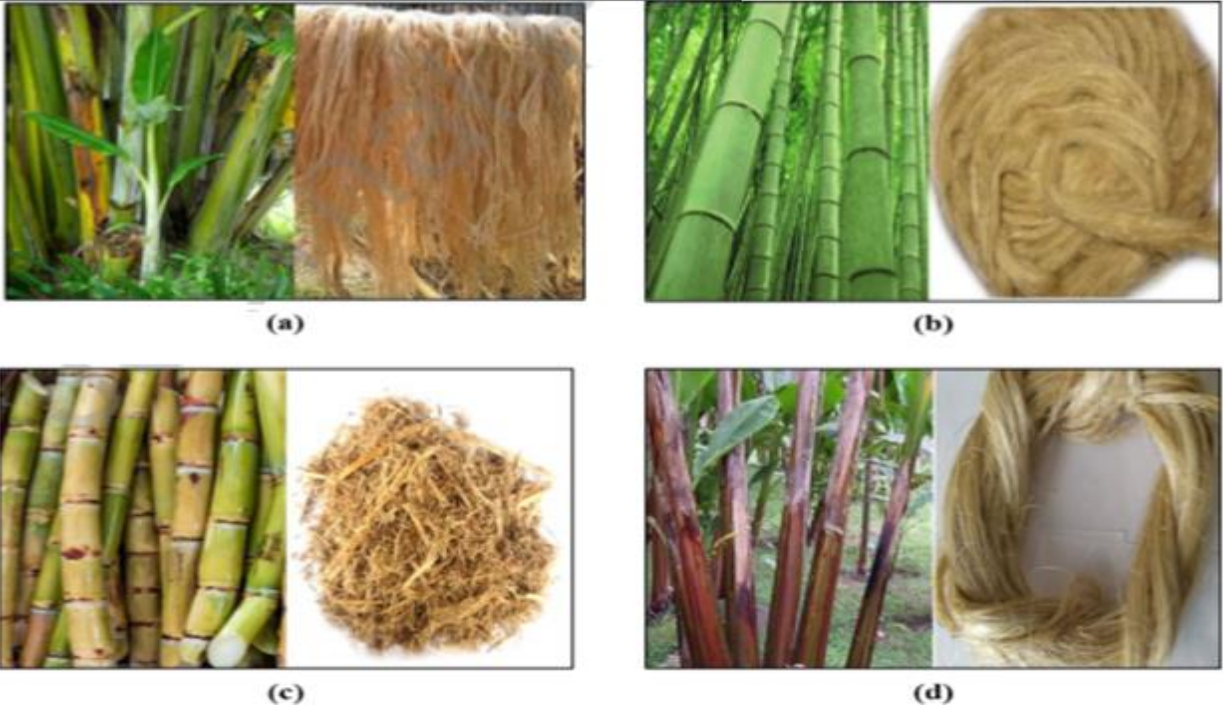


Fig.1.20 a) Banana fibers,b) Bamboo fibers,c) Sugarcane bagasse fibers) Abaca fibers[72].



Fig.1.21 House made with hemp concrete [81, 82].

### **1.6.6 Industrial fibers (Carbon and glass fibers)**

Since the industrial revolution in Europe, new materials have appeared through new features of materials made by steel and iron. Depending on the innovation and new technologies, several companies sought to produce new materials with excellent mechanical properties such as carbon fibers, glass fibers, or hybrid fibers due to their characteristics representing high resistance, durability of hybridization of natural fibers and biodegradation [83-90].

### **1.6.7 Hybridization of natural fibers with synthetic fibers**

Many studies have been performed using natural and industrial fibers as well as hybridization of natural fibers with synthetic fiber, K. Karthik carried out an experimental study through hybridization of natural fibers and carbon fibers with the addition of other materials to improve the mechanical properties [91-92]. Due to the excellent mechanical features, including the low costs and high mechanical resistance, both natural and synthetic fibers become an important pillar of the global economy, especially mechanical industries, as vehicle interior design parts, and high-strength structures [93-99]. Nowadays, this technique becomes used in various fields, such as in the repairing of piping systems and in many other products [93-99].

### 1.6.8 Application of Natural fiber in automobile

Technological innovations take into consideration the environmental problem, also the legislation of productive wages implemented laws for industrialists and manufacturers for the preservation of resources. Car manufacturers are considered the most polluting on the planet because of CO<sub>2</sub> emissions and toxic gases. However, the use of biodegradable materials on composites of car accessories (Fig.1.22) is a major advantage [80,100-103]. On the other hand, the scientific research on new materials is based on natural fibers [101-103]. has been carried out to replace synthetic fibers, including the application of composites such as jute, hemp and bamboo fibers cited Fig.1.19,20 [72], which are already used in various industrial products, building construction, packaging and automotive, aerospace, sport equipment, textiles, furniture, etc. [80, 104, 105]. These materials come from light and strong qualities, which allowed an economic gain on the reduction of weight of 40% according to BMW [102], the reduction of CO<sub>2</sub> emissions [103] and the use of fiberglass in automotive components [104]. Also car manufacturers have tried to replace several automotive components with natural fiber composites because of their advantages of better quality and good mechanical properties, as well as the ease of design with low cost which gives better fuel economy results. In this regard, the world leader of the Mercedes Benz brand, used 50 components on the E-Class see Fig 22, these components were produced from linen, wool, hemp sisal and other natural fibers [80,105].



Fig.1.22 five tine (50) components of Mercedes Benz E class were produced from natural fibers [80,106].

### **1.6.9 Piping systems corrosion**

Energy of Hydrocarbons has become a heart of the world economy however, the corrosion has been considered as an industrial development danger, where this phenomenon is the principal causes of piping damage. The corrosion generates more defects along of piping systems where it is divided into two states: interaction between internal and external defects on pipelines [28]. All these reasons allow corrosion to occur at critical zones especially in elbows, welded zones and valves as well as an industrial defect [107-109].

In order to treat this dangerous phenomenon, many energy companies have been sought to treat and to avoid depending on the techniques which is based on strategy by changing the damaged part by welding process or patch such as composite patch including natural fibers and synthetic fibers [110,111].

Due to the increase of corrosion resistance, increasing stiffness and high resistance, this strategy is a result of the technique efficiency allowing for an increasing lifetime [111-114].

In addition, many laboratories in the worldwide sought to use hybridization process between natural fibers and synthetic fibers to develop a new material with high resistance, low costs and recyclable where it can use in many fields such as mechanical industry, medicine and others domains.

Many solutions have been presented to avoid the issue of degradation of environment which have changed the climate, where all industrial countries took suitable decisions to decrease the negative effect on the environment.

This problem has become a great challenge for all countries that have used the aggressive materials [61-64].

To decrease of CO<sub>2</sub> rates, many products need to decrease for protecting the environment such as Non-biodegradable materials, complex chemicals, and toxic materials [61-64].

In this project, Jute fibers reinforced with Steel wires, fiberglass, and polyester were used as patch to repair defects along of piping systems due to their excellent mechanical properties [71,72]. However, the natural composite became a sustainable alternative to the materials used due to the high resistance, resistance of corrosion, low costs and recyclable [100,101, 120-121].

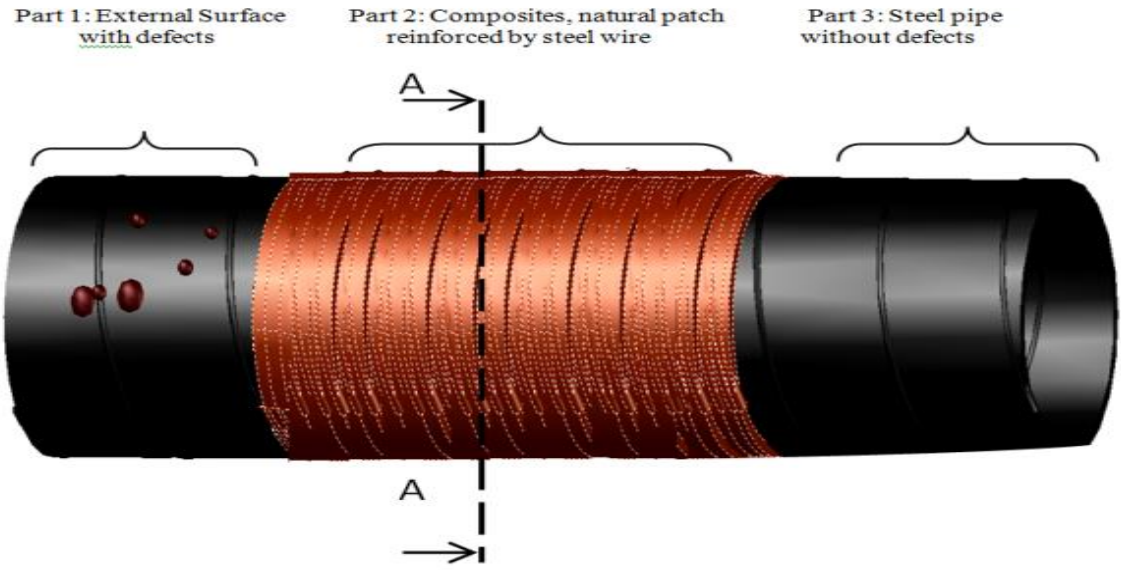


Fig.1.23The sketch corroded pipeline repaired by hybrid composites (natural fiber and synthetic fiber) [122].

**1.7 Conclusion**

The pipeline systems consist of all the tubes intended to transport gas or oil. These tubes are protected by a coating system during manufacturing and protection and reinforcement systems during installation and / or during operation. However, scientific research has been carried out for the development of new grades with high mechanical characteristics such as grades X60, X65, X70, X80 and X100, which are the most used today because of their advantages in profitability and productivity in large quantities with large diameters and high pressures that can reach 120 bar. Also, various studies have been conducted on the safety of pipeline systems in particular corrosion, fatigue and others, where the control of these problems that generate tube failures is essential to ensure continuous operation and avoid natural disasters.

## **Chapter 2: Corrosion and Repair by patches**

### 2.1 Introduction

the appearance of fragile areas and points of damage on the metal of wall and welding zones due to the complex chemical reactions constitutes a great challenge facing many petroleum companies where defects can take many forms, such as elliptical, semi-elliptical or other forms. The concentration of corrosion defects along piping systems is one of problems that is considered difficult challenge facing for engineers to repair the defects.

The technique welding or using the composite patch are considered as better solutions which are very important solutions although more difficulties as results of the occurred the defects at critical zones. The occurrence of corrosion defects in the piping system has become one of among mains of challenges facing engineers of many companies of energy including the hydrocarbons transported. Many defects have been occurred at critical positions along of piping systems such as during manufacture of the pipes or in the assembly as well as in service. The defects problems have become dangerous causes to failure of systems, where they are able to lead to fragile walls and zones of damage such as superficial cracks or profounder crack on the base metal and at the welded positions. Due to the complex chemical reactions ( oxidation ) during the transport of energy although the presence of aggressive compounds in crude oils such as H<sub>2</sub>S or acids such as Naphthenic acids, where this issue leads to deterioration of the metal.

In fact, these defects may form as pits form, elliptical forms or ellipsoidal and other complex forms.

This problem has become the first of among problems, which have treatment the safety, and integrity of piping systems in the worldwide.

In order to avoid and to protect of the piping systems, it is obligatory to investigate of defects and to find the reasons through many techniques which have been used by the most energy companies in the global, where the specimens took from defects can analyze to reach to solutions taken into account the nature of materials , nature of transported liquids and operating conditions including high pressure and high temperature.

Depending on causes of defects , many energy companies have proposed many solutions about maintenance or reinforcing or addition a special liquids including inhibitors.

According all these propositions, it can help to enhance of safety to some extent through the welding technique or repairing by composite patches which allows that enhance the

Thickness of the walls against pipeline failure to prove the continuous of energy transport the increasing.

### 2.2 Corrosion

Corrosion phenomenon have involved all defects occurred during many processes such as manufacturing, structure and welding operation, where it is considered as natural event due to the complex chemical reactions (interaction between transported liquid and wall of piping systems).

The presence of adequate conditions for interaction chemical as sulfur, naphthenic acids, oxygen, temperature, chemical salts, contaminations and pollutants can accelerate of corrosion. The corrosion problem has depended on the components of steel piping systems and nature of transported liquids where it has the relationship with operating conditions through with mechanical or physical properties such as operating conditions and presence of aggressive compounds with temperature and pressure). Thus, these conditions allow accelerating occurring of corrosion serious on the safety of energy transported.

Due to the degree of deterioration of metal which occurred on level of system of transport, where many companies sought to find the suitable technique to prevent the failure of systems through electrochemical protection, cathodic protection, anode protection, protection from external effects, coating and surface treatment, decreasing oxidation as well as using all most inhibitors including green inhibitors.

### 2.3 External corrosion of hydrocarbon pipelines

The defects of corrosion in the defected wall of the piping systems that hydrocarbons transport are controlled and analyzed through centers examined and stations existing control to evaluate the impact of the corrosion on the external environment. All strategies have been used to prevent and to eliminate the severe effects on the tools of energy transport.

During the transport, lots of events have occurred as results of severe failures and damages. including different types of failures as results of the external corrosion (interaction steel-water) where the small cracks along of piping systems have helped full to generate the corrosion by complex chemical reactions including hydrogen, corrosion fatigue, corrosion cracking, microbiologically corrosion for hydrocarbons as shown in the Fig.2.1.

In fact, several forms of corrosion can be taken to appear on of wall piping systems, where two types of corrosion have been existed including the external wall and the internal wall which can creates the interactions between factors of environment and external steel wall On

the other hand the internal corrosion is considered as the interaction between crude oil with/without gas and wall of steel as shown in Fig.2. 2.

General forms of external corrosion (Fig.2. 2 and 3) [107,108]:

- Differential corrosion of cells,
- Galvanic coupling,
- Crevice corrosion,
- Corrosion of deposits,
- Uniform corrosion,
- Pitting corrosion,
- Delaminating-swelling,
- Various corrosions.

### 2.3.1 Corrosion of different cells

Corrosion of cells is one of among kinds of corrosion which occurs underground pipelines through nature of soils such as the presence of different oxygen concentration in the soils, including clay soil that has less permeable to oxygen compared to sand. The characteristics of humidity and oxygen levels and the pH degree are very favorable to corrosion depending on the nature of the soils and aggressive compounds with/without the presence of salt. All these reasons included in external corrosion can lead the damage and failure of piping systems [107,108].

### 2.3.2 Galvanic corrosion

The contact of piping systems wall with different compounds is one of among reasons to lead the corrosion with presence of humid environments, pH, effects of oxygen and hydrogen.

It can occur the corrosion phenomenon when to contact more than two elements where this operation is considered as galvanic corrosion due to the speed of corrosion process [123,124].

in addition, the difference between material steel and materials anti-corrosion although mechanical properties can provide the environment of corrosion despite of the presence of material classified as anti-corrosion due to change in the microstructure of the acids. This phenomenon can be occurred by the presence of the base metal, soil, and temperature as shown in Figs. 2.2 and 2.3, Zhou 2016[125].

### 2.3.3 Uniform Corrosion

This form of corrosion is considered as classical form of external corrosion which characteristic as general corrosion due to their know causes as show in Fig.2.2and 2.3 (a). The uniform corrosion is the simple to analyze and located and it can be led the medium failure or damaged on the one hand.On the other hand, the environment effected can play of the rapidly degrading depending on more factors such as the pH value of the soil; the humidity; the temperature, the nature of the materials, etc.

It can evaluate the degradation of this kind of corrosion using measuring the decrease in thickness of piping systems per year ( $\mu\text{m}/\text{year}$ ) or others techniques to predict the average values of the pipeline life, K.Y. Wu et al 2019[126].

### 2.3.4 Pitting corrosion

Pitting corrosion is one of kinds of localized corrosion that is considered as form of localized corrosion, where the features of this case allow forming of layer which is very small deposit on the wall of piping systems.

These reasons can lead to decrease the flow of hydrocarbons, thus it can lead to reduce the integrity of systems, where it allows to appear the concave pits due to the decrease the oxygen the oxygen rate as shown in Figs.2.2 and 2.3(b).

### 2.3.5 Caving corrosion

This type of corrosion has related with the presence of small volumes of solution in the spaces within cracks, where that penetrate of the metal is independent through chemical reaction in  $\text{Cl}^-$  and  $\text{H}^+$ .

This phenomenon allows the material a very aggressive behavior that the metal and the creation of corrosion layers may lead to failure of the pipeline wall as shown in Fig.2.2 et 2.3(c). Parameters contributing to create the crevice corrosion are the exterior wall of the piping system in addition to pH variation, humidity of the external environment.

### 2.3.6 Under Deposits Corrosion (external)

This type of corrosion can form in the reservoir or in pipeline (UDC) which occurs under the deposits and is an external corrosion present in the piping systems, and this corrosion is heterogeneous. Due to the galvanized process; the corrosion local leads to corrosion localized to appear of deposits and local cathodes and anodes which can form on the wall of the pipelines putted in water for a long time. Indeed, this phenomenon leads to concentration of oxygen in the catalytic cells. The diffusion of oxygen across different position of wall with different concentrations anther diffusion of chlor in high temperature can lead to form

different corrosion cells and increasable the electrochemical corrosion through the complex chemical reaction. The presence of chlor with high quantities in high temperature and Ph value are proportional to the corrosion and the deepest corrosion on the wall of piping systems. The UDC mechanism allows to evaluate this type of corrosion through the cover and protection of deposits and local corrosion Z.B. Wang et al. 2022 [127].

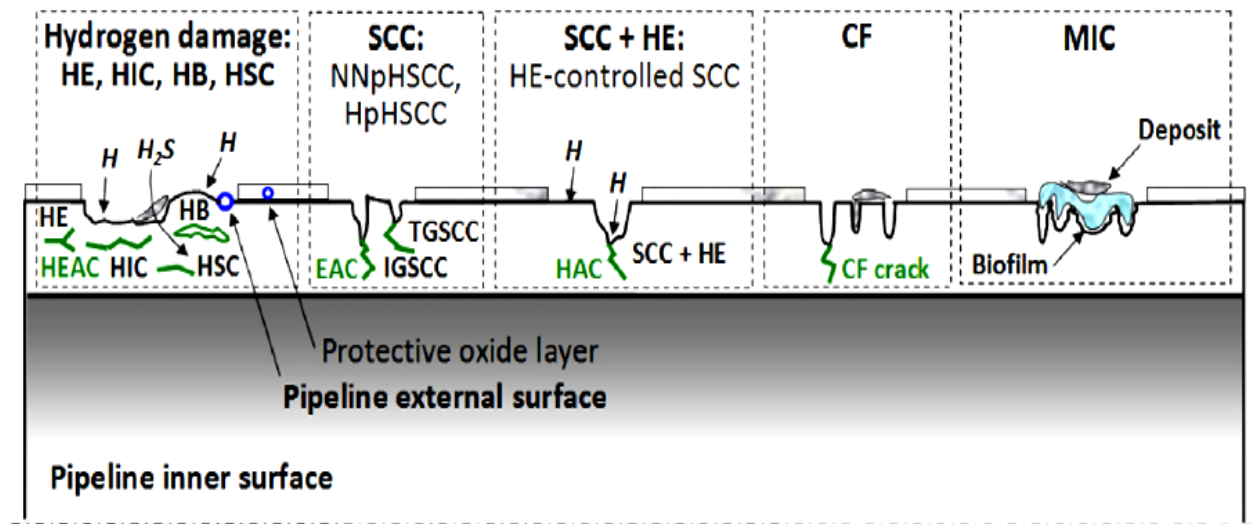


Fig.2.1 External corrosion-induced failure mechanisms of oil and gas pipelines acting on the exterior of the pipe due to corrosive soil [30].

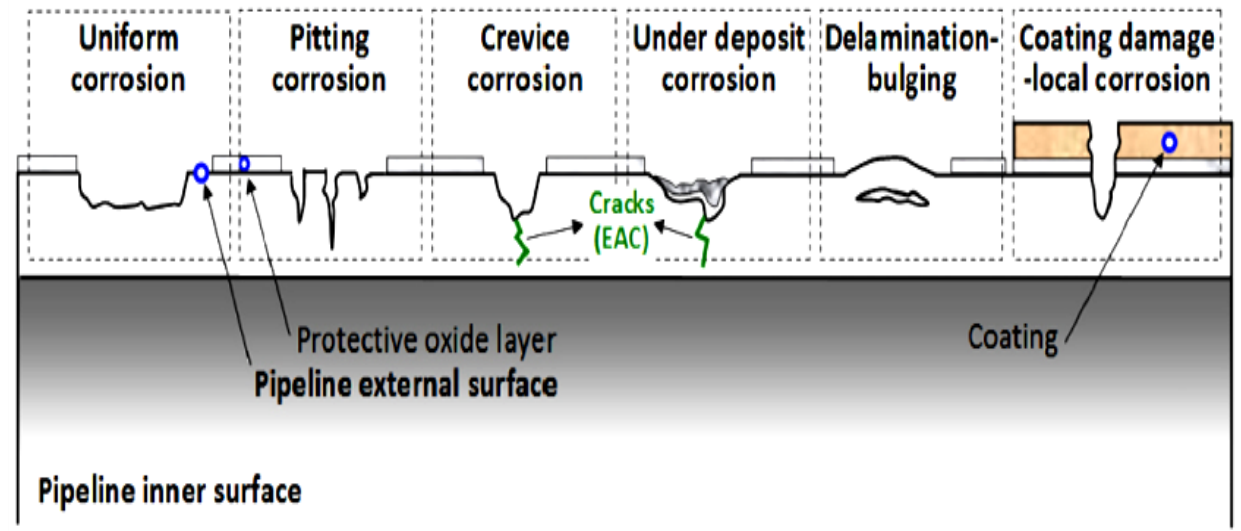
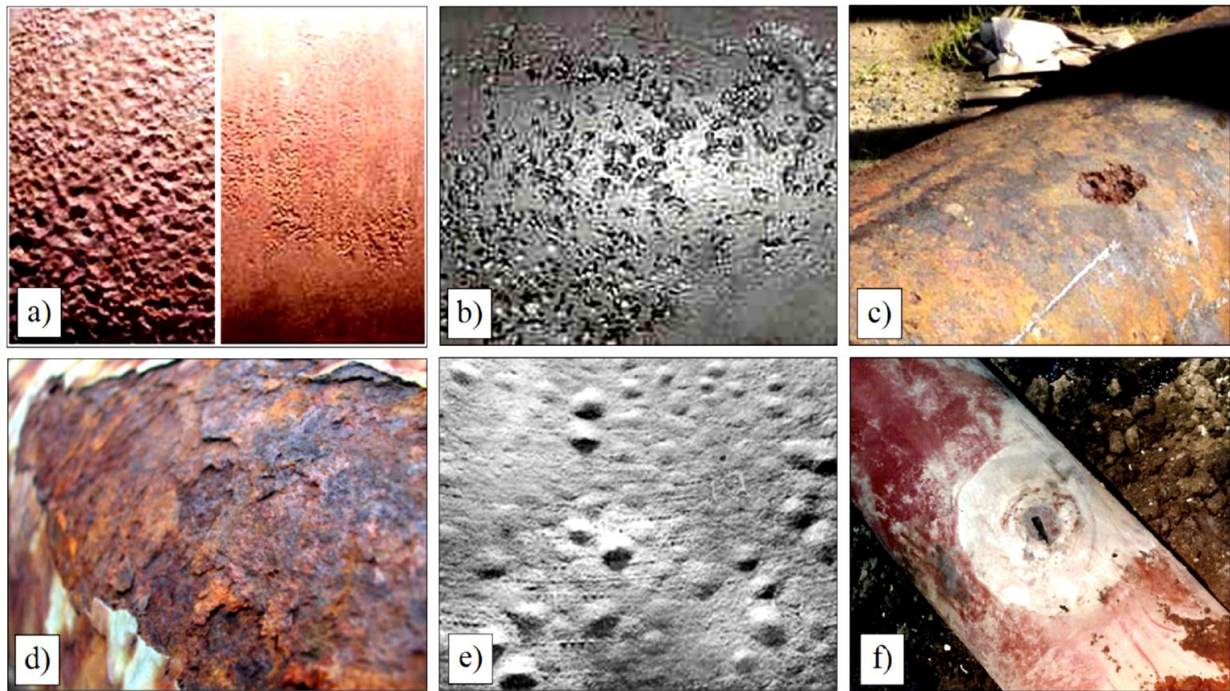


Fig.2.2 Représentation schématique en coupe transversale de toutes les formes caractéristiques présentées de corrosion externe [30].



a) Uniform corrosion (Ginzel, Kanters); b) Pitting corrosion (Ginzel, Kanters); c) Crevice corrosion (Asadi and Melchers, 2017); d) Underdeposit corrosion (By Corrvie.com and Reviewed by Gopal R., 1484); e) Delamination-bulging, hydrogen blisters (Mostert, 2005). f) Coating damage - local crevice corrosion (Norsworthy, 2009).

Fig.2.3 Représentation schématique de plusieurs formes de corrosion externe [30].

### 2.4 Corrosion interne of pipeline

This type of corrosion is considered as part of the internal corrosion of pipelines wall which is occurred through the physical, chemical effects of fluids in the internal piping systems, however the transported fluids including simple or complex, suspension or emulsion are generally in the form of liquid, gas and other impurities or aggressive compounds under high pressure and temperature. These operating conditions can lead to internal corrosion where it can appear failures along piping systems. Thus, it can lead to occur troubles for origins of energy such as oil companies and environmental damage [127-129].

During the last decades the Carbon steels becomes an important material in oil industries due to the high mechanical characteristics where it used a lot of in the hydrocarbons transport.

The fields of hydrocarbons as the wells can create a suitable environment to presence of acids in the used water in extraction operations including, acid naphetic, sulfur, carbon dioxide, chlorhydric acid, hydrogen sulfide and acetic acid.

This phenomenon allows to occur the electrochemical corrosion of acid which in turn leads to internal corrosion of piping systems where it can lead into a difficult problem with the presence fit environment as silicon sand particles, calcite, argillaceous, aluminum, corrosion, organic matter, etc. [130].

In piping systems, the corrosion problems subject at critical positions especially welded positions, valves, refinery stations and links positions between two parts of pipeline.

In fact, the corrosion issue can create various defects along of transport systems such as the deterioration of the internal walls and generate the propagation of cracks [131-133]. However, electrochemical corrosion of steel by NaCl acid containing oxygen gives the cathodic reaction below for equations 1-6 [134 and 135].



### 2.4.1 Under Deposit Corrosion (internal piping)

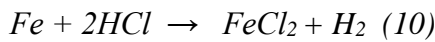
Under deposit, corrosion is one of the corrosion types, which is dangerous on the safety of pipeline network, where this phenomenon is considered as origin of dangers corrosion as other the classic corrosion previously [136]. Depending on the nature of transported hydrocarbons, including the nature of crude oil is an important factor, where the presence of aggressive compounds in crude oil like deposit on the wall layers compounds of sand, argillaceous and lime. (CaCO<sub>3</sub>, MgCO<sub>3</sub>, BaSO<sub>4</sub>, Naphetic acid, sulfur, etc.) of siliceous silicon, calcite, aluminum, organic matter.etc.

Depending on many techniques to prevent the piping networks from generate of corrosion in the pipeline, there are many strategies to evaluate the behavior of corrosion through UDC, which based on nature of reservoirs and nature of storage liquids. Moreover, the presence of acids and bacteria such as Naphetic acid and Sulfate-Reducing Bacteria (SRB) is considered as an important property which allows to improve of UDC. Many analyses of defects have proved by the presence of SRB inside reservoirs and in pipeline [137-138].

### 2.4.2 Defects of corrosion in the piping systems

During this decade, many kinds of corrosion are discovered along piping systems. However, the corrosion defects are still concentrated in the internal and external of walls through transported of hydrocarbons and their compounds, the analysis of defects is still better manner to evaluate the corrosion through depth and expansion shape of defects by many techniques of control the effect of corrosion.

The control of safety and to measure the degree of corrosion depending the time and environment are main factor of many companies of energy on the one hand [42]. On the other hand, there are many factors include into reasons of corrosion in the most of energy petroleum such as carbon dioxide (CO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), water (H<sub>2</sub>O), salts (NaCl, CaCl<sub>2</sub>, MgCl<sub>2</sub>, NH<sub>4</sub>Cl, ..) and organic acids (HCOOH, CH<sub>2</sub>COOH, ..). In addition the effect of bacterial activities and soluble materials through high temperature and pressure which allow to generate the complex chemical reaction below for equations 7-14 [140-142]:



## 2.5 Method of calculating corrosion defects.

### 2.5.1 Corrosion defect evaluation

Corrosion issue is still dangerous problem on the piping systems to transport hydrocarbons energy where it appears the problem on external and internal of walls due the presence of aggressive compounds during the flow of fluids taking into account the nature of transported liquids on one hand.

On the other hand the positions of systems network in the in a corrosive environment [42], allows to in grease the degree of corrosion. there are many factor used to analyses the corrosion along of piping systems such as ASME B31G [15], B31G [27], DNV-RP F101 [111] which can determine the techniques of safety and efficiency of treat the corrosion problems depending to evaluate the ultimate resistance based on conditions operating. Due to the presence of many kinds of corrosion defects, it can simplify to simple geometry form order to understand including regular or irregular forms such as semi-elliptical, elliptical, rectangular, or square or circle, as shown in Fig.2.4.

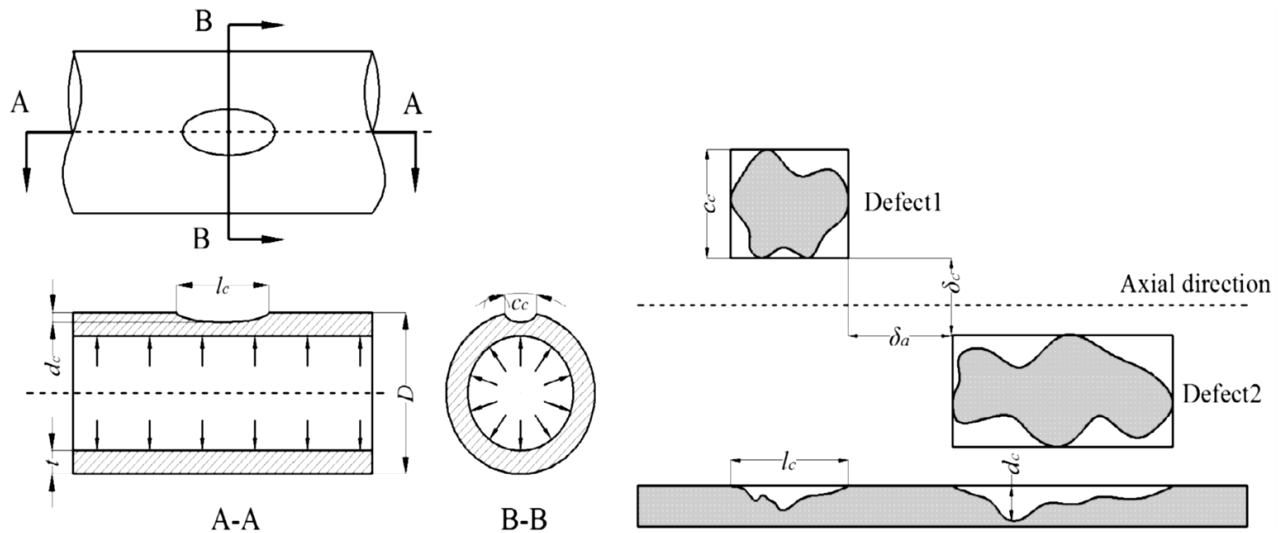


Fig.2.4 Schematic of the numerical model with corrosion defects [42].

### 2.5.2 Evaluate depending the time

Based on many studies have been performed to evaluate the safety of piping systems through the deterioration protective cover due to the corrosion problems due the directly contact with external aggressive environment such as humidity or wetly.

Infact, the defect corrosion occurs an internal wall by complex oxidation however, the external corrosion occurred due the directly contact with wall and an aggressive environment. Extensive research has shown that the degradation by pitting corrosion increases with time, also the decrease in pipe strength this phenomenon is one of the main causes of pipeline burst [40]. A corrosion defect in a pipeline under static internal pressure stress propagates with time and by can calculate the growth rate of corrosion defect, It can evaluate the corrosion through corrosion rate and the service life of the pipe basing empirical equation (15):

$$V_k = 10^{-3} [1.03 + 0.23(t_0 + t)], \left( \frac{m}{year} \right). \quad (15)$$

Where:

$V_k \approx (t)$  : the equation for approximate determination of the crack growth rate dependent on the operation time  $t$ ,

$t_0$  : is the time of pipe operation before gas pipeline residual lifetime evaluation.

The energy approach, as a result, it is reduced to the mathematical model that renders the following governing equation (16), [40]:

$$\frac{d\rho}{dt} = VV_K(t) \sqrt{1 + \rho^{-2} \frac{d^2\rho}{d\alpha^2}} \quad (16)$$

Where:  $\alpha, \rho$ —coordinates of polar system  $O\alpha\rho$  which follows the shape of the corrosion-mechanical crack.

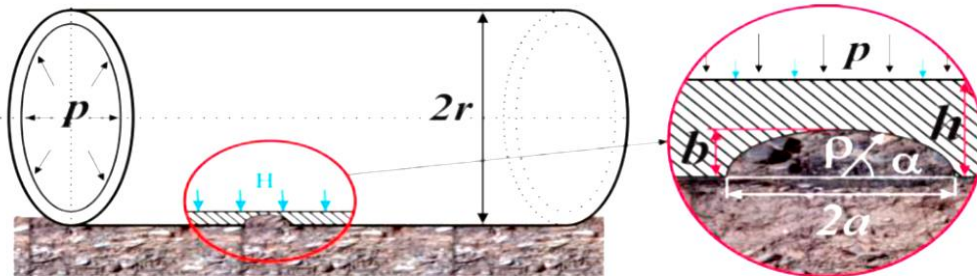


Fig.2.5 Loading scheme of the pipe with an external crack under soil environment action [40].

### 2.5.3 Data pressure evaluation

To measure the operating pressure of corroded piping systems, it used the standard norms ASME B 31.4 and API 1160. Applying these norms lead to take the decisions which provide suitable solutions by changing the corroded part by new part or reinforced by patch including carbon fibers or hybrid fibers. In the corroded parts of piping systems, many companies face constraints of transport of hydrocarbons where the finding solutions requires according to many norms such as ASME B31G [15], ASME B31G modified [143]. These norms have been proved by several studies through validation by experiment tests on the one hand [144,146]. On the other hand, new norms have been developed by models, such as DNV-RP-F101 [111] and PCORRC [147] have been developed and are designed for high-strength steel (HSS) [148,149]:

$$\sigma_{\theta} = P_r/t, \sigma_l = Pr/2t = 0.5\sigma_{\theta}, \sigma_r \approx 0 \quad (17)$$

Where,  $\sigma_{\theta}, \sigma_l, \sigma_r, P, r,$  and  $t$  are hoop stress, longitudinal stress, radial stress, internal pressure, average radius and wall thickness of pipeline.

After defining the evaluation models related by nature of materials and transported liquids depending the operating conditions such as the pressure ( $P$ ) which have to less than the maximum value of pressure ( $PL$ ) where ( $P < PL$ ) to avoid the failure of piping systems.

For ancient corroded such as X42, X52 and X54, it can calculate the maximum pressure through several norms such as ASME B31G, ASME B31G modified and RSTRENG on the

one hand, on the other hand, the steel of API X75, X80-X120 are based on many norms DNV RP-F101 and PCORRC [111,147].

### **2.6 Maintenance of piping systems**

Many companies sought to protect and to avoid the failure of piping systems including rupture and damage, where various defects lead to corrosion, which becomes the challenge facing on more companies of energy.

According to failure the systems of transport, many companies such as maintenance companies seek to use the better techniques.

Two steps are necessary processes, firstly during installation or begin of exploitation are used by adding inhibitors for decreasing the micro compounds and electrical elements laden in transported fluids.

Second step is based by using the patch or reinforce of piping systems through patches on corroded pipelines that contain corrosion defects and metal damage into cases internal or external defects. According to many studies about repairing by patch that proved its efficiency due to their reasons such as high resistance, resist of corrosion, low costs and eco-friendly.

#### **2.6.1 Uses of inhibitors**

Inhibitors is considered as the one of better solutions used by the most companies as efficiency techniques to avoid the causes of corrosions including on deterioration and brutal rupture of the pipe as well as production stoppage [150].

Nowadays, there are many kinds of inhibitors used to change the behavior of transported crude oil, where this technique is based on the complex chemical reactions with wide applications [150] where it has a good effect on the protection against corrosion of piping systems in aggressive environment [150- 154] .

In addition, the role of inhibitor has an important although high temperature as results of thermal expansion and low density [155] as operating conditions as shown in Fig.2.6.the corrosion of the structure on the surfaces presents a high corrosion sensitivity on critical zones [156],solutions with added inhibitors react as a denser protective layer Fig.2.7 The choice of use of anti-corrosion inhibitors in the petroleum industry sectors have a detrimental effect on inhibition efficiencies reported on corrosion compatibility problems between inhibitors [157- 159].

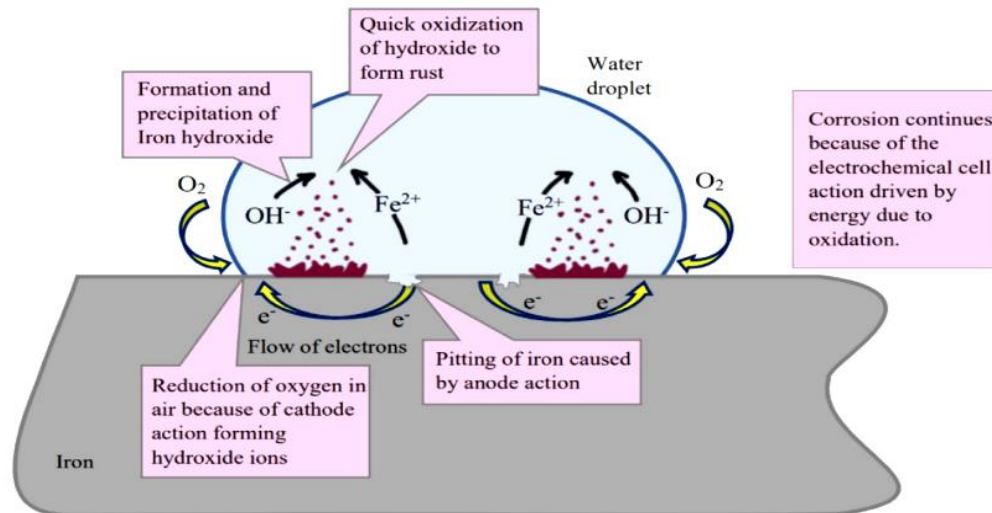


Fig.2.6 Corrosion as an electrochemical process (Hyper Physics)[155].

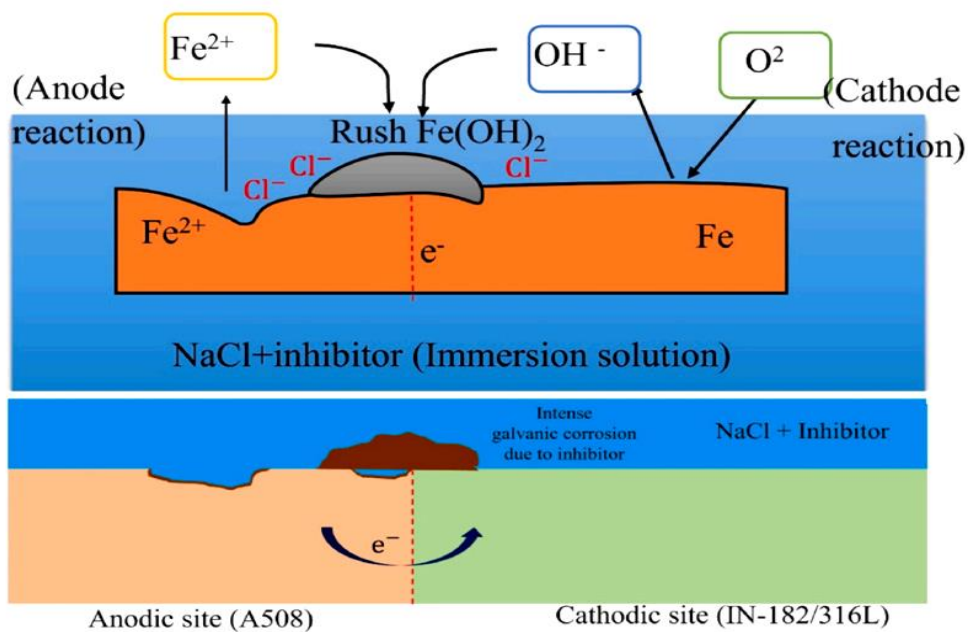


Fig.2.7 Corrosion mechanism on the surface of the DMW [156].

### 2.6.2 Repairing by Patch

During the last years, the mechanical industries used new techniques of repaired through patch of composite material including carbon fiber, glass fibers or hybrid composite. This manner proved that the repairing by patches which provided more solutions for various fields such as cars, trains, ships, planes, piping systems. There are several solutions used between many companies in the worldwide, where it used the composite material depend on

its efficiency through their compounds. In addition, many factories focus to use of new patches [160-161] through composite clamp [163] or patch of carbon with adhesive [163-164]. These techniques of reparation can allow to keep the structure of piping systems although reparation by patch, thus it leads to continue of the hydrocarbons transported .

The repairing by patch is better solution for any form of crack or defects such as the semi-elliptical or elliptical forms [112-117,165].

### **2.6.3 Repairing with welding**

The reparation by welding operation is still one of an important method to repair the piping systems corroded, where this method is based on remove the damaged part and replace it by new part taking into account has a same mechanical properties Fig.2.8. This technique is considered as old traditional technique [166-167], where the using the process of welded steel sleeves to repair pipelines, which is an important in the transportation of hydrocarbons on the one hand.

On the other hand, the welded steel sleeves processes is effective step to protect of pipeline or defects along of piping systems [109,110,170,171]. To restore the mechanical properties of piping systems corroded through sleeve steel which is used to repair them as shown in Fig.2.9.

Y. Shuai[45], where they were able to develop numerical model for repairing of defects. Depending the experimental results, which provided more solutions of defect of piping network taking into account the dimensions and sizes of defects as shown in Fig.2.10.

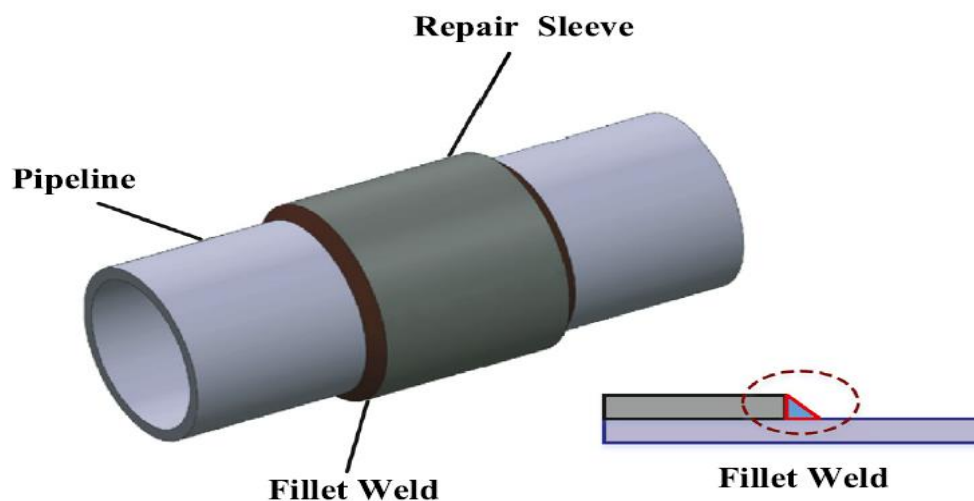


Fig.2.8 Schematic diagram of type-B sleeve repair method for a corroded pipeline [109].



Fig.2.9 Pipeline repair via type B Sleeve [110].

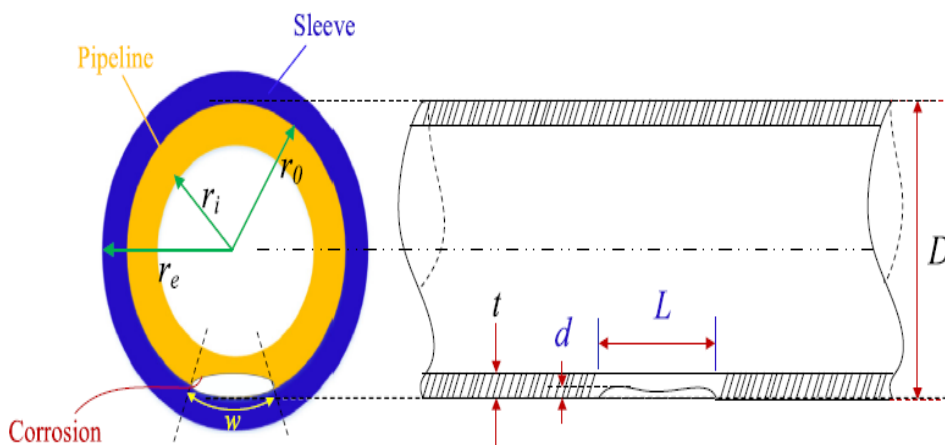


Fig.2.10 Composite structure of corroded pipeline repaired by sleeve [170].

#### 2.6.4 Pipeline Repair by FRP

Fiber glass composite polymer (FRP) is considered as better solution to repair the defects or corrosion along of piping systems, where is used as patch in corroded wall due to the external environment or internal through the interaction wall-crude oil.

This kind of industrial fiber has an excellent features especially corrosion resistance, their advantage of weight/high resistance and quality/price ratio. Using the glass fiber allows to in force the damaged parts of piping systems which help many energy of companies to improve the techniques of reparation through increasing of stiffness, resistance of stress

and increasing of the life time. Furthermore, the use of polymer matrix composites (FRP) to repair damaged pipelines in the oil industry has become common practice, increasingly used as an alternative to installing welded ring sleeves or bolted sleeves. Energy companies are seeking to develop the techniques for repairing defects, corrosion, cracks at different positions by FRP, where many laboratories provide more time to find the smart solutions in order to repair all kinds of defects especially at zone of connections through the quality of the correction of cracks [111,112].

In fact the using of glass fiber is based on adhesive matrix where it can play to connect between fibers and surface defected. This technique can provide many solutions, which may be allowed partly to increase the resistance of the piping system and maintain production and partly to protect the environment from the pollution.

To investigate the efficiency of a new composite layer to repair wall faults was investigated using hydrostatic testing according to TS24817 standards, the results indicate that composites are a viable tool for the rehabilitation of damaged of piping network that may lead to damage [112].

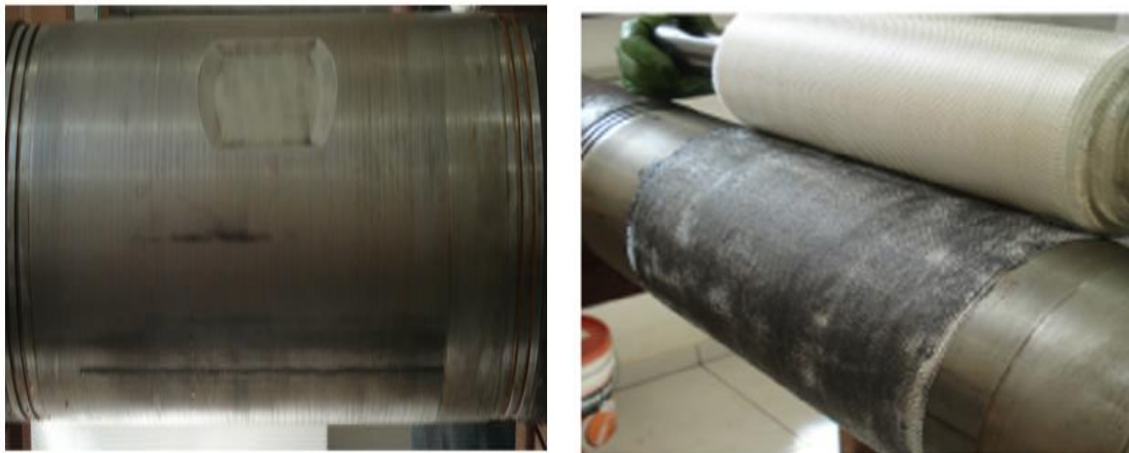


Fig.2.11 Specimen repair preparation of defect for hydrostatic testing [112].

The feature of Glass fiber allows to increase the efficiency for reinforcing the zones corroded where Kar Sing Lim et al [113] proved that this type of patch are very important to provide the safety of piping systems as shown in Fig.2.12 and 2.13. Depending on the several studies, the results proved the importance of glass fibers, which was increased by 23% in equal relationship with the defective piping systems.

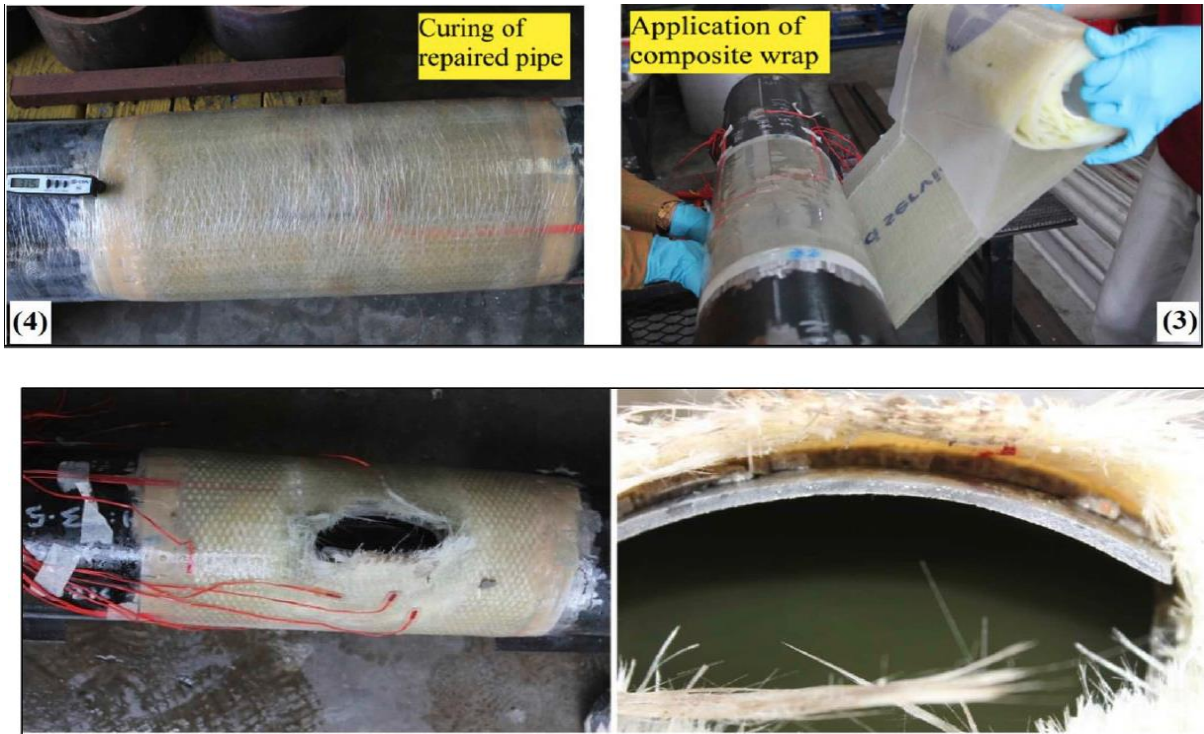


Fig.2.12 Application of composite wrap on the defective pipe [113].

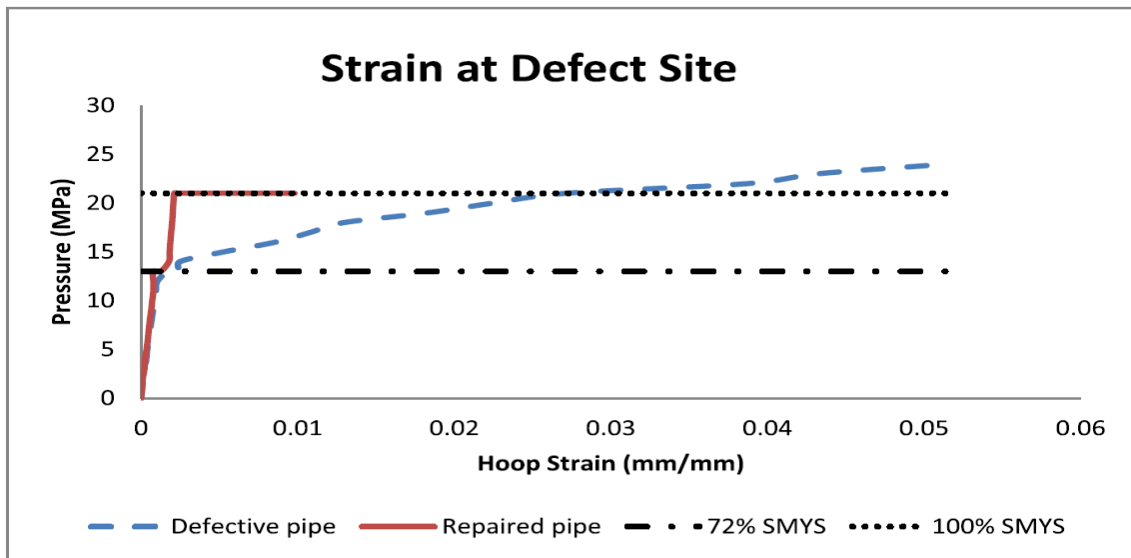


Fig.2.13. Comparison of strains in the defective and repaired pipes [113].

Doyle et al. [114] have been proved that carbon fiber composite (CPRF) patches is one of better solutions to reinforce the piping systems corroded through the acid structure of pipes for external corrosion sections.

The creation of defects in piping systems was wrapped with carbon fiber/epoxy which can be reinforced by patch as shown in the Figs.2.14 and 2.15.

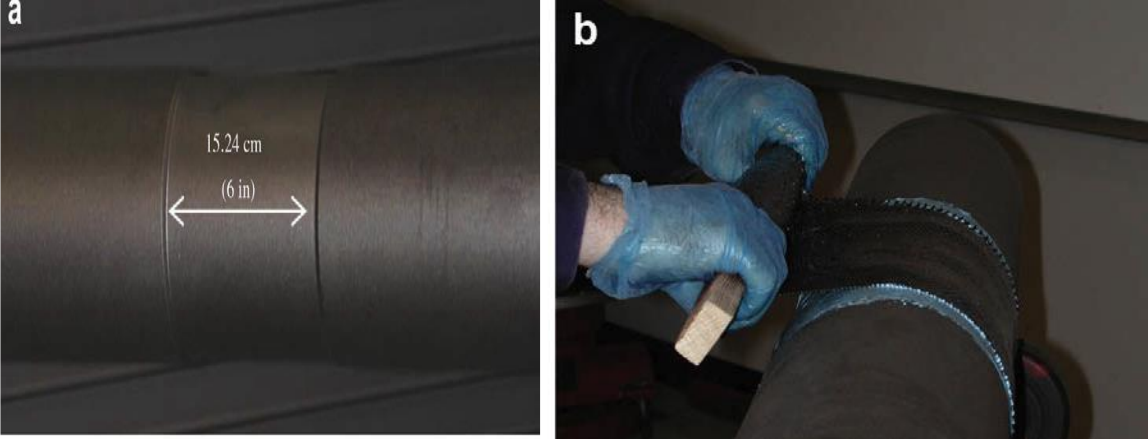


Fig.2.14 Pipe test vessels with machined flaws with a depth of 50% wall thickness for (a) and (b) Pipe repair process filling defect with putty[114].

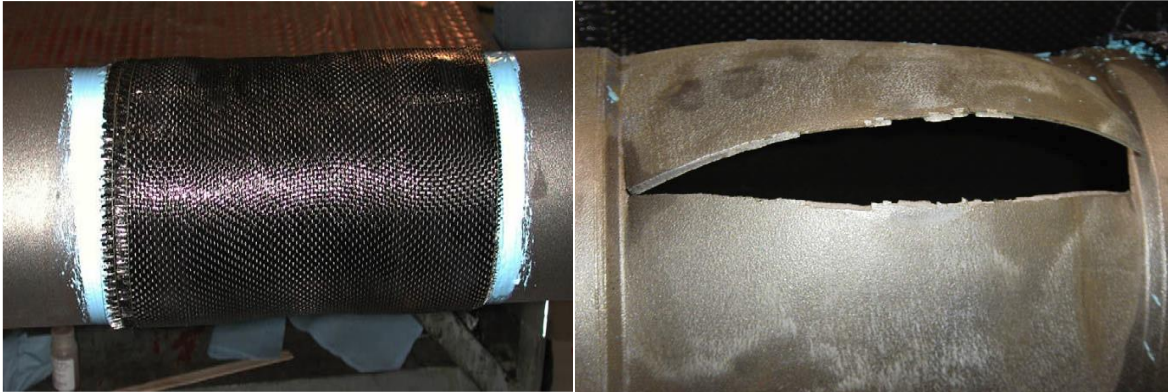


Fig.2.15 Wrapping epoxy wetted carbon fabric around the defecting and b Example of a ruptured vessel with an axisymmetric defect [114].

**2.6.5 Pipeline Repair by composite hybrid**

Using the hybrid composite of double patches of same materials or different double in same matrix can combine the performance mechanical and chemical of Hybrid composites. Hybridization technique is better step to improve the FRP composites made for different materials due to a combination between high abrasion resistance and high stretch or other mechanical properties. These composite fibers can be combined in various categories as shown in Fig.2.16.

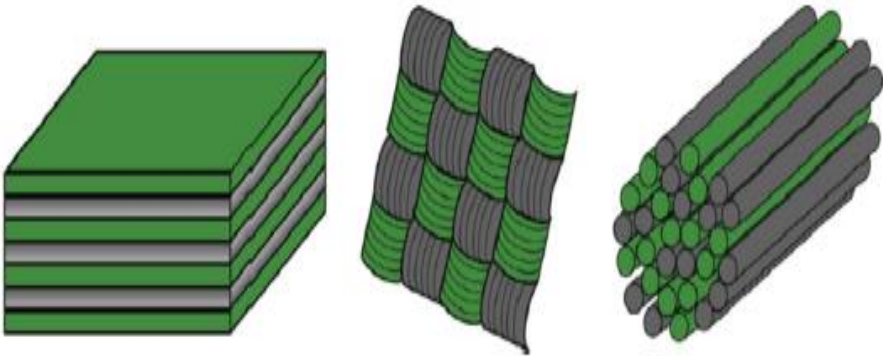


Fig.2. 16 The three main hybrid configuration (a) interlayer or layer by layer,(b)interlayer or yarn-by-yarn, and (c) interlayer or fiber by fiber[ 172-174].

Hybrid composites or hybrid materials including glass fiber and carbon fiber are used in piping systems applications or in industrial applications. Evaluation of steel piping systems repaired with FRP hybrid glass/carbon composite patches, when the flexural strength is highlighted, as shown in Figs.2. 17and18.



Fig.2. 17 Repairing in water with hybrid glass/carbon layers [175].



Fig.2.18 Testeafter combined axial compression [175].

Finally, Dong [176-177] performed a study about carbon/glass hybrid composites of the evaluation of pipelines proved that carbon and glass fibers have features by excellent advantages including weight and quality properties see Fig 2;19.

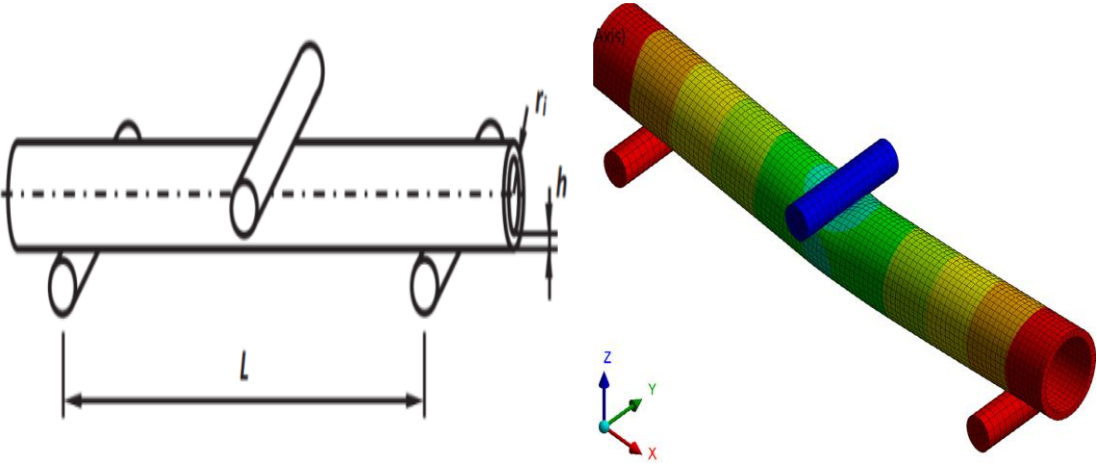


Fig.2.19 A composite pipe in three point bending [176].

## **2.7 Conclusion**

In internal pipeline systems, the transported fluids, in the form of liquids, gases, and other impurities, are composed of aggressive elements attacking the walls of the tube. These fluids enter into chemical interaction with other high pressure and temperature. These can lead to internal corrosion in several forms; the most widespread is the semi-elliptical shape, which degrades the mechanical properties of the steel, and risks of failures may appear along the piping systems. In this research, the survey process and composite materials in the form of patches are used to repair pipelines to ensure the continuity of the flow of hydrocarbons. In addition, the use of inhibitors, which are considered as the solutions, is provided to reduce the impact of corrosion and extend the life of pipelines.

## **Chapter 3: Experimental study of specimens with/without defect and repaired by welding**

### **3.1 Introduction:**

Many hydrocarbon companies have been used to transport crude oil and gas through the steel piping systems, where the use of the steel in piping systems leads to appearance of various defects including small cracks, cracks and corrosion at critical zones, such as welding zones, valves and elbow.

These causes have become a great challenge facing several companies to improve the mechanical properties in order to reach the energy to factories with more safety under operating conditions such as nature of pipeline material as well as nature of liquids transported. Due to the demand of energy on level global, several manners have been used to transport the hydrocarbons especially trains, ships and planes trade. Many techniques have been used to repair the defects along the piping systems such as welding processes and reinforce by composite patch natural fibers or industrial fibers. According to manners of the energy transport various problems have been occurred during the transport of hydrocarbons although the basing on the international norms such API 5L [14] and ASME B31G [15]. To design, size and product according to adequate conditions such temperature and pressure. In addition, there are special paints in internal and external of piping systems to protect from corrosion with using others solutions such inhibitors including industrial or natural (green inhibitor).

Indeed, the international norms can protect from internal or external [30] corrosion of the piping systems through special conditions such as dimensions, sizes, nature of materials and nature of products transported with presence of different aggressive compounds such as naphthenic acid corrosion [32], corrosion related by sulfur and bacteria [33], small cracks results of high pressures and temperature which reach to 410° especially at refinery stations [60].

Many companies have been decided to use others techniques to analysis and treat the corrosion problems by using new systems and tools which allow to control to and examine while the transported hydrocarbons [34].

On the other hand, they used also other techniques to prediction all scenarios of defects including using many codes basing on the finite element method, which can help to study the critical positions as elbows, and welded zones [35-38]. In fact, the corrosion problems is considered a serious step which highlight on defects to weak of the structures of the piping systems and can detected the critical positions through explosions under high pressures [39]. Some defects can appear as results of complex chemical reactions where the piping systems lead to loss of the brown layer and to decrease of the thickness of walls along the

time service [39-40]. In fact, the pits forms as results of defects leads to elliptical and semi-elliptical forms depending on the values of pressures [40-42]. According to these serious problems faced of many companies, several studies were performed to find the better solutions of all types of corrosion through welding process and reinforced by material composites [67, 68]. On the other hand, I.S. Raju and JC Newman [55-57] studied the effects of corrosion on surfaces to predict the defects semi-elliptical or semi-elliptical through finite element methods, where this project allowed to develop more ideas about corrosion taking into account the crack geometries on the wall of piping systems [115]. Stefan Strobl [116] provided an important result about the semi-elliptical cracks taking into account accuracy of selected conditions.

In the other side, K. Yuan [117] presented other idea about the weight factor, in order to compare the lost layer and the used patch to repair the defected zones.

The general purpose, how reach the companies to provide many solutions for many cases in order to a guarantee the transport of energy to factories [118-120].

In addition, there are many-based factor to analysis the behavior of cracks such as the stress intensity factor or J-integral method using the finite element methods [59, 60].

Many studied [61-63] examined the effect of multi-crack through the finite element methods to the safety of piping systems, where they based on the mechanical characteristics and the geometry of semi-elliptical crackssuch as the tensile and the bending stress with different crack depth ratios of shape semi-elliptical on the one hand and on the other hand the crack distance[61-63]. Many researchers sought to study the behavior of cracks [64] through the nature of transported fluids ( Newtonian or Non-Newtonian) on the one hand and basing on the mechanical properties on the other hand.

The hydrogenation phenomenon have been studied to analyze it effect on the piping systems through two processes Charpy and tensile operations which highlight of hydrogenation on safety of pipeline [178- 181].

Occurring of the Complex chemical reactions during the energy transport leads to defects of the degradation of materials such as API X70 and API X80 [182]. The purpose of this study is to analyze the effect of cracks including semi-elliptical forms on the mechanical characteristics of API X 52 steel. This project is divided into two parts of reparations processes, firstly repaired by welding technique and secondly repaired by material composite. In order to study the behavior of cracks especially semi-elliptical forms and compared with specimen without cracks to evaluate the effect of cracks along of piping systems depending on their (a/c) and (a/t) of cracks. Many parameters used to study the behavior of crack and it is

repairing by welding through the behavior of structure with/without defects. In fact, the welding processes is still an important technique to reinforce the part defected which is considered as one of sustainably solutions of big cracks.

**3.2 Modeling the corrosion defects of pipeline**

Corrosion is the principal reason of pipeline damage, where corrosion defects are appeared along of pipeline in external and internal walls especially at weak areas. The pipeline failure is examined using the corrosion dimension parameters based on the services conditions and the nature of soil taking into account the external environment and complex chemical reaction between crude oil and internal wall. In addition, the different techniques to treat the corrosion failure through to the penetration of the layer protect, where this may lead to partial deterioration of the piping systems results of nature of transported fluid (crude oil and gas) or sounds from high-pressure pipes due to the propagation wave of flow and the interaction liquid-solid (crude oil-internal wall).Indeed, the failure piping systems occurs when the pressure produced exceeds the maximum authorized pressure. The corrosion depth of the pipeline can be measured the failure using the maximum deep of corrosion as well as the lifetime. The corrosion defects depend on the service conditions and the differences in depth and axial length as shown in Fig.3.1 [168].During service, the resistance of the piping systems depends on many factors through the effect of corrosion on the movement of the sun and other environment factors as shown in Fig.2.3 and 2.5.In this field, the American Society of Mechanical Engineers (ASME) has developed the standard norms in the worldwide to keep the safety of piping systems.

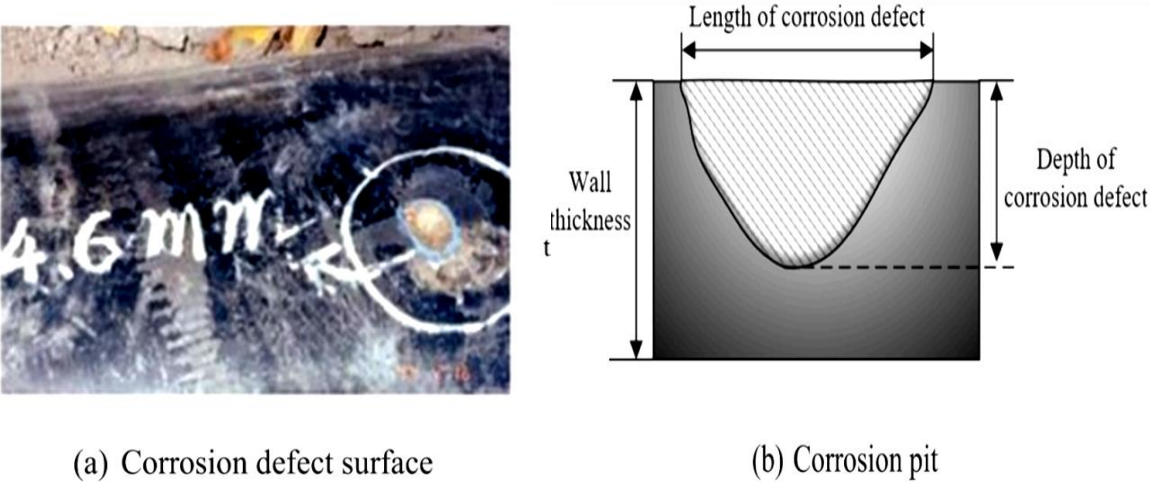


Fig.3.1 Pipeline corrosion morphology [168].

### **3.3 Piping System Welding**

After the assembly operations, the welding processes an important place in the engineering construction industries due to the desired dimensions and shapes as well as the resistance supported by the service. The welding is a process that consists of assembling two or several ends to ensure continuity between the ends of the assembly using different techniques by pressure. There are many applications using the welding technique as the suitable solution to repair the defects along of piping systems, where the SMAW welding which is widely used to make of piping systems by constrained, such as high pressure, storage tanks, bridges, ships and wagons.

### **3.4 Choice to proceed with the assembly of the tubes**

Companies and/or institutions that realize the gas and oil transmission line such as SONELGAZ, SONTRACH and COSIDER group files are very necessary for developing the Algeria economy as well as the institutions that realize the status of the piping systems projects and others equally transport pipelines were used by various welding techniques such as manual welding and electric automatic injection (shielded metal arc welding –SMAW-).

#### **3.4.1 Manuelwelding**

Pipeline transportation companies achieve the continuity of the X60 steel pipes by joining them together by arc welding; using the electrode induced welding process.

To perform the welding operation, there are many compounds including a power source, an electrode holder clamp, a linking cable, and a ground cable, all these parts allows carrying out welding operation as shown in Fig.3.2.

#### **3.4.2Automated welding**

It is necessary to highlight the importance of automated welding used by pipe construction companies, which is performed using an automated welding machine in order to speed up the

assembly of pipelines and even in pipeline manufacturing machines Fig. 3.2.

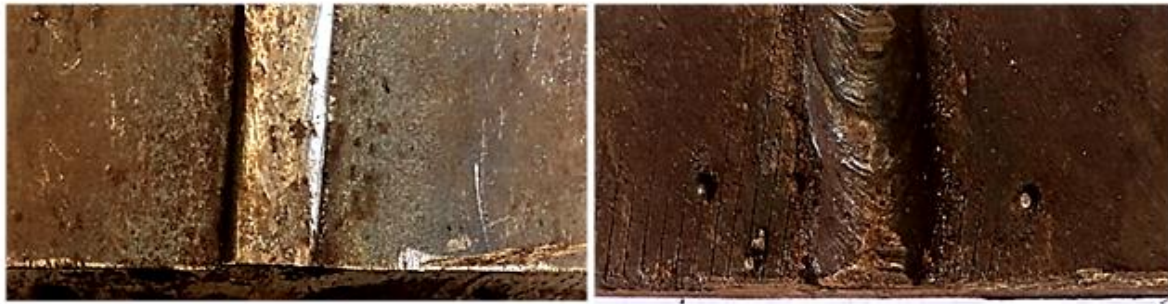


Fig.3.2 X52 steel pipes by arc welding, a)Manuel welding, b) Automated welding.

### 3.5 Material and experimental methods

#### 3.5.1 Material

The API X52 steel selected to use in this study which was supplied by company ALTUMET (Algeria).This project allowed analyzing the impact of defects along of piping systems through using the traction machine.

In fact, the corrosion problems concentrated along of piping systems through the defects, which are considered as cracks or small cracks at critical zones. The most cracks take semi-elliptical forms where the sizes of defects have directly affected by the mechanical properties of used material. Table.1 summaries the physic-chemical characteristics of API X52 specimens of this project, where the experiments were performed in the company of the ALTUMET in Algeria.

Table3.1 Chemical composition and mechanical characteristics of API X52[14].

Chemical composition (%)	C	SI	Mn	P	S	Cr	Mo	Ni	AL
	0,038	0,258	1,12	0,0093	0,0019	0,0306	0,003	0,024	0,0214
	Cu	V	Nb	Ti	Pb	Sn	B	Ca	Co
	0,0188	0,0019	0,349	0,0018	0,001	0,004	0,0001	0,0002	0,0008
Mechanical properties	Young Modulus E (GPa)		Yield Strength, $\sigma_y$ (MPa)		Ultimate Strength $\sigma_u$ (MPa)		Elongation [%]		
	210		$\geq 360$		$\geq 460$		32		

### 3.5.2 Test specimen and experiment

#### 3.5.2.1 Tensile test specimens

Many problems have been appeared along of piping systems during the last decades, especially the corrosion problems due to many reasons as results of small cracks, manufacturing defects, occurring the complex chemical reactions related with the nature of transported liquid and natural of used materials.

In recently, there aren't enough experimentally studies treat this problem especially for the semi-elliptical form which is considered the great problem, where it has been menace the most energy companies depending on the operating conditions such as the high pressure and temperature.

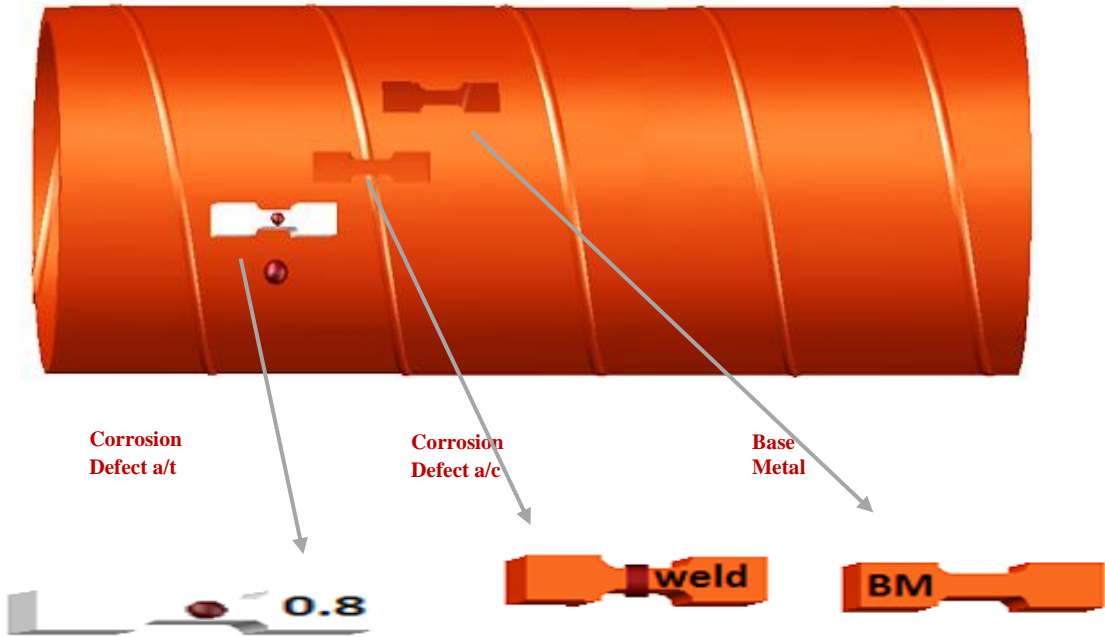
The most energy companies have been sought to find the durable solutions depending on the defects geometry, where the welding technique is still an important strategy to repair the corroded piping systems. In fact the technique of welding has been used in the worldwide through its features and its role to improve the mechanical characteristics.

Depending on the standard norms, all specimens of steel pipeline API X52 have been prepared through ASTM A370 [183] norm which is suitable for our study taking into account the size of defects including the semi-elliptical forms basing on length cracks ( $a/c$ ) and profounder cracks ( $a/t$ ). All specimens were prepared at same material in two types with/without welding in the longitudinal direction of semi-elliptical form as shown in Fig 3.3. To perform the experimental study, we used same size of semi-elliptical shape in order to find the correct results with high accuracy through using frieze hollowed as shown in Fig.3.5.a.

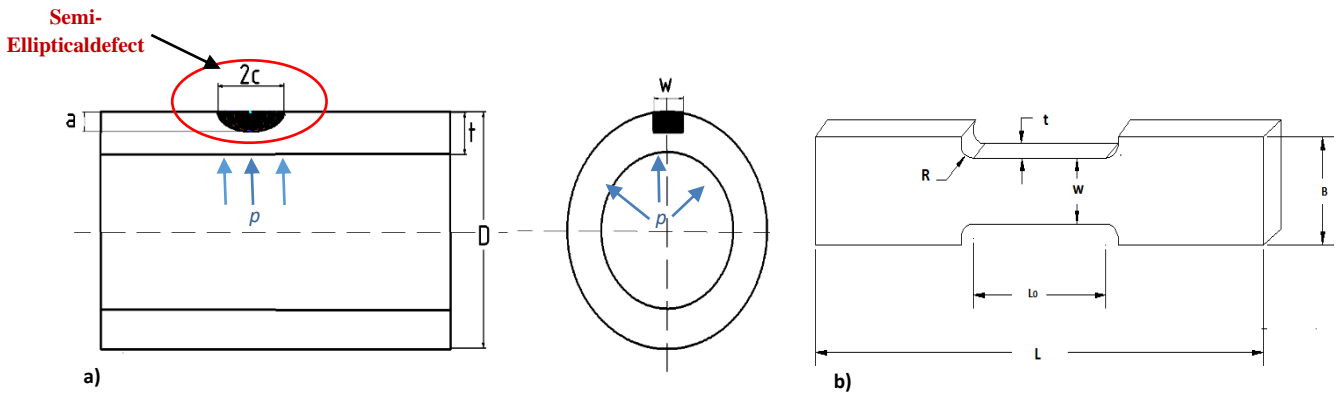
Two categories selected to study the behavior of defects firstly has concentrated on the parameter of length ( $c$ ), and the second has concentrated on parameter of depth ( $t$ ) [184]. The obtained results of experiment of the semi-elliptical defects specimens are summarized in table 3.2.

**Table3.2: Dimension of specimens for the forms of experiment tested with/without defects**

N°	Specimens	t (mm)	a mm	C (mm)	W (mm)	L (mm)	L <sub>0</sub> (mm)	B (mm)	R (mm)
1	Base metal specimen without defect	10.3	-	-	38	340	100	55	20
2	Base metal specimen with welding	10.3	-	-	38	340	100	55	20
<b>First type : corrosion length</b>									
3	Specimen with defect a/c = 1	10.3	5	5	38	340	100	55	20
4	Specimen with defect a/c = 0.7	10.3	5	7.5	38	340	100	55	20
5	Specimen with defect a/c = 0.4	10.3	5	14	38	340	100	55	20
6	Repaired specimen defect a/c = 0.1	10.3	5	5	38	340	100	55	20
7	Repaired specimen defect a/c = 0.7	10.3	5	7.5	38	340	100	55	20
8	Repaired specimen defect a/c = 0.4	10.3	5	14	38	340	100 <td 55	20	
<b>Second type : corrosion depth</b>									
9	Specimen with defect a/t = 0.2	10.3	2	5	38	340	100	55	20
10	Specimen with defect a/t = 0.5	10.3	5	5	38	340	100	55	20
11	Specimen with defect a/t = 0.8	10.3	8	5	38	340	100	55	20
12	Repaired specimen defect a/t = 0.2	10.3	5	5	38	340	100	55	20
13	Repaired specimen defect a/t = 0.5	10.3	2	5	38	340	100	55	20
14	Repaired specimen defect a/t = 0.8	10.3	8	5	38	340	100	55	20

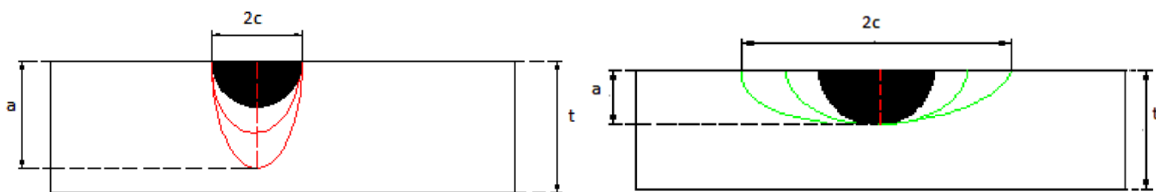


**Fig.3.3: Location of tensile specimens in API 5L X52 pipe.**



Model of a corroded pipeline (w: corrosion width, c: corrosion length, a: corrosion depth).

Fig.3.4: a) Geometry standards of semi-elliptical defects b) Dimension of the test specimen.



a) Length Semi-elliptical defect ratios on  $0 < a/c \leq 1$ . b) Profounder Semi-elliptical defect ratios on  $0 < a/t \leq 0.8$ .

Fig.3.5 Forms of defect geometry used in the test tensile.

### 3.5.2.2 Experimental method

The purpose of this study is to analyse the behavior of the effect of corrosion on the security of piping through using the test tensile to the crack of semi-elliptical depending on longitudinal and deep shapes at ambient temperature. the protocol of test is based on putting the specimens on the traction machine than withdraw from both ends of specimens until maximum deformation (damaged) through subjected of load in order to control the displacement. These tests have been saved by computer which linked with experiment tool. The saving the obtained results were used by computer related directly by experiments tool, where the welding technique is still important to repair the corroded especially semi-elliptical forms.

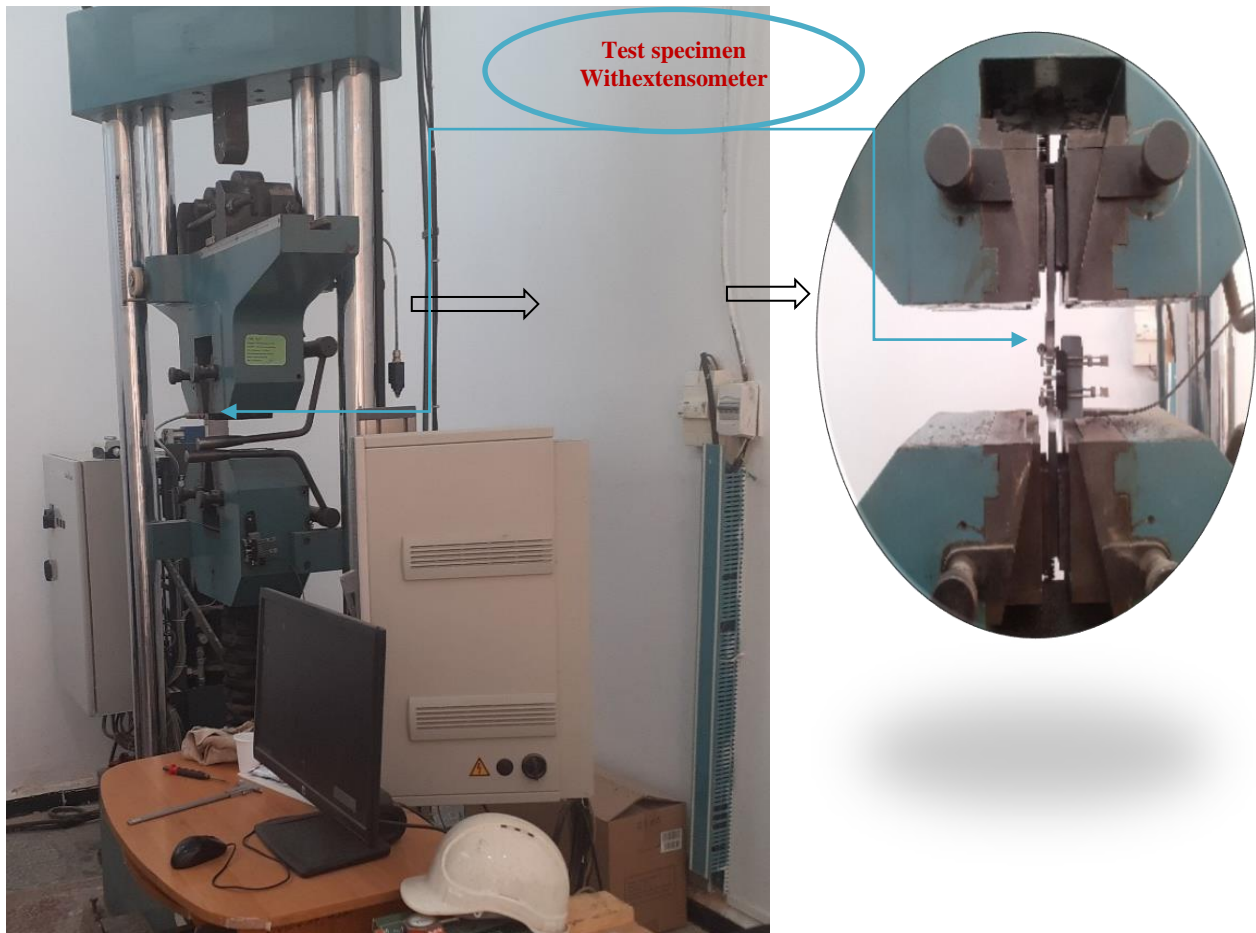


Fig.3.6 a) Zwick-Roell brand universal testing machine, b) Specimen with defect and without defect.

### 3.5.3 Test results and Analysis

#### 3.5.3.1 Experimental method

In order to highlight on the effect of defects on piping systems, where the defects took a complex forms which are semi-elliptical forms. Many energy companies sought to use welding technique to repair the corroded piping systems, where the experiments on welded specimens can evaluate the role of welding process. This project can compare between many cases such as origin specimen, defected specimen with semi-elliptical defect for different dimensions (ratios of  $a/c$  and  $a/t$ ) and welded specimens in order to illustrate the effect of defects on the structure of piping systems and its effect on the mechanical properties on used materials in order to identify the resist of API X52 as material of piping system.

The experimented results are shown in Fig.3.9 and 3.11, where Fig.3.9 expressed the affecting of defects on the longitudinal forms of cracks (corrosion) on the one hand, on the other hand, Fig.3.11 indicates to the effect of defects geometry, especially the depth case, on safety of piping systems[45]. The Fig.3.10 and 3.12 are indicated that the using of welding process

allows to reinforce the corroded pipeline through improving the mechanical properties taking into account longitudinal (a/c) and depth (a/t) cases [185,186].

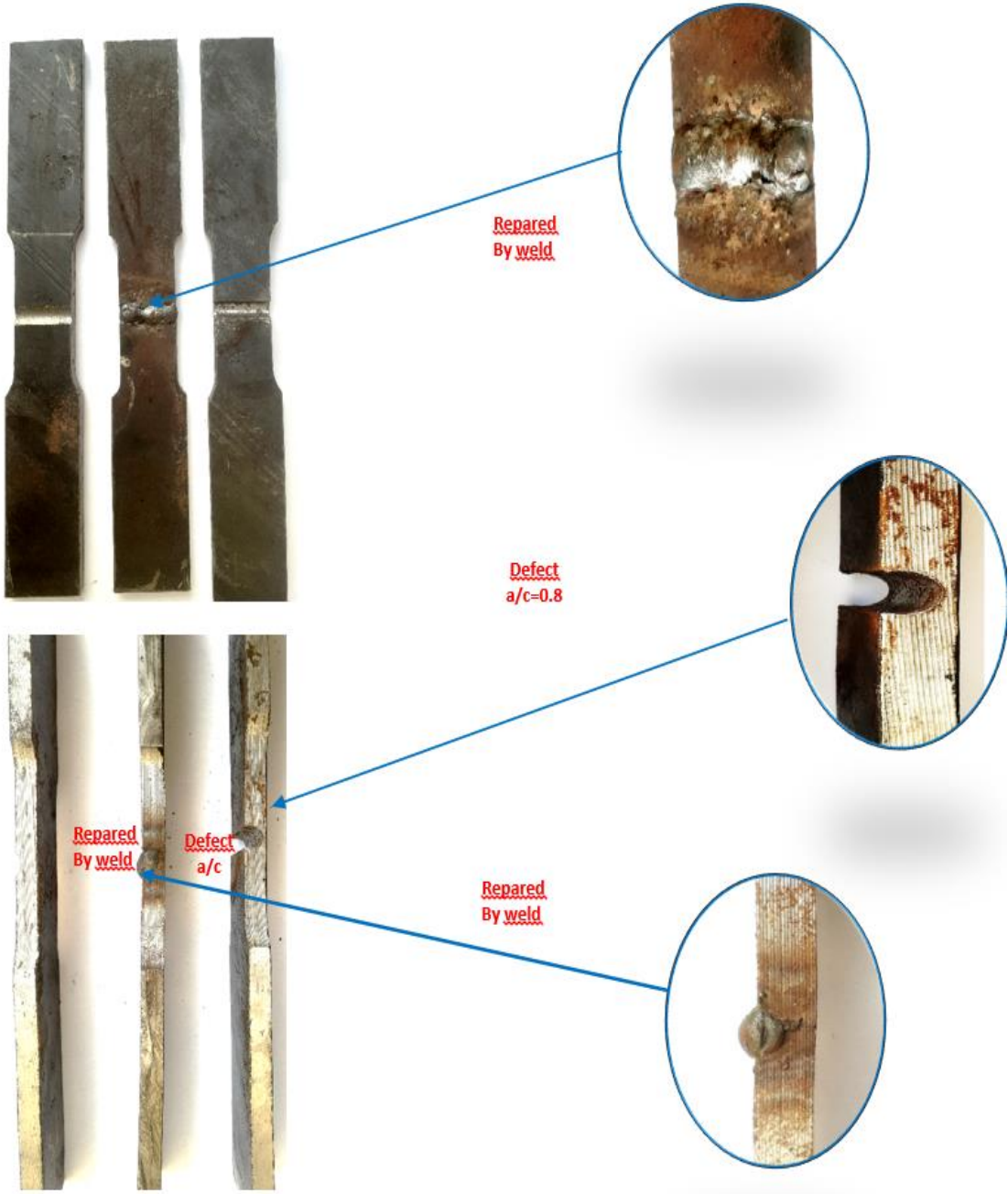


Fig.3.7 Specimen with defect, without defect, and repaired by weld.

**Table 3.3 Tensile mechanical properties of processed specimens**

Specimen	Yield Stress (MPa)	Ultimate Stress (MPa)	Strain Elongation (%)	Yield Ultimate Ratio	Toughness (KJ m <sup>-3</sup> )
Specimen of base metal	452	558	40.86	0.81	20646.47
Specimen of welded metal	456	572	25.56	0.79	12465.14
<b>First configuration</b>					
Specimen with defect a/c = 1	-	311	07.36	-	1895.72
Specimen with defect a/c = 0.7	-	306	07.12	-	1914.94
Specimen with defect a/c = 0.4	-	259	07.9	-	1696.42
Specimen repaired a/c = 1	455	531	25.36	0.85	12374.17
Specimen repaired a/c = 0.7	452	533	24.67	0.84	11125.6
Specimen repaired a/c = 0.4	418	480	16.62	0.87	6736.38
<b>Second configuration</b>					
Specimen with defect a/t = 0.2	448	488	12.71	0.92	5912.10
Specimen with defect a/t = 0.5	-	311	07.36	-	1895.72
Specimen with defect a/t = 0.8	-	160	01.98	-	274.59
Specimen repaired a/t = 0.2	520	559	33.62	0.93	17729.03
Specimen repaired a/t = 0.5	455	531	25.36	0.85	12374.17
Specimen repaired a/t = 0.8	330	399	05.18	0.83	1704.68

### 3.5.3.2 Tensile test of different specimens

The results represented in Fig.3.8 has been expressed to stress-deformation curves through the tensile experimented between origin specimen and welded specimen of API X52 metal. The experiments results of stress-deformation in the beginning stage which expresses linear elastic increase to 452 MPa through 0.5% of strain. In next stage the plastic deformation are appeared through the parabolic obeys of the stress reach to a top value of 558MPa for the base metal specimen and of 572MPa for the automatic welding specimen. The last stage is highlighted by increasing plastic deformation to rupture state through values 41.86% of the original specimen and 25.56% for the automatic welded specimen.

The test experiments and stress-strain results concordance with industrial. The tensile test results and the stress-strain curve correspond with the industrial standard [14] of steels API X52 [187].

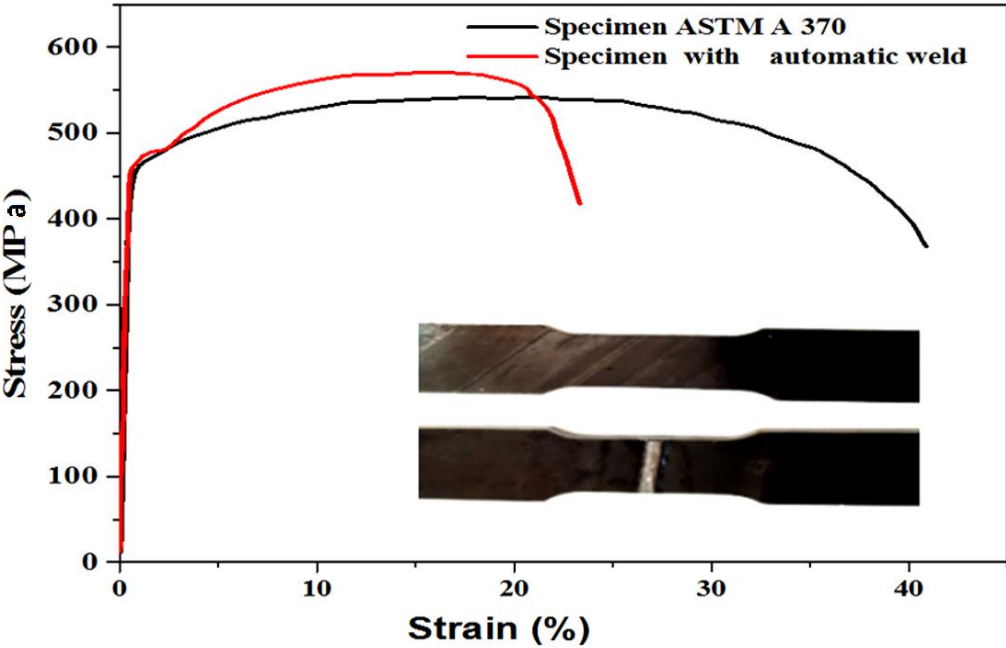


Fig.3.8 Stress-Strain curve for API X 52 pipeline steel when tested with specimen automatic weld and without weld.

**3.5.3.3 Tensile test of specimen with defect through ratio  $0 < a/c \leq 1$**

The samples with defects which were divided into three shapes of semi-elliptical, were tested by the tensile experiments with varying the parameters: length  $c$  and depth  $a$  of defects geometry according to conditions of the ratio  $0 < a/c \leq 1$  as explained in the table 2 [57].

Figure 3.9 showed the effect of defects on the safety of the API X52 pipeline, where this problem illustrated that decreasing of ultimate stresses to 259 MPa for  $a/c = 0.4$  compared with original sample valued by 558 MPa. It can note that the elongation was decreased from 40.86% to 7.12% [188].

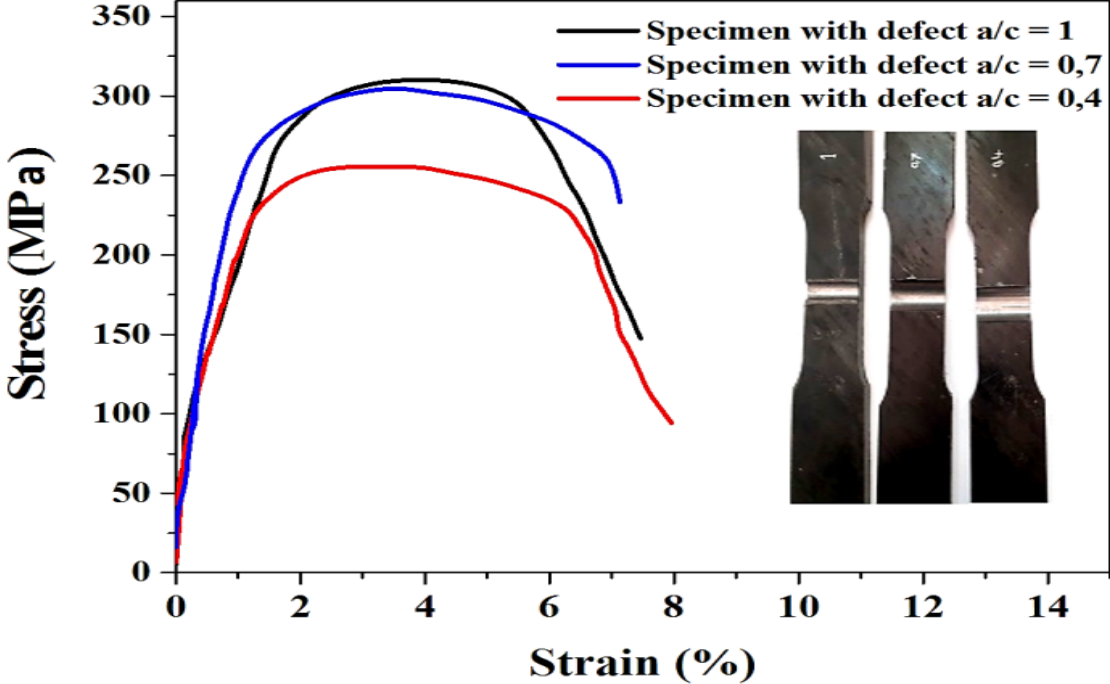


Fig.3.9 Stress-Strain curve for API X 52 pipeline steel when tested with the various defect tensile specimen of  $0 < a/c < 1$ .

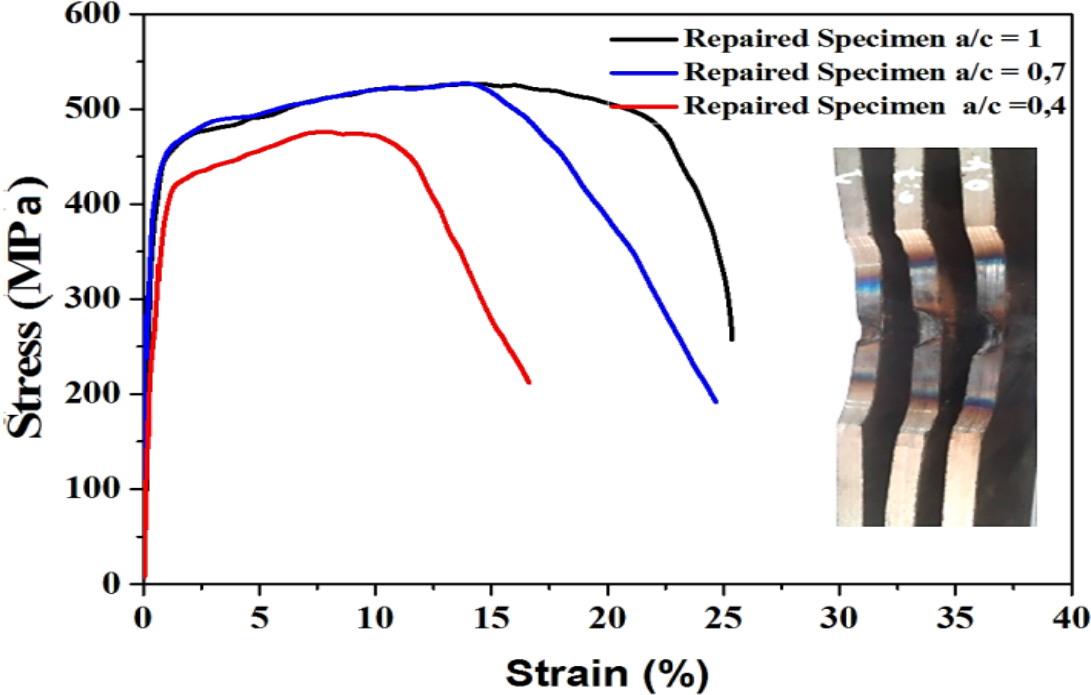


Fig.3.10 Stress-Strain curve for API X 52 pipeline steel when tested with the repaired welding tensile specimens of  $0 < a/c \leq 1$ .

Decreasing of mechanical properties from 40% to 50% for the three defects forms comparing with the original metal as expressed in the Fig. 3.10, where the variation of defects geometry allowed decreasing the safety of piping networks. The repairing of corroded defects by welding is efficiency solution through the test of samples as shown in Fig 3.11 [184-186].

The most companies of energy sought to remains the mechanical properties through the welding technique basing on nature of product transported and selected material of piping networks.

Depending on the rate of  $a/c=1$ . Consequently, the keep the mechanical characteristics of pipeline by weld repairing are considered as challenge for many companies basing on the nature of piping systems and kind of transported liquids. The stress and the elongation maximum for first sample when the ratio  $a/c =1$  reaches to 531MPa and 25.36% respectively. The stress and the elongation maximum for second sample when the ratio  $a/c =0.7$  reaches to 533MPa and 24.67% respectively. The stress and the elongation maximum for third sample when the ratio  $a/c =0.4$  reaches to 480MPa and 16.62% respectively.

**3.5.3.4 Tensile test of specimen with defect for ratio  $0 < a/t \leq 0.8$**

The second type of defects of specimens which focused on the ratio  $a/t$  by changing the depth (a) with a constant length (c) using the condition  $0 < a/t \leq 0.8$  [26]. The tensile experiment results of the sample with defects presented in Fig.3.11 and in the Table 3.2.

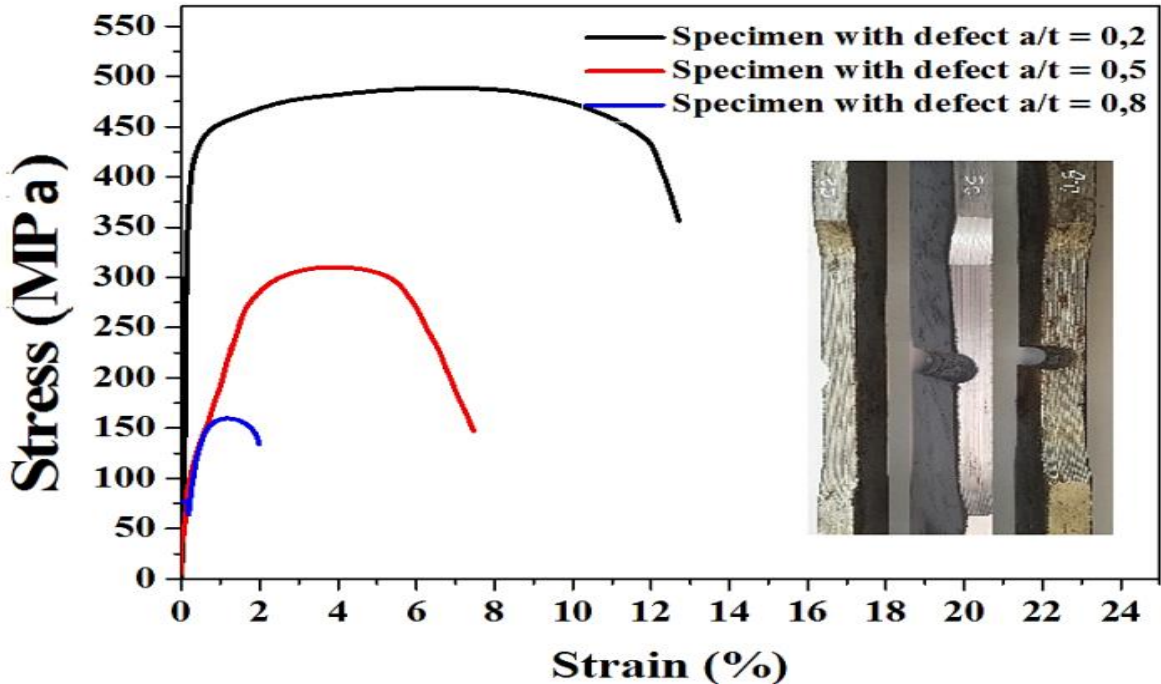


Fig.3.11 Stress-Strain curve for API X 52 pipeline steel when tested with the various defects tensile specimen of  $0 < a/t \leq 0.8$ .

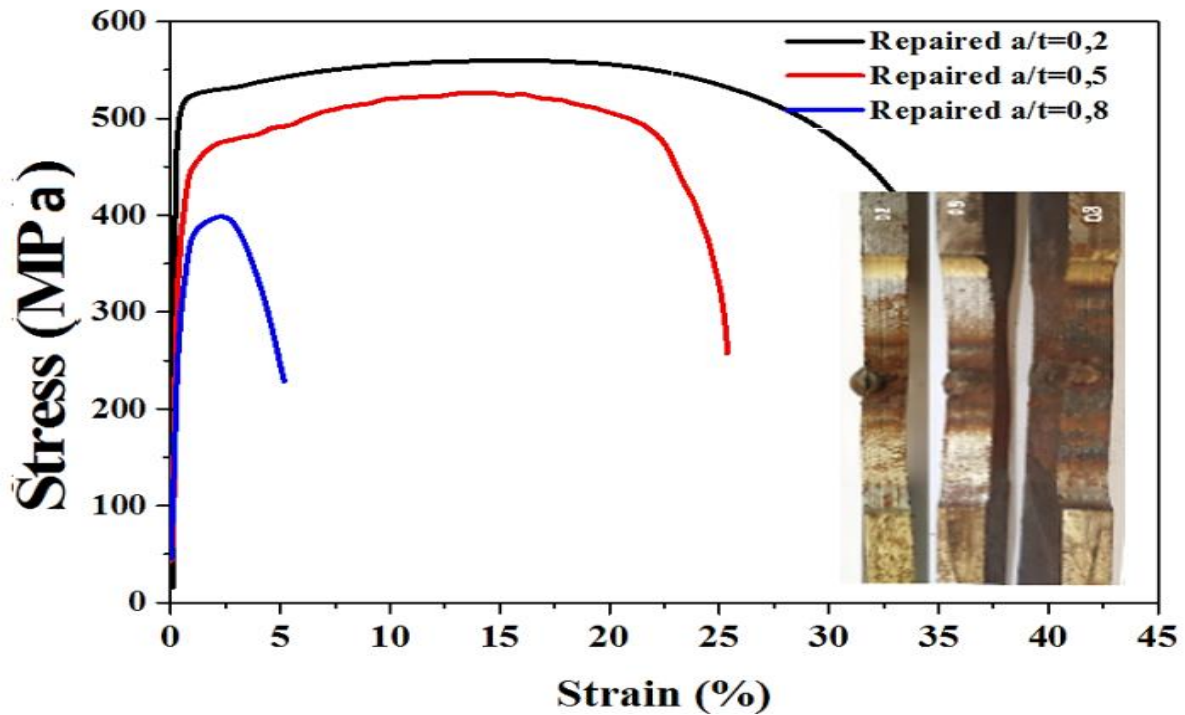


Fig.3.12 Stress-Strain curve for API X 52 pipeline steel when tested with the repaired welding tensile specimen of  $0 < a/t \leq 0.8$ .

At first case  $a/t = 0.2$  of semi-elliptical defect where the stress maximum and elongation are reach 488MPa and 12.71% respectively. At second case  $a/t = 0.5$  of semi-elliptical defect, where the stress maximum and elongation are reach to 311MPa and 7.36% respectively. At third case  $a/t = 0.8$ , of semi-elliptical defect, where the stress maximum and elongation are reach to 160MPa and 1.98 % respectively.

The experiment results of semi-elliptical defect problem proved that the defects lead to decrease of the ultimate stress from 558 MPa for original samples to 160 MPa for corroded samples[42].The obtained results proved that the decreasing of elongation from 40.86% to 1.98% has relationship with depth (a) of defects, where it indicates the decreasing of the mechanical properties [45]. The increasing of the ultimate stress and elongation at first case with ratio  $a/t = 0.2$  are reached 559MPa and 36.62% respectively, where it allowed increasing the mechanical properties.

For second case of  $a/t = 0.5$ , the increasing of the ultimate stress and elongation are reached to 531MPa and 25.36% respectively, where it allows to increase the mechanical properties.

For second case of  $a/t = 0.8$ , the decreasing of the ultimate stress and elongation reached to 399MPa and 5.18% respectively, where it allowed decreasing the mechanical properties.

These three cases can illustrate the behavior of defects problems and their repairing by weld techniques basing on two factors:  $a/c$  and  $a/t$  through depth and length at the critical zones.

According to the norm of API [14] standard of steel X52, the technique of welding is based on the geometry of defects [189], and this technique cannot be efficiency when the value of ratio  $a/t$  is greater than 0.5.

The welding process is still one of important solutions to increase the mechanical properties, where it can increase efficiency from 80% to 98% at  $a/t= 0.2$ , where the results of welded sample agreed with original sample of used steel API X52.

### **3.6 Automatically and manually welding operations**

#### **3.6.1 Results of repaired pipes and compared**

In all factories in the world wire, the welding technique is still one of best methods to repair the sample of semi-elliptical defects in order to save the piping networks.

To illustrate the impact of welding technique on the continuity of energy transport, the major challenges facing industrial companies to improve this method are highlighted. To confirm the role of welding, we performed the comparison between stress-strain results for two samples by two kinds of welding: automatic welding and manually welding at the ratio  $a/c=1$  as following in Fig.3.13.

In order to show the importance of welding operations in the safety of piping systems, the comparison between stress versus strain curves for two tests specimens related with welding operation through two cases taking into account. the mechanical characteristics of materials where the first specimen was carried out automatically by using making machine and the second specimen was carried out manually for repairing the semi-elliptical defect depending on the ratio  $a/c=1$  as shown in Fig.3.13.

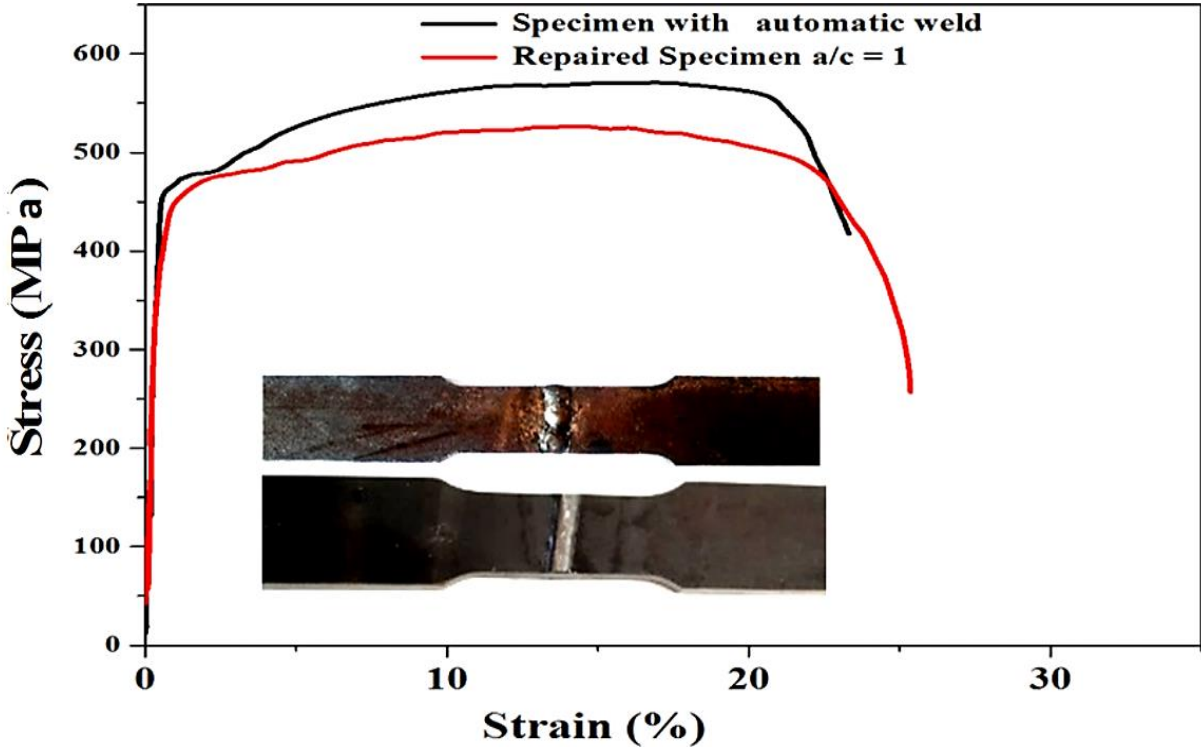


Fig.3.13 Stress-Strain curve for the compared to different with repaired specimen of  $a/c = 1$  and with specimen automatic weld.

The results of welding repairs showed that the values of the ratio  $a/c=1$  of repaired specimen are identical to those of automatic welding (SMAW) by machine, the two stress-strain curves are in concord with a difference of 7% for the ultimate stress and 1% for the elongation. It is clear that the repair has increased the mechanical characteristics of the steel; especially these results are in accordance with the API X52 standard. Moreover, the repair by manual welding can rehabilitate the piping systems [190].

3.7 Discussions of results

3.7.1 Results of Ultimate strength, Ratio of  $0 < a/c \leq 1$

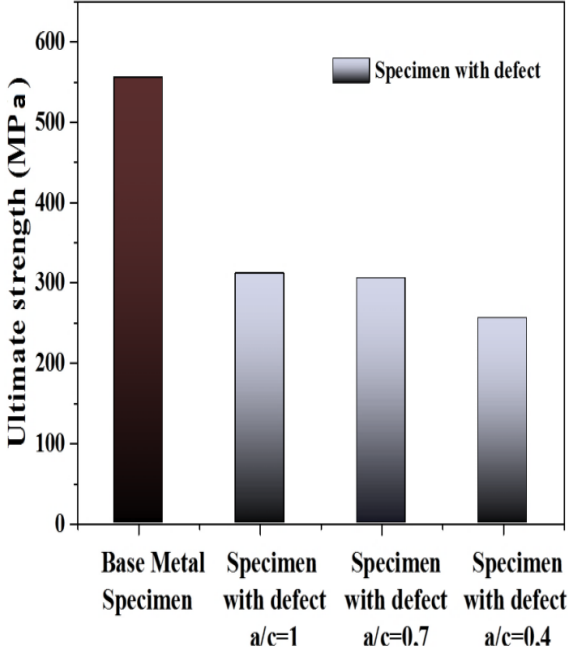


Fig.3.14 Results of ultimate strength when tested with the defect specimens  $0 < a/c \leq 1$ .

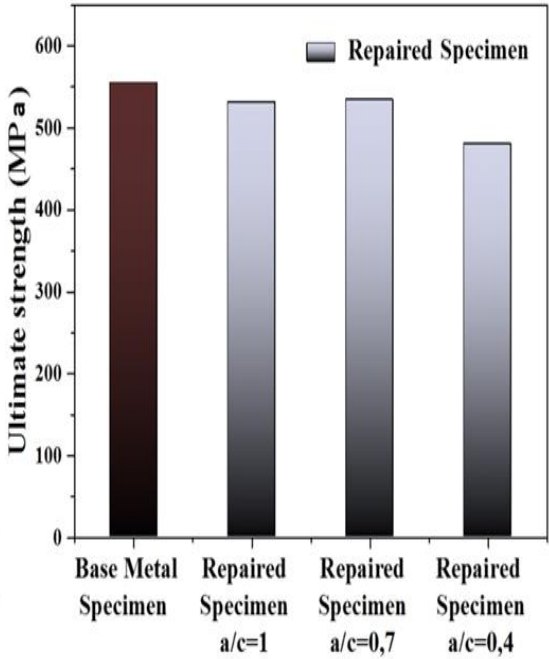


Fig.3.15 Results of ultimate strength when tested with the repaired welding specimens  $0 < a/c \leq 1$ .

Fig.3.14 Expressed that three ratios ( $a/c$ ) for 1, 0.7 and 0.4 of defected samples gave values 311 MPa, 306 MPa and 259 MPa respectively where they compared with original sample of 558 MPa[42].

It can be noted that the three ratios ( $a/c$ ) for 1, 0.7 and 0.4 of repaired specimens gave values 531 MPa, 533 MPa and 480 MPa respectively which compared with the original sample 558 MPa as shown Fig.3.15.

**3.7.2 Results of Ultimate strength, Ratio  $0 < a/t \leq 0.8$**

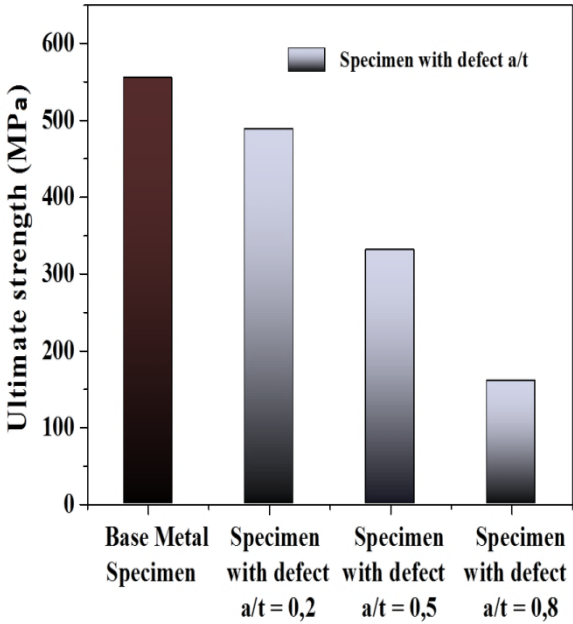


Fig.3.16 Results of Ultimate strength when tested with the defect specimens  $0 < a/t \leq 0.8$ .

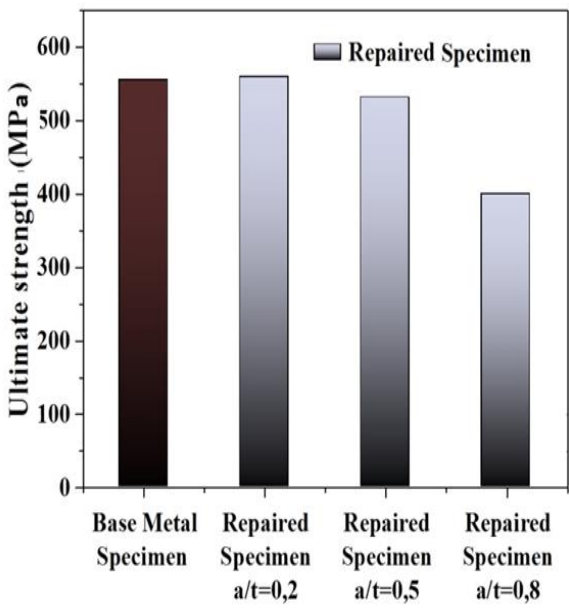


Fig.3.17 Results of Ultimate strength when tested with the repaired welding specimens  $0 < a/t \leq 0.8$ .

The results of Ultimate strengths appear that the samples of ratio  $a/t$  at 0.2, 0.5 and 0.8 gave the values 488 MPa, 331MPa and 160MPa respectively as shown in the Figs.3.16 and 17. In fact, the effect of defect decreased the mechanical properties particularly at the ratio  $a/t=0.8$ . However, the measures at  $a/t=0.2$  and  $a/t=0.5$  expressed that the depth ( $a$ ) for semi-elliptical forms proved the efficiency of defect on the security of piping systems [13].

**3.7.3 Elongation test tensile of base metal, defect metal and repaired metal**

**- Ratios  $0 < a/c \leq 1$  and  $0 < a/t \leq 0.8$**

The defect of piping systems along on the pipeline especially are considered as challenge faced on piping systems security, where the defects take many forms and Ratios  $a/c$  and  $a/t$  Fig 3.5.

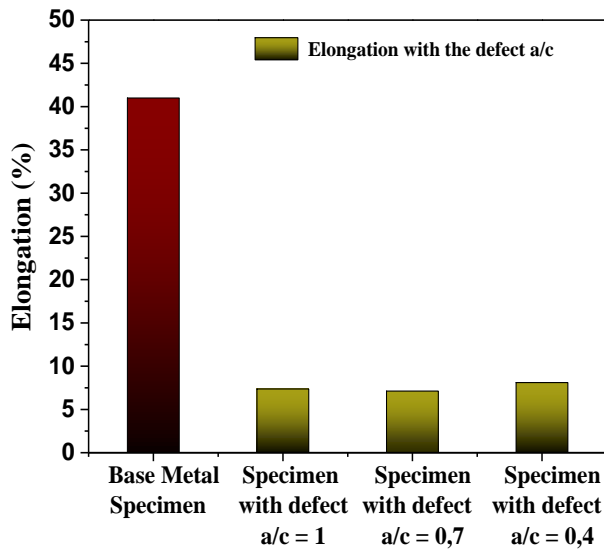


Fig.3.18 Results of elongation in tensile specimen of base metal and with defect specimens of  $0 < a/c \leq 1$ .

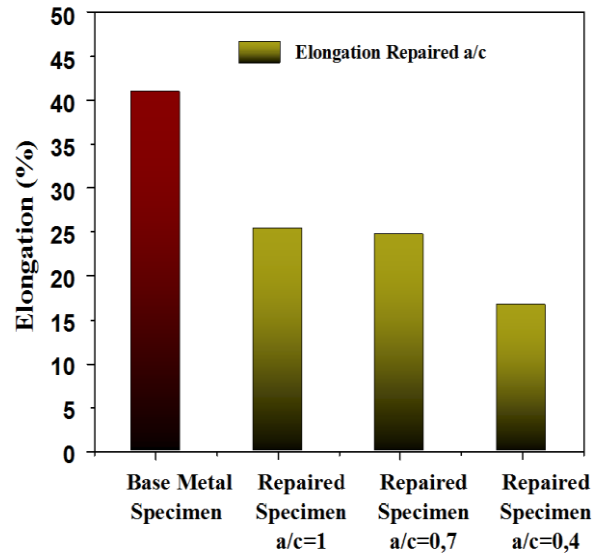


Fig.3.19 Results of elongation in tensile specimen of base metal and repaired welding specimens of  $0 < a/c \leq 1$ .

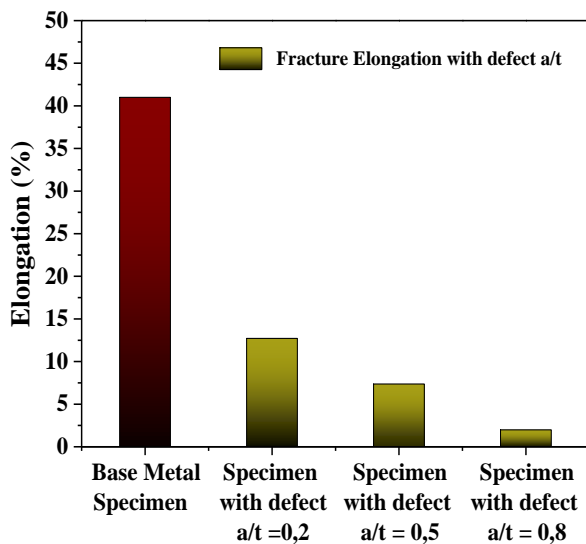


Fig.3.20 Results of elongation in tensile specimen of base metal and with defect specimens of  $0 < a/t \leq 0.8$ .

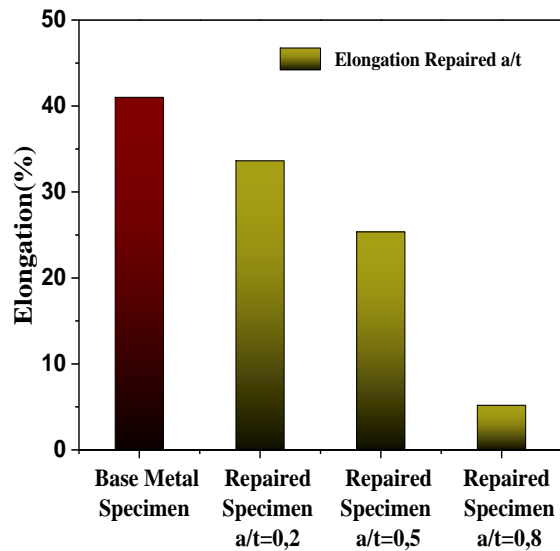


Fig.3.21 Results of elongation in tensile specimen of base metal and repaired welding specimens  $0 < a/t \leq 0.8$ .

The elbows, pipe and the welded zones are critical parts along of piping systems, where the using two ratios  $0 < a/c \leq 1$  and  $0 < a/t \leq 0.8$  allowed to measure the elongation of metal with/without defects to illustrate the resistance of material and to analyze the behavior of crack and safety of transport of energy.

The Figs.3.18 and 3.20 expressed that the tensile tests of the defected sample the ratio  $a/c$  decreased nearly the mean of 80% and the ratio  $a/t$  decreased between 67% and 95% compared to original sample .

The experimental results of elongation showed that the ratios  $a/c$  ranged 7.36% to 7.9% where this variation represented a simple change. However, the high difference of elongation of the ratios ( $a/t$ ) decreased from 12.36 % down to 1.98%.

From the values obtained in the Figs.3.19 and 3.21 show in the results of elongation in tensile specimens repaired welding at ratios  $a/c=1$  and  $a/c=0.7$  gave of 25.36% and 24.36% respectively. Depending on the conditions, the values at ratios  $a/c=0.4$  and  $a/t=0.8$  are disagree with the API 5L standard to keep the mechanical properties.

**3.7.4 Toughness: Test tensile of base metal, defect metal and repaired metal**

Propagated energy and plastically deformed without damaging during service can measure by Toughness.

The integration of the stress-strain can use to measure the toughness factor curve through three ranges: elastic, plastic and rupture, where the equation mathematical energy used to represent of the mechanical deformation by per unit volume as following (Fig.3.22).

$$W = \int_0^\epsilon \sigma d\epsilon \quad (18)$$

$\epsilon$ : is strain,  $\sigma$ : is stress,  $W$ : Toughness, Energy absorbed to fracture of material in tension.

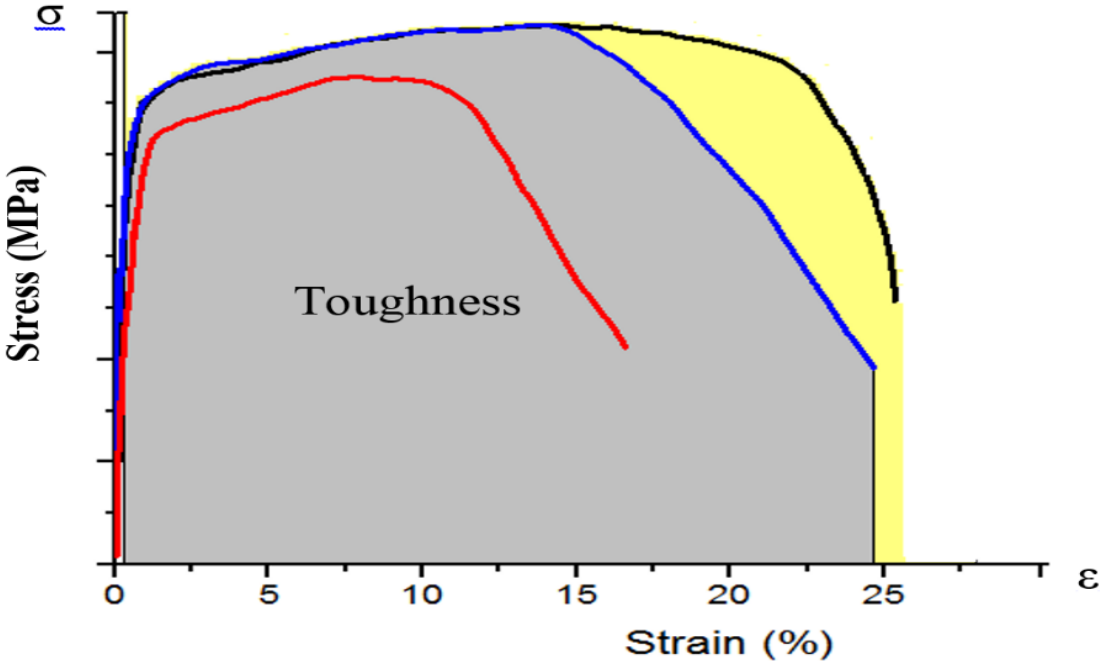


Fig.3.22 Toughness is by calculating the areas under the stress-strain curves.

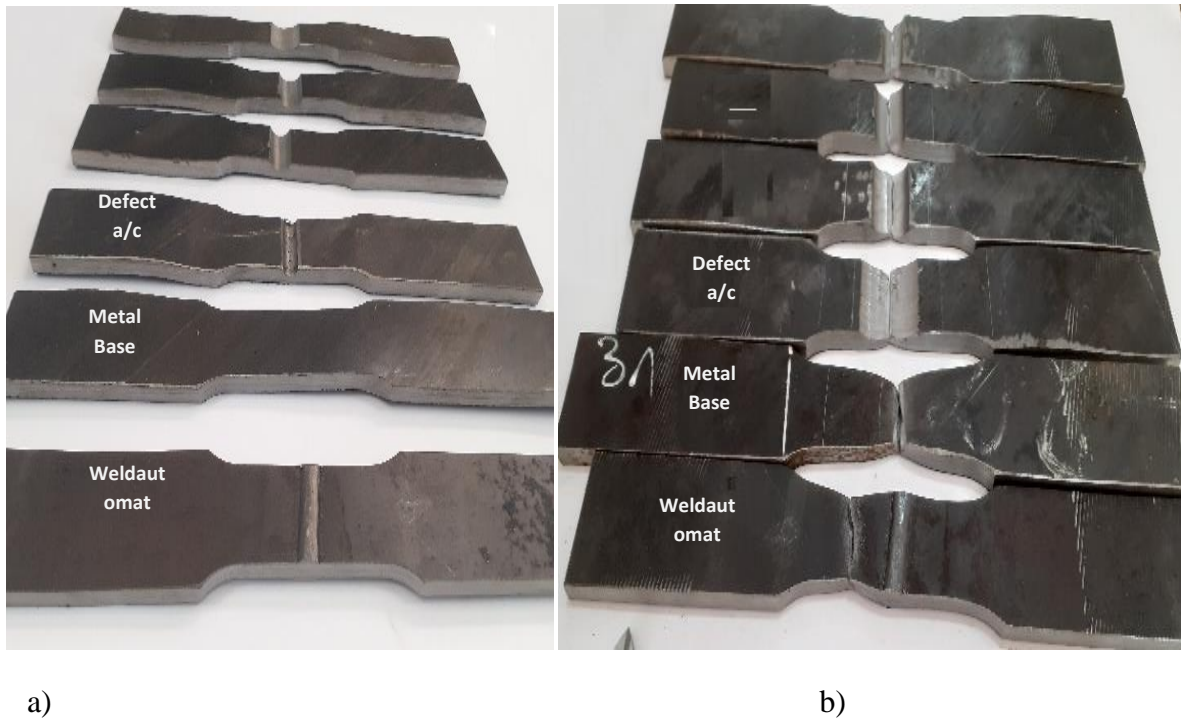


Fig.3.23 Experimental set up (a) Before Failure, (b) After Failure.

### 3.7.5 Toughness results for Ratios $0 < a/c \leq 1$ and $0 < a/t \leq 0.8$

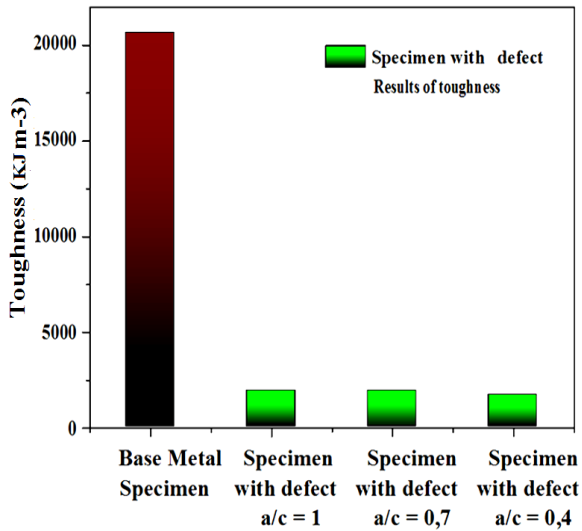


Fig.3.24 Results of toughness in tensile specimen of base metal and with the defect specimens of  $0 < a/c \leq 1$

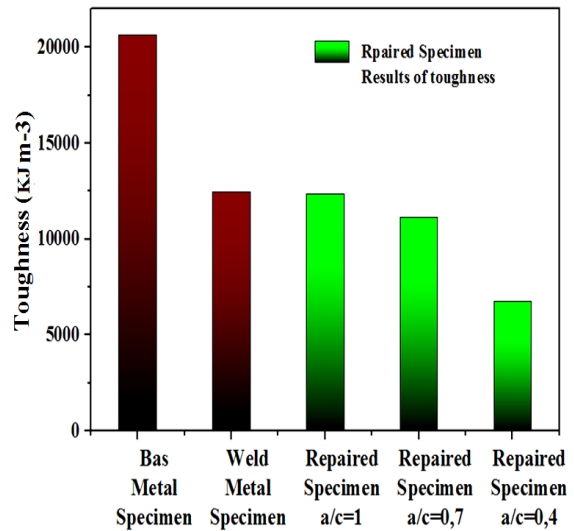


Fig.3.25 Results of toughness in tensile specimen of base metal, weld metal specimen and repaired welding specimens of  $0 < a/c \leq 1$ .

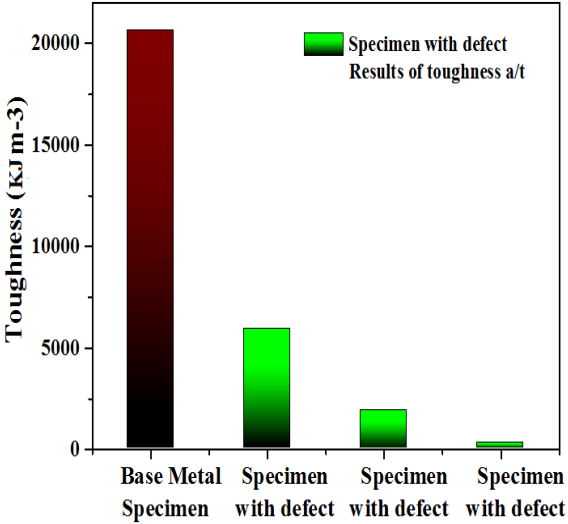


Fig.3.26 Results of toughness in tensile specimen of base metal and with the defect specimens of  $0 < a/t < 0.8$ .

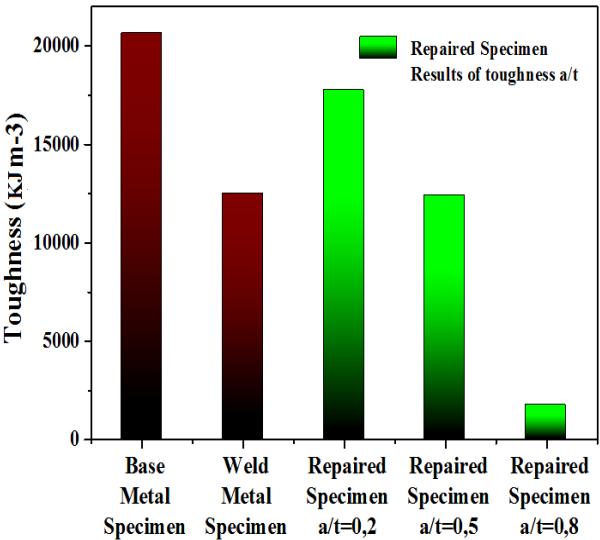


Fig.3.27 Results of toughness in tensile specimen of base metal, weld metal sp. and repaired welding specimens of  $0 < a/t < 0.8$ .

The obtained results of Figs 24, 25, 26 and 27 provided that the toughness and the energy absorbed during fracture have relationship with properties of mechanical taking into account the conditions of tested. The results of ( Figs. 24 and 26) with defects and without defects for two ratios ( $a/c$ ,  $a/t$ ) are an important, where the maximum values of toughness and the energy absorbed of defect at  $a/c = 1$  and  $a/t = 0.2$  are 1895.72 kJ m<sup>-3</sup> and 5912.10 kJ m<sup>-3</sup> respectively, where the energy propagation can make internal rupture without bruit. The test samples of original proved that can propagate high internal energy where it reached to 20646, 47 kJ m<sup>-3</sup> compared with 17729.03 kJ m<sup>-3</sup> at ratio  $a/t = 0.2$ . The toughness results of repaired sample reached to 17729.03 kJ m<sup>-3</sup> where, this solution illustrated that the depth of defect is serious problem than the defect length and its repair less suitable efficient in API X52 pipeline. Figs 25 and 27 showed that the ratios  $a/c$  and  $a/t$  of toughness of tensile are among necessary factors to illustrate the impact of defect of semi-elliptical along of piping systems including refinery stations, elbows and welded positions taken into account the geometry of defects and nature of material.

### 3.8 Conclusion

To analyze the behavior of corroded piping systems, the experimental results have illustrated by using the tensile test through two important factors of defects (semi-elliptical form) resented by ratios  $a/c$  and  $a/t$  on are criteria evaluate the safety of API X52. It can be noted that the complex behavior of semi-elliptical form became the challenge faced the security of energy transport.

Depending on the decrease of ultimate stress through compared between defected sample and original sample was highlighted the principal causes of defected especially the dimensions of defects and nature of used materials.

The decrease of the defected sample compared with original sample were cleared through the experimented results , where the ultimate stress disunited from 558MPa of original sample to 259 MPa for ratio  $a/c$  0.4 and 160 MPa for ratio  $a/t = 0.80$  for defected samples. Thus the elongations results decreased from 40.86% for original defect to 7.12% for the ratio  $a/c$ , and 1.98% for the ratio  $a/t$ , similarly the toughness results of base metal decreased from 20646, 47 kJ m<sup>-3</sup> and to 274.59 kJ m<sup>-3</sup> for the ratio  $a/t= 0.8$  and 1696.42kJ m<sup>-3</sup> for the ratio  $a/t=0.4$  where the value of ratio  $a/t = 0.8$  is the lowest value which is reached to 274.59 kJ m<sup>-3</sup>.

Through experimented results , it can evaluate the effects defects on safety of piping systems depends on the dimensions of defects ( Cracks, corrosion) which became one of among sources of failure of networks energy transport. In fact, using the welding as one of solutions becomes as the better selection to treat the corrosion problems for both sides internal and external due to complex chemical reactions, industrial defects especially at critical zones.

**Chapter 4: Experimental study of specimens with/without defect  
and repaired by patches composites hybrid**

## 4.1 Introduction

Nowadays, the increasing energy demand with the occurrence of many kinds of defects along the piping systems as a results of cracks, corrosion and industrial defects may treated by using classical manners, such as welding techniques or repairing with carbon fibers and glass fibers or modern techniques, such as natural fibers or hybrid fibers.

This project presented all these solutions to evaluate the defects on the safety of piping networks with and without one of these techniques.

In this chapter, the natural and industrials fibers were used, reinforced with metal wires and polyester to produce a new solution with excellent features to avoid corrosion on the one hand and on the other hand such as low cost , facility of preparation, eco-friendliness and wide availability (the efficient solutions without cutting the corroded pipe).

The use of the natural fibers and hybrid fibers have become very important through numbers of layers with other material or other fibers to improve their mechanical characteristics and their features including the high resistance, sustainable alternative and recyclable [71,72]. Due to the expensive of material and their scarcity, the natural composite became suitable solutions to the materials used due to excellent mechanical properties.

A hybrid material composite of glass fiber, carbon fiber or jute with resin are the mainly compounds to product new material with high mechanical properties on the one hand, and on the other hand, the natural fibers reinforced by synthetic fibers(FRP).These types of composite materials have been used in various modern applications [73,74]. Many factories in Asia are based on the many sources of plants, such as jute fiber, sisal fiber, Banana fiber, Bamboo fibers..., due to widely available. The develop of these materials, it has based on the many ideas through many studies and experiments have been provided.

These type of materials can used in many fields such as the mechanical industries including Cars, trains, ships, drones, houses roofs, specials clothes of fires and body organs [75,76].

Depending on the literature review, Reducing the use of synthetic fiber composites such as glass fiber and carbon fiber is the objective of several scientific researches, experimental, theoretical and numerical studies have been carried out to improve the original natural fiber materials despite the different properties chemical and physical, such as jute fiber, sisal fiber, Banana fiber, Bamboo fibers..., these fibers have been used in many fields instead of industrial fibers (carbon fiber or glass fiber) due to many characteristics such as low density, high strength, biodegradable and environmentally friendly) [75,76]. In fact, the natural fiber composite (jute fiber) and the industrial hybrid composite have already been increased using

in many industrial domains due to many features such as biodegradability and low cost and great benefits in the mechanical industries [191,192]. Historical studies have proven that natural fibers have been present since ancient Egyptian civilization, where many sources were used, including sheep wool, some types of plants and animal skins, to make house roofs, war clothes and shields on the one hand, and on the other hand, wool and papyrus fibers were used to form ropes in building pyramids and ribbons to wrap mummies [77-79]. The energy is considered the engine of the global economy, where these several sources of energy were focused to use organic and synthetic resources, such as petroleum, coal, solid materials and natural gas due to the use of the mechanical industries, where these materials have negative impacts on the environment.

During time, many fields industrial used several materials as steel, iron, Aluminum, Copper, Silver, Gold, plastic, semi-plastic, composite synthetics, composite natural and composite hybrid. The synthetic fibers have been replaced natural fibers such as bamboo, hemp, jute, coconut and other natural fibers, hybrid fibers as well as biofibers where all fibers can be used in 3D through polymer using chemical and medical treatments [78,79]. The development of synthetic fibers with natural fibers to obtain hybrid fibers has opened up innovation avenues to adapt to the rapid changes in the global market as well as growth opportunities [91-99].

The second objective of this study is based on the using of natural and synthetic fibers reinforcing with material wires and polyester. According to the nature of piping systems (API X52-X 80, etc.) and nature of transported petroleum are considered as a causes of corrosion taking into account the operating conditions, carbon dioxide (CO<sub>2</sub>), Hydrogen sulfide (H<sub>2</sub>S), salts (NaCl, CaCl<sub>2</sub>,... etc.) and organic acids (HCOOH, sulfur and naphthenic acids). Thus, the impact of corrosion on the integrity of the systems has directly relationship on ratio (a/c) and ratio (a/t) [141-143]. The purpose of project is to reinforce the semi-elliptical defect using the patch natural fibers, synthetic fibers and fibers hybrid by adding metal wires and polyester.

To prepare these product, it had used by experiments using the natural fibers to improve the mechanical features for patch through their strength properties by bending and tensile testing.

Measuring the patch efficiency of semi-elliptical defect of API 5L X52 grade pipeline steel can be focused the natural materials and number of layers with material wires and polyester

where it can test by tensile and bending experiment under the ASTM D790 and ASTM D3039 norms [193,194].

Using the five samples of natural and hybrid can be a suitable solution to repair the piping systems where this study based on the hand layup method, which was used to prepare the composite samples. Tensile and bending tests of semi-elliptical shape of ratios (a/t) have been repaired five samples of natural and hybrid patch by experimental study to evaluate the resistance of the propagation of corrosion.

Through the analyze the obtained results the problem of corroded pipes in hydrocarbon transportation systems can be repaired by using the natural fiber as patch taking into account the number of layer and percentages of additives compounds.

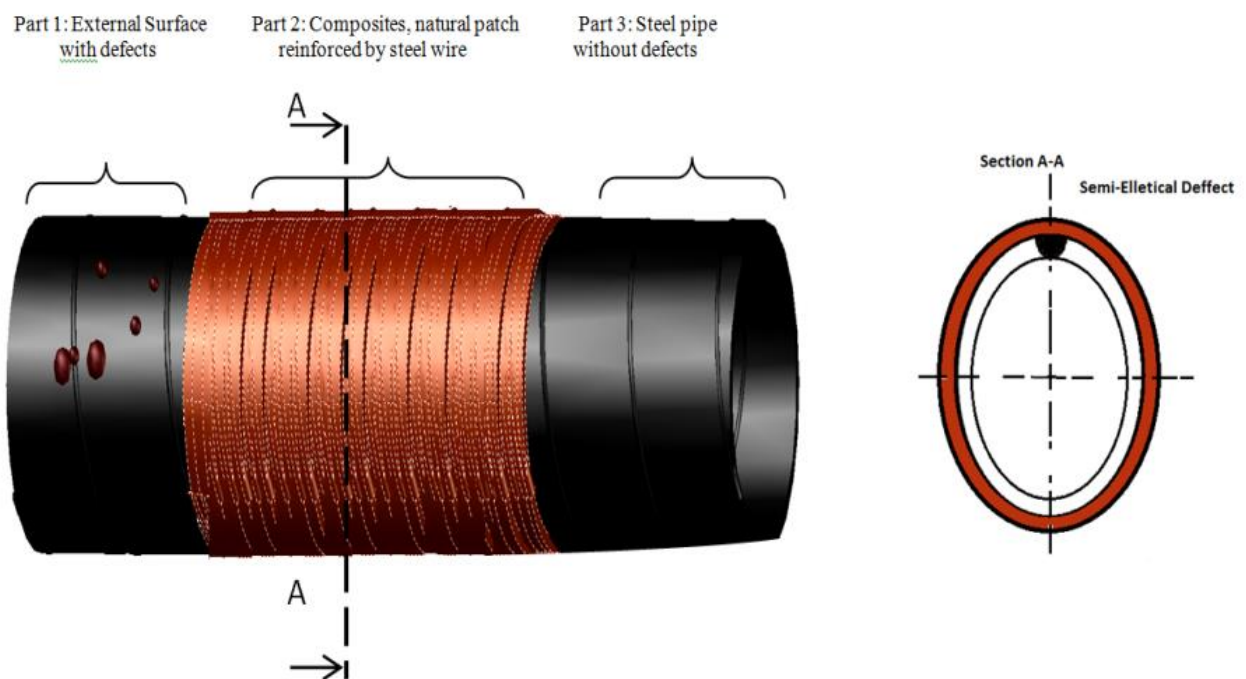


Fig.4.1 The sketch corroded pipeline repaired by hybrid composites (natural fiber and synthetic fiber).

#### 4.2 Industrial of natural fiber composite and hybrid.

Many studies have been provided various ideas about the corrosion of piping systems as results of the contact with external environment on the one hand, on the other hand, the complex chemical reactions between the wall of pipe and the aggressive compounds of crude oil such as acid naphthenic and sulfur.

Environmental degradation becomes the one of among great problems in the energy field in due to the difficulty the decrease of CO<sub>2</sub> rates, as results of using the complex chemical industries such as the refinery of hydrocarbons which is an important part of piping systems. Non-biodegradable materials becomes the obstacle in the face of the petroleum companies, which sought to treat the ecologic problem results of complex chemicals, and toxic materials, where many studies provided the solutions about this phenomenon but it is not still enough the answer on all reasons and consequences. However, many projects have been achieved related by new durable solutions and materials which allows to overcome on all obstacles through natural or synthetic or hybrid fibers for making a new materials with high mechanical properties such as weight reduction, recyclability, corrosion resistance, low cost through the plant source (Jute, cotton, palms and cactus) and animal source (silk and wool) which have an excellent chemical and mechanical properties. On the other aspects, the hybridation process natural-synthetic fibers becomes a new version to develop the industries on the all of fields including mechanical products, medicine, building, clothe through the norms NFC (natural fiber composite), SFC (Synthetic fiber composite) and FRP (Fiber reinforce polymer, [195–198].

Several studies covered the problem of environmental degradation and climate change, which are among of the great challenges to treat the ecologic problem such as Non-biodegradable materials, complex chemicals, and toxic materials as well as seek to decrease of CO<sub>2</sub> rates, as results of using the complex chemical industries. According to these conditions, many researchers sought to fond the suitable solutions in order to production a new materials characterized with excellent mechanical performance in order to be sustainable fibers on the one hand, and decrease environmental damage weight reduction, recyclability, corrosion resistance, low cost on the other hand. A composite material is made through two or more compounds materials including plant source (Jute, cotton, palms and cactus) and animal source (silk and wool) which have a good features of physical and chemical properties, where the natural fiber with adding an industrial (synthetic) fibers is a great step to hybridization process [195]. In fact, natural fiber composites (NFC) have become the suitable solution to synthetic fiber composites because the industry has become basing on the cultivable which consists on fibers including Jute, [195–198].

### **4.3 Uses of Composite Patch in Repair**

Depending on the norms of material composites, glass fiber reinforced polymer (GFRP) composites is one of efficiency solutions to reinforce and to repair the defects (semi-elliptical

with depth (a/c) and length (a/t)) or make composite material with excellent properties in order to safety the piping systems. These solutions can use to reinforce the cracks, small cracks, general defects or rust through ensure the security, safety and increasing lifetime [74-84]. There are many events concentrated at critical zones due to the complex chemical reactions, as carbon dioxide (CO<sub>2</sub>), Hydrogen sulfide (H<sub>2</sub>S), silica (NaCl, CaCl<sub>2</sub>, ... etc.) and organic acids (HCOOH), with presence defects in the internal or external walls taking into account the nature of pipeline materials (X60, X70, X80, etc.) and the nature of the transported liquids (crude oil and gas) [141-143,30].

#### **4.4 Pipeline repair with natural fiber**

##### **4.4.1 Materials**

The objective of this project is to analyze the effects of semi-elliptical defects on structure of piping systems and it's repaired by composite materials contained on natural and synthetic fibers to increasing the material quality. The hybrid jute fiber-glass fiber and natural fiber composite jute fiber reinforced by metal wires using the polyester resin are a necessary compounds to form an excellent composite materials, where these materials can use to repair or to reinforce the defects due to their good properties [199-202] depending on the ASTM D3039 standard [193,194].

##### **4.4.2 Composite materials**

In this study, the composite material selected the API 52 as piping systems defected which repaired by composite material such as industrial, natural and hybrid fibers, where it used two or four layers with/without steel wires of diameters (1.5mm) for reinforcing the defected positions.

##### **4.4.3 Jute fiber**

Jute is considered as the principal material in this project where it is based on the natural and it has features of biodegradable fibers (Fig.4.2and Fig.4.3). In fact the jute has been become necessary material for each fields due to the properties positive taking into account rather than others materials which has high features of mechanical characteristics [191,192].

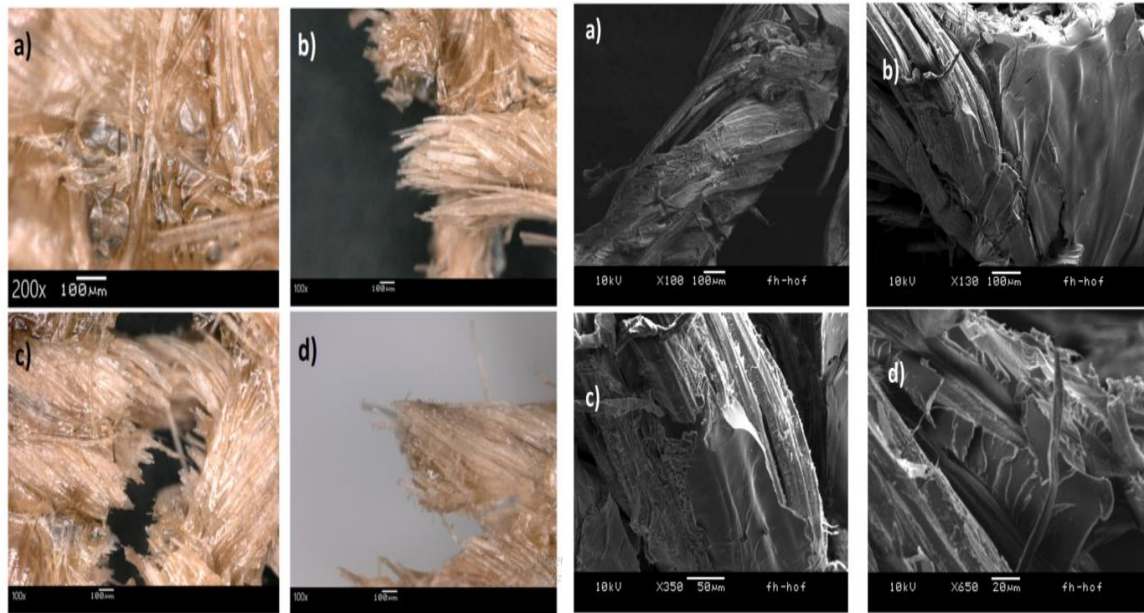


Fig.4.2 Optical images of characteristic locations. a) To d) SEM images of characteristic locations [191].

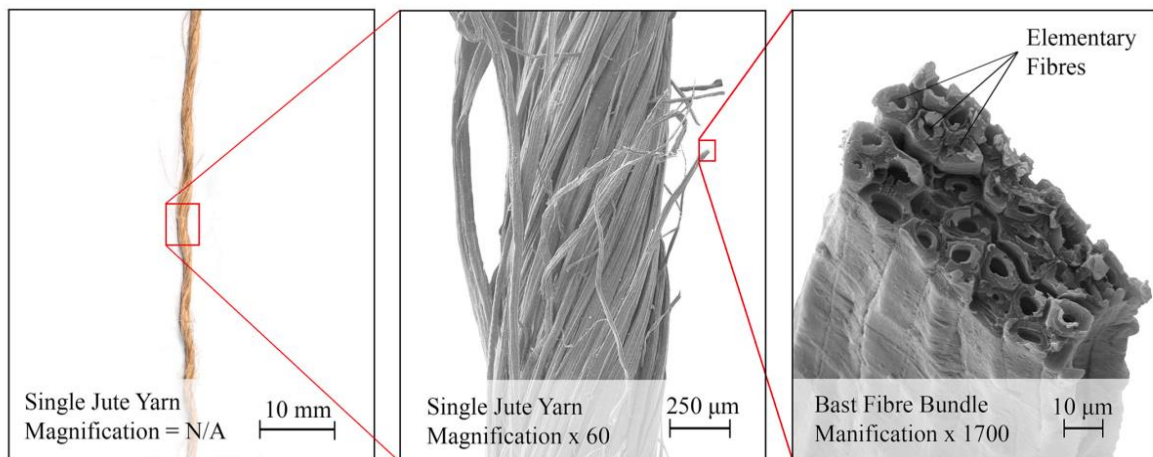


Fig. 2. Images obtained during Scanning Electron Microscopy (SEM).

Fig.4.3 Images obtained during Scanning Electron Microscopy (SEM) [192].

#### 4.4.4 Glass Fibers

All kinds of fibers have been become an important in the industries mechanical , medicine , ships, building materials, cars , trains, planes, roof of houses and some clothes. These materials composite are based on the natural and synthetic fibers, which can enter to make of many kinds of products to reinforce the composite materials [25, 42].

Table 4.1 Characteristics of Jute and Glass fibers [203,85].

Characteristics	Jute fiber	Glass fiber
Density (g/cm <sup>3</sup> )	1.3-1.5	2.5-2.6
Diameter (mm)	20-00	<17
Elongation (%)	1-1.8	1.8-4.8
Tensile strength (MPa)	320-800	2000-3500
Tensile modulus (GPa)	8-78	70-76
Specific modulus (approx.)	30	29
Moisture content (wt. %)	12.5-13.7	-

#### 4.4.5 Metal wires

A metal wire is formulate from drawing a ductile material such as steel, aluminum, copper, etc., where the metal wires are fabricated for diameter (1,5mm) and shapes according to standard conditions (Fig.3.2). Indeed, the most wires are used in the field of industrial especially the manufacturing of automobile tires and buildings and bridges. In our project, we used metal wires for reinforcing the structure patch of natural fiber composites.

Table 4.2 Physical properties of Steel Wire [207].

Properties	Values
Diameter (mm)	1.5-4
Elongation (%)	25-32
Tensile strength (MPa)	35-50
Wire type	Black Wire, Quality Standard NF A35-051, ISO 16120
Applications	Tie Wire for Construction

#### 4.4.6 Polyester resin

To make composite material it must assembly many parts such as natural fibers, synthetic fibers, additives and polyester, where there are many kinds of polyester which can steady the structure of composites materials.

The polyester allows saving the mechanical properties for materials formed. It can play an important role in the coherence between the laminates in despite of the different of natures.

Among features of polyester treated not only the cracks propagate off failure at weak positions but also avoided the separate and fiber-fracture and damage the structure. The available technical features of the polyester during of operating conditions: Viscosity at 20°C: 4 Pas, density at 25°C: 1.1, acid number: 18 mg KOH/g [5].

Table 4.3 Properties of polyester resin[87].

Properties	Values
Appearance	Opaque, blue color change resin solution
Viscosity at 30 °C	4–5
Water absorption (%) (7 day value)	0.35
Heat distortion temperature (°C)	67.3
Elongation at break (%)	3.2
BS (kgf/mm <sup>2</sup> )	8.4
BM (kgf/mm <sup>2</sup> )	536.1
TS (kgf/mm <sup>2</sup> )	3

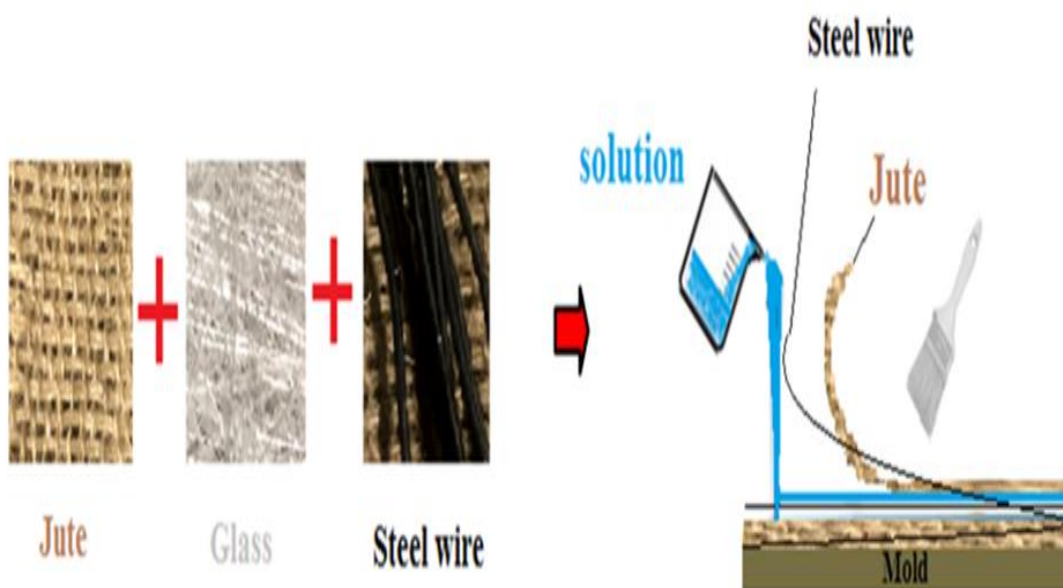


Fig.4.4The photo of the Jute, Glass, and Steel wire and layer jute by hand lay-up method.

#### 4.4.7 Mass Fraction of composite

The mass fraction ( $M_i$ ) of the composite is factor to measure of contains weight of the composite material to reinforce natural fiber by steel wire through the matrices which based on the polyester. The composite is divided into three parts of the total loads of the composite composition (equation19). The reinforcement strategy is based on the assembly the compounds of samples as following

$$M_c = M_{rp} + M_r + M_v = 1 \quad (19)$$

The calculation of the proportion for each compound is based on the equation (20) as presented in the table 1:

$$M_i = (M_i / M_c) \times 100. \quad (20)$$

$M_i$ : weight for each compound,  $M_c$ : the total mass of composite.

In Figure 2a, presents the size of the composite component design on the hand, and on the other hand the Figures 2b,a. Expressed that the proportion of the composite may exceed the mass fraction (% of loads) or the volume fraction (% of volume).



Fig.4.5 Device for measuring the weight of components (jute, glass, steel wire).

Table 4.4 Composites Fabricated and weight fraction.

Prepared Samples	Designa.	Code	Jute Fiber (wt.%)	Glass Fiber (wt.%)	Steel-(SW) (wt.%)	Fiber-(J+G+ST) (wt.%)	resin polyester (wt.%)
Pure Jute composite 1	(JJJJ)	S1	14%	-	-	14%	86%
Hybrid composites 2	JGJG	S2	7%	5%	-	12%	88%
Hybrid composites 3	JJ(1.5ST)JJ	S3	10%	-	19%	29%	71%
Hybrid composites 4	J(1.5ST)J (1.5ST)JJ	S4	10%	-	31%	41%	59%
Hybrid composites 5	J(1.5ST)J (1.5ST)J (1.5ST) J	S5	10%	-	38%	58%	42%

#### 4.4.8 Pipeline material

API X52 steel is an iron-based alloy with a small percentage of carbon from X42 to X65 consisting of up to 0.3% C, 1.6% Mn, 0.7% Si. Also, API X52 steel is a hydrocarbon transport steel with properties. As well as this type of steel also has a high yield strength and good weld ability.

#### 4.5 Manufacturing method of composite materials

The process of hand lay-up was used to manufacture hybrid laminated composites consisting of polyester resin, 2% of the accelerator and 2% of the catalyst which are mixed to obtain a liquid solution forms glue (matrix), the latter is applied on the surface of the burlap or fiberglass in a time not exceeding 10 minutes quickly, then, we add metal wire recess materials not exceeding 15 minutes, finally The laminate was compressed at a pressure between two plates, and let it harden under pressure, for 24 hours at room temperature. However five types of laminated composite plate were manufactured see Fig.4.6.

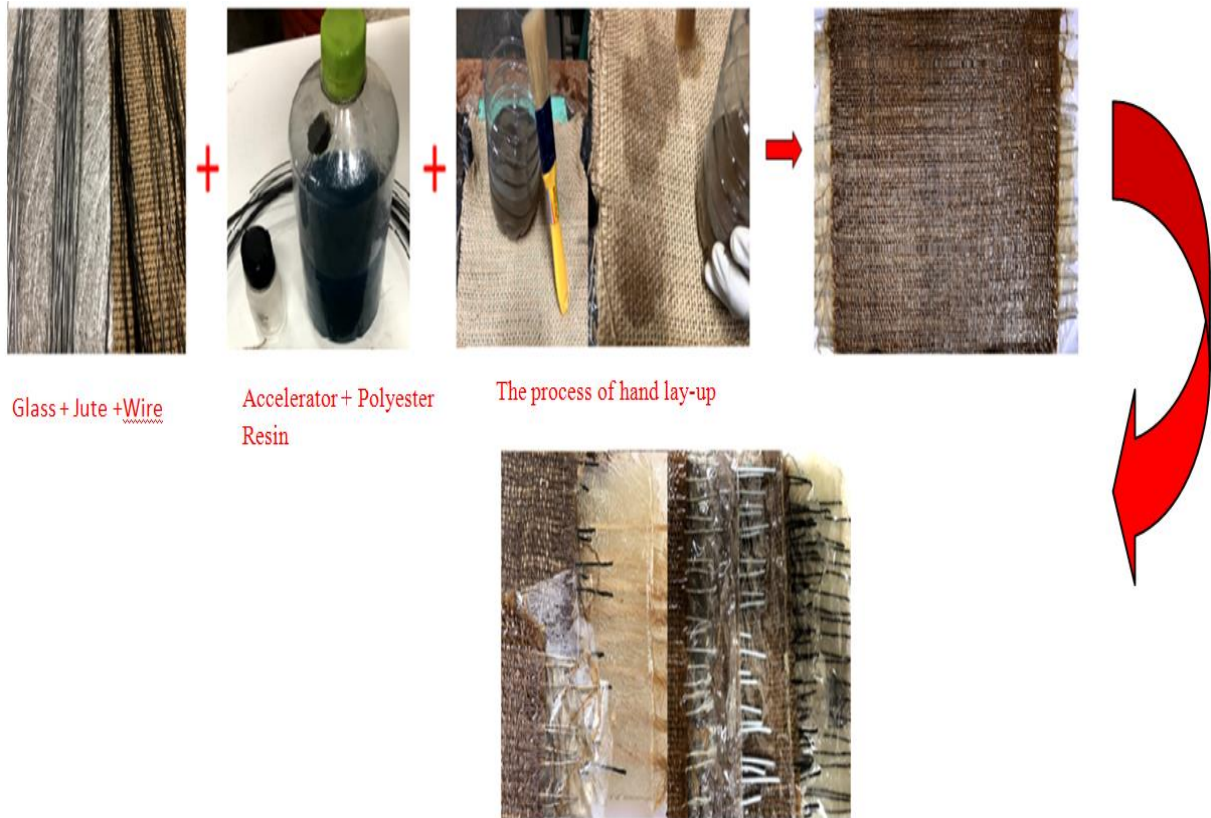


Fig.4.6 Manufacturing processes of five plates of composite by hand lay-up method.

## 4.6 Experimental specimens

### 4.6.1 Composite specimens

Depending on the composite materials the five samples that were prepared using chainsaw machine as shown in Fig.4.6. Table.4.5 (below) presented all types of samples which based on three compounds such as glass fibers, jute fibers, and steel wire with polyester.

Dimensions of samples were selected through ASTM to perform two types of samples firstly ASTM-D 3039 norm for dimension (250x25x2.6-6.5mm) specially for tensile test shown in Fig.4.7a [192], and secondly ASTM-D790 norm for dimension (127x12.7x2.6-6.5mm) specially for tests bending shown in Fig.4.7b[193].

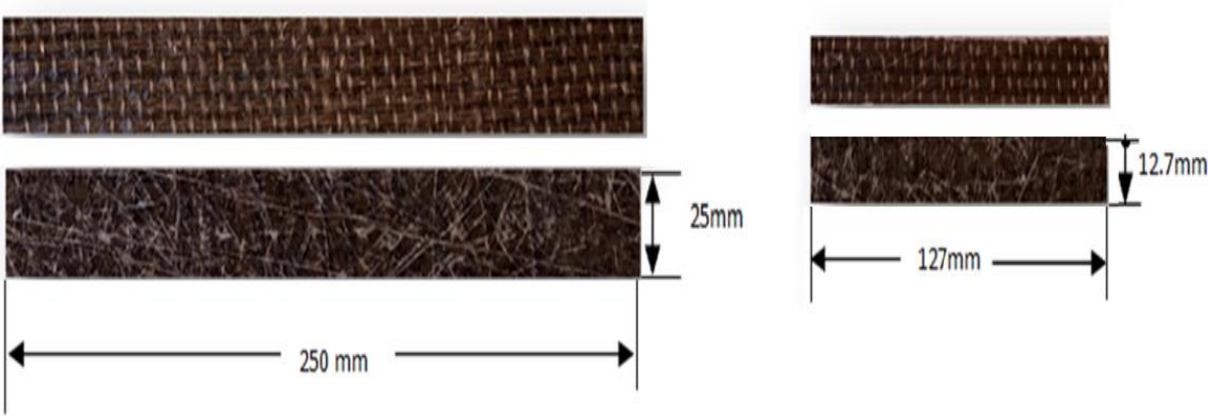


Fig.4.7 Sspecimens dimension of test traction and flexion for two methods a) ASTM-D 3039,b) see left ofspecimensASTM-D790.

**4.6.2 Specimens API X52 pipeline steel**

The objective of this project is to analyze the piping systems made from API X52 supplied by ALTUMET company, where this study illustrated the effect of defects (cracks, rust, erosion, corrosion and welded zones as shown in Fig.4.8). The preparation of defects is based on the form of semi-elliptical in the external side (Fig.4.10) with three defects shape a/t: 0.2, 0.5 and 0.8 as shown in Fig 4.9a and 9.

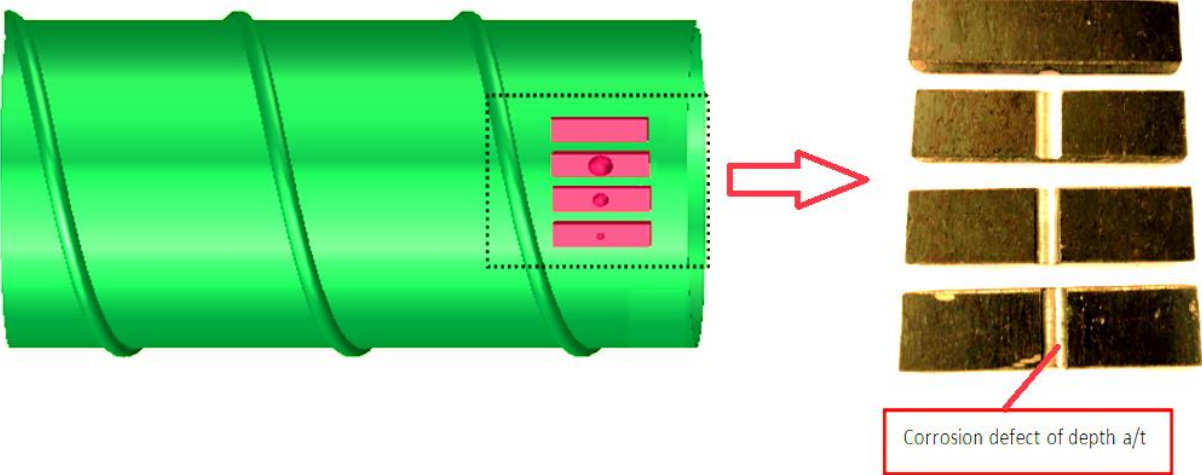


Fig.4.8 Location of bending specimen in API 5L X52 pipe with/without defect.

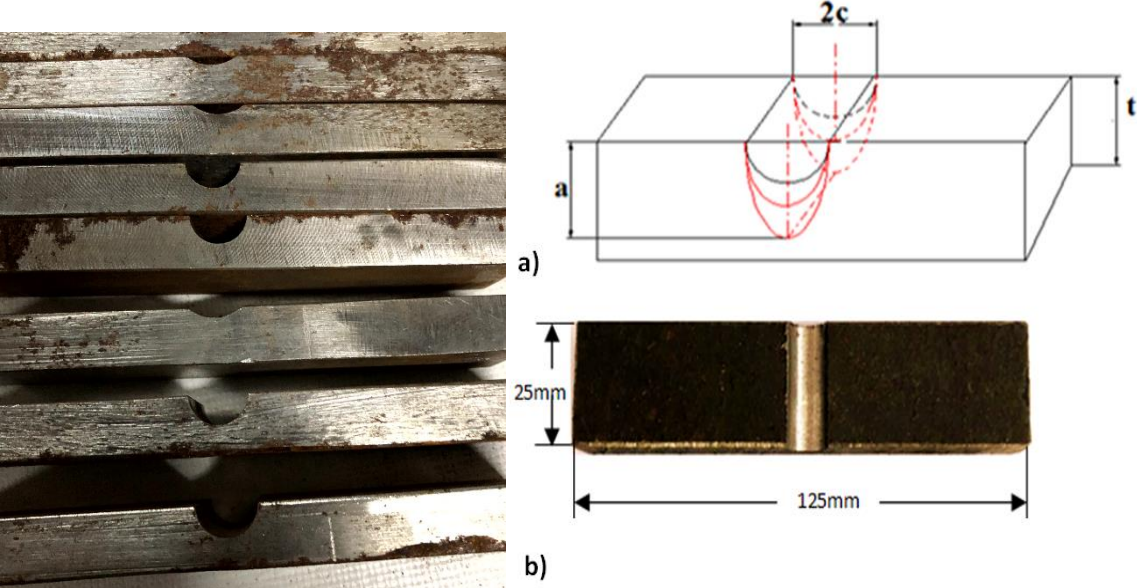


Fig.4.9 a) Geometry standard of semi-elliptical defects, b) Dimension of the test specimen.



Fig.4.10 Geometry standard of semi-elliptical defects top view.

## **4.7 Experimental tests**

A hybrid composite material is focused on the compounds from various fibers such as natural fibers and synthetic fibers with metal wires and polyester. Using the multi-fiber is considered as the solution for the defects of piping systems where it can improve the mechanical characteristics through then forcing by patch at the corroded zones.

One point of this project, it focused on the assembly natural fibers, industrial fibers with metal wires and polyester through the percentage for each element to carry out the tensile tests.

Second point of this project, it based on the reparation by patch through the 3-point bending test is used to determine the mechanical properties [204] as shown in Fig.4.1and 4.12.

### **4.7.1 Mechanical tests**

Unidirectional tensile test and three-point bending test by a universal machine with capacity of 50kN (Fig 4.11) to perform different samples made of various fibers including natural and synthetic ( hybrid composite) are experimented. To carry out these samples, it used the displacement speed is 2 mm/min for all tensile and bending mechanical tests[205, 206].

### **4.7.2 Tensile testing**

To perform the tests of tensile and three points bending on the different samples until breaks to appear the resistance of material with / without repair. This technique can illustrate many factors such as ultimate tensile strengths, tensile stress load, elongation and strain, where all these factors highlight the behavior of composite structure through the mechanical properties including the elastic limit, the elastic module and other factors. The experimented results of tensile are shown in the table 4.6 and the Fig. 4.11.

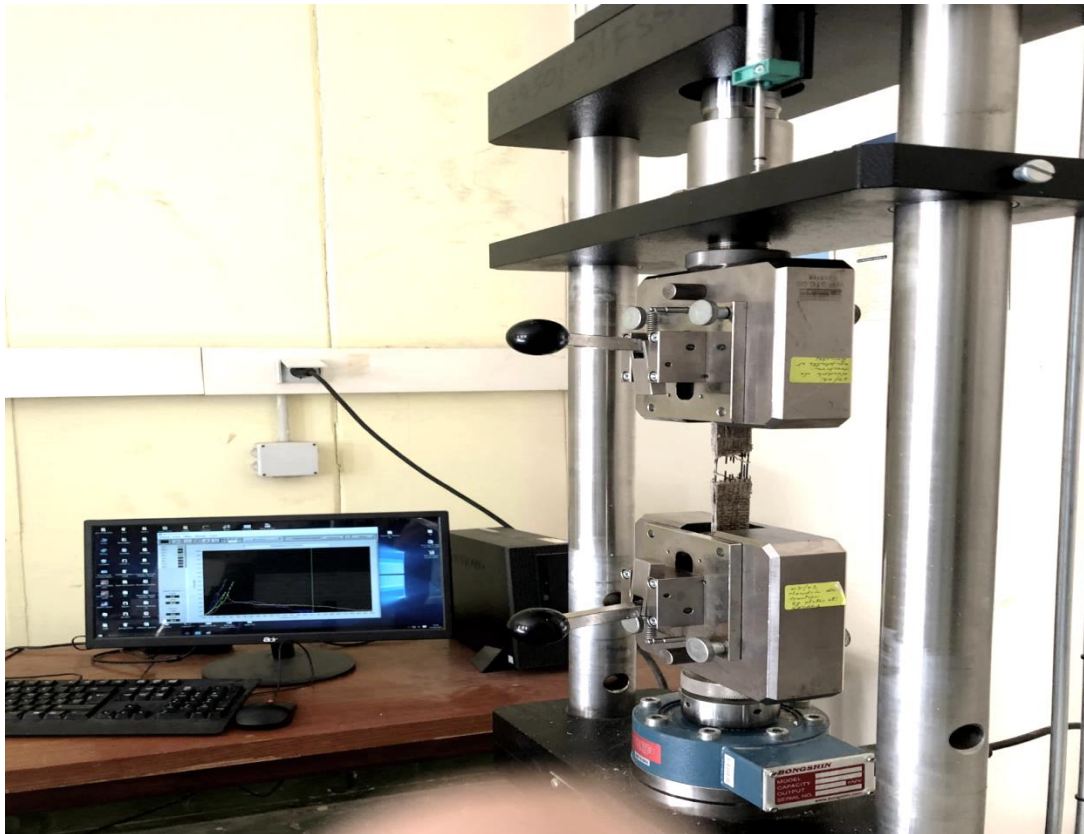


Fig.4.11 Test of the composite specimen (S5) on a universal machine capacity of 50kN.

Table 4.5 Designation of different composites.

N° S	Designation	Specimens with ASTM 3039 and D 790	Composites
01	<b>Pure jute :</b> Jute +Jute+ Jute+ Jute(JJJJ)		
02	<b>Hybrid :</b> Jute + Glass+ Jute+ Glass, (JGJG )		
03	<b>Hybrid :</b> Jute+ Jute+ 1.5 mm Steel wire +Jute+ Jute(JJ(1.5ST) JJ)		
04	<b>Hybrid :</b> Jute+ 1.5 mm Steel wire +Jute+1.5Steel wire +Jute ( J (1.5ST)J(1.5ST)J)		
05	<b>Hybrid :</b> Jute+ 1.5 mm Steel wire + Jute+ 1.5Steel wire + Jute+ 1.5 Steel wire+ Jute (J(1.5ST) J(1.5ST) J(1.5ST) J)		

Table 4.6 Tensile and flexural properties of different composite specimen (Average of five samples).

N <sup>o</sup>	Specimen Types	Composite Designation/Stacking sequences	Thickness (mm)	Flexural Load (N)	Tensile Load (KN)	Tensile Strength (MPa)	Strain at Failure (%)	Toughness (kJ m <sup>-3</sup> )
1	S1	JJJJ	2,8	97,7	3,3691	35,0952	18,099	279,25
2	S2	JGJG	2,6	248	4,7119	59,9888	21,3542	545,51
3	S3	JJ(1.5ST) JJ	5	341,8	6,1523	41,9032	19,2708	356,91
4	S4	J (1.5ST)J(1.5ST)J (JJ2(1.5)JJ)	6	366,2	6,9336	46,15	20,0521	351,15
5	S5	J(1.5ST) J(1.5ST) J (1.5ST) J (JJ3(1.5)JJ)	6,5	488,3	7,3965	47,42014	103,9062	2357,42

### 4.7.3 Flexural testing

The natural fibers with/without synthetic fibers and metal wire and the polyester is considered as a new technique to repair and reinforce of the defected or corroded of piping systems to increase the efficiency of safety using patch made of composite fibers. The resistance of flexural and flexural modulus of composite material can be measured by the flexural testing, where the both factors are based on the structure of composite material and its components.

The hybridization technique is method of mixture two or more compounds to make of the hybrid composite material from natural fiber (jute), synthetic fiber (glass), other compound (metal wire) and polyester with high resistance and mechanical properties with excellent features.

Nowadays, The hybrid material composite became as the important product in the global industries especially in the mechanical and medicine fields, and one of solution to repair the defects along of piping systems where it used as patch to repair and to reinforce, thus it can improve its role as patch for repairing the piping systems [204]. The sample of patch has used along of the pipeline where the load subjected to deformation (Fig. 4.12).



Fig.4.12 Equipment of flexural Testing and defect specimen with patch.

The flexural experimental of samples composite and samples with patch are shown in Tables 4.1 and 4.2, where the Equipment of Flexural Testing with defect samples of composite patch is shown in the Fig.4.12 shows.

Table 4.7 Tensile properties of different specimen in API 5L X52 (Average of three samples).

N°	Specimen Types	Thickness t (mm)	Defect		Flexural Load (KN)
			a (mm)	c (mm)	
1	Specimen Without Defect	10.3	/	/	30,4932
2	Specimen Defect a/t = 0,2	10.3	2	5	20,3125
3	Repaired a/t=0,2 by patch	16.8 (10.3+6.5)	2	5	25,6836
4	Repaired a/t=0,2 by 2 patch	23.3 (10.3+2x6.5)	2	5	31,4246
5	Specimen Defect a/t = 0,5	10.3	5	5	8,4961
6	Repaired a/t=0,5 by patch	16.8 (10.3+6.5)	5	5	11,9385
7	Repaired a/t=0,5 by 2 patch	23.3 (10.3+2x6.5)	5	5	14,0879
8	Specimen Defect a/t = 0,5	10.3	8	5	1,5869
9	Repaired a/t=0,5 by patch	16.8 (10.3+6.5)	8	5	4,7852
10	Repaired a/t=0,5 by 2 patch	23.3 (10.3+2x6.5)	8	5	6,9092

### 4.8 Results and desiccations

#### 4.8.1 Tensile test

In figure 4.13, to illustrate the behavior of defects on the safety of piping systems five compounds have been prepared by using the natural fiber composite with reinforced by synthetics which are fibers (jute, glass), metal wires (steel wires) with polyester to cohesion between them. This technique allowed creating hybrid composites through hybridizations operation due to increasing the resistance of traction and the resistance of flexural.

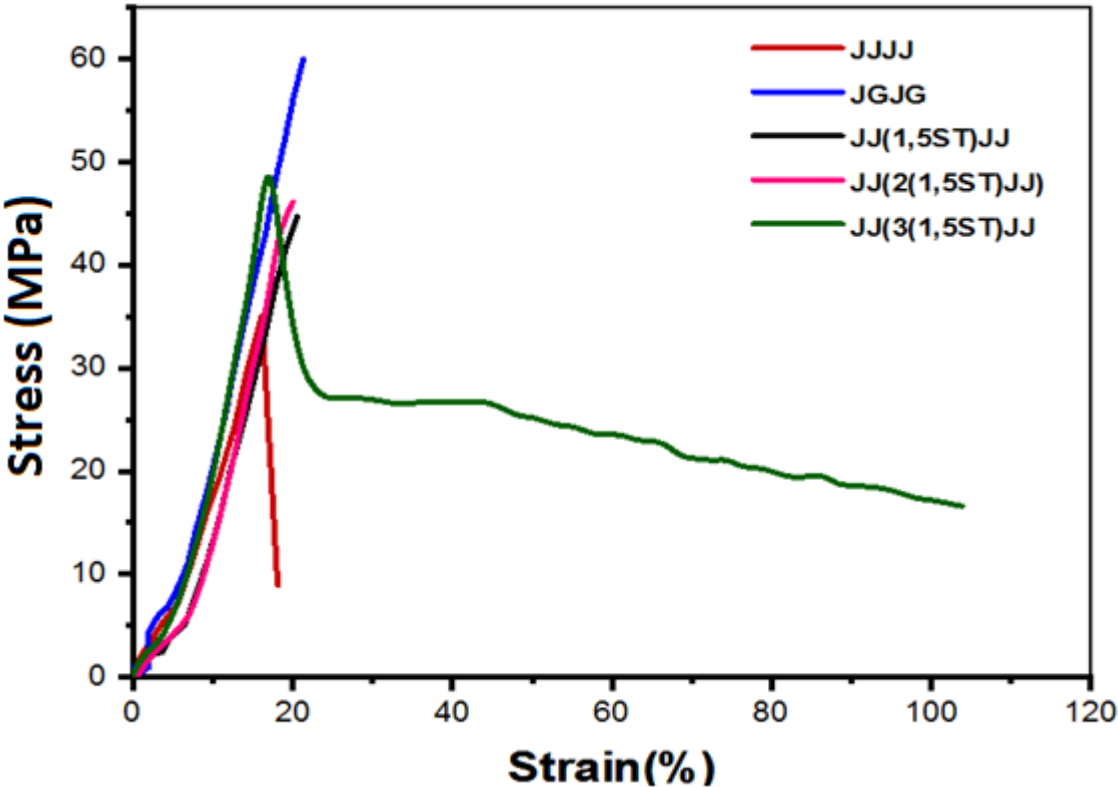


Fig.4.13 Tensile test stress-strain curve of different composite hybrid Jute-Steel wire

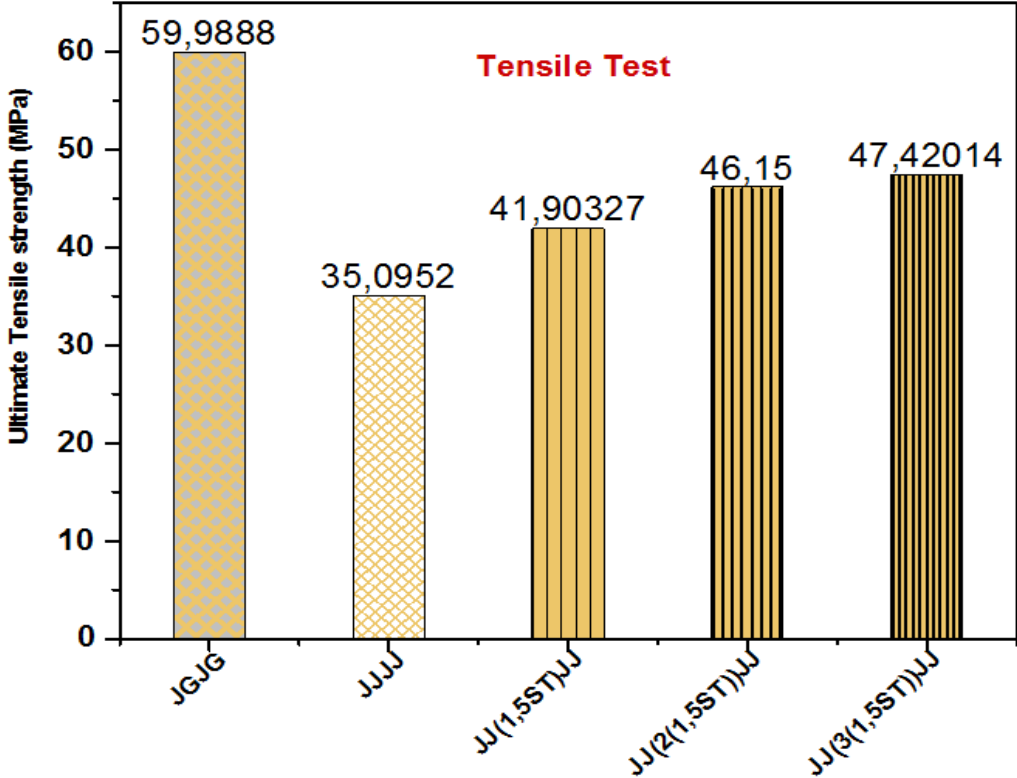


Fig.4.14 Comparison of the ultimate strength between of composite glass hybrid and composite Jute hybrid.

The samples were examined across the different composites where the hybrid composite of JGJG (S2) recorded the highest tensile strength, which was achieved at 59.98MPa. But the natural fibers compounded by Jute with reinforced by metal wires (JJ.ST.JJ), the tensile strength maximal value reached to 47, 42 MPa.

The experimental results provided more illustrate about the using of jute with presence of metal wires (S5), where it has proved that the elongation value has ductility feature as results of the reinforcement by metal wires elastic-plastic characteristics see Fig 4.13.

The strength of the hybrid composite (JJ.ST.JJ) represents is reached at 47.42 MPa, an increase of 35.12% compared to the pure jute composite (JJJJ) which represents 35.0952 MPa, to reinforce the piping system. Fig 4.14, expresses the comparison of tensile test strength between the hybrid of composite samples and jute composite samples.

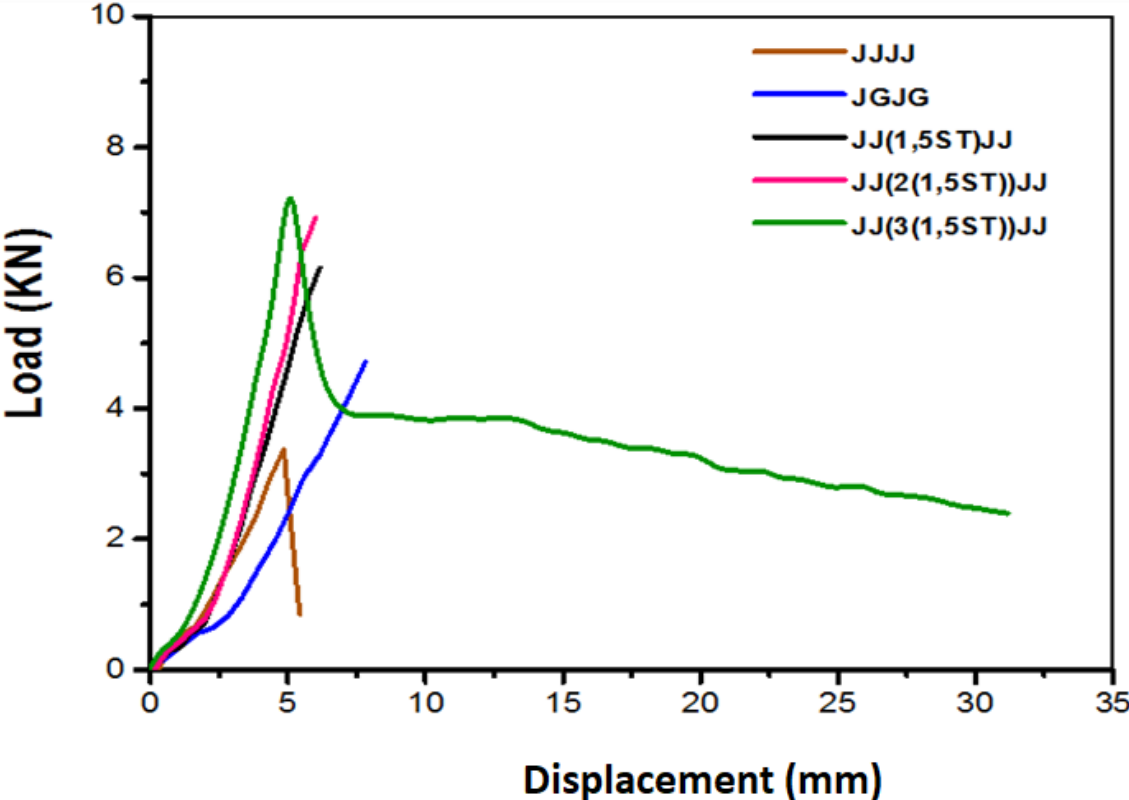


Fig.4.15 Tensile test load-load-displacement curve of different composites.

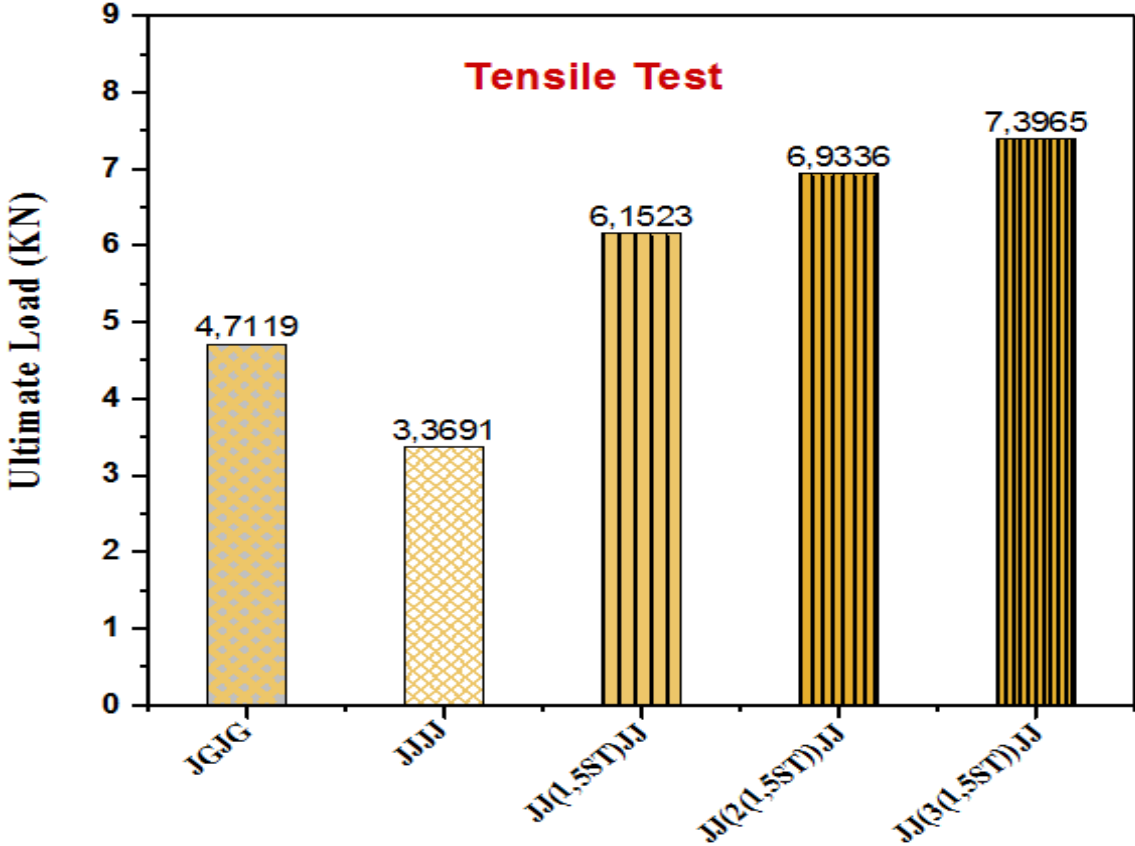


Fig.4.16 Comparison ultimate load of different composites.

Fig.4.15, shows the results of load-displacement for five 5 samples consisted jute, glass and metal wires.

The Fig.4.16 shown that the maximum load-displacement is 7,3965 KN for J(1,5ST)J(1,5ST)J(1,5ST)J (S5) hybridized composition sample, where the results is presented in the table 4.6.

It was cleared that the composite for jute fibers reinforced by steel wire (S5) has been better than pure jute composite (S1) and hybrid composite contained jute and glass fiber (S2).

Depending on the experiments results, all samples appeared only one stage elastic except the fifth sample (J(1.5ST) J(1.5ST) J(1.5ST) J)) appeared three stage including elastic zone, elastic-plastic zone and plastic zone as shown in Fig. 4.15 and Table 4.6.

#### **4.8.2 Toughness composites**

The toughness factor is necessary parameter to study the elastic-plastic stage (Fig.3.22) taking into consideration the nature of fibers and forms/sizes of defects with/without metal wires.

This parameter can be used to determine the absorption of energy at defects by integrating of the stress-strain function, through deformation per unit volume using the equation mathematical as following (18)

Figure 4.17 is expressed that the jute composite with metal wires were experimented sample with good features as original material patch.

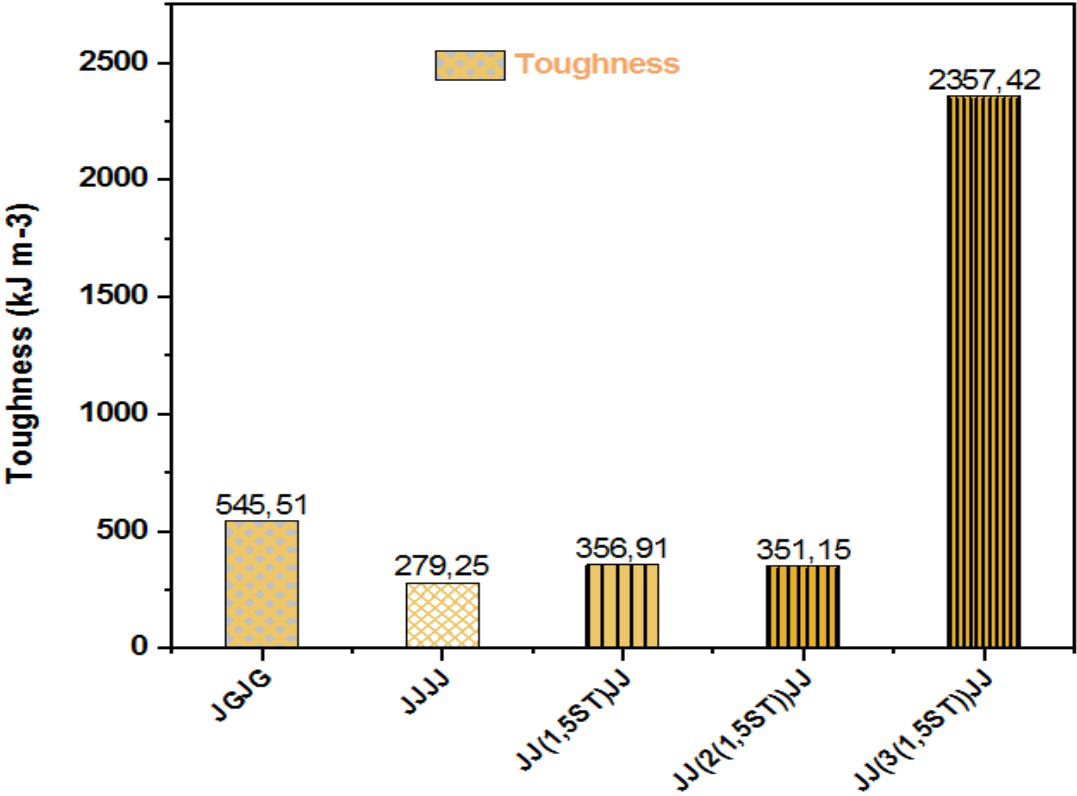


Fig.4.17 Results of toughness in tensile specimen of composite laminates.

The maximum toughness values were measured for the composite material (S5) J(1,5ST)J(1,5ST)J(1,5ST)J and hybrid composite material (S2) JGJG equal to 2357,42kJ m<sup>-3</sup> and 545,51 kJ m<sup>-3</sup> respectively. The composite material (S1) provided the least value of toughness with 279,25 kJ m<sup>-3</sup>. The complete of experimental results are shown in the table 2, where the variation of the toughness is proportional to the number of metal wires and their layers.

**4.8.3 Test flexural**

In this study, the bending tests were carried out for different types of composite material including nature fiber, industrial fiber, metal wires and polyester (table.4.1-4) on the one hand. On the other hand, the bending tests were performed for the specimens of API X52 steel from piping systems without/with defect according to the dimension of the specimen as illustrated in Fig.4.8and reinforced by patches according the ratio a/t (table.4-7).

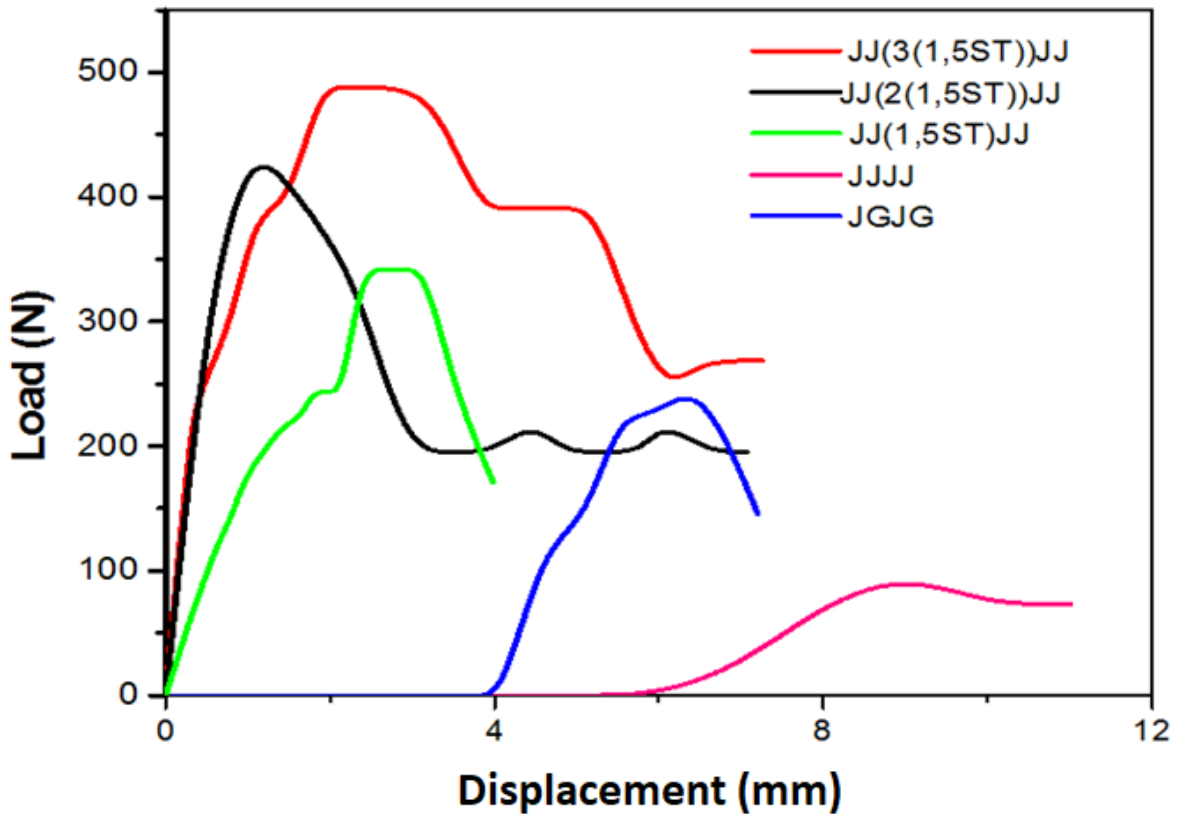


Fig.4.18 Test flexural load-displacement curve of the composite laminates.

Figs 4.18 and 4.19, represents the bending test results of the load-displacement curves of 5 specimens including hybrid composite material (jute fiber and glass fiber) JGJG, composite material jute( JJJJ) and natural fiber composite of jute fiber reinforced with steel wires JJ(1,5ST)JJ, J(1,5ST)J(1,5ST)J and J(1,5ST)J(1,5ST)J(1,5ST)J.

It can be noted that the results show that hybridization with metal wires led improve the mechanical properties of the materials composites taking into account the layers of wires as well as their numbers.

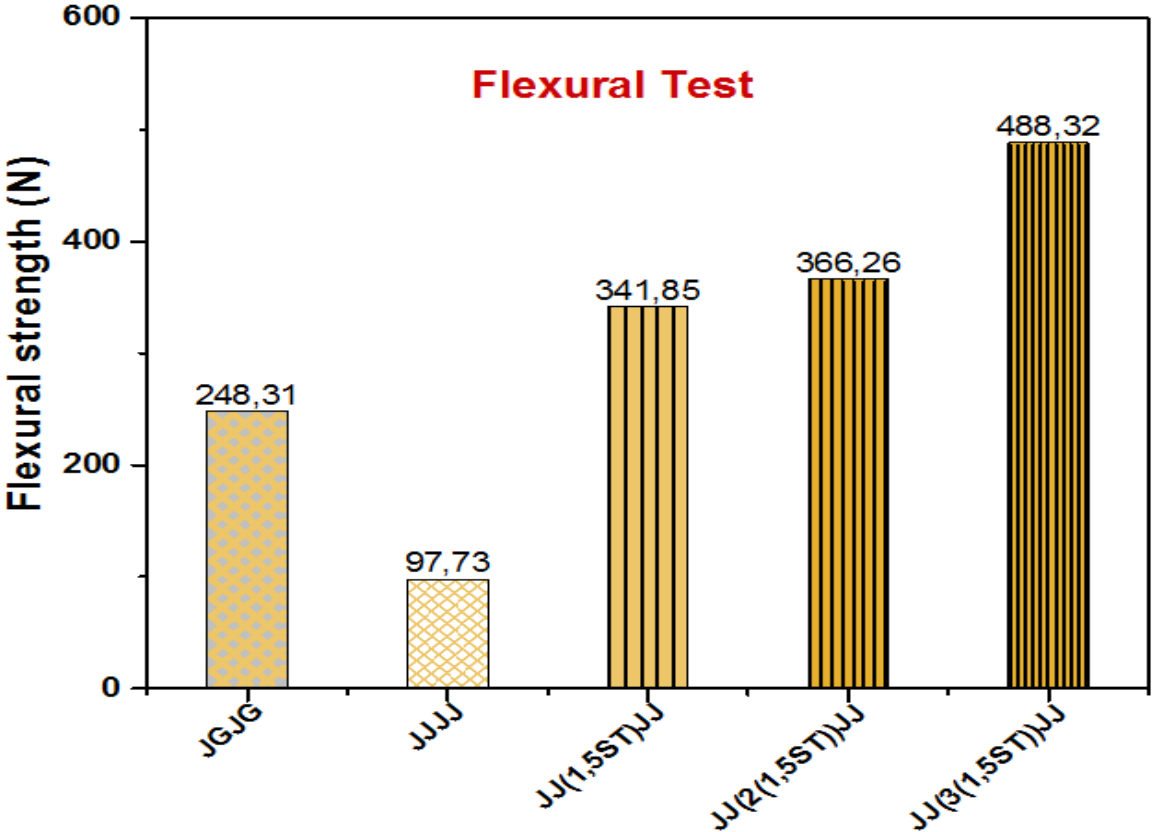


Fig.4.19 Comparison of flexural strength of the composite laminates.

**4.9 Reparations with patches and calculated Efficiency**

**4.9 .1 Reparation with patch**

The goal of this project is to investigate the composite patch through mechanical properties for repairing defects using the composite patch using the hybrid (jute fiber-fiber glass)/natural fiber composite (jute fiber reinforced by metal wires) with the polyester.

Synthetic and natural fibers have been analyzed. The behavior has been studied through five samples where sample (S5) is a better sample than other samples, which consists of four layers of jute and three layers of metal.

The five samples of industrial fiber, natural fiber and natural fiber composite reinforced by metal wires are analyzed, where specimen (S5) was selected among the specimens as a composite patch, which consists of four (04) layers of jute fabric and 3 layers of metal wires. To evaluate the safety of piping systems the variation of the depth of the defect (a) through the total depth (t=10 mm) and fixed defect length (2C =10 mm) of samples is based on the thickness of the defects, which depends on the ratio  $0 < a/t \leq 0,8$ .

This project provided solutions to reduce the corrosion through the use of the patch made on natural fiber with metal wires of 1.5 mm diameter of and polyester to decrease the defect of corrosion through the sample (S5) and to improve the mechanical properties of the reinforced sample by using three ratios  $a/t=0,2$ ,  $a/t=0,5$ , and  $a/t=0,8$  respectively (see Fig 4.9 and 4.10).

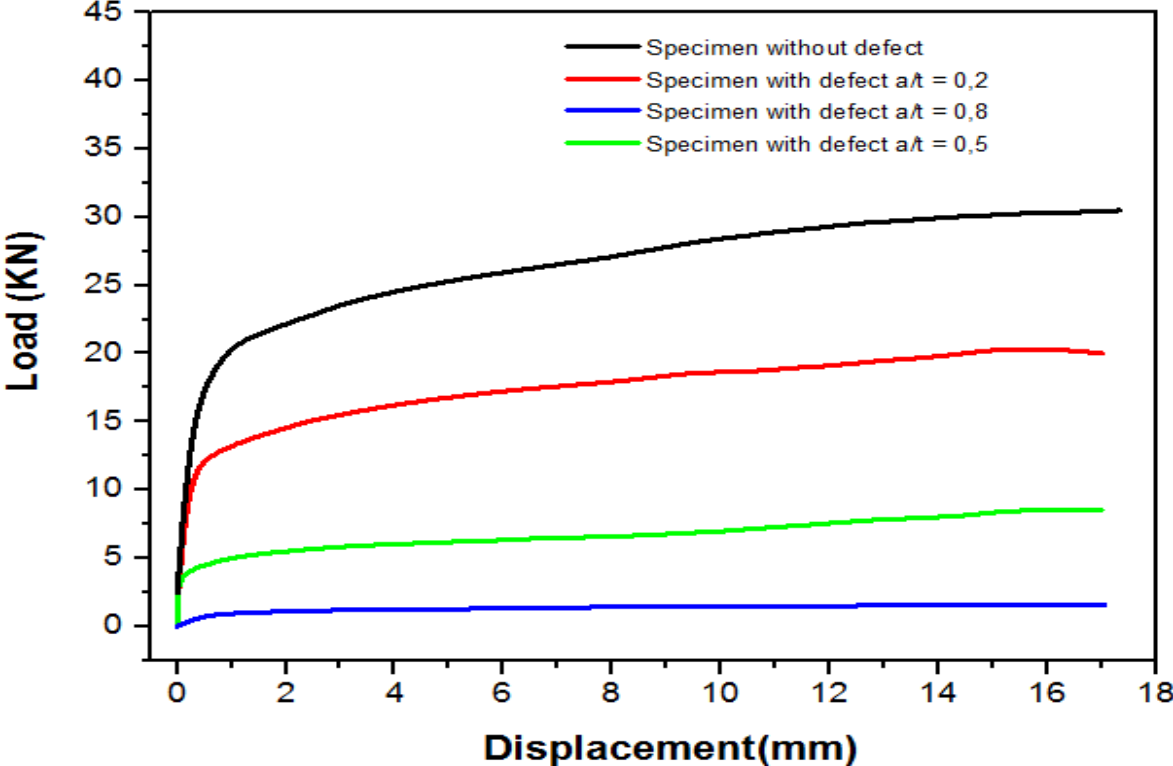


Fig.4.20 Load–displacement curve for API X 52 pipeline defected for various ratios of  $a/t$  ( $0 < a/t \leq 0,8$ ).

Figure 4.20 describes the curves of the bending test results of the specimens with and without defects in Table 4.7 according to the ratio  $a/t$ . We recorded respectively the maximum value in the specimen without defects is 30.4932KN, in the first form of defect ( $a/t=0,2$ ) is 20.3125 KN, in the second ( $a/t=0,5$ ) is 8.4961 KN and in the third form ( $a/t = 0,8$ ) is 1.5869 KN. These results revealed that the thickness becomes very brittle due to the semi-elliptical surface defects of API X52 pipeline which characterized by a significant reduction in bending load from 30.4932KN for the base metal specimen, down to 1.5869KN for the specimen with depth defect ( $a/t=0,8$ ). However, the corrosion defects have effects of the order proportional to the depth ( $a$ ), hence the impact of mechanical property degradation.

Using metal wires in laminates of jute fiber as composite patch natural reinforced for repairing the defected pipelines lead to improve the mechanical tensile strength. It can be

noted that the double patches of jute fiber reinforced by metal wires shows the maximum tensile strength compared to the single patch [184].

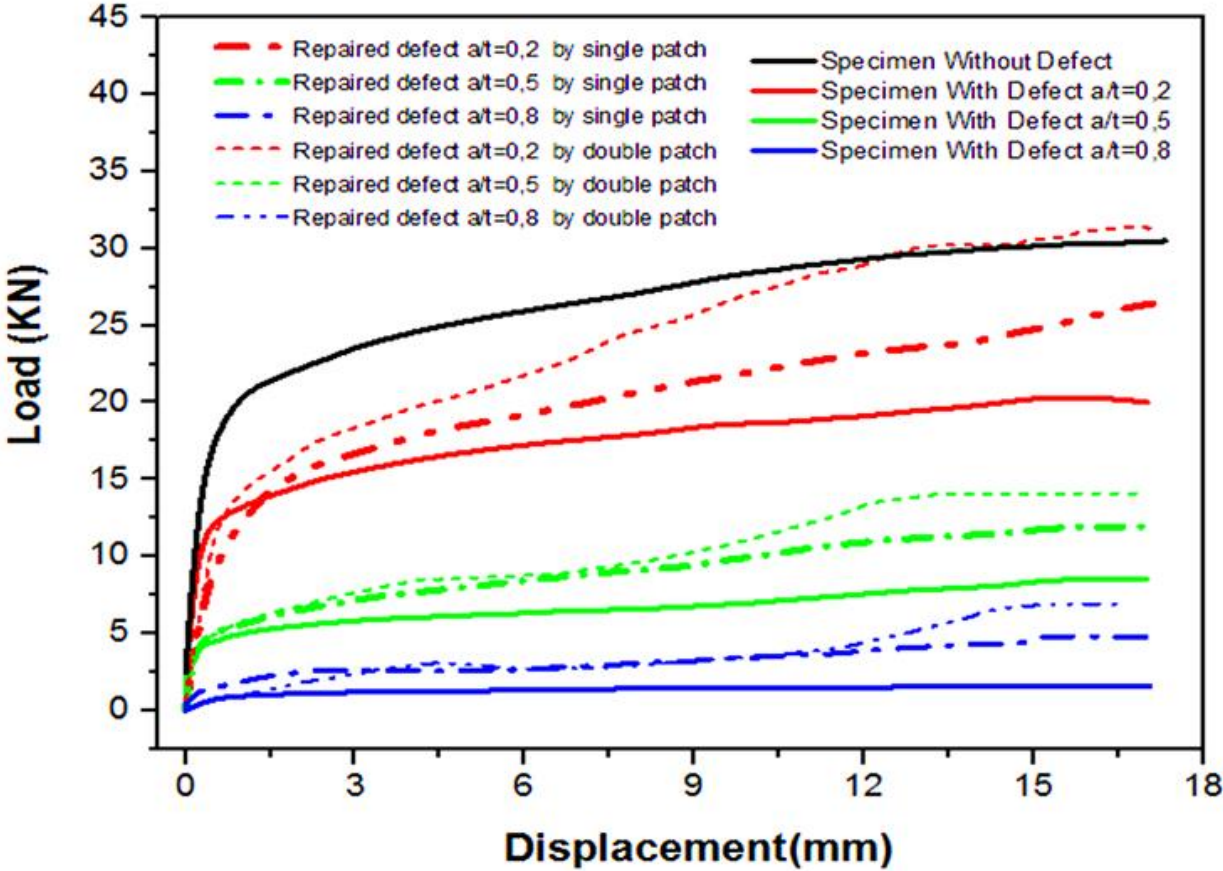


Fig.4.21 Load–displacement curve for API X 52 pipeline steel repaired using the patch composite natural

Figs 4.21 and 22, shows that the S5 hybrid nature composite patch repair has a considerable beneficial effect compared to the results of the experiments with defects, it was recorded the considerable increase in mechanical properties in the first form of  $a/t = 0.2$ , where the bending load value with a single patch is 25.6836 KN and 31.4246 KN for double patch.

The latter can improve the load property to 103.05% in comparison with specimen without defects. In both forms  $a/t = 0.5$  and  $a/t = 0.8$  the patch repair gives values of 11.9385KN, 4.7852KN for a single patch and 14.0879KN, 6.9092KN for double patch respectively, the improvement in load is of the order of less than 50% for deep defects ( $a$ ) which exceed half thickness ( $a/t \leq 0.5$ ). The improvement in the results is due to the fact that the defect (semi-elliptical defect) was repaired through the method of hybrid composite stratifications (natural patch: jute with metal wire)



Fig.4.22 Specimen API X 52 pipeline steel test with and without repaired using the patch composite natural.

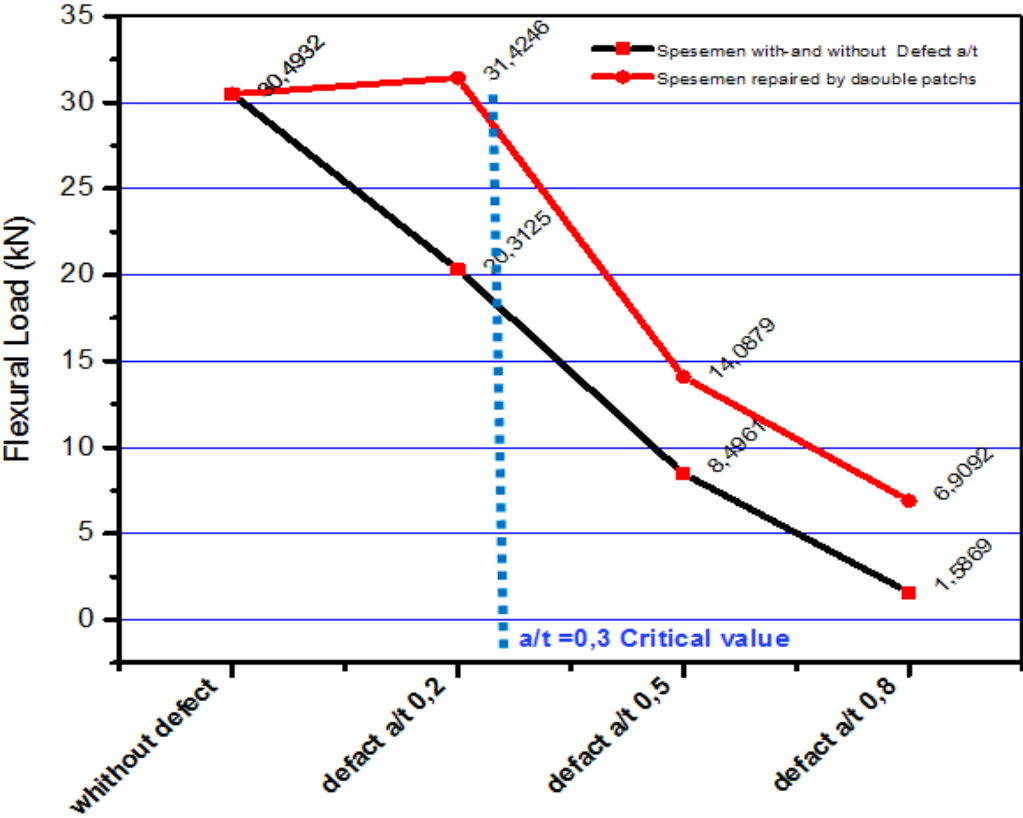


Fig.4.23 Flexural load versus state of specimens of API X 52 pipeline steel: specimens without defects and defected specimens with/without repaired.

Fig.4.23 highlights on the comparison of the loads results of the bending test for the specimens with/without defects where the API X52 pipeline specimens with defects were repaired through jute fiber reinforced with steel wires.

Using metal wires with jute fibers as sustainable materials for increasing the loading and resist the force acting on cracked pipeline is necessary considered as patch to solve the defect problems such as corrosion due to complex chemical reactions which related to the nature of pipeline and hydrocarbons.

the purpose of this study is to form natural fiber composite patch with strong mechanical characteristics to repair the semi-elliptical defected of piping systems using the composites hybrid S2 (jute fiber-glass fiber) and thirdly three configurations S3,S4,S5 (jute fiber reinforced by steel metal wires using polyester resin is studied).Where this operation can useful for deficiencies in the used materials.

These natural fibers have the capability to replace synthetic fiber due to its positives features such as recycling and environment friendly.

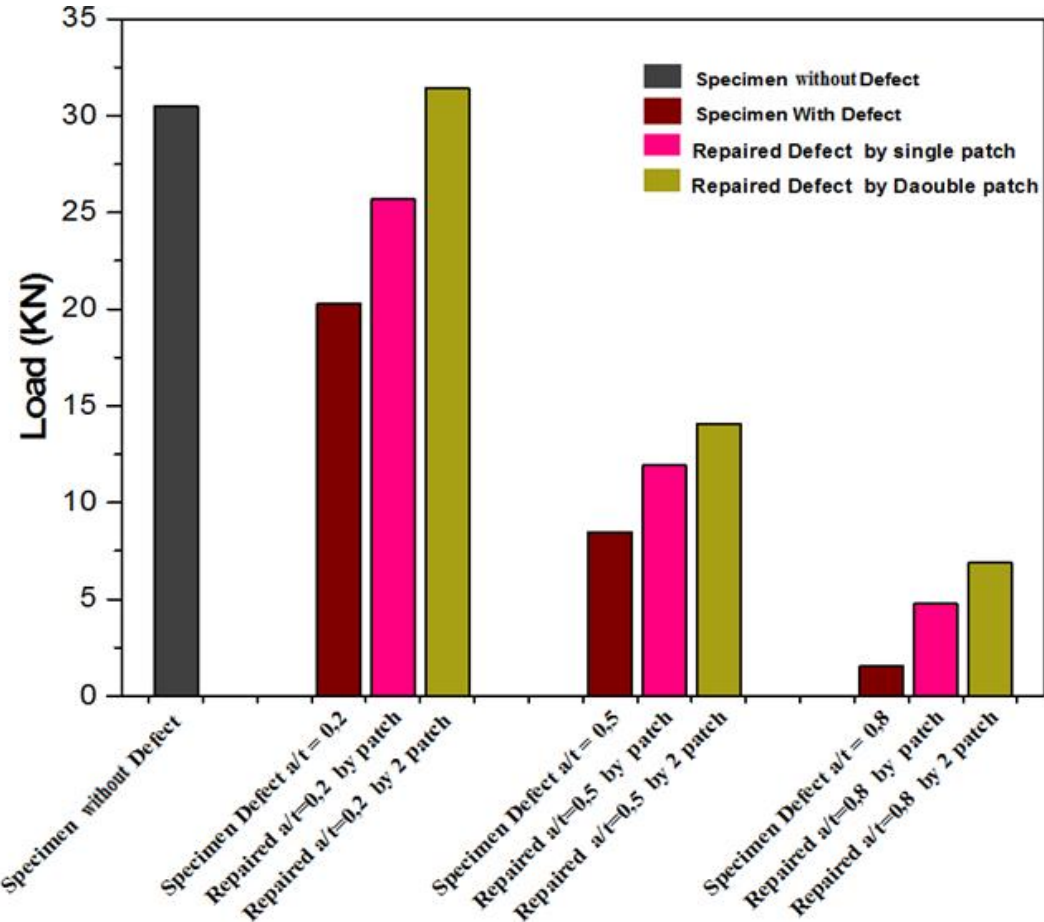


Fig.4.24 Comparison of ultimate load of API X52 pipeline steel between specimen without defect and specimens with defect for different ratios ( a/t ) which were repaired using composite of natural hybrid (S5).

Furthermore, the repair can be estimated at a recovery of mechanical characteristics of 100% for pipelines with less deep defects using the double patch, where the defect sizes of the ratio a/t less than 0,3 (a/t<0,3) see Fig4.23and Fig 4.24. Hence, double composite patch have greater load than simple composite patch due to the number of laminates of jute and number of metal wires.

4.10 Fractography and failure analysis of samples

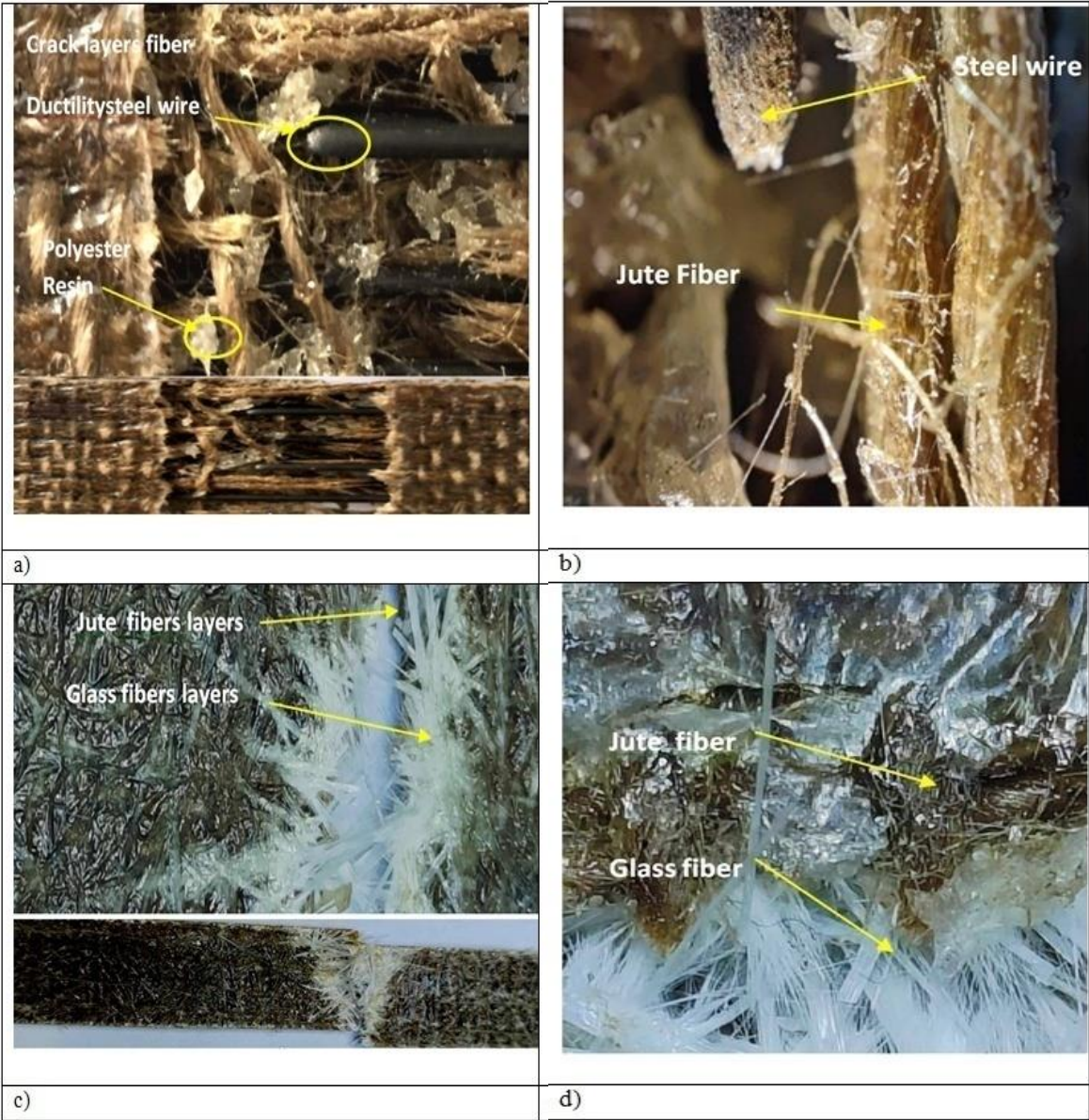


Fig.4.25 Failure analysis fractography, a) and b) Sample of natural fiber composite (S5),(c) and (d)Sample of hybrid composite (S2).

The fractography analysis of the rupture of the samples validates the performance of natural composite fiber reinforced with three layers of steel wires (S5). Figure 4.25.a shows the morphological structure of jute composites with steel wire.

It was observed the rupture ductility of the steel wires without delaminating Figure 19.b; the latter increased the elongation and strength of the sample. Figure 4.25.c and d, illustrates the sudden rupture of samples of hybrid composite (S2) of the fiber of jute hybridized with fiber

glass which favorably influences the mechanical tensile properties in despite of good adhesion of the samples by the polyester resin.

#### 4.11 Conclusion

The natural fibers have become appreciated for various industrial and emerging applications and are also considered an alternative solution to synthetic fibers due to their availability at less cost, cultivability and environmentally friendliness, in addition to giving superior results in the physical, chemical and mechanical properties of natural fiber composites [1-5,18]. It is interesting to note that the technology of composite material is one of the technologies used in modern industries for the mechanical features, including high resistance.

In addition, the natural fiber becomes a new material where it competes with the glass fiber and carbon fiber in the mechanical industries due to its features of mechanical properties, especially when it used with other fibers [69, 70].

The aim of this present project is to study the hybridization effects of glass fibers and steel metal wires on the natural fibers to increase the mechanical characteristics and use them in industry domains and hydrocarbon transport. In this study, the hand layup technique was utilized to manufacture non-hybrid and hybrid composite laminates. All testing was performed using the ASTM D3039 and ASTM D790 standards. This paper presents five specimens, such as the hybrid jute fiber and glass fiber and the natural fiber composite of jute reinforced by steel metal wires using polyester resin.

The tests are performed to study the physical and mechanical behavior of three types of composites. According to the experimental results, the maximum values of the results obtained on bending tests for samples with defects repaired by the S5 patch are proved. The bending load is 20,3125 KN for the ratio  $a/t=0.2$  without the use of a patch and with the patch it is 25,6836 KN or the equivalent of 84,2%, where the performance with a double patch is 31,4246 KN or the equivalent of 103%. The lowest values are recorded in the deepest defects with a ratio of  $a/t = 0.5$  and  $0.8$ . Thus, these results show that the natural fiber composite patch can be used in the mechanical reparation of pipelines containing defects of small thickness or damage points. The final results show that hybridization with metal wires and the number of stackings of steel wire improved properties of the composite materials.

According to the obtained results, it can be noted that this project has provided further insights into natural jute fiber reinforced with metal wires and its use as a patch on semi-elliptical defects of API X52 corroded pipes according to the  $a/t$  ratio.

## **General conclusion**

## General conclusion

---

### General conclusion

Oil and gas companies seek to develop pipeline transportation systems that meet the major environmental challenges, service continuity and low cost on the one hand. On the other hand, the mechanical characteristics of pipelines are considered key factors in the development and improvement of pipeline systems.

In fact, the welding repair operation is one of the solutions used in the field of mechanical constructions especially in the safety of piping systems considering the geometry of the shape of the most generalized corrosion defects is semi-elliptical shape by two ratios  $a/c$  and  $a/t$ . However, the results of the samples repaired by welding have shown significant improvements in the mechanical properties.

These can explain that defects less than 0.5 are 100% recoverable by the weld repair; moreover, the variation of the shape in depth ( $a/t$ ) for the semi-elliptical geometry has a more serious influence in relation to the defect of ( $a/c$ ) in the safety of piping systems.

In the second part of the project, a hybrid composite patch was used as a second solution to repair API X52, using natural fibers, synthetic fibers, metal wires and polyester, where the big challenge was to perform all the steps based on international standard norms. For these reasons, the natural fibers were increasingly appreciated for various industrial applications and are also considered as an alternative solution due to their availability, low cost and environmental friendliness. In addition, natural fiber becomes a new material where it has become a competitor of glass fiber and carbon fiber which is more expensive with a very high difficulty of industrial manufacturing processes unlike natural fiber which is cultivable, easy to plant and ecological. Furthermore, the experimental results of bending tests for samples of API X52 steel that were repaired by the composite patches reached to 100% at the ratio  $a/t=0.3$ .

Finally, based on the experimental results, it is evident that semi-elliptical defect shapes, defined by the  $a/c$  and  $a/t$  ratios, are key parameters for evaluating material properties and pipeline safety. Larger defects lead to a decrease in strength, elongation, and toughness compared to the base metal. However, welding proves to be an effective repair method when these ratios remain below **0.5**. Alternatively, composite patch repair presents a reliable solution, especially for oil and gas pipelines, as it can restore up to **100%** of a pipe's capacity, provided that corrosion does not exceed **30%** of the original wall thickness.

## References

---

### References

- [1] <https://x.com/Algeria3New/status/1757667019086766469/photo/1>.
- [2] <https://pgjonline.com/news/2022/june/algeria-niger-nigeria-take-steps-to-build-13-billion-trans-saharan-gas-pipeline>
- [3] <https://www.steel-industrial.com/factory/seamless-pipe-production-line.html>.
- [4] M. NAHAL, Etude mécano-fiabiliste des pipelines destinées aux hydrocarbures, Thèse de doctorat en génie mécanique université, Badji Mokhtar -Annaba, 2016.
- [5] A. Bouziane, contribution à la détermination de critères de qualité des tubes soudés soumis à une pression intérieure. Thèse de magister en génie mécanique université M'Hamed Bougara Boumerdes 2007/2008.
- [6] D. ZELMATI, Etude mécano-fiabiliste des propriétés mécaniques et ténacité des pipelines en acier revêtus, Thèse de doctorat en génie mécanique université, Badji Mokhtar - Annaba, 2018.
- [7] C. Matthews, A Quick Guide to API 653 Certified Storage Tank Inspector Syllabus Example Questions and Worked Answers, Book 2011, <https://doi.org/10.1533/9780857095275.1>.
- [8] T. Byrnes, Trends in Oil and Gas Corrosion Research and Technologies, Production and Transmission, A volume in Woodhead Publishing Series in Energy, Book 2017 Pages 563-591; <https://doi.org/10.1016/B978-0-08-101105-8.00024-3>.
- [9] J. Gourmand : 'Les aciers dans la construction', Article, Les grands ateliers, 2006.
- [10] S. Shiga (1981), T. Hatomura, J-I. Kudoh, A. Kamada, K. Hirose et T. Sekine, Development of Large Diameter High Strength Line Pipes for Low Temperature Services, Kawasaki steel technical report No.4, 97-109, 1981.
- [11] J.M. Gray (2001), Niobium bearing steels in pipeline projects, Niobium Science and Technology, Dec 2 & 5, 2001.
- [12] B. ISSASFA, Etude de l'endommagement, entretien et réparations des pipes de transport des hydrocarbures en utilisant des matériaux composites, Thèse de magister en génie mécanique, Université 08 Mai 45 de Guelma 2010.
- [13] F. HADJOU, Etude du comportement en fatigue des aciers pour pipelines à différents grades, Thèse de magister en Génie Mécanique, Université Abou Bekr Belkaid – Tlemcen 2012/2013.
- [14] API Specification 5L, Specification for Line Pipe, American Petroleum Institute, Washington, D.C, 2004.

## References

---

- [15] American Society of Mechanical Engineers (ASME) B31G-2009, Manual for Determining the Remaining Strength of Corroded Pipelines, A supplement to ASME B31 Code for Pressure Piping, 2009.
- [16] S. Lee, D. Kwon, Y.K. Lee, O. Kwon, Metall Mater Trans., Vol. 26A 1093, 1995.
- [17] M. Zhao, K. Yang, Y. Shan, Comparison on strength and toughness behaviors of microalloyed pipeline steels with acicular ferrite and ultrafine ferrite, Materials Letters 57, 1496–1500, 2003.
- [18] J.M. Gray, Niobium bearing steels in pipeline projects, Niobium Science and Technology, Dec 2 & 5, 2001.
- [19] K. HULKA, HSLA ,Large diameter pipe plate from standard production to X80/X100, Niobium Information, 1997.
- [20] F.H. Kamp and T. Carneiro, NIOBIUM: Future Possibilities – Technology and the market place, 2001.
- [21] N.N. Jia, K. Guo ,M. He, Y.H. Wang, J.G. Peng ,T.S. Wang , A thermomechanical process to achieve mechanical properties comparable to those of quenched-tempered medium-C steel, Materials Science and Engineering: Volume 700, 17 July 2017, Pages 175-182 <https://doi.org/10.1016/j.msea.2017.06.011>.
- [22] L. Jeanette Smart, Review of materials property data for nondestructive characterization of pipeline materials; Graduate Theses and Dissertations; Iowa State University ; 2015.
- [23] H. Brand, Gras, Kalwa, Development and production of High strength pipeline steels, Proceedings of the International Symposium Niobium, ed. P.J.P. Bordignon, Florida, USA, publications Europipe n°43, 2001.
- [24] H. Asahi, E. Tsuru, S. Ohkita, N. Maryama, K. Koyama, H. Akasaki, M. Murata, H. Miyazaki, T. Hara, H. Morimoto, M. Sugiyama, K. Shinada, Y. Terada, N. Ayakawa, N. Doi, T. Yoshida, Development of Ultra-high-strength Linepipe, X120, Nippon Steel technical report No. 90, 82-87, 2004.
- [25] Y. Rezaie, S.M.H. Sharifi, G.R. Rashed, “Probabilistic fracture assessment of snake laid pipelines under high pressure/high temperature conditions by engineering critical assessment, Engineering Fracture Mechanics, vol. 271, p. 108592, 2022.
- [26] Sh. Zangeneh, H.R. Lashgari, H.R. Sharifi, Fitness-for-service assessment and failure analysis of AISI 304 demineralized-water (DM) pipeline weld crack, Engineering Failure Analysis, vol. 107, p. 104210, 2020.
- [27] Standards Australia Limited, Pipelines, Gas and Liquid Petroleum, Part 1 - Design and Construction, Standards Australia, pp. 328, 2012.

## References

---

- [28] Z. Zhang, L. Guo, Y. F. Cheng, Interaction between internal and external defects on pipelines and its effect on failure pressure Author links open overlay panel, *Thin-Walled Structures* Volume 159, February 2021, 107230, <https://doi.org/10.1016/j.tws.2020.107230>.
- [29] Davis, J.R., 2000. Chapter 1: the Effects and economic Impact of corrosion. In: *Corrosion: Understanding the Basics*, vol. 164, pp. 62–66. <https://doi.org/10.31399/asm.tb.cub.t66910001.163>.
- [30] M. Wasim, M.B. Djukic, External corrosion of oil and gas pipelines: A review of failure mechanisms and predictive preventions, *Journal of Natural Gas Science and Engineering*, vol. 100, p. 104467, 2022.
- [31] Z. Tang, Z. Wang, Y. Lu, P. Sun, Cause analysis and preventive measures of pipeline corrosion and leakage accident in alkylation unit, *Engineering Failure Analysis*, vol. 128, p. 105623, 2021.
- [32] API RP 5L2, Recommended Practice for Internal Coating of Line Pipe for Non-Corrosive Gas Transmission Service, 2002.
- [33] B. Wei, J. Xu, Q. Fu, Q. Qin, Y. Baia, C. Sun, C. Wang et al., Effect of sulfate-reducing bacteria on corrosion of X80 pipeline steel under disbonded coating in a red soil solution, *Journal of Materials Science & Technology*, vol. 87, pp. 1-17, 2021.
- [34] Z. Yan, L. Wang, P. Zhang, W. Sun, Z. Yang, B. Liu et al., Failure analysis of erosion-corrosion of the bend pipe at sewage stripping units, *Engineering Failure Analysis*, vol. 129, p. 105675, 2021.
- [35] R. Ashari, A. Eslami, M. Shamanian, S. Asghari, Effect of weld heat input on corrosion of dissimilar welded pipeline steels under simulated coating disbondment protected by cathodic protection, *Journal of Materials Research and Technology*, vol. 9, no. 2, pp. 2136–2145, 2020.
- [36] Pipeline Accident Report NTSB/PAR-11/01, Pacific Gas and Electric Company Natural gas Transmission Pipeline Rupture and Fire, San Bruno, California, 2011.
- [37] Z.F. Chen, W. Wang, H. Yang, S.T. Yan, Z.J. Jin, On the effect of long corrosion defect and axial tension on the burst pressure of subsea pipelines, *Applied Ocean Research*, vol. 111, p. 102637, 2021.
- [38] W. Wang, Y. Wang, B. Zhang, W. Shi, C.Q. Li, Failure prediction of buried pipe network with multiple failure modes and spatial randomness of corrosion, *International Journal of Pressure Vessels and Piping*, vol. 191, p. 104367, 2021.
- [39] B.Q. Chen, X. Zhang, C. Guedes Soares, The effect of general and localized corrosions on the collapse pressure of Subsea pipelines, *Ocean Engineering*, vol. 247, p. 110719, 2022.

## References

---

- [40] I. Shtoyko, J. Toribio, V. Kharin, M. Hredil, Prediction of the residual lifetime of gas pipelines considering the effect of soil corrosion and material degradation, *Procedia Structural Integrity*, vol. 16, pp. 148–152, 2019.
- [41] L.Y. Xu, Y.F. Cheng, Reliability and failure pressure prediction of various grades of pipeline steel in the presence of corrosion defects and pre-strain, *International Journal of Pressure Vessels and Piping*, vol. 89, pp. 75-84, 2012.
- [42] H. Wang, Y. Yu, W. Xu, Z. Li, S. Yu. Time-variant burst strength of pipe with corrosion defects considering mechano-electrochemical interaction. *Thin-Walled Structures*, vol. 169, p. 108479, 2021.
- [43] B.G.N. Muthanna, O. Bouledroua, M. Meriem-Benziane, M.R. Setvati, M.B. Djukic, Assessment of corroded API 5L X52 pipe elbow using a modified failure assessment diagram, *International Journal of Pressure Vessels and Piping*, vol. 190, p. 104291, 2021.
- [44] A.R. Alian, M. Shazly, M.M. Megahed, 3D finite element modeling of in-service sleeve repair welding of gas pipelines, *International Journal of Pressure Vessels and Piping*, vol. 146, pp. 216-229, 2016.
- [45] Y. Shuai, X. Wang, J. Wang, H.G. Yin, Y.F. Cheng, Modeling of mechanical behavior of corroded X80 steel pipeline reinforced with type-B repair sleeve, *Thin-Walled Structures*, vol. 163, p. 107708, 2021.
- [46] B. Amadeus, S. Dirk, K. Arne, K. Thomas, Determination of residual stress evolution during repair welding of high-strength steel components, *Forces in Mechanics*, vol. 6, p. 100073, 2022.
- [47] F.G. Alabtah, E. Mahdi, F.F. Eliyan, The use of fiber reinforced polymeric composites in pipelines, *Composite Structures*, vol. 276, p. 114595, 2021.
- [48] M. Shamsuddoha, A. Manalo, T. Aravinthan, M.M. Islam, L. Djukic, “Failure analysis and design of grouted fiber-composite repair system for corroded steel pipes,” *Engineering Failure Analysis*, vol. 119, p. 104979, 2021.
- [49] L.P. Djukic, W.S. Sum, K.H. Leong, W. D. Hillier, T.W. Eccleshall, A.Y.L. Leong, Development of a fibre reinforced polymer composite clamp for metallic pipeline repairs, *Materials and Design*, vol. 70, pp. 68-80, 2015.
- [50] T.D. Williamson Inc, Steel Repair Sleeves, 2007.[accessed 14.09.12].<https://www.tdwilliamson.com>.
- [51] PLIDCO Split Sleeve, Permanently repairs a variety of pipelines, 2012,<https://tremcopipeline.com.au/maintenance-equipment/plidco-fitting/plidco-split-sleeve>.

## References

---

- [52] The Clock Spring Company. Clock Spring; 2011. <http://www.clockspring.com/wp-content/uploads/2011/12/brochure1.pdf> [accessed 14.09.12].
- [53] M. Green, Fiber glass repair systems give corrosion, impact protection to pipelines and risers. *Offshore* 2010;70(10). <http://www.offshore-mag.com/articles/print/volume-70/issue-10/flowlinespipelines/composites-offer-effective-offshore-pipe-repair-alternative>;
- [54] Md. Shamsuddoha, Md. Mainul Islam, T. Aravinthan, A. Manalo, K.T. Lau, Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs. <http://dx.doi.org/10.1016/j.compstruct.2012.12.019>.
- [55] J.C. Newman, I.S. Raju, An empirical stress-intensity factor equation for the surface crack, *Engineering Fracture Mechanics*, vol. 12, no. 1-2, pp. 185-192, 1981.
- [56] I.S. Raju, J.C. Newman, Stress-intensity factors for a wide range of semi-elliptical surface cracks in finite thickness plates, *Engineering Fracture Mechanics*, vol. 11, pp. 817-829, 1979.
- [57] X. Wang, S. B. Lambert, Stress intensity factors and weight functions for longitudinal semi-elliptical surface cracks in thin pipes, *International Journal of Pressure Vessels and Piping*, vol. 65, no.1, pp. 75-87, 1996.
- [58] C.Q. Li, S.T. Yang, Stress intensity factors for high aspect ratio semi-elliptical internal surface cracks in pipes, *International Journal of Pressure Vessels and Piping*, vol. 96-97, pp. 13-23, 2012.
- [59] W. Wang, W. Yang, C.Q. Lia, S. Yang, A new method to determine elasto-plastic J-integral for steel pipes with longitudinal semi-elliptical surface cracks, *Engineering Failure Analysis*, vol. 118, p. 104915, 2020.
- [60] Y. Lei, J-integral and limit load analysis of semi-elliptical surface cracks in plates under bending, *International Journal of Pressure Vessels and Piping*, vol. 8, pp. 31-41, 2004.
- [61] L. Xu, L. Zhao, H. Jing, Y. Han, Characterization of the creep interaction effect for twin semi elliptical surface cracks under combined tension and bending loading, *Engineering Fracture Mechanics*, vol. 192, pp. 148-162, 2018.
- [62] H.E. Coules, Stress intensity interaction between dissimilar semi-elliptical surface cracks, *International Journal of Pressure Vessels and Piping*, vol. 146, pp. 55-64, 2016.
- [63] R. B. Stonesifer, F. W. Brust and B. N. Leis, Mixed-mode stress intensity factors for interacting semi-elliptical surface cracks in a plate, *Engineering Fracture Mechanics*, vol. 45, no. 3, pp.357-380, 1993.

## References

---

- [64] A.M. Souza Sant Anna, I. N. Bastosc, J.M.A. Rebellod, M.P. Cindra Fonseca, Influence of hydrogenation on residual stresses of pipeline steel welded joints, *Materials Research*, vol. 19, no. 5, pp. 1088-1097, 2016.
- [65] W. Xu, S. Jian, A calculation method for limit load of the gas pipelines with girth weld surface cracks, *Natural Gas Industry B*, vol. 6, no. 5, pp. 481-487, 2019.
- [66] S.W. Hong, J.M. Koo, C.S. Seok, J.W. Kim, J.H. Kim, S.K. Hong, Fatigue life prediction for an API 5L X42 natural gas pipeline, *Engineering Failure Analysis*, vol. 56, pp. 396-402, 2015.
- [67] S. Hertelé, A. Cosham, P. Roovers, Structural integrity of corroded girth welds in vintage steel pipelines, *Engineering Structures*, vol. 124, pp. 429-441, 2016.
- [68] L. Wang, Y. Tang, T. Ma, J. Zhong, Z. Li, Y. Zhang, H. Xuan, Stress concentration analysis of butt welds with variable wall thickness of spanning pipelines caused by additional loads International, *International Journal of Pressure Vessels and Piping.*, vol. 182, p. 104075, 2020.
- [69] J.A. Ronevich, E.J. Song, Z. Feng, Y. Wang, C. D' Elia, M.R. Hill, Fatigue crack growth rates in high pressure hydrogen gas for multiple X100 pipeline welds accounting for crack location and residual stress, *Engineering Fracture Mechanics*, vol. 228, p. 106846, 2020.
- [70] A.A. Abd-Elhady, H. El-Din M. Sallam, M.A. Mubaraki, Failure analysis of composite repaired pipelines with an inclined crack under static internal pressure, *Structura l Integrity Procedia*, vol. 15, p. 123-130, 2017.
- [71] E.F. Issam, A. Fethi, H. Mohamed, A. Furqan, G. Mohamed, N. Mondher, G. Christian, Comprehensive review of natural fibers and their composites: aneco-friendly alternative to conventional materials, *Results in Engineering* 19 (2023)101271.
- [72] A.A. Jamal, R.A. Hawileh, A.B. ahurudeen, G. Jyothsna, A. Sofi, H.S. Vignes, B. S. Thomas, A comprehensive review on the use of natural fibers in cement/geopolymer concrete: a step towards sustainability, *Journal Pre-proof* (2016), <https://doi.org/10.1016/j.cscm.2023.e02244>.
- [73] A. Emmanuel, OI.Sikiru, N. Hom, Dhakal. Review on natural plant fibres and their hybrid composites for structural applications: recent trends and future perspectives, *Composites Part C: Open Access* 9 (2022) 100322, <https://doi.org/10.1016/j.jcomc.2022.100322>.
- [74] S. Velu, J.K. Joseph, M. Sivakumar, V.K. Bupesh Raja, K. Palanikumar, N. Lenin, Experimental investigation on the mechanical properties of carbonglass-jute

## References

---

- fiberreinforced epoxy hybrid composites, *Mater. Today: Proc.* 46 (2021) 3566–3571, <https://doi.org/10.1016/j.matpr.2021.01.333>.
- [75] S. Shweta, K.G. Pankaj, Effect of fiber orientation on mechanical properties of jute/carbon/glass hybrid composite, *Mater. Today: Proc.* 68 (2022) 2574–2580, <https://doi.org/10.1016/j.matpr.2022.09.419>.
- [76] G.S. Mann, N. Azum, A. Khan, M.A. Rub, M.I. Hassan, K. Fatima, A.M. Asiri, Green composites based on animal fiber and their applications for a sustainable future, *Polymers* 15 (2023) 601, <https://doi.org/10.3390/polym15030601>.
- [77] Britannica, The Editors of Encyclopedia. “Natural Fiber”. *Encyclopedia Britannica*, 2023 <https://www.britannica.com/plant/jute-plant>.
- [78] S.V.D. Thapliyal, R.K. Pramita Sen, A. Thakur, A.K. Tiwari, D. Singh, G. D. Verros, R.K. Arya, Natural fibers composites: origin, importance, consumption pattern, and challenges, *Journal of Composites. Science.* 7 (2023) 506, <https://doi.org/10.3390/jcs7120506>.
- [79] Fisher, Charles H, History of natural fibers, *Journal of Macromolecular Science: Part A - Chemistry* Volume 15, 1981 - Issue 7, <https://doi.org/10.1080/00222338108056788>.
- [72] Jamal, A. Abdalla, Rami, A. Hawileh, A Bahurudeen, G Jyothsna, A. Sofi, V. Shanmugam, B.S. Thomas, A comprehensive review on the use of natural fibers in cement/geopolymer concrete: A step towards sustainability, *Case Studies in Construction Materials*, DOI: <https://doi.org/10.1016/j.cscm.2023.e02244>.
- [80] A. Hasan, M.S. Rabbi, Md. M. Billah, Making the Lignocellulosic Fibers Chemically Compatible for Composite: a Comprehensive Review PII: S2772-3976(22)00038-7 DOI: <https://doi.org/10.1016/j.clema.2022.100078>.
- [82] <https://constructionmanagement.co.uk/building-with-hemp-blocks-qa>.
- [83] S.C. Das, A.D. La Rosa, S. Goutianos, S. Grammatikos, Glass fibre hybridization to improve the durability of circular flax fibre reinforced composites with off-the shelf recyclable polymer matrix systems for large scale structural applications, *Composites Part C: Open Access* 14 (2024) 100491, <https://doi.org/10.1016/j.jcomc.2024.100491>.
- [84] S. Rahman, S.C. Das, J. Saha, M.A. Khan, Fabrication and physico-mechanical characterization of short natural/synthetic fiber-reinforced hybrid composites: effects of biodegradation and chemical aging, *Material Circular Economy* (Springer Nature) 6 (14) (2024), <https://doi.org/10.1007/s42824-024-00105-0>.
- [85] S.H. Mahmud, S.C. Das, M.Z.I. Mollah, M.M. Ul-Hoque, K.S. Al-Mugren, M.R.I. Faruque, R.A. Khan, Thermoset-polymer matrix composite materials of jute and glass fibre

## References

---

- reinforcements: radiation effects determination, *J. Mater. Res. Technol.* 26 (2023) 6623–6635, <https://doi.org/10.1016/j.jmrt.2023.08.298>.
- [86] S.C. Das, S. Srivastava, A.D. La Rosa, S. Goutianos, S. Grammatikos, On the response to hygrothermal ageing of fully recyclable flax and glass fibre reinforced polymer composites, *Materials* 16 (17) (2023) 5848, <https://doi.org/10.3390/ma16175848>.
- [87] S.C. Das, A.D. La Rosa, S. Goutianos, S. Grammatikos, Effect of accelerated weathering on the performance of natural fibre reinforced recyclable polymer composites and comparison with conventional composites, *Composites Part C:Open Access (Elsevier)* 12 (IF 4.2) (2023) 100378, <https://doi.org/10.1016/j.jcomc.2023.100378>.
- [88] S.C. Das, et al., Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates, *Compos. Struct.* 276 (2021), <https://doi.org/10.1016/j.compstruct.2021.114525>.
- [89] S.C. Das, D. Paul, M.A. Khan, S.A. Grammatikos, S. Papatzani, A comparative study between jute and glass fiber reinforced composites, *Key Eng. Mater.* 891 (2021) 125–130. <https://dx.doi.org/10.4028/www.scientific.net/KEM.891.125>.
- [90] S.C. Das, A.D. La Rosa, S. Grammatikos, Life cycle assessment (LCA) of plant fibers and their composites, in: *Plant Fibers, Their Composites and Applications*, Elsevier, 2022.
- [91] V. Ramesh, K. Karthik, K. Arunkumar, N.K. Unnam, R. Ganesh, C. Rajkumar, Effect of sawdust filler with Kevlar/basalt fiber on the mechanical properties epoxy-based polymer composite materials, *Mater. Today: Proc.* 72 (2023) 2225–2230.
- [92] I. Ahmed, R.R. Renish, K. Karthik, M. Karthik, Experimental investigation of polymer matrix composite for heat distortion temperature test, *Int. J. Mech. Eng. Technol.* 8 (8) (2017) 520–528.
- [93] K. Karthik, A. Manimaran, Wear behaviour of ceramic particle reinforced hybrid polymer matrix composites, *Int. J. Ambient Energy* 41 (14) (2020) 1608–1612.
- [94] B. Murali, K. Karthik, S.S. Marotrao, G. Laxmaiah, A.S. Yadav, I.S.N.V.R. Prasanth, M. Abbas, Mechanical and dynamic mechanical properties of hybrid kevlar/natural fiber composites, *Mater. Res. Express* 10 (10) (2023) 105305.
- [95] K. Karthik, A. Manimaran, J. Udayaprakash, Experimental investigation of the distortion temperature parameter of polymer matrix composites for solar panel applications, *Int. J. Ambient Energy* 42 (5) (2021) 500–504.
- [96] K. Karthik, A. Manimaran, J.V. Rayudu, D.I.V.A. Sharma, Optimization of the process parameter in drilling of GFRP using HSS drill, *Int. J. Mech. Prod. Eng. Res. Dev.* 7 (6) (2017) 403–408.

## References

---

- [97] S. Rahman, S.C. Das, J. Saha, M.A. Khan, Fabrication and physico-mechanical characterization of short natural/synthetic fiber-reinforced hybrid composites: effects of biodegradation and chemical aging, *Material Circular Economy* (Springer Nature) 6 (14) (2024), <https://doi.org/10.1007/s42824-024-00105-0>.
- [98] S.H. Mahmud, S.C. Das, M.Z.I. Mollah, M.M. Ul-Hoque, K.S. Al-Mugren, M.R.I. Faruque, R.A. Khan, Thermoset-polymer matrix composite materials of jute and glass fibre reinforcements: radiation effects determination, *J. Mater. Res. Technol.* 26 (2023) 6623–6635, <https://doi.org/10.1016/j.jmrt.2023.08.298>.
- [99] K. Karthik, D. Rajamani, T. Raja, K. Subramani, Experimental investigation on the mechanical properties of Carbon/Kevlar fibre reinforced epoxy LY556 composites, *Mater. Today: Proc.* 52 (2022) 668–674.
- [100] S. D. Satyabodh M. Kulkarni, S. Joladarashi, M. Kumar T S, A.K. Gurja, Analysis of light weight natural fiber composites against ballistic impact: A review, *International Journal of Lightweight Materials and Manufacture* Volume 6, Issue 3, September 2023, Pages 450-468. <https://doi.org/10.1016/j.ijlmm.2023.01.003>.
- [101] S. Kumara, R.S. Bharj, Emerging composite material use in current electric vehicle: A review. *Materials Today Proceedings* Volume 5, Issue 14, Part 2, 2018, Pages 27946-27954, <https://doi.org/10.1016/j.matpr.2018.10.034>.
- [102] J. Holbery, D. Houston, Natural-fiber-reinforced polymer composites in automotive applications *JOM*, pp. 80-86; *Low-Cost Composites in Vehicle Manufacture* Volume 58, pages 80–86, (2006). <https://link.springer.com/article/10.1007/s11837-006-0234-2>
- [103] J. Knothe, K. Rebstock, T. Schloesser, Natural fiber reinforced plastics in automotive exterior applications. In: *The 3rd international wood and Natural fiber composites symposium* Kassel, Germany (2000), pp. 1-1.
- [104] V. Feuillade, A. Bergeret, J.-C. Quantin, A. Crespy, Characterisation of glass fibres used in automotive industry for SMC body panels, *Composites Part A: Applied Science and Manufacturing* Volume 37, Issue 10, October 2006, Pages 1536-1544. *Composites Part A: Applied Science and Manufacturing*, <https://doi.org/10.1016/j.compositesa.2005.11.010>.
- [105] B. Priya, V.K. Gupta, D. Pathania, A.S. Singha, Synthesis, characterization and antibacterial activity of biodegradable starch/PVA composite films reinforced with cellulosic fiber *Carbohydr. Polym.*, 109 (2014), pp.
- [106] Kabir, M.A., Huque, M.M., Islam, M.R., Bledzki, A.K., 2010. Mechanical Properties Of Jute Fiber Reinforced Polypropylene Composite; Effect Of Chemical Treatment By Benzenediazonium Salt In Alkaline Medium. *BioResources* 5 (3), 1618–1625.

## References

---

- [107] M. Wasim, S. Shoaib, N.M. Mubarak, A.M. Asiri, Factors influencing corrosion of metal pipes in soils, *Environ.Chem.Lett.* 16 (3) (2018)861–879,<https://doi.org/10.1007/s10311-018-0731-x>.
- [108] J.A. Beavers, N.G. Thompson, External corrosion of pipelines in soil. In: oil and gas pipelines, in: *Corrosion: Environments and Industries* (#05145), 13C, ASM International, USA, 2006. <https://www.asminternational.org/documents/10192/1849770/ACFAB96.pdf>.
- [109] R.A. Ahmed, S. Mostafa, M.M. Mohammad, 3D finite element modeling of in-service sleeve repair welding of gas pipelines, *Int. J. Pres. Ves. Pip.* 146 (2016)216–229.
- [110] China West East Gas Pipeline Company, Successful application of automatic online welding of X80,  $\phi$  1219mm pipe B-type sleeve for the first time in China, in: *China International Pipeline Conference*, Sohu News, 2020.
- [111] D.N.V. Corroded pipelines, Recommended Practice DNV-RP-F101, Det Norske Veritas (DNV), 2010.
- [112] N.R.F. Rohem, L.J. Pacheco, S. Budhe, M.D. Banea, E.M. Sampaio, S. de Barros, Development and qualification of a new polymeric matrix laminated composite for pipe repair, *Compos. Struct.* 152 (2016) 737–745.
- [113] K.S. Lim, S.N. Afifah Azraai, N. Yahaya, N.Md. Noor, L. Zardasti, J.-H. Jay Kim, Behaviour of steel pipelines with composite repairs analysed using experimental and numerical approaches, *Thin-Walled Struct* 139 (2019) 321–333,<https://doi.org/10.1016/j.tws.2019.03.023>.
- [114] J.M. Duell, J.M. Wilson, M.R. Kessler, Analysis of a carbon composite overwrap pipeline repair system, *Int. J. Pres. Ves. Pip.* 85 (2008) 782–788,<https://doi.org/10.1016/j.ijpvp.2008.08.001>.
- [115] C.Q. Li a, S.T. Yang, Stress intensity factors for high aspect ratio semi-elliptical internal surface cracks in pipes, *International Journal of Pressure Vessels and Piping* 96-97 (2012) 13e23.
- [116] S. Strobl, P. Supancic, T. Lube, R. Danzer, Surface crack in tension or in bending – A reassessment of the Newman and Raju formula in respect to fracture toughness measurements in brittle materials, *Journal of the European Ceramic Society* 32 (2012) 1491–1501.
- [117] K. Yuan, Y. Jiang, J. Liu, M. Hong, 2D weight functions of stress intensity factors for high aspect ratio semi-elliptical surface cracks in finite thickness plate, *Theoretical and Applied Fracture Mechanics*.<https://doi.org/10.1016/j.tafmec.2020.102808>.

## References

---

- [118] K.P. Kou, F.M. Burdekin, Stress intensity factors for a wide range of long-deep semi-elliptical surface cracks, partly through-wall cracks and fully through-wall cracks in tubular members. *Engineering Fracture Mechanics* 73 (2006) 1693–1710.
- [119] PK. Chidambaram, A. Buckshumiyam, E. Venkatesh, K. Keyan, Experimental analysis of natural composite material for helical gear, *Materials Today: Proceedings*, <https://doi.org/10.1016/j.matpr.2023.04.020>.
- [120] A. Zareei, S.M. Nabavi, Calculation of stress intensity factors for circumferential semielliptical cracks with high aspect ratio in pipes. *International Journal of Pressure Vessels and Piping* 146 (2016) 32-38.
- [121] M. Imraan, RA. Ilyas, Norfarhana, S.P. Bangar, FK. Victor, Norrahim, Sugar palm (Arengapinnata) fibers: new emerging natural fibre and its relevant properties, treatments and potential applications, *Journal of Materials Research and Technology* 2023 ; 2 4 :4551 e 4572, <https://doi.org/10.1016/j.jmrt.2023.04.056>.
- [122] Z. Messaoud, M. Meriem-Benziane, Experimental study of natural fiber Jute reinforced by metal wires and its using as patch on semi-elliptical defected of the API X52 pipelines corroded according to ratio  $a/t$ , *International Journal of Pressure Vessels and Piping* Volume 212, Part B, December 2024, 105346. <https://doi.org/10.1016/j.ijpvp.2024.105346>.
- [123] E. Escalante, 1988. *Galvanic corrosion*. ASTM International, USA.
- [124] Y. Fan, Chen, C. Zhang, Y. Liu, H. Liu, 2021. Early corrosion behavior of X80 pipeline steel in a simulated soil solution containing Desulfovibrio desulfuricans. *Bioelectric Chemistry* 141, 107880, <https://doi.org/10.1016/j.j>.
- [125] Zhu, J, Xu, L., Feng, Z., Frankel, G.S., Lu, M., Chang, W., 2016. Galvanic corrosion of a welded joint in 3Cr low alloy pipeline steel. *Corrosion Sci.* 111, 391–403. <https://doi.org/10.1016/j.corsci.2016.05.032>.
- [126] Wu K.Y., Mosleh A., Effect of temporal variability of operating parameters in corrosion modelling for natural gas pipelines subject to uniform corrosion. *2019. J. Nat. Gas Sci. Eng.* 69, 102930. <https://doi.org/10.1016/j.jngse.2019.102930>.
- [127] Z.B. Wang, Y.G. Zheng, Critical flow velocity phenomenon in erosion-corrosion of pipelines: determination methods, mechanisms and applications, *J. Pipeline Sci. Eng.* 1 (2021) 63–73.
- [128] G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, J.H. Payer, Corrosion costs and preventive strategies in the United States, Report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Report FHWA-RD-01-156, September, 2001.

## References

---

- [129] C. Wan, A. Mita, Recognition of potential danger to buried pipelines based on sounds, *Struct. Control Hlth.* 17 (2010) 317–337, <https://doi.org/10.1002/stc.302>.
- [130] V. Pandarinathan, K. Lepková, S.I. Bailey, R. Gubner, Impact of mineral deposits on CO<sub>2</sub> corrosion of carbon steel, in: *Proceedings of the Corrosion 2013 NACE International*, Orlando, Florida, USA, 2013 Paper No. 2579 .
- [131] J. Owen, C. Ramsey, R. Barker, A. Neville. Erosion-corrosion interactions of X65 carbon steel in aqueous CO<sub>2</sub> environments. *Wear*, volumes 414–415, 15 November 2018, Pages 37, <https://doi.org/10.1016/j.wear.2018.09.004>.
- [132] H.X. Guo, B.T. Lu, J.L. Luo, Interaction of mechanical and electrochemical factors in erosion-corrosion of carbon steel. *Electrochim Acta* 2005;51:315e23, <https://doi.org/10.1016/j.electacta.2005.04.032>.
- [133] Lu BT, Luo JL. Correlation between surface-hardness degradation and erosion resistance of carbon steel-Effects, *Electrochim Acta*, 53 (2008), pp. 7022-7031, DOI: [10.1016/j.electacta.2008.02.083](https://doi.org/10.1016/j.electacta.2008.02.083).
- [134] Y. Xua, b, Q. Zhang, H. Chen, Y. Huang, Understanding the interaction between erosion and corrosion of pipeline steel in acid solution of different pH, *Journal of Materials Research and Technology* 2023.25/6550E6566. <https://doi.org/10.1016/j.jmrt.2023.07.109>.
- [135] Gao S, Zhou X, Zhao Y, Chen H, Zhang Q, Xu Y. Sand impingements on cathode protection of marine carbon steel in natural sea water. *Corrosion EngSci Technol* 2023;58:12e22 slurry chemistry. *TribolInt* 2015;83:146e55.
- [136] J.R. Vera, D. Daniels, M.H. Achour, Under deposit corrosion (UDC) in the oil and gas industry: a review of mechanisms, testing and mitigation, in: *Proceedings of the Corrosion 2012 NACE International*, Salt Lake City, Utah, USA, 2012, pp. C2012–0001379.
- [137] J. Yang, Z.B. Wang, Y.X. Qiao, Y.G. Zheng, Synergistic effects of deposits and sulfate-reducing bacteria on the corrosion of carbon steel, *Corrosion Science* (2022) 110210, <https://doi.org/10.1016/j.corsci.2022.110210>.
- [138] S. Paise, J.F. Ghiglione, F. Marty, B. Abbas, H. Gueune, J.M.S. Amaya, G. Muyzer, L. Quillet, Sulfate-reducing bacteria inhabiting natural corrosion deposits from marine steel structures, *Appl. Microbiol. Biot.* 97 (2013) 7493–7504.
- [139] P. Kannan, S.S. Su, M.S. Mannan, H. Castaneda, S. Vaddiraju, A review of characterization and quantification tools for microbiologically influenced corrosion in the oil and gas industry: current and future trends, *Ind. Eng. Chem. Res.* 57 (2018).
- [141] M. Meriem-Benziane, Benyebka B., B.G. Nasser Muthanna, Ismail Boudissa, Numerical study of elbow corrosion in the presence of sodium chloride, calcium chloride, naphthenic

## References

---

- acids, and sulfur in crude oil ,Journal of Petroleum Science and Engineering 198 (2021) 108124, <https://doi.org/10.1016/j.petrol.2020.108124>.
- [142] S.K. Kairy, S. Zhou, A. Turnbull, G. Hinds, Corrosion of pipeline steel in dense phase CO<sub>2</sub> containing impurities: A critical review of test methodologies, Corrosion Science 214 (2023) 110986,<https://doi.org/10.1016/j.corsci.2023.110986>.
- [143] Yi Zhou, Fei Xie , Dan Wang, Yuxin Wang, Ming W ,Carbon capture, utilization and storage (CCUS) pipeline steel corrosion failure analysis: A review; <https://doi.org/10.1016/j.engfailanal.2023.107745>.
- [143] JF Kiefner, PH Vieth. A modified criterion for evaluating the remaining strength of corroded pipe; AGA Catalog No. L51609. Final Report on Project PR 3-805, Battelle Memorial Institute, Columbus, OH, 1989, 1989.
- [144] D. Zelmati, O. Bouledroua, Z. Hafsi, M.B. Djukic, Probabilistic analysis of corroded pipeline under localized corrosion defects based on the intelligent inspection tool, Eng. Fail. Anal. 115 (2020) 104683, <https://doi.org/10.1016/j.engfailanal.2020.104683>.
- [146] A.K. Escoe, Piping and Pipelines Assessment Guide, Gulf Professional Publishing, Burlington, MA, 2006, <https://doi.org/10.1016/B978-0-7506-7880-3.X5000-4>.
- [147] D.R. Stephens, B.N. Leis, Development of an alternative criterion for residual strength of corrosion defects in moderate-to high-toughness pipe, in: 3rd International Pipeline Conference, Canada American Society of Mechanical Engineers, Calgary, Alberta, 2000, pp. IPC2000–I2192, <https://doi.org/10.1115/IPC2000-192>. October 1–5, 2000.
- [148] A. Cosham, P. Hopkins, K.A. Macdonald, Best practice for the assessment of defects in pipelines–Corrosion, Eng. Fail. Anal. 14 (7) (2007) 1245–1265, <https://doi.org/10.1016/j.engfailanal.2006.11.035>.
- [149] D. Ritchie, S. Last, Burst criteria of corroded pipelines-defect acceptance criteria. Proceedings of the EPRG/PRC 10th Biennial Joint Technical Meeting on Line Pipe Research, 1995.
- [150] M. Askari, M. Aliofkhaezrai , R. Jafari, P. Hamghalam, A. Hajizadeh, Downhole corrosion inhibitors for oil and gas production – a review, Applied Surface Science Advances 6 (2021) 100128, <https://doi.org/10.1016/j.apsadv.2021.100128>.
- [151] Mohammed H. O. Ahmed , Ahmed A. Al-Amiery, Yasmin K. Al-Majedy , Abdul Amir H. Kadhum, A. Mohamad , Tayser Sumer Gaaz, Synthesis and characterization of a novel organic corrosion inhibitor for mild steel in 1 M hydrochloric acid, Results in Physics 8 (2018) 728–733, <https://doi.org/10.1016/j.rinp.2017.12.039>.

## References

---

- [152] G. Mubarak, C. Verma, Barsoum, A. Alfantazi , KyongYop Rhee, Internal corrosion in oil and gas wells during casings and tubing: Challenges and opportunities of corrosion inhibitors. *Journal of the Taiwan Institute of Chemical Engineers* 150 (2023) 105027,<https://doi.org/10.1016/j.jtice.2023.105027>.
- [153] T. Yan, L.C Xu, Z.X Zeng , Wei-Guo, Mechanism and anti-corrosion measures of carbon dioxide corrosion in CCUS: A review, *iScience* 27, 108594, January 19, 2024/2023,<https://doi.org/10.1016/j.isci.2023.108594>.
- [154] A. H. Khalaf , Y.Xiao, NingXu , B. Wu, H. Li, B. Lin, Z. Nie, J.Tang, Emerging AI technologies for corrosion monitoring in oil and gas industry: A comprehensive review, *Engineering Failure Analysis* 155 (2024) 107735,<https://doi.org/10.1016/j.engfailanal.2023.107735>.
- [155] A. Retnanto<sup>1</sup>, R. Yrac, A. Shaikh<sup>1</sup>, R. Alagha<sup>1</sup>, F. Alsulaiti<sup>1</sup> , T. Chagouri, Experimental evaluation of corrosion inhibitors for completion fluids in the petroleum production systems, *Journal of Petroleum Exploration and Production Technology* (2024) 14:331–342.<https://doi.org/10.1007/s13202-023-01708-0>.
- [156] W.Chaur-Jeng , P. Kusdiyart, Yi-Hong Li, Potentio dynamic polarization analysis with various corrosion inhibitors on A508/IN-182/IN-52M/308L/316L welds, *Kuwait Journal of Science* 51 (2024) 100202,<https://doi.org/10.1016/j.kjs.2024.100202>.
- [157] I. BasseyObot a, A. Ahmad . B.Soroura, Y.C. Malede , T. Chen , Q.Wang, N. Aljeaban, A review study on the challenges and progress of corrosion inhibitor testing under extreme conditions in the oil and gas industries, *Geoenergy Science and Engineering* 226 (2023) 211762,<https://doi.org/10.1016/j.geoen.2023.211762>.
- [158] Z.B. Wang, L. Pang, Y.G. Zheng ,A review on under-deposit corrosion of pipelines in oil and gas fields: Testing methods, corrosion mechanisms and mitigation strategies, *Corrosion Communications* 7 (2022) 70–81, <https://doi.org/10.1016/j.corcom.2022.03.007>.
- [159] A. Farhadian , W. Go, S. Yun, A. Rahimi , M.R. Nabid , DanialIrvani , Y. Seo, Efficient dual-function inhibitors for prevention of gas hydrate formation and CO<sub>2</sub>/H<sub>2</sub>S corrosion inside oil and gas pipelines, *Chemical Engineering Journal* 431 (2022) 134098, <https://doi.org/10.1016/j.cej.2021.134098>.
- [160] T. Chen, C. Huang, L. Hua, X. Song, Experimental study on mixed-mode fatigue behavior of center cracked steel plates repaired with CFRP materials, *Thin-Walled Structures*, vol. 135, pp. 486-493, 2019.<https://doi.org/10.1016/j.tws.2018.11.030>.
- [161] T. Chen, C. Huang, Fatigue tests on edge cracked four-point bend steel specimens repaired by CFRP, *Composite Structures*,<https://doi.org/10.1016/j.compstruct.2019.03.055>.

## References

---

- [162] L.P. Djukic , W.S. Sum, K.H. Leong , W.D. Hillier, T.W. Eccleshall, A.Y.L. Leong, Development of a fiber reinforced polymer composite clamp for metallic pipeline repairs, *Materials & Design*, vol. 70, pp. 68-80, 2015. <https://doi.org/10.1016/j.matdes.2014.12.059>.
- [163] Z. Li, X. Jiang, H. Hopman, L. Zhu, Z. Liu, External surface cracked offshore steel pipes reinforced with composite repairsystem subjected to cyclicbending: An experimental investigation, *Theoretical and Applied Fracture Mechanics*, vol. 109, p. <https://doi.org/10.1016/j.tafmec.2020.102703>.
- [164] E. Mahdi, E. Eltai, Development of cost-effective composite repair system for oil/gas pipelines, *Composite Structures* vol ,202, pp. 802-806, 2018. <https://doi.org/10.1016/j.compstruct.2018.04.025>
- [166]T.D. Williamson Inc. Steel Repair Sleeves; 2007. <http://www.tdwilliamson.com/en/Products/RehabilitationProducts/SteelRepairSleeves/Documents/Steel%20repair%20Sleeve>.
- [167] Md. Shamsuddoha, Md. Islam, T.Aravinthan, Allan Manalo, Kin-tak Lau. Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs, *Composite Structure*, <http://dx.doi.org/10.1016/j.compstruct.2012>.
- [168] X. Li, J. Wang, R. Abbassi, G. Chen , A risk assessment framework considering uncertainty for corrosion-induced natural gas pipeline accidents, *Journal of Loss Prevention in the Process Industries* , <https://doi.org/10.1016/j.jlp.2021.104718>.
- [169]Amr A. Abd-Elhady, Hossam El-Din M. Sallam, Ibrahim M. Alarifi, Rizwan A. Malik, Tarek M.A.A. EL-Bagory, Investigation of fatigue crack propagation in steel pipeline repaired by glass fiber reinforced polymer, *Composite Structures* 242 (2020) 112189, <https://doi.org/10.1016/j.compstruct.2020.112189>.
- [170] H.S.D.C. Mattos, J.M.L. Reis, L.M. Paim, et al., Failure analysis of corroded pipelines reinforced with composite repair systems, *Eng. Fail. Anal.*59 (2016) 223, 223-236. <https://doi.org/10.1016/j.engfailanal.2015.10.007>.
- [171]B.G. Nasser Muthanna, O. Bouledroua, M. Meriem-Benziane, M.R. Setvati, M.B. Djukic, Assessment of corroded API 5L X52 pipe elbow using a modified failure assessment diagram, *International Journal of Pressure Vessels and Piping* 190 (2021) 104291.
- [172] A. Shahzad, S.U. Nasir, S.U, Mechanical Properties of Natural Fiber/Synthetic Fiber Reinforced Polymer Hybrid Composites, Springer International Publishing, Cham, 2017, pp. 355–396, [https://doi.org/10.1007/978-3-319-46610-1\\_15](https://doi.org/10.1007/978-3-319-46610-1_15).

## References

---

- [173] Y. Swolfs, L.Gorbatikh,I.Verpoest, Fiberhybridization in polymer composites, Review,Compos Part A67 (2014) 181–200,<https://doi.org/10.1016/j.compositesa.2014.08.027>.
- [174] S.O. Ismail, E. Akpan, N. Hom, Dhakal, Review on natural plant fibres and their hybrid composites for structural applications: Recent trends and future perspectives, Composites Part C: Open Access 9 (2022) 100322,<https://doi.org/10.1016/j.jcomc.2022.100322>.
- [175] JM. George, M. Kimiaei, M. Elchalakani, S. Fawzia, Experimental and numerical investigation of underwater composite repair with fiber-reinforced polymers in corroded tubular offshore structural members under concentric and eccentric axial loads ,Eng Struct ,2021;227. <https://doi.org/10.1016/j.>
- [176] C. Dong. Flexural behavior of carbon and glass reinforced hybrid composite pipes. Compos.Part C Open Access, vol. 4, no. ISSN 2666-3597, p. 100090, 2021, [doi: 10.1016/j.jcomc.2020.100090](https://doi.org/10.1016/j.jcomc.2020.100090).
- [177] C. Dong. Optimal design of carbon and glass reinforced hybrid composite pipes under flexural loading. Forces Mech., vol. 2, no. ISSN 2666-3597, p. 100003, 2021, [doi: 10.1016/j.finmec.2020.100003](https://doi.org/10.1016/j.finmec.2020.100003).
- [178] T. Zhang, W. Zhao, T. Li, Y. Zhao, Q. Deng, Y. Wang,W. Jiang, Comparison of hydrogen embrittlementsusceptibility of threecathodic protected ubsea pipeline steels from a point of view of hydrogen permeation, Corrosion Science 131 (2018) 104–115, <https://doi.org/10.1016/j.corsci.2017.11.013>.
- [179] Y.D. Han, R.Z. Wang, H. Wang, L.Y. Xu , Hydrogenembrittlementsensitivity of X100 pipeline steelunderdifferentpre-strain, International journal of hydrogenenergy 44 ( 2019) 22380-22393.
- [180] J.J. Hoyos, M. Masoumi, V.F. Pereira, A.P. Tschiptschin,M.T.P. Paes f, J.A. Avila g, Influence of hydrogen on the microstructure and fracture toughness of friction stirwelded plates of API 5L X80 pipeline steel, International journal of hydrogenenergy44 (2019) 23458-23471,[DOI:10.1016/j.ijhydene.2019.06.210](https://doi.org/10.1016/j.ijhydene.2019.06.210).
- [181] A.A. Khalili Tabas, B. Beidokhti, A.R. Kiani-Rashid, Comprehensivestudy on hydrogen in duced cracking of electrical resistancewelded API X52pipeline steel, International journal of hydrogen energy 46(2021)1012-1022.<https://doi.org/10.1016/j.ijhydene.2020.09.219>.
- [182 ] T.T. Nguyen, J. Park, WooSikKim, S.H. Nahm, U.B. Beak, Effect of low partial hydrogen in a mixture with methane on the mechanicalproperties of X70 pipeline steel,

## References

---

international journal of hydrogenenergy 45 (2020)2368-2381,<https://doi.org/10.1016/j.ijhydene.2019.11.013>.

[183] ASTM A370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products 1. ASTM International, PA 19428-2959. United States.

[184] M. Meriem-Benziane, A. Sabah, A. Wahab, H. Zahloul, B. Babaziane, M. Hadj-Meliani, G. Pluvillage, Finite element analysis of the integrity of an API X65 pipeline with a longitudinal crack repaired with single- and double-bonded composites, *Composites Part B* 77 (2015) 431e439,<https://doi.org/10.1016/j.compositesb.2015.03.008>.

[185] P. Dai, Y. Wang, S. Li, Sh. Lu, Guangjie Feng, D. Deng, FEM analysis of residual stress induced by repair welding in SUS304 stainless steel pipe butt-welded joint, *Journal of Manufacturing Processes* 58 (2020) 975–983,<https://doi.org/10.1016/j.jmapro.2020.09.006>.

[186] A. Manai, A framework to assess and repair pre-fatigued welded steel structures by TIG dressing, *Engineering Failure Analysis* 118(2020)104923,<https://doi.org/10.1016/j.engfailanal.2020.104923>.

[187] A. Blanco, J.M. Hallen, T.S. Nguyen, Tu Le Manh, Influence of crystallographic texture on susceptibility to stress corrosion cracking mechanism of API 5L X52 steel for sour service, *Engineering Failure Analysis* 119 (2021) 105002.

[188] T.A. Netto, U.S. Ferraz, S.F. Estefen, The effect of corrosion defects on the burst pressure of pipelines, *Journal of Constructional Steel Research* 61 (2005) 1185–120,<https://doi.org/10.1016/j.jcsr.2005.02.010>.

[189] S.G. M. Chiodo, C. Ruggieri, Failure assessments of corroded pipelines with axial defects using stress-based criteria: Numerical studies and verification analyses, *International Journal of Pressure Vessels and Piping* 86 (2009) 164–176,<https://doi.org/10.1016/j.ijpvp.2008.11.011>.

[190] S. K. Sharma, S. Maheshwari, A review on welding of high strength oil and gas pipeline steels, *Journal of Natural Gas Science and Engineering* 38 (2017) 203-217,<https://doi.org/10.1016/j.jngse.2016.12.039>.

[191] Thüroff, R. Fick b, R. Honke, Factor analysis for stiffness and strength of fully biogenic and biodegradable jute-soy protein composites, *Industrial Crops & Products* 201 (2023) 116920, <https://doi.org/10.1016/j.indcrop.2023.116920>.

[192] J. A. Cottrell, M. Ali, A. Tatari, D. B. Martinson, Effects of Fibre Moisture Content on the Mechanical Properties of Jute Reinforced Compressed Earth Composites, *Construction and Building Materials* 373 (2023) 130848,<https://doi.org/10.1016/j.conbuildmat.2023.130848>.

## References

---

- [193] ASTM D3039, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, USA, 2008.
- [194] ASTM D790-17, Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, ASTM International, 2014. West Conshohocken, PA.
- [195] S.C. Das, A.D. La Rosa, S. Goutianos, S. Grammatikos, Hybridation de fibres de verre pour améliorer la durabilité des composites renforcés de fibres de lin circulaires avec des systèmes de matrice polymère recyclables disponibles dans le commerce pour des applications structurelles.
- [196] S.C. Das, S. Ashek-E-Khoda, M.A. Sayeed, D. Paul, S.A. Dhar, S.A. Grammatikos, On the use of wood charcoal filler to improve the properties of natural fiber reinforced polymer composites, *Mater. Today Proc.* 44 (2021) 926e9, <https://doi.org/10.1016/j.matpr.2020.10.808>.
- [197] M.P.M. Dicker, P.F. Duckworth, A.B. Baker, G. Francois, M.K. Hazzard, P. M. Weaver, Green composites: a review of material attributes and complementary applications, *Compos. Part a-Applied Sci. Manuf.* 56 (2014) 280–289, <https://doi.org/10.1016/j.compositesa.2013.10.014>.
- [198] V. Binaz, Navneet Arora, Inderdeep Singh, Selection of natural fiber for sustainable composites using hybrid multi criteria decision making techniques, *Aditi Mahajan, Composites Part 7* (2022), <https://doi.org/10.1016/j.jcomc.2021.100224>.
- [199] S. Senthilrajan, Venkateshwaran N, Naresh K, Velmurugan R, Gupta NK., Effects of jute fiber length and weight percentage on quasi-static flexural and dynamic mechanical properties of jute/polyester composites for thin-walled structure applications, *Thin-Walled Structures* 179 (2022) 109719, <https://doi.org/10.1016/j.tws.2022.109719>.
- [200] M. Dhinesh Kumar, C. Senthamarai Kannan, S. Jayasrinivasan, S. Aushwin, Study on static and dynamic behavior of jute/sisal fiber reinforced epoxy Composites, *Materials Today: Proceedings* 46 (2021) 9425–9428, <https://doi.org/10.1016/j.matpr.2020.03.064>.
- [201] K.C. Chaturvedi, H.C. Chittappa, Study of tensile nature of jute hybrid composite by the variation of S-glass fibers- an outlook from experimental perspective, *Materials Today: Proceedings* 46 (2021) 2783–2786, <https://doi.org/10.1016/j.matpr.2021.02.593>.
- [202] Dayalen P, Shahul Hameed EA, Thangarasan VS, Arun D, Arul MMA. Investigation on the influence of fiber loading on the tensile behavior of Glass/Jute hybrid composites using ANSYS 17.1, *Materials Today: Proceedings* 68 (2022) 1968–1974, <https://doi.org/10.1016/j.matpr.2022.08.225>.

## References

---

- [203] D.B. Dittenber, H.V. GangaRao, Critical review of recent publications on use of natural composites in infrastructure, *Compos. Appl. Sci. Manuf.* 43 (8) (2012) 1419–1429, <https://doi.org/10.1016/j.compositesa.2011.11.019>.
- [204] S. Shetty Manjunath Pattan, J. Bipin, S.C. Sajjan, Experimental study on mechanical properties of hybrid composite material, *Int. J. Eng. Res. Technol.* (2019) 2278–2279, <https://www.ijert.org/research/experimental-study-on-mechanical-properties-of-hybrid-composite-material-IJERTCONV7IS07003.pdf>
- [205] Y K Muhammad, R Ansari, Zia UA, Muhammad FS, A Hassan, Muhammad AN. Tensile strength evaluation of glass/jute fibers reinforced composites: An experimental and numerical approach *Results in Engineering* 10 (2021) 100232, <https://doi.org/10.1016/j.rineng.2021.100232>.
- [206] K Madhavi, GN Vinay, D MV Renuka, SM Basutkar, Shear behavior of brick masonry strengthened with jute fiber reinforced composite, *Materials Today: Proceedings* 46 (2021) 4746–4751, <https://doi.org/10.1016/j.matpr.2020.10.307>.
- [207] ISO 16120-2-4:2017(E), Non-alloy Steel Wire Rod for Conversion to Wire- Part 2 and 4 international standard ISO 16120, 2017.