COMPUTATIONAL AND EXPERIMENTAL ANALYSIS OF NICKEL CHROMIUM METALLIC COATING IN DEEP SEA STRUCTURES.

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COMPUTATIONAL AND EXPERIMENTAL ANALYSIS OF NICKEL CHROMIUM METALLIC COATING IN DEEP SEA STRUCTURES.

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Master of Technology Pipeline Engineering

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BONAFIDE CERTIFICATE

This is to certify that the work in this thesis titled "**Computational and Experimental analysis of Nickel Chromium Metallic Coating in Deep Sea Structures**" has been carried out by **Ajay Balachandran** under my supervision and has not been submitted elsewhere for a degree.

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Abstract:

The Oil and Gas industries are expanding their reach to the harshest environments around the globe. These expansions are performed with the help of expensive equipment's which are supposed to be used for the maximum number of years. Offshore barges, pipelines, jack up rigs and unmanned subsea vehicles are some of the equipment that requires long term protection from the corrosive environment. Polymer coatings and surface paints are mainly used for asset protection due to their low cost and significant operational life. This thesis deals with the theoretical and experimental testing of Nickel Chromium as metallic coating for asset protection. Due to the higher cost of pipeline and subsea raw materials the specimens where made from low cost medium carbon steel EN8 also known as AISI 1040 Oil quenched steel. The specimens were then machined as per ASTM standards for tensile testing and impact testing. The corrosion was induced by immersing the specimens in 5% Sodium chloride Solution for a period of 96 hours. The corrosion rate is determined by the metal loss occurred during the immersion period. The results obtained from the experimental testing were used as input for theoretical testing in ansys. The simulations were performed with temperatures and pressure of deep sea conditions. Based upon theoretical and experimental testing it was determined that Nickel Chromium protected the bare material and increased the mechanical properties in a significant manner.

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Nomenclature:

Nacl	Sodium Chloride
CR	Corrosion Rate
K	Corrosion rate constant
I	Current in coulombs per second
w	weight of plated metal in grams
t	time in seconds
A	Atomic weight of metal in grams per mole
n	Valence of dissolved metal in grams per mole
F	Faradays constant in coulombs
u_d	Distortion energy per unit volume
σ_1	Stress in x axis
σ_2	Stress in y axis
σ_3	Stress in z axis
TSA	Thermally Sprayed Aluminum
BS	British standard
HPCC	High Performance composite
FBE	Fusion Bond Epoxy
AISI	American Iron and Steel institute
ASTM	American society of testing materials
ISO	International Standards Organization
ASME	American society of mechanical engineers
KN	Kilo Newton
Mpa	Mega Pascal

1. INTRODUCTION

Most of the Oil and Gas structures are located in the world's harshest environments which includes deep waters. Corrosion is one of the significant components that reduce the operational life of these structures. Over the years major oil and gas industries expand their territories into deepest part of the ocean and they depend upon polymer coatings such as fusion bond epoxy, polyethylene, and polyurethane, high density polyethylene for protecting the structures. These polymers being low cost with service temperature ranging from 110˚C to -45˚C [1] are one of the foremost reasons of acceptance. Metallic coating then again increment the wear resistance, toughness, heat resistance and corrosion resistance of bare material [2]. This project involves in the computational and experimental analysis of Nickel Chromium for external protection of subsea structures in order to increase the operational life.

1.1 CORROSION OF METALS

Corrosion could be defined as the destruction of a material due to the interactions between the environment and the material. These interactions maybe due to the presence of chemical, electrochemical or metallurgical interactions between the elements. Billions of dollars are spent each year on corrosion research and prevention. It is a complex problem about which a great deal is known yet despite extensive research and experimentation there is still a lot to learn. At the point where the metals are fabricated they destabilized from their original energy level and transformed into higher levels to obtain the required properties. Corrosion occurs when these metals try to return to their original energy level [3] .

1.2 ELECTROCHEMICAL PRINCIPLES

Corrosion is essentially an electrochemical process resulting in part or all the metal being transformed from metallic to the ionic state. Corrosion requires flow of electricity between certain areas of the metal surface through electrolyte. The electrolyte may be plain water, saltwater or corrosive sums. To complete the electric circuit there must be two electrodes an anode and a cathode and they must be connected. The electrodes may be two different kinds of metals or they may be different areas on the same piece of metal. The connection between the anode and cathode may be by metallic bridge or by simple contact [3]. The electrolyte used in this thesis is 5% Nacl solution.

1.3 FACTORS INFLUENCING CORROSION

One of the most important factors contributing to corrosion is the change in energy level when converted from its oxide forms to its metallic form. Table 1.1 provides an electromotive series for a number of metals and alloys in sea water moving at high velocity [3].

Table 1.1 Galvanic series of Metals and Alloys in Sea Water

Anodic (Corroded) End
Magnesium
Zinc
Aluminum
Cadmium
Aluminum Alloy
Low steel
Alloy steel
Cast Iron
Stainless steel
Muntz metal
Yellow brass
Aluminum Brass
Red Brass
Copper
Aluminum bronze
Copper Nickel Alloys
Monel
Nickel
Inconel
Silver
Titanium
Gold
Platinum

In any couple the metal near the top of the series will be anodic and suffer corrosion while the metal nearer the bottom will be cathodic and receive some galvanic protection. The difference in electrical potential between the two metals is related to distance between them in the galvanic series. The removal of metallic ion by the formation of an insoluble compound which precipitates on the anode result in the formation of an oxide film thus forming insulation and preventing corrosion. These types of films are formed on aluminum and chromium coatings thus resulting in superior corrosion resistance [3].

Moreover the higher the availability of the oxygen to the metal surface, the higher the potential rate of corrosion. Oxygen access to a bare metal surface increases as the temperature of the water decreases or as the flow rate over the surface increases [4]. Therefore pipelines are at the highest risk of corrosion in cold water moving at high velocity.

1.4 SPECIFIC CORROSION TYPES

Specific corrosion descriptions are generally used for certain types of industrially important corrosion. When the entire face of the metal is attacked to the same degree it is known as *uniform corrosion.* This type is unusual in metals since they are rarely so homogeneous that the surface will be evenly corroded [3]. *Pitting Corrosion* is an example of nonuniform corrosion resulting from in homogeneities in metal due to inclusions, coring and distorted zones. These inn homogeneities set up differences of potential at localized spots to cause deep isolated holes [3]. *Cavitation corrosion* is caused by the collapse of bubbles and cavities within a liquid. Vibrating motion between a surface and liquid is such that repeated loads are applied to the surface causing high stresses when these bubbles form and collapse on a regular basis. [3]. *Crevice corrosion* is a universal term including accelerated attack at the junction of two metals exposed to a corrosive environment. *Fretting corrosion* is a common type of surface damage produced by vibration which results in striking or rubbing at the interface of close fitting highly loaded surface [3]. *Intergranular corrosion* could be defined as an example of nonuniform corrosion when a potential difference exits between the grain boundaries and the rest of the alloy. *Stress corrosion* is acceleration of corrosion in certain environments when metals are externally stressed or contains internal tensile stress due to cold working [3]. *Preferential corrosion* occurs in single phase solid solution alloys. Dezincification in brass is an example of this kind of corrosion. *Galvanic corrosion* occurs at the interface where two metals are in contact in a corroding medium. *Anaerobic corrosion* occurs in subsea pipelines due to the sulfate reducing microorganisms. These microorganisms produce organic sediments containing high concentrations of organic acids that can dissociate near the pipe to form hydrogen ions that act as cathodic reactants to remove electrons and form hydrogen gas [4] . The corrosion rates due to these bacteria's are sufficiently high to perforate a pipeline within 5 to 6 years [4].

The corrosion rate can be obtained by determining of weight loss

$$\text{Corrosion rate (CR) in mm per year}$$

$$= \frac{weight\ loss\ in\ grams\ * K}{Alloy\ density \frac{g}{cm^2} * exposed\ area\ in\ cm^2 * \ Exposure\ time\ in\ hr}$$

The constant k= 8.76 x 10^4

1.5 METHODS FOR COMBATING CORROSION

Many methods are used industrially to prevent corrosion by selection of proper alloy and structure or by surface protection of given material. The most important types are

- Use of high-purity metals
- Use of alloy additions
- Use of special heat treatments
- Proper design
- Cathodic protection
- Use of inhibitors
- Surface coatings

In most cases the use of high purity metals tends to reduce pitting corrosion by minimizing in homogeneities thereby improving corrosion resistance. Surface coating includes paints, salt, oxide films and metallic coatings. Paint provides a protective film to the metal and is effective only as long as the film is unbroken. Salt and oxide films are obtained by reacting the metal with a solution which produces the anticipated film. Metallic coatings may be acquired by an assortment of methods such as metallizing, hot dipping, electroplating, diffusion and cladding [3].

1.5.1 ELECTROPLATING

Electroplating is done in industries for corrosion protection, wear resistance, high electrical conductivity and toughness. The metals most commonly used for plating are chromium, nickel and rhodium [3].Electroplating is an electrolytic process for depositing a layer of metal upon a substrate to enhance the appearance or properties of the component. Electroplating is a form of electrodeposition [2]. The basic process of electroplating essentially involves in passing electric current between two electrodes immersed in electrolyte. The positively charged electrode is known as the anode and the negatively charged electrode is known as cathode. When an electrical potential or voltage is applied between the electrodes these ions migrate towards the electrode with the opposite charge – positively charged ions to the cathode and negatively charged ions to the anode. These outcomes in the exchange of electrons, that is a current flow, between the electrodes thus completing the electrical circuit [2].

Electroplating depends upon Faraday’s law which states the relationship between current, time and rate of material deposition. The weight of the metal deposition can be calculated based upon the formula [2].

$$W = \frac{I * t * A}{n * F}$$

Where:

W= Weight of the plated metal in grams
I= Current in coulombs per second
t= Time in seconds
A= Atomic weight of metal in grams per mole
n= valence of the dissolved metal in grams per mole
F= Faraday’s constant in coulombs per equivalent F= 96,485.309 coulombs/equivalent

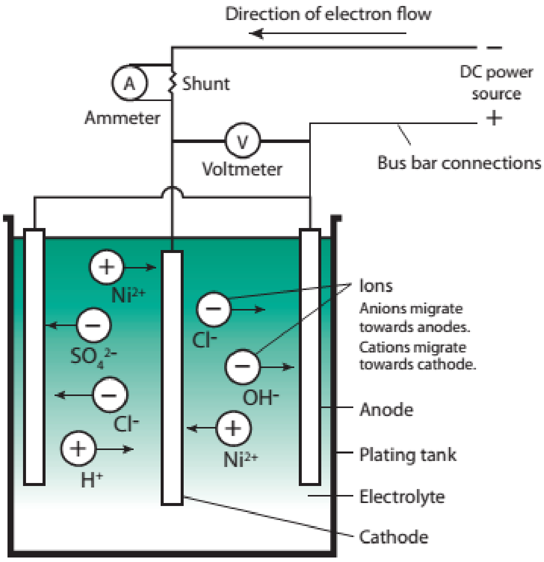


Figure 1.1 Process of Electroplating

1.6 MECHANICAL PROPERTIES

1.6.1 HARDNESS

The property of hardness is difficult to define except in relation to the particular test used to determine its value. It should be noted that a hardness number or value cannot be utilized directly in design, as can a tensile strength value, since hardness numbers have no intrinsic significance [5]. Hardness is not a fundamental property of a material but can be associated with elastic and plastic characteristics. The hardness values obtained in a particular test serves only as a comparison between materials and treatment's. The test Strategy and sample arrangement and sample preparation are usually simple and the results may be used in estimating other mechanical properties [5].

Hardness tests are performed as a part of quality control and inspection. It can be determined that hardness values would change while the specimen is being heat treated or being cold worked or hot worked. It bears a fast and basic means of inspection and control for the particular material and process. The various hardness tests may be divided into three categories [5].

- Elastic hardness
- Resistance to cutting or abrasion
- Resistance to indentation

The hardness in the project was determined based upon *Rockwell Hardness Test*. The test uses a direct- reading instrument based upon the principle of differential depth measurement. The test is performed by gradually raising the specimen against the indenter until a fixed minor load is applied. The major load is applied by the lever and removed when the needle in the dial gauge remains constant [5].

1.6.2 STRESS AND STRAIN

When an external force is applied to a body which tends to change in its size or shape, the body resists the external force. The internal resistance of the body is known as stress and accompanying changes in the dimensions of the body are called strain [5]. The total stress is the total internal resistance acting on the section of the body. The stress and strain of a specimen are determined by tensile testing. The *Universal Testing Machines* are used perform these tests. A specially prepared specimen is prepared and placed in the machine and by the application if axial hydraulic or mechanical loading system the values are calculated. The force is indicated on a calibrated dial and if the original cross sectional area is know the stress developed in any load can be calculated [5]. Use of heating and cold chambers helps many metallurgists to determine the variation of properties at varying temperatures. The tensile testing specimens are prepared based upon ASTM E8 Standard.

Proportional Limit is found for many structural materials in the early part of the stress-strain graph. In this range the stress and strain are directly proportional to each other so that the increase in stress increases the strain [5].

Elastic Limit can be defined as the minimum stress above which the deformation in material is permanent [5].

Yield Point could be point above which the material continues to deform without a rise in load. The stress could essentially increase or decrease momentarily resulting in upper and lower yield point [5].

Yield Strength is mainly defined for most nonferrous materials and high strength steels that do not consist a suitable yield point. [5].

Ultimate Strength or *Tensile Strength* is the maximum stress developed by the material based upon the original cross section area. A brittle material breaks when stressed to the ultimate strength whereas the ductile material continuous to stretch [5].

Breaking Strength can be determined as the ratio of braking load by the original cross sectional area. It is always less than the ultimate tensile strength. For a brittle material the ultimate strength and breaking strength coincide [5].

Elongation can be determined by assembling the fractures pieces in such a manner that we can determine the final gauge length base on its original gauge marks [5].

$$Elongation\ \% = \frac{L_f - L_o}{Lo} * 100$$

Where

L_f= final gauge length in mm

L_o= Original gauge length in mm

Modulus of Elasticity or *Young's Modulus* is an indication of the stiffness of a material. It is an important engineering property and is commonly used while dealing with beams and columns [5].

Impact Testing is done to determine the toughness of the specimen. Generally notch type specimens are used for impact tests prepared based upon ASTM E23. The impact specimen has a swinging pendulum of fixed weight which is raised to a standard height depending upon the type of the specimen. The charpy specimen will be striked behind the v-notch facing the pendulum. The force produced by the pendulum will be used to rupture the specimen so that the pendulum will rise to a height lower than the initial height on the opposite side of the specimen [5].

1.7 FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) could be defined as a numerical method to solve engineering and mathematical physics complications. They are used in the circumstance complicated geometries, use of material properties and test environments where analytical solution cannot be obtained. FEA mainly came into existence from the aerospace industry [6] where there was a requirement of light weight structures and accurate analysis [6]. Finite element analysis mainly depends upon Von Mises Stress which determines the failure point [7]. When the Von Mises stress is greater than the yield strength the material and the design tends to fail [7].

The term Von Mises Stress is derived from the concept of *Distortion Energy Failure Theory* which is a comparison between distortion energy in the actual case and distortion energy in a simple tension case at the time of failure [7]. The Distortion energy required per unit volume u_d for general 3 dimensional cases is given in terms of principle stress value as [7]

$$u_d = \frac{1+v}{3E}\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]$$

The Distortion Energy theory for a unidirectional case of tension at the time of failure can be determined by

$$u_d = \frac{1+v}{3E}\sigma_y^2$$

If the value of u_d is greater than σ_y ie yield strength of the material then failure occurs. The specimen is modeled in SOLIDWORKS and static analysis is performed in ANSYS Workbench. The simulations are performed with subsea conditions with varying temperature and external pressure.

2. LITERATURE REVIEW

Wolfson et al [8] have documented the operating performance of thermal sprayed aluminum (TSA) coatings in seawater environments. Based on the research of Wolfson and team the performance of these coatings in saline muds has not been previously quantified. These types of data are required for projects involving subsea piping systems. Four- and twelve month exposure tests were conducted in natural Gulf of Mexico sea mud, and the performance of the metallic coatings enumerated in terms of their ability to adequately cathodically protect various amounts of uncoated steel. Performance has been further computed by determining their corrosion rate and corresponding life in these environments [8]. More over an North American based Metal coating establishment have started using Thermal sprayed zinc for subsea conditions for the purpose of pipeline protection [9].

Zinc is one of the most commonly used metallic coatings. Hot dipping, metal spraying or electrodeposition is some of the commonly used techniques for coating zinc on a substrate material. They provide good corrosion resistance when used in most environments particularly when used in the combination of chromate or phosphate [10]. Zinc provides good protection for steel in atmospheric conditions and in the presence of Sulphur contamination, in the case of oceanic, chloride environments zinc coatings are less effective [10]. Zinc is an ideal coating for steel used under immersed conditions in scale forming waters or sea waters since it is less toxic than cadmium when being used during welding. The life of zinc coatings is generally proportional to thickness and independent of the method of application.

Nickel has an inherently high corrosion resistance particularly in chloride free atmosphere and is widely used as a coating material in the chemical industry [10]. When exposed to the atmosphere rapid tarnishing and slow superficial corrosion occurs for this reason nickel coatings are seldom used alone but they are widely used as undercoats beneath chromium to give decorative and protective schemes for steel, zinc alloy and copper alloy [10]. The corrosion of nickel undercoat is confined to localized pitting which develops as discontinuities in the chromium layer and which will eventually penetrate to the substrate. Many special processing variations have been developed to improve these composite coatings and recommended systems are detailed in standards documents such as BS 1224, 1970 [10].

Copper is seldom used as coating material in its own right to the rapidity with which it tarnishes particularly in Sulphur polluted environments. Its atmospheric corrosion resistance is good owing to the development of the well-known green patina of basic copper salts which gives protection against further corrosion of metal. Copper coatings are used for their decorative effect at the high lusture and distinctive color are retained by applying a protective coating of transparent lacquer which may contain an inhibitor. Copper by far are used as under coats for other protective schemes such as nickel chromium systems where they offer great benefit by leveling the surface so as to improve the brightness of the finished specimen [10].

Chromium is highly resistant to atmospheric corrosion, being almost inert in most atmospheres and it’s therefore used as thin bright overlay to other coatings to retain decorative appeal for long periods. The thickness of these coatings applied by electrodeposition is normally in the range of 0.3 -0.2μm. In the lower thickness range the coating contains minute discontinuities which cannot eliminate by increasing the thickness, since spontaneous cracking of the deposit occurs as the thickness builds up. The tendency to cracking of chromium electrodeposits is encourages and put to good use by inducing cracking on a micro scale by processing revisions. When this is performed the micro cracked deposits so produced provide greater protection to nickel plated steel and zinc alloy substrates exposed to the atmosphere by increasing the area of nickel exposed at the micro discontinuities and so reducing the corrosion current density at individual corrosion sites with a consequent reduction in rate of penetration through nickel layer [10]. Chromium is also a very hard metal with excellent wear resistance and so is widely used as coating material for engineering applications. For these purposes coatings are applied by electro deposition which may be several millimeters thick. These hard engineering chromium coatings invariably contain fine cracks and fissures which can allow corrodents to attack the substrate but this is not often a hazard in service and in many cases they are advantageous in providing a means of retaining lubricants on the working surface during use [10].

The Oil & Gas Industry is currently working on High Performance Composite Coating system (HPCC), a single layer all powder coated multi component coating system consisting of a Fusion Bond Epoxy (FBE) base coat a medium density polyethylene outer coat and a tie layer containing a chemically modified polyethylene adhesive [11]. All materials of the three components of the composite coating are applied using an electrostatic powder coating process. The tie layer is an amalgam of adhesive and FBE with a gradation of FBE concentration. Thus, there is no sharp and well-defined interface between the tie layer and either of the FBE base coat or the polyethylene external coat. The adhesive and polyethylene are alike to each other and intermingle easily to disperse any boundary. The coatings are consequently interconnected and behave as a single layer coating system without the risk of delamination. The model has been a performance issue with some three layer polyethylene coatings, principally under repeated conditions. Being a single layer coating and thinner, the HPCC will have less internal stress development when subjected to large temperature changes [11].

3. THEORETICAL DEVELOPMENT

The Oil and Gas industry majorly relies on the use of polymer coatings and surface paintings for its asset protection. This proposal mainly deals with exhausting metallic coatings to reduce the corrosion rate as well as to increase the operational life to a great extent. As the days are progressing vast amounts of Oil and Gas reserves are found on the harshest environments which include extreme pressures and temperatures. As we proceed under water the pressure increases with depth and water density [12].Based upon the economic consideration of the project the material is chosen as AISI 1040 EN8 a medium carbon steel.

Table 3. 1 AISI 1040 Oil Quenched steel Material Composition and Mechanical Properties

COMPONENT	PERCENTAGE
Carbon	0.37-0.44
Iron	98.6-99
Manganese	0.60-0.90
Phosphorous	<=0.040
Sulphur	<=0.050
Density	7.845g/cc
Ultimate Tensile Strength	571Mpa
Yield Strength	360Mpa
Modulus of Elasticity	200Gpa
Bulk Modulus	160Gpa
Poisson Ratio	0.29

The EN8 Specimen was machined with respect to ASTM E8 standard for tensile testing and ASTM E23 for Impact testing. The raw material in the form of billets where then machined to the required specifications. The replication was done by designing a 4 Inch pipeline i.e. 114.3 mm pipeline with a thickness of 5.56mm.

The temperature at a particular depth of water can be determined based upon the surface temperature of the sea [12].

$$\text{Temperature at a Particular depth in }^{\circ}\mathrm{C} = \frac{Surface\ Temperature\ in\ ^{\circ}\mathrm{C}}{(1.84 * 10^{-4} * Surface\ Temperature\ ^{\circ}\mathrm{C} * Depth\ in\ m) + 1}$$

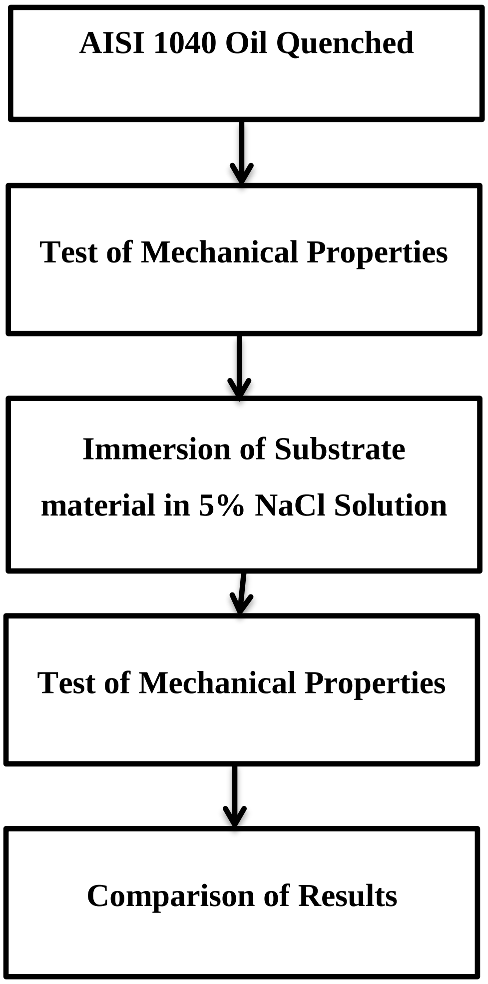


Figure 3. 1 Process Work Flow

The machined specimen was tested for its mechanical properties with the help of Universal Testing Machine. The yield strength was determined using 0.2% offset method. The Tensile strength can be determined by dividing the maximum load by the crossectional area. The impact energy of the bare material is determined by Impact test. The specimens are then electroplated with 10 Microns of Nickel and 10 Microns of chromium as per ISO 1456:2009.

In order to determine the corrosion rate the specimens are immersed in 5% Nacl solution [13]. Based upon the weight loss and density of the material the corrosion rate is determined in mm per year. After determining the corrosion rate the coated specimen is tested for its mechanical properties and compared with the results of the bare material.

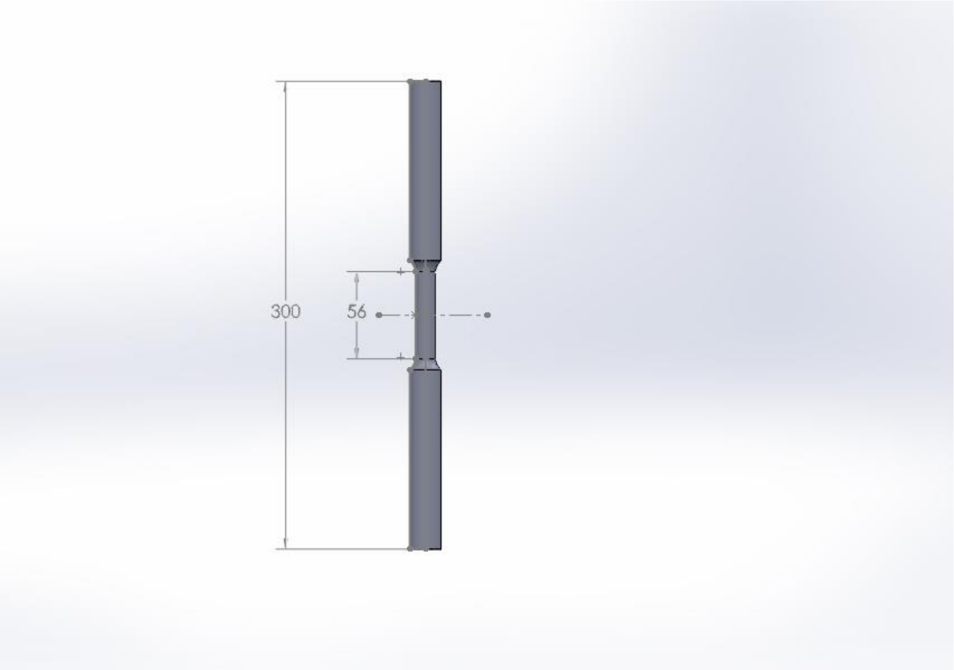


Figure 3. 2 Tensile Test Specimen as Per ASTM E8

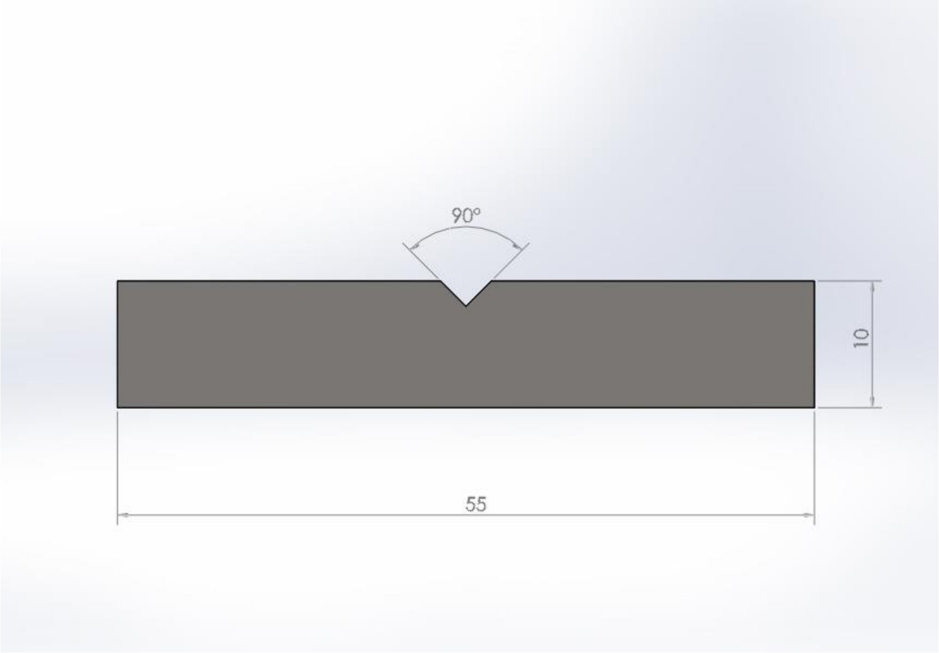


Figure 3. 3 Charpy Specimen as Per ASTM E23

The experimental results are fed into ANSYS and analyzed for deep sea temperature and pressure. A 4 inch pipeline designed as per ASME B36.10 is used for finite element analysis. Due to its hollow structure the deviation of yield strength can be easily determined.

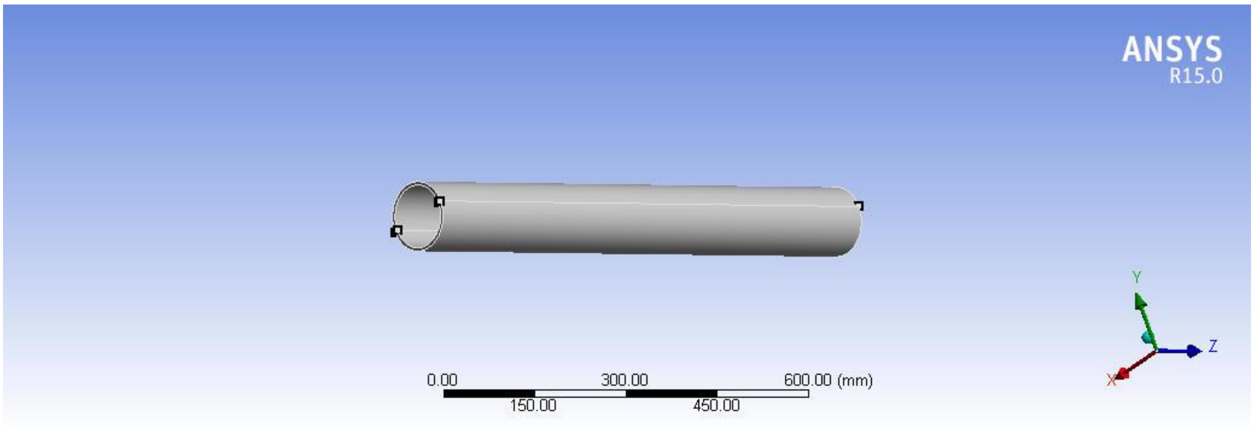


Figure 3. 4 Finite Element Analysis Model

The model is then preprocessed with its fixtures, loads and pressures. The material properties are entered into the system based upon the experimental testing results. Based upon the system processing speed the mesh size is selected.

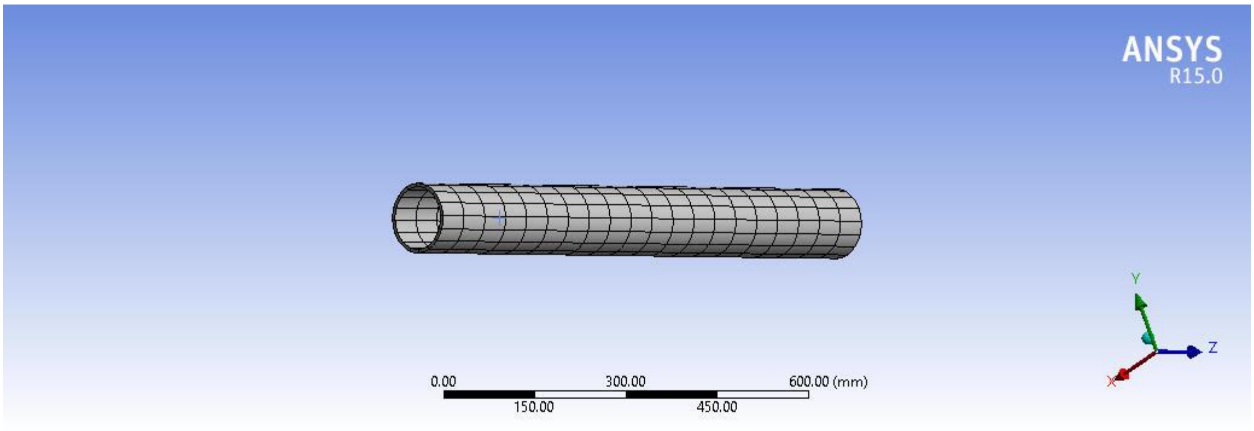


Figure 3. 5 FEM Meshing

After solving the conditions the stress, strain and deformation in each unit of the mesh is calculated and the stress values are displayed and as per the energy distortion theory we can determine when the base material fails. Similarly the pipe specimen is applied the coatings effects and investigation is done. The consequences are then compared.

4. EXPERIMENTAL AND COMPUTATIONAL PROCEDURE

The Experimental procedure was performed in a 400KN Universal Testing Machine with specimens each with an average length of 300mm and average gauge length of 56mm. The Diameter of the specimen varies from 11.56mm to 12.5mm. The impact test was performed with specimens of dimensions 55mm x 10mm x 10mm. The broken impact test specimens where then used to test the Rockwell hardness.

4.1 BARE MATERIAL TESTING

4.1.1 TENSILE TEST

The test is performed as per standard procedure and the dimensions are measured using Vernier calipers.

Table 4. 1 Dimension before Tensile Test

PARAMETER	VALUE
Gauge Length	56mm
Gauge Diameter	11.90mm
Cross sectional Area	111.22mm^2

Table 4. 2 Tensile Test Tabulation

Load KN	Elongation mm	Stress N/mm^2	Strain
2	0	17.98237727	0
4	0	35.96475454	0
6	1	53.94713181	0.017857143
8	2	71.92950908	0.035714286
10	3	89.91188635	0.053571429
12	3.5	107.8942636	0.0625
14	3.5	125.8766409	0.0625
16	4	143.8590182	0.071428571
18	4	161.8413954	0.071428571
20	4.2	179.8237727	0.075
22	4.5	197.80615	0.080357143
24	4.8	215.7885272	0.085714286
26	5	233.7709045	0.089285714
28	5	251.7532818	0.089285714
30	5.2	269.7356591	0.092857143
32	5.5	287.7180363	0.098214286
34	5.7	305.7004136	0.101785714

36	5.7	323.6827909	0.101785714
38	5.9	341.6651681	0.105357143
40	6	359.6475454	0.107142857
40.8	6.2	366.8404963	0.110714286
41.2	6.4	370.4369718	0.114285714
42	6.6	377.6299227	0.117857143
42.4	6.8	381.2263981	0.121428571
44	6.8	395.6122999	0.121428571
46	6.9	413.5946772	0.123214286
48	6.9	431.5770545	0.123214286
50	6.95	449.5594318	0.124107143
52	7	467.541809	0.125
54	7	485.5241863	0.125
56	7.2	503.5065636	0.128571429
58	7.4	521.4889408	0.132142857
60	7.8	539.4713181	0.139285714
62	7.85	557.4536954	0.140178571
62.4	7.9	561.0501708	0.141071429
64	8	575.4360726	0.142857143
64	8.4	575.4360726	0.15
63.8	8.8	573.6378349	0.157142857
63.4	8.9	570.0413595	0.158928571
62.4	9	561.0501708	0.160714286
61.4	9.2	552.0589822	0.164285714
61	9.4	548.4625067	0.167857143
60.4	9.8	543.0677936	0.175
60	9.9	539.4713181	0.176785714
58.4	10	525.0854163	0.178571429
58.4	10.2	525.0854163	0.182142857
58	10.4	521.4889408	0.185714286
57.8	10.85	519.6907031	0.19375
57.8	10.9	519.6907031	0.194642857
57.4	11	516.0942277	0.196428571

From the data we know that the extreme load provides is 64 KN hence we can determine the ultimate tensile strength which is given by

Ultimate Tensile Strength in N/mm^2 =

$$\frac{Maximum\ force\ applied\ in\ N}{Cross\ Sectional\ Area\ in\ mm^2}$$

Therefore we have

$$\frac{64000}{111.22} = 574.01\ N/mm^2$$

Table 4. 3 Dimensions after failure

PARAMETER	VALUE
Gauge Length after Break	63.22mm
Gauge Diameter after Break	8.32mm

The stress value in table 4.2 can be determined by dividing the loads by the crossectional area. Similarly the strain can be determined by dividing the elongation by original gauge length. The stress and strain graphs are then plotted.

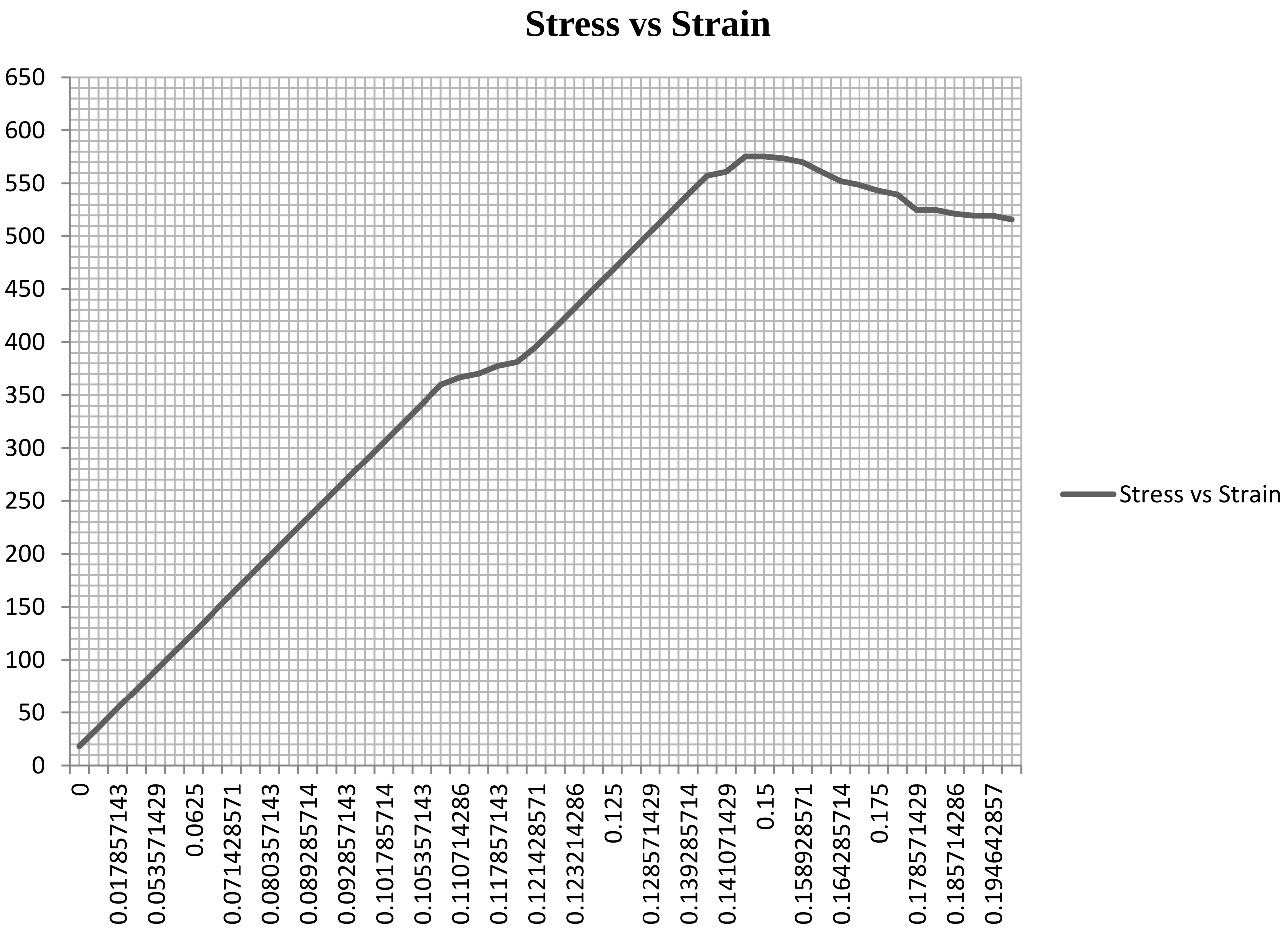


Figure 4. 1 Stress Vs Strain graph of AISI 1040 Oil Quenched

The yield strength is determined by 0.2% offset method by marking a line parallel to the strain. The yield strength from figure 4.2 is 360 N/mm^2

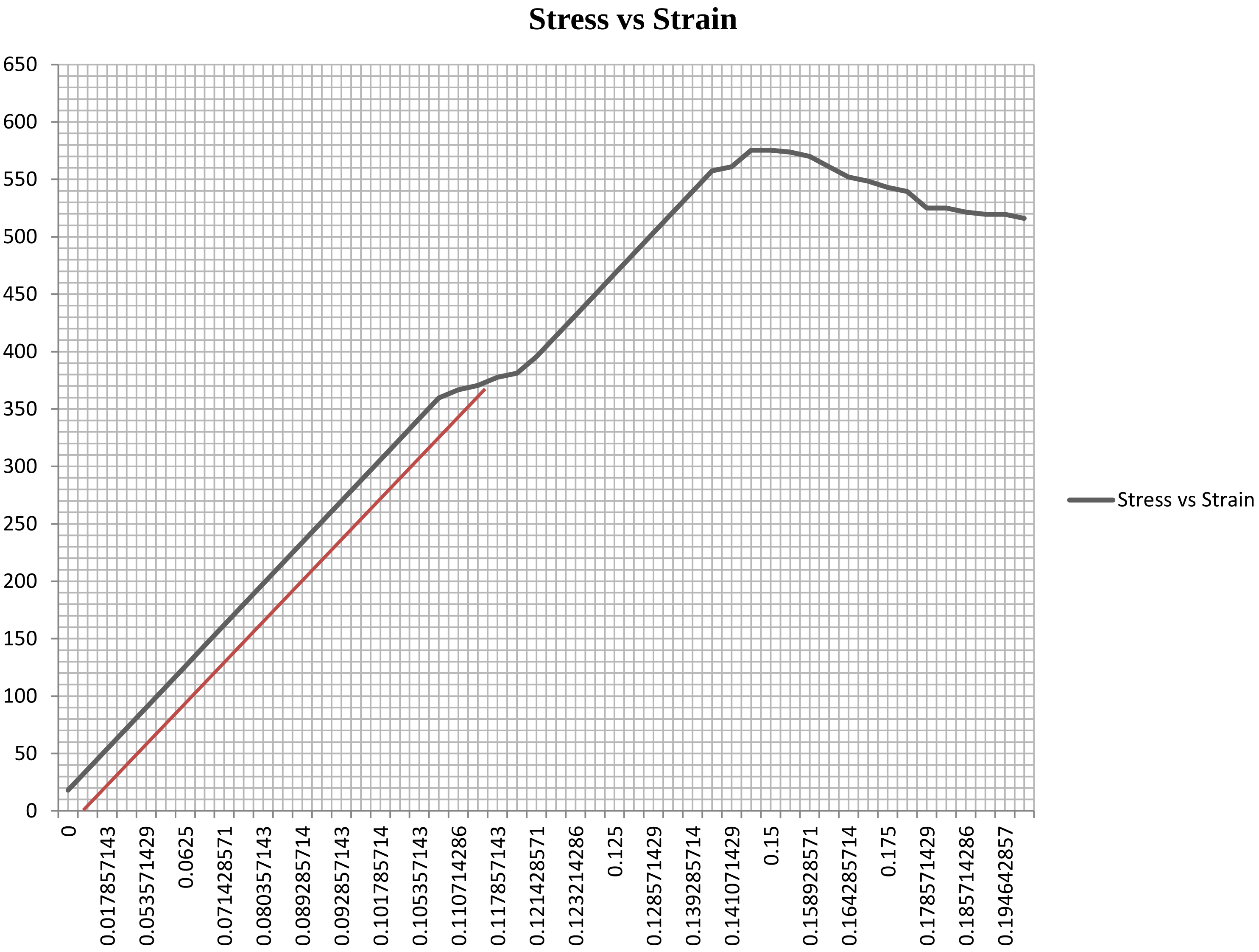


Figure 4. 2 Strain from 0.2% offset

Table 4. 4 AISI 1040 Results

PARAMETER	VALUE
Ultimate Tensile Strength	574.01 N/mm^2
Yield Strength	360 N/mm^2

4.1.2 IMPACT TEST

The charpy specimen made as per ASTM E 23 Standards is tested for its impact energy as per standard techniques. The Dimensions are gauged using Vernier calipers.

Table 4. 5 Impact test Tabulation

Material	Length mm	Breath mm	Height mm	Depth of Notch mm	Initial Reading Joules	Final Reading Joules
Bare	54.74	9.41	9.41	0.9	2	37.5

The Impact Energy U= Final reading in Joules – Initial Reading in Joules

U= 37.5- 2

U= 35.5 joules

Notch Impact Strength I =

$$\frac{Impact\ Energy\ in\ Jules}{Effective\ area\ of\ specimen\ in\ m} \quad 1\ joule = 1\ N/m$$

Based upon the above formula we have the effective area of specimen as 8.85481x10^{-05}m^2 Therefore Notch Impact strength = 400.912KN/m

Modulus of Rupture =

$$\frac{Impact\ Energy}{Effective\ volume\ in\ mm^3} \quad joules/mm^3$$

Therefore Modulus of rupture = 0.007324 joules/mm^3

4.1.3 HARDNESS TEST

Rockwell hardness test is performed as per the standard procedure for hardness test with a load value of 150kgf.

Table 4. 6 Rockwell Hardness Tabulation

MATERIAL	HARDNESS	AVERAGE HARDNESS
AISI 1040 Oil Quenched	32	33.166
	39.5	
	28	

4.2 CORRODED BARE MATERIAL TESTING

The AISI 1040 oil quenched specimen is placed in 5% Nacl Solution to induce stress corrosion as per the tests of Dawood Nawal Muhammed [13]. Stress corrosion cracking induces 100% changes in Ultimate Tensile Strength, Yield strength [3]. After 96 hours the specimen is taken from the salt solution and placed into testing.

4.2.1 TENSILE TEST OF CORRODED SPECIMEN

Table 4. 7 Initial Dimensions of Corroded Specimen

PARAMETER	VALUE
Gauge Length	57.23mm
Gauge Diameter	11.93mm
Cross sectional Area	111.78mm^2

Table 4. 8 Corroded Specimen Tensile Test Tabulation

Load KN	Elongation mm	Stress MPa	Strain
0	0	0	0
1	0	8.94614	0
2	0.1	17.8923	0.00175
3	0.4	26.8384	0.00699
4	0.6	35.7846	0.01048
5	1	44.7307	0.01747
6	1.2	53.6769	0.02097
7	1.6	62.623	0.02796
8	1.8	71.5692	0.03145
9	1.8	80.5153	0.03145
10	2	89.4614	0.03495

11	2.1	98.4076	0.03669
12	2.4	107.354	0.04194
13	2.6	116.3	0.04543
14	2.8	125.246	0.04893
15	2.9	134.192	0.05067
16	3	143.138	0.05242
17	3.2	152.084	0.05591
18	3.3	161.031	0.05766
19	3.5	169.977	0.06116
20	3.7	178.923	0.06465
21	3.8	187.869	0.0664
22	3.9	196.815	0.06815
23	4	205.761	0.06989
24	4	214.707	0.06989
25	4	223.654	0.06989
26	4.1	232.6	0.07164
27	4.2	241.546	0.07339
28	4.2	250.492	0.07339
29	4.3	259.438	0.07514
30	4.5	268.384	0.07863
31	4.7	277.33	0.08212
32	4.9	286.277	0.08562
33	5	295.223	0.08737
34	5	304.169	0.08737
35	5	313.115	0.08737
36	5	322.061	0.08737
37	5	331.007	0.08737
38	5.1	339.953	0.08911
39	5.2	348.9	0.09086
40	5.2	357.846	0.09086
41	5.3	366.792	0.09261
42	5.5	375.738	0.0961
43	5.5	384.684	0.0961
44	5.6	393.63	0.09785
45	5.8	402.576	0.10135
46	5.9	411.523	0.10309
47	5.9	420.469	0.10309
48	6	429.415	0.10484
49	6	438.361	0.10484
49.9	6	446.413	0.10484
50	6.1	447.307	0.10659
51	6.1	456.253	0.10659

52	6.2	465.199	0.10833
53	6.2	474.146	0.10833
54	6.2	483.092	0.10833
55	6.3	492.038	0.11008
56	6.3	500.984	0.11008
57	6.3	509.93	0.11008
58	6.4	518.876	0.11183
59	6.5	527.823	0.11358
60	6.7	536.769	0.11707
61	6.8	545.715	0.11882
62	6.9	554.661	0.12057
63	7	563.607	0.12231
63.1	7.1	564.502	0.12406
63.2	7.3	565.396	0.12756
63.4	7.7	567.186	0.13454
63.3	7.3	566.291	0.12756
63.2	7.7	565.396	0.13454
63.11	8	564.591	0.13979
63.5	8.2	568.08	0.14328
63.2	8.3	565.396	0.14503
63.2	8.5	565.396	0.14852
63.2	8.8	565.396	0.15377
63.2	8.9	565.396	0.15551
63.2	9	565.396	0.15726
63.2	9.1	565.396	0.15901
63.2	9.5	565.396	0.166
63.2	9.9	565.396	0.17299
63.1	10	564.502	0.17473
63.1	10.1	564.502	0.17648
63.1	10.5	564.502	0.18347
63.1	10.9	564.502	0.19046
63.1	11	564.502	0.19221
63.1	11.1	564.502	0.19395
63.1	11.6	564.502	0.20269
63	12	563.607	0.20968
63	12.1	563.607	0.21143
63	12.3	563.607	0.21492
63	12.8	563.607	0.22366
63	13	563.607	0.22715

From the above table 4.8 we know that the maximum load generated is 63.5KN and it forms an ultimate tensile strength of 568.08N/mm^2.

Table 4. 9 Failure Parameters of Corroded AISI 1040

PARAMETER	VALUE
Gauge Length after Break	63.92mm
Gauge Diameter after Break	7.82mm

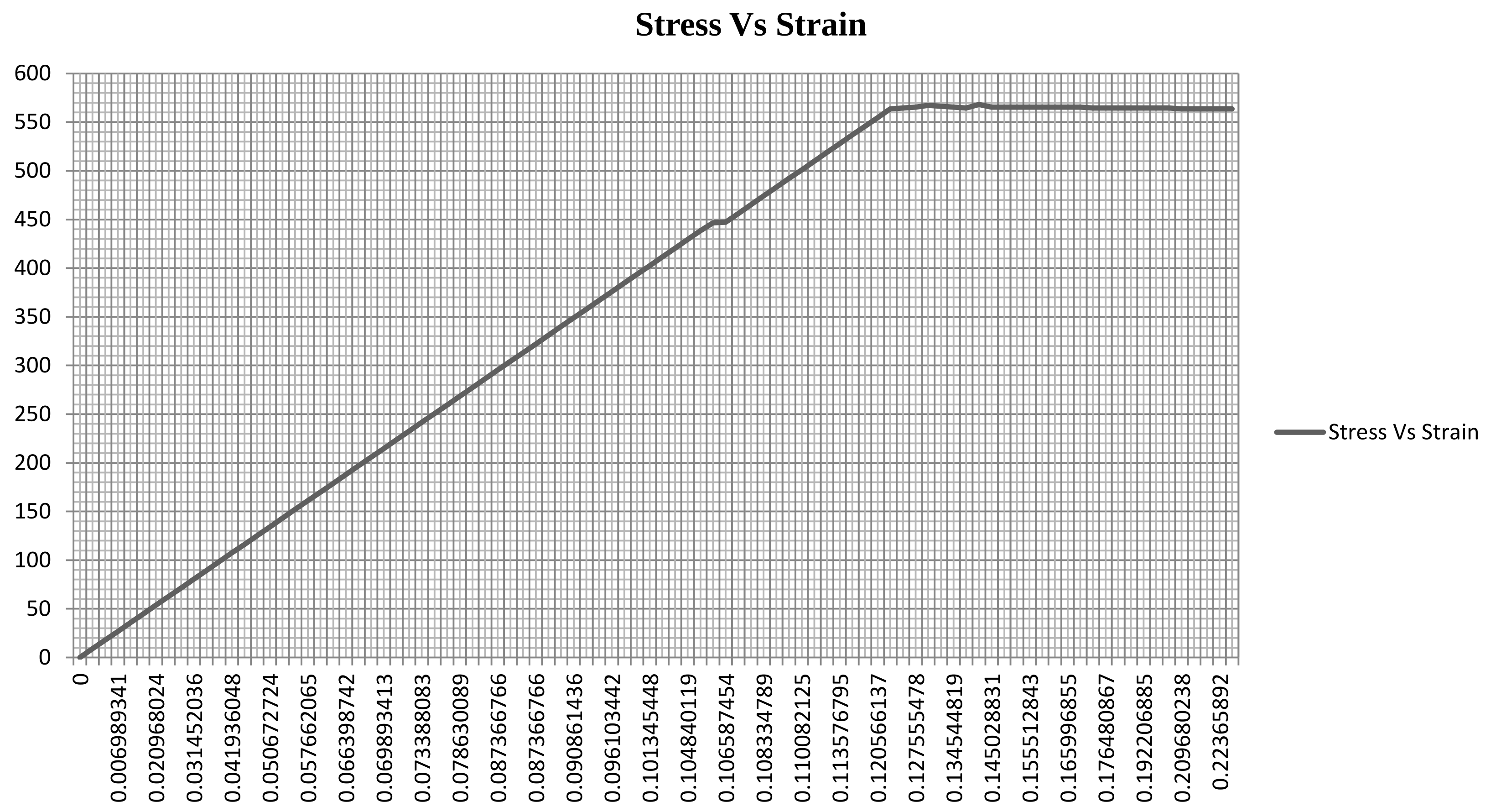


Figure 4. 3 Stress Vs Strain of Corroded AISI 1040

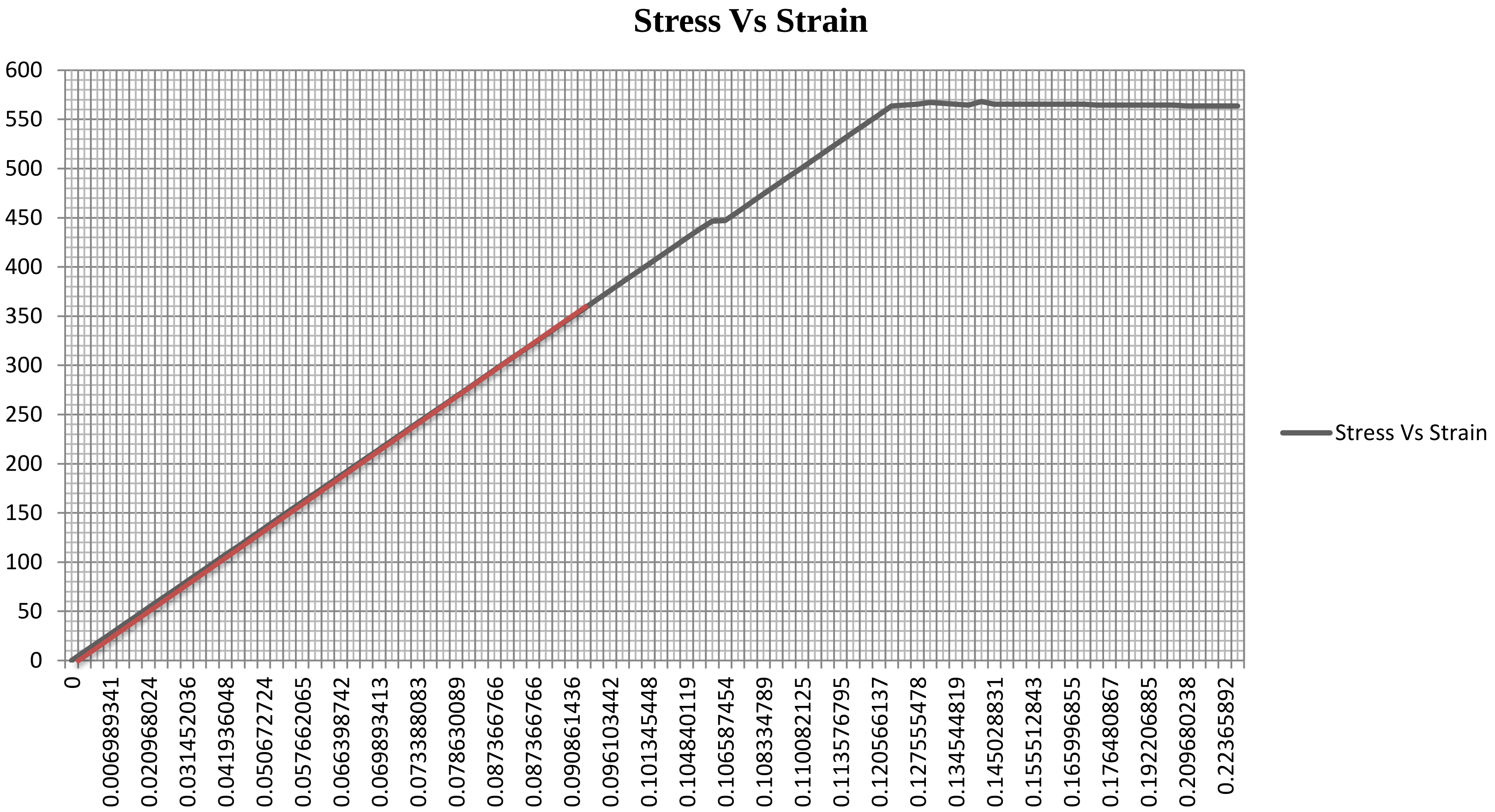


Figure 4. 4 0.2% offset of Corroded Yield Strength

Table 4. 10 Corroded AISI 1040 Results

PARAMETER	**VALUE**
Ultimate Tensile Strength	568.01 N/mm^2
Yield Strength	352 N/mm^2

4.2.2 IMPACT TESTING OF CORRODED AISI 1040

The corroded specimen is impact tested as per the standard testing procedure.

Material	Length mm	Breath mm	Height mm	Depth of Notch mm	Initial Reading Joules	Final Reading Joules
Corroded AISI 1040	55.52	9.43	9.43	1.21	2	33.8

The Impact Energy U= Final reading in Joules – Initial Reading in Joules

U= 33.8- 2

U= 31.8 joules

Notch Impact Strength I =

$$\frac{Impact\ Energy\ in\ Jules}{Effective\ area\ of\ specimen\ in\ m} \qquad 1\ joule = 1\ N/m$$

Based upon the above formula we have the effective area of specimen as 8.89249x10^{-05}m^2 Therefore Notch Impact strength = 357.605KN/m

Modulus of Rupture =

$$\frac{Impact\ Energy}{Effective\ volume\ in\ mm^3} \qquad joules/mm^3$$

Therefor Modulus of rupture = 0.006441 joules/mm^3

4.2.3 HARDNESS TEST

Rockwell hardness test is accomplished as per the standard procedure for hardness test with a load value of 150kgf.

Table 4. 11 Corroded AISI 1040 Hardness

MATERIAL	HARDNESS	AVERAGE HARDNESS
Corroded AISI 1040	29	29.667
	29	
	31	

4.3 NICKEL CHROMIUM COATING

4.3.1 TENSILE TEST

The bare specimen is coated with a layer of nickel and Chromium. The thickness of the coating is based upon ISO 1456:2009 and Nickel Plating institute’s standard.

Table 4. 12 Corroded Nickel Chromium Plated Specimen parameters

PARAMETER	VALUE
Gauge Length	61.1mm
Gauge Diameter	11.52mm
Cross sectional Area	104.230mm^2

Table 4. 13 Nickel Chromium Plated Specimen tensile test

Load KN	Elongation mm	Stress MPa	Strain
0	0	0	0
1	0	9.59417	0
2	0	19.1883	0
3	0	28.7825	0
4	0.5	38.3767	0.00818
5	0.5	47.9708	0.00818
6	1	57.565	0.01637
7	1.5	67.1592	0.02455
8	1.5	76.7533	0.02455
8.7	2	83.4693	0.03273
9	2	86.3475	0.03273

10	2	95.9417	0.03273
11	2	105.536	0.03273
11.7	2.5	112.252	0.04092
12	2.5	115.13	0.04092
13	2.5	124.724	0.04092
14	2.5	134.318	0.04092
15	3	143.913	0.0491
16	3	153.507	0.0491
17	3.2	163.101	0.05237
18	3.2	172.695	0.05237
19	3.5	182.289	0.05728
20	3.5	191.883	0.05728
21	3.6	201.478	0.05892
22	3.8	211.072	0.06219
23	3.9	220.666	0.06383
24	4	230.26	0.06547
25	4.1	239.854	0.0671
26	4.1	249.448	0.0671
27	4.2	259.043	0.06874
28	4.4	268.637	0.07201
29	4.5	278.231	0.07365
30	4.5	287.825	0.07365
31	4.7	297.419	0.07692
32	4.8	307.013	0.07856
33	4.9	316.608	0.0802
34	5	326.202	0.08183
35	5	335.796	0.08183
36	5.1	345.39	0.08347
37	5.1	354.984	0.08347
38	5.3	364.578	0.08674
39	5.3	374.173	0.08674
40	5.4	383.767	0.08838
41	5.5	393.361	0.09002
42	5.5	402.955	0.09002
43	5.7	412.549	0.09329
44	5.9	422.143	0.09656
45	6	431.738	0.0982
46	6	441.332	0.0982
47	6	450.926	0.0982
48	6	460.52	0.0982
49	6.1	470.114	0.09984
50	6.1	479.708	0.09984

51	6.1	489.303	0.09984
52	6.2	498.897	0.10147
53	6.3	508.491	0.10311
54	6.5	518.085	0.10638
55	6.5	527.679	0.10638
56	6.6	537.273	0.10802
57	6.9	546.868	0.11293
58	7	556.462	0.11457
59	7	566.056	0.11457
59.3	7.1	568.934	0.1162
59.7	7.4	572.772	0.12111
59.9	7.6	574.691	0.12439
60.2	7.7	577.569	0.12602
59	8	566.056	0.13093
58	8.5	556.462	0.13912
57	9	546.868	0.1473
56	9.5	537.273	0.15548
55	9.8	527.679	0.16039
54.7	10	524.801	0.16367
54.5	10.5	522.882	0.17185
54	11.5	518.085	0.18822

With reference to the table 4.13 we know that the maximum load exerted on the specimen is 60.2KN.The Ultimate tensile strength of the specimen can be determined by dividing the maximum force exerted by the original cross sectional area.

Ultimate tensile strength= 577.569 MPa

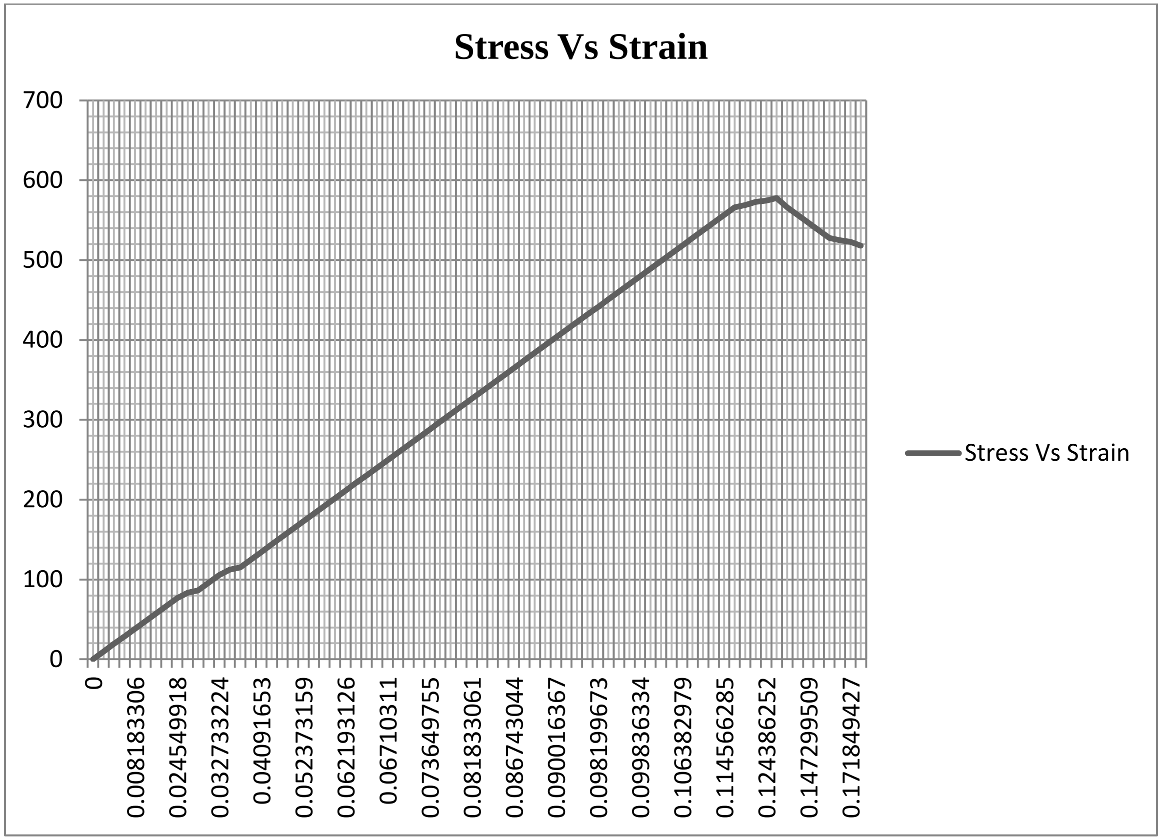


Figure 4. 5 Stress Vs Strain of Electroplated Nickel Chromium

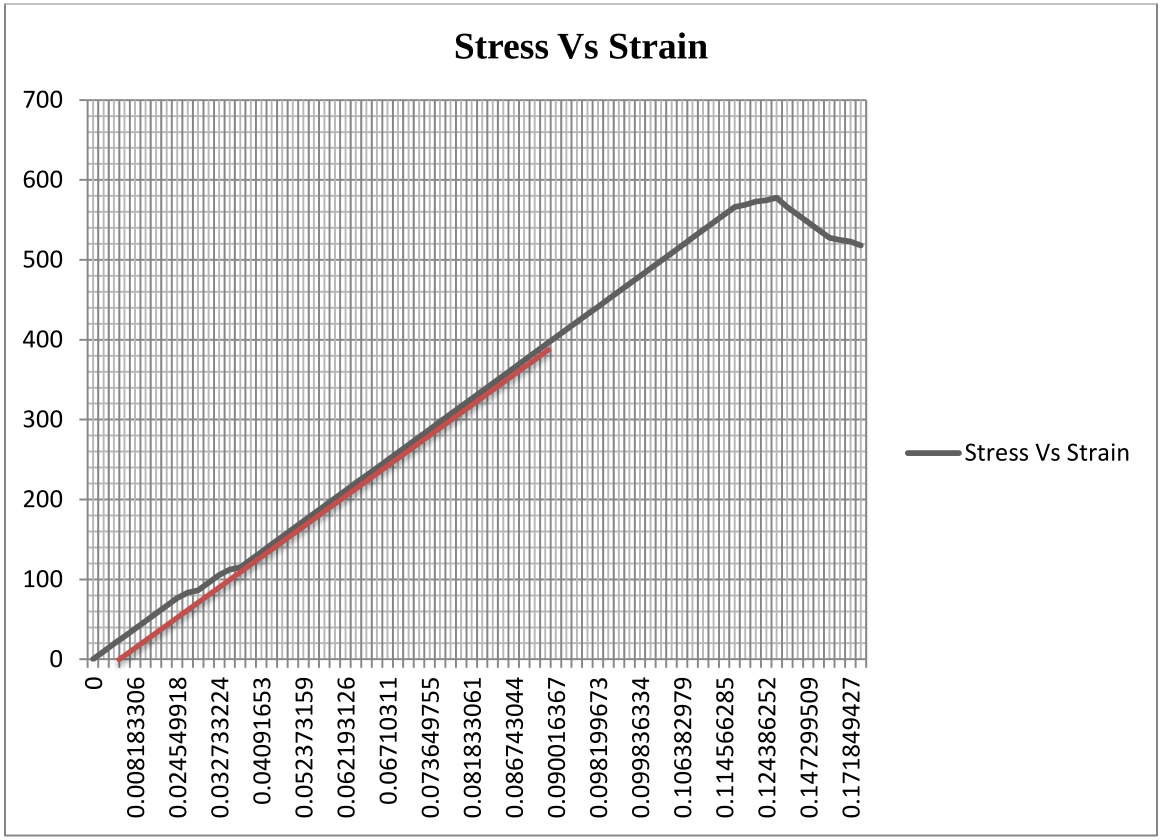


Figure 4. 6 0.2% offset of Electroplated Nickel Chromium

Table 4. 14 Tensile Test results of Nickel Chromium Plated specimen

PARAMETER	VALUE
Ultimate Tensile Strength	577.569 N/mm^2
Yield Strength	372 N/mm^2

4.3.2 IMPACT TESTING OF NICKEL CHROMIUM PLATED AISI 1040

The specimen is impact tested as per the typical testing procedure.

Table 4. 15 Impact test results of Nickel Chromium Plated AISI 1040

Material	Length mm	Breath mm	Height mm	Depth of Notch mm	Initial Reading Joules	Final Reading Joules
Nickel Chromium Plated AISI 1040	55.40	9.44	9.44	1.39	2	48

The Impact Energy U= Final reading in Joules – Initial Reading in Joules

U= 48- 2

U= 46 joules

Notch Impact Strength I =

$$\frac{Impact\ Energy\ in\ Jules}{Effective\ area\ of\ specimen\ in\ m} \quad 1\ joule = 1\ N/m$$

Based upon the above formula we have the effective area of specimen as 8.91135x10^{-5}m^2 Therefore Notch Impact strength = 516.195KN/m

Modulus of Rupture =

$$\frac{Impact\ Energy}{Effective\ volume\ in\ mm^3} \quad joules/mm^3$$

Therefor Modulus of rupture = 0.009318 joules/mm^3

4.3.3 HARDNESS TEST

Rockwell hardness test is executed as per the standard procedure for hardness test with a load value of 150kgf.

Table 4. 16 Hardness of Nickel Chromium Plated AISI 1040

MATERIAL	HARDNESS	AVERAGE HARDNESS
Nickel Plated AISI 1040	33.2	30.56
	32	
	33.5	

4.4 CORRODED NICKEL CHROMIUM PLATED AISI 1040

4.4.1 TENSILE TEST

The bare specimen is coated with a layer of nickel and Chromium. The thickness of the coating is based upon ISO 1456:2009 and Nickel Plating institute's standard. The specimen is then placed in 5% Nacl solution [13] for 96 hours.

Table 4. 17 Corroded Nickel Chromium Plated Specimen parameters

PARAMETER	VALUE
Gauge Length	58.53mm
Gauge Diameter	11.9mm
Cross sectional Area	111.163mm^2

Table 4. 18 Tensile Test of Corroded Nickel Chromium Plated Specimen

LOAD KN	ELONGATION mm	STRESS MPA	STRAIN
0	0	0	0
1	0	8.9958	0
2	0	17.9916	0
3	0	26.9874	0
4	0.5	35.9832	0.00854
4.7	0.5	42.2803	0.00854
5	0.5	44.979	0.00854
5.6	1	50.3765	0.01709
5.9	1.5	53.0752	0.02563
6	1.5	53.9748	0.02563
6.7	2	60.2719	0.03417
7	2	62.9706	0.03417
7.8	2.5	70.1672	0.04271

8	2.5	71.9664	0.04271
8.7	3	78.2635	0.05126
9	3	80.9622	0.05126
9.6	3.5	86.3597	0.0598
10	3.5	89.958	0.0598
11	3.5	98.9538	0.0598
12	3.5	107.95	0.0598
13	4	116.945	0.06834
14	4	125.941	0.06834
15	4.5	134.937	0.07688
16	4.5	143.933	0.07688
17	4.5	152.929	0.07688
18	4.5	161.924	0.07688
19	5	170.92	0.08543
20	5	179.916	0.08543
21	5	188.912	0.08543
22	5	197.908	0.08543
23	5.5	206.903	0.09397
24	5.5	215.899	0.09397
25	5.5	224.895	0.09397
26	5.5	233.891	0.09397
27	6	242.887	0.10251
28	6	251.882	0.10251
29	6	260.878	0.10251
30	6	269.874	0.10251
31	6	278.87	0.10251
32	6	287.866	0.10251
33	6	296.861	0.10251
34	6.5	305.857	0.11105
35	6.5	314.853	0.11105
36	6.5	323.849	0.11105
37	6.5	332.845	0.11105
38	6.5	341.84	0.11105
39	6.5	350.836	0.11105
40	6.5	359.832	0.11105
41	6.5	368.828	0.11105
42	7	377.824	0.1196
43	7	386.819	0.1196
44	7	395.815	0.1196
45	7	404.811	0.1196
46	7	413.807	0.1196
47	7.5	422.803	0.12814

48	7.5	431.798	0.12814
49	7.5	440.794	0.12814
49.7	7.5	447.091	0.12814
50	7.5	449.79	0.12814
51	7.5	458.786	0.12814
52	7.5	467.782	0.12814
53	7.5	476.777	0.12814
54	7.5	485.773	0.12814
55	7.5	494.769	0.12814
55.7	8	501.066	0.13668
56	8	503.765	0.13668
57	8	512.761	0.13668
57.7	8	519.058	0.13668
58	8	521.756	0.13668
59	8	530.752	0.13668
59.7	8.5	537.049	0.14522
60	8.5	539.748	0.14522
60.8	8.5	546.945	0.14522
61.4	8.5	552.342	0.14522
62	8.5	557.74	0.14522
63	8.5	566.735	0.14522
63.2	9	568.534	0.15377
63.4	9.5	570.334	0.16231
63.7	9.5	573.032	0.16231
63.8	9.5	573.932	0.16231
63.7	10	573.032	0.17085
62.8	10.5	564.936	0.1794
62.5	10.5	562.237	0.1794
61	11	548.744	0.18794
60	11	539.748	0.18794
59	11	530.752	0.18794
58	11.5	521.756	0.19648
57	11.5	512.761	0.19648
56	12	503.765	0.20502
55	12	494.769	0.20502
54	12	485.773	0.20502

Based upon the results of table 4.12 the maximum force used is 63.8KN and hence we can determine the ultimate tensile strength value by dividing the maximum force by the original cross sectional area. The ultimate tensile strength value is 573.932 N/mm^2

Table 4. 19 Failure Parameters of Nickel chromium plated AISI 1040

PARAMETER	VALUE
Gauge Length after Break	63.63mm
Gauge Diameter after Break	9.4mm

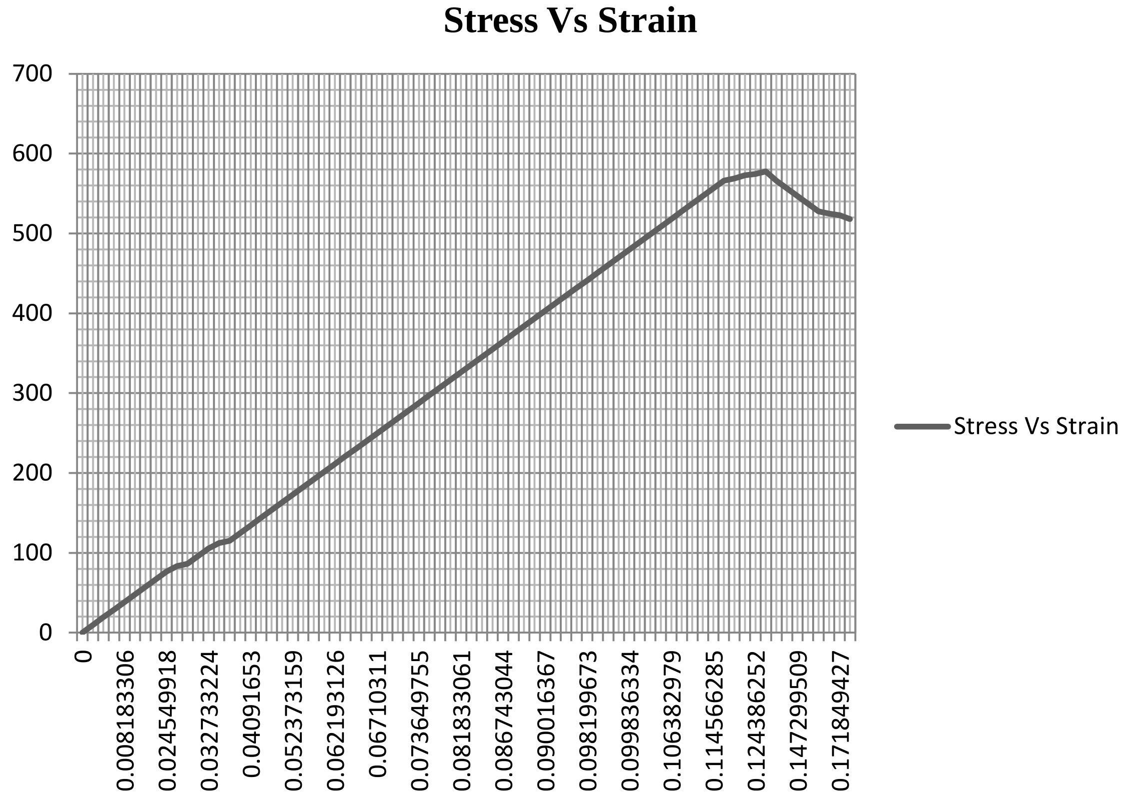


Figure 4. 7 Stress vs Strain of Corroded Nickel Chromium Plated Specimen

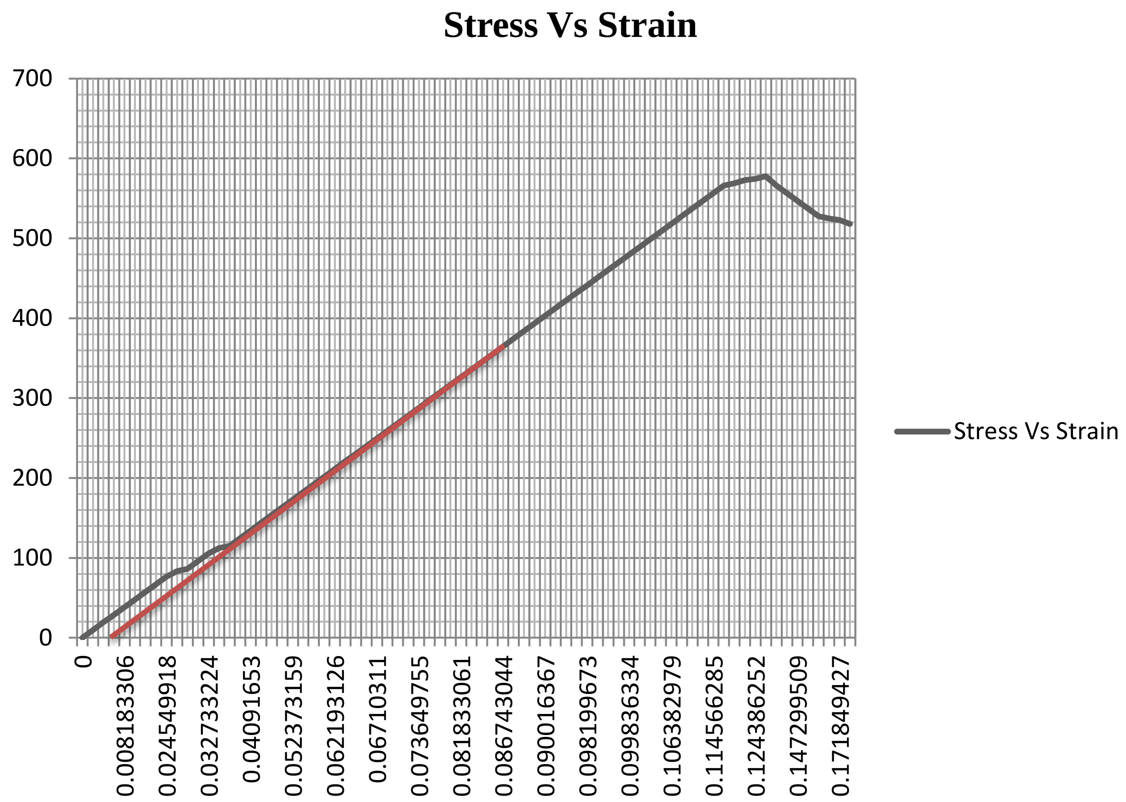


Figure 4. 8 0.2% offset for yield strength

Table 4. 20Corroded Nickel Chromium Plated AISI 1040 Results

PARAMETER	**VALUE**
Ultimate Tensile Strength	572.721 N/mm^2
Yield Strength	365 N/mm^2

4.4.2 IMPACT TESTING OF CORRODED NICKEL CHROMIUM PLATED AISI 1040

The specimen is impact tested as per the standard testing procedure.

Table 4. 21 Impact test results of Corroded Nickel Chromium Coating on AISI 1040

Material	Length mm	Breath mm	Height mm	Depth of Notch mm	Initial Reading Joules	Final Reading Joules
Corroded Nickel Chromium Plated AISI 1040	55.70	9.50	9.50	1.27	2	35.95

The Impact Energy U= Final reading in Joules – Initial Reading in Joules

U= 35.95- 2

U= 33.95 joules

Notch Impact Strength I =

$$\frac{Impact\ Energy\ in\ Jules}{Effective\ area\ of\ specimen\ in\ m} \quad 1\ joule = 1\ N/m$$

Based upon the above formula we have the effective area of specimen as 0.00009025m^2 Therefore Notch Impact strength = 376.175KN/m

Modulus of Rupture =

$$\frac{Impact\ Energy}{Effective\ volume\ in\ mm^3} \quad joules/mm^3$$

Therefor Modulus of rupture = 0.006754 joules/mm^3

4.4.3 HARDNESS TEST

Rockwell hardness test is performed as per the standard procedure for hardness test with a load value of 150kgf.

Table 4. 22 Hardness of Corroded Nickel Chromium Coating on AISI 1040

MATERIAL	HARDNESS	AVERAGE HARDNESS
Corroded Nickel Plated AISI 1040	37.5	36.33
	36.5	
	35	

4.5 CORROSION RATE

The corrosion rate in mm per year can be determined by the following equation [10].

$$\frac{weight\ loss\ in\ grams\ *\ K}{Alloy\ density\frac{g}{cm^2}\ *\ exposed\ area\ in\ cm^2\ *\ Exposure\ time\ in\ hr}$$

4.5.1 CORROSION RATE OF BARE MATERIAL

Weight of AISI 1040 UTM specimen before inducing stress corrosion= 646g

Weight of AISI 1040 UTM Specimen after 96hrs in 5% Nacl Solution= 642g

Therefore corrosion rate of bare material in mm per year =

$$\frac{4 * 8.74 * 10^4}{7.845 * 180.57 * 96} = 2.5707\ mm/year$$

$$\frac{4 * 3.45 * 10^6}{7.845 * 180.57 * 96} = 101.477\ mils/year$$

4.5.2 CORROSION RATE OF NICKEL CHROMIUM COATED AISI 1040

Weight of the specimen before inducing stress corrosion=632g

Weight of specimen after 96hrs in 5% Nacl Solution= 630g

$$\frac{2 * 8.74 * 10^4}{7.7 * 541.71 * 96} = 0.436\ mm/year$$

$$\frac{2 * 3.45 * 10^6}{7.7 * 541.71 * 96} = 17.1653\ mils/year$$

Thus from the corrosion rate the we have reduced the corrosion by 82.56%

4.6 SIMULATION OF MATERIAL PROPERTIES IN SUBSEA CONDITIONS

Based upon the results obtained from the experimental testing, the values are fed into ANSYS workbench to simulate deep sea conditions. The input parameters required for ansys are as follows

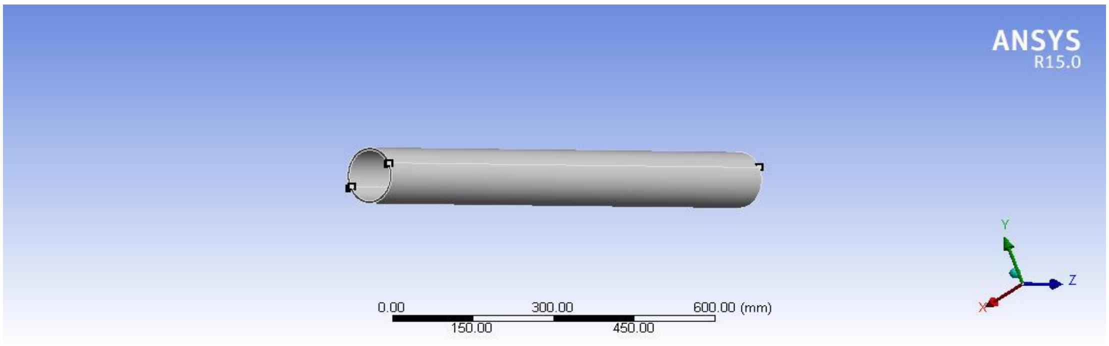
Property	AISI 1040	Nickel	Chromium
Density kg/m^3	7845	8880	7190
Poisson ratio	0.29	0.31	0.21
Ultimate Tensile Strength MPa	571	317	282
Yield Strength Mpa	360	59	135
Modulus of Elasticity GPa	200	209	279

The pressure is determined by the formula depth * density of sea water (1250kg/m^3) [12]. The variation of temperature is determined by the equation [12].

$$\frac{Surface\ Temperature\ in\ ℃}{(1.84 * 10^{-4} * Surface\ Temperature\ ℃ * Depth\ in\ m) + 1}$$

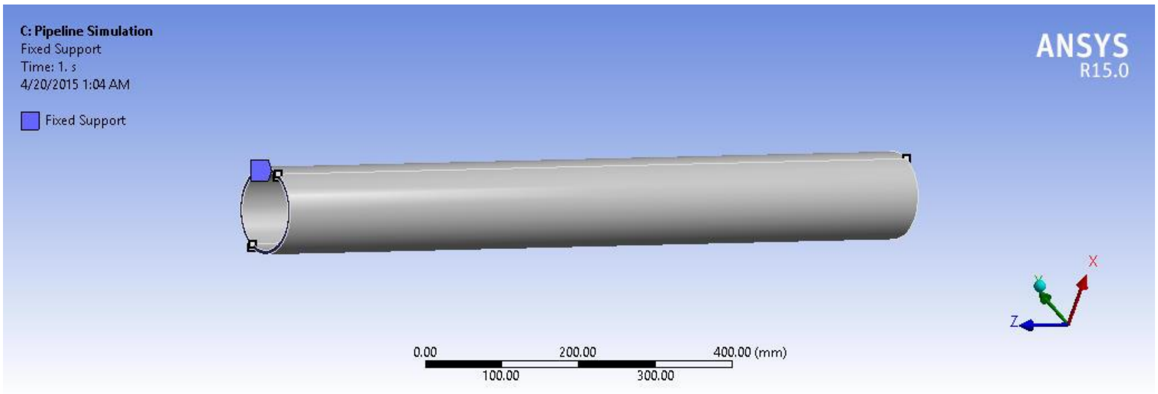
For this simulation the surface temperature of the ocean is measured as 25˚C. The specimen for testing is considered to be a 4inch spool with a thickness of 5.56mm, length of 1m and manufactured from AISI 1040.

Table 4. 23 Simulation Test Specimen



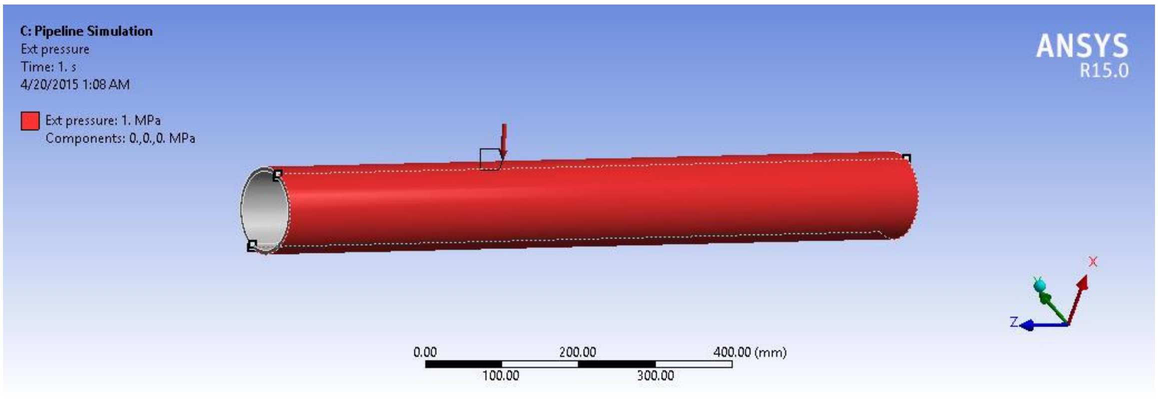
After inserting the material properties in ansys the pre-processing parameters are inserted. They include the type of fixtures, external pressure and temperature of the water at the vital depth. The specimen is considered to be welded at both the ends hence both the ends are taken as fixed.

Table 4. 24 Simulation fixed support


C: Pipeline Simulation
Fixed Support
Time: 1. s
4/20/2015 1:04 AM

Assuming that the pipeline is being constructed into deep water condition to test the yield strength, the internal pressure is ignored. The external pressure is applied on the outer surfaces based upon the values obtained by the depth value and density of sea water.

Table 4. 25 Simulation specimen area of External pressure Exerted



C: Pipeline Simulation
Ext pressure
Time: 1. s
4/20/2015 1:08 AM

🟥 Ext pressure: 1. MPa
Components: 0.,0.,0. MPa

The Temperature of the sea water is obtained by the thermocline equation are inputted into the system for processing.

Table 4. 26 Temperature and Pressure at various depths

Depth	Temperature in ˚C	Pressure in Mpa
0	25	0.1
100	17.47	1
200	13.35	2
300	10.782	3
400	9.049	4
500	7.7963	5
600	6.848	6
700	6.1055	7
800	5.508	8
900	5.0174	9
1000	4.606	10
1100	4.2584	11
1200	3.959	12
1300	3.6989	13
1400	3.4709	14
1500	3.2694	15
1600	3.09	16
1700	2.924	17
1800	2.7843	18
1900	2.6531	19
2000	2.5338	20
2100	2.424	21
2200	2.324	22
2300	2.2324	23

2400	2.1472	24
2500	2.0684	25
2600	1.995	26
2700	1.926	27
2800	1.863	28
2900	1.8034	28.9
3000	1.7474	30
3100	1.69	31
3200	1.64	32
3300	1.59	33
3400	1.55	33.1
3500	1.51	33.2
3600	1.47	33.3
3700	1.43	33.4
3800	1.39	33.5
3900	1.36	33.6
4000	1.33	33.7
4100	1.33	33.8

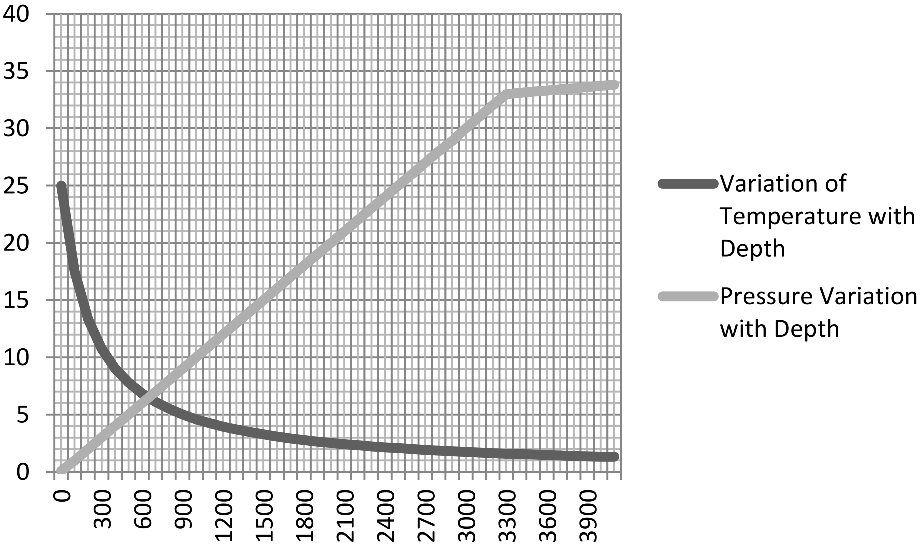


Figure 4. 9 Temperature and Pressure variation with respect to depth

After providing the required inputs the specimen is then meshed to determine the stress values at various points. The lower the value of the mesh the better the result but would result in longer processing times. The mesh size for simulation is taken as 50mm for prompt results. The problem is then solved for results.

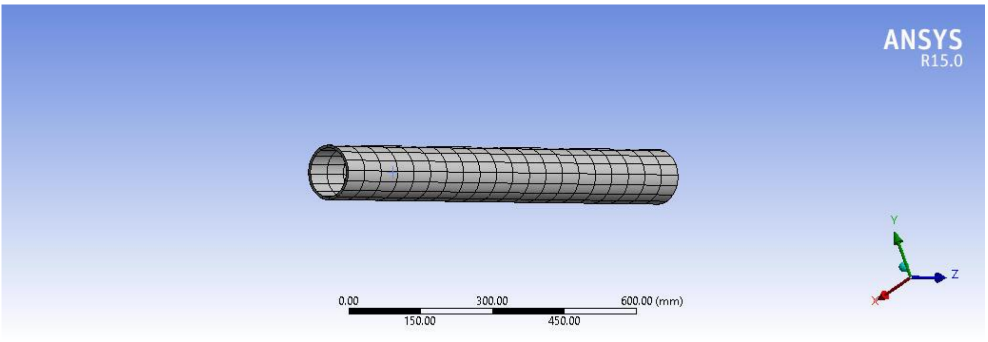


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Figure 4. 10 Specimen Mesh

As per simulation the bare material pipeline fails at a yield stress of 360.47Mpa which is produced at a depth of 2830m and temperature of 1.80˚C.

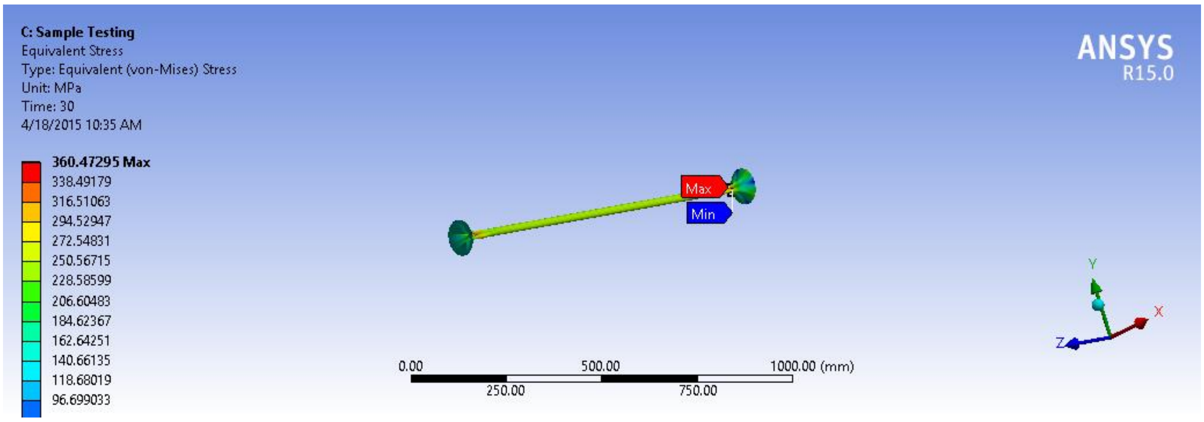
C: Sample Testing
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 30
4/18/2015 10:35 AM

Figure 4. 11 Bare Material Pipeline Failure in Deep Sea conditions

The corroded bare material pipeline fails at a yield stress of 352.83 Mpa which is at a depth of 2800m.

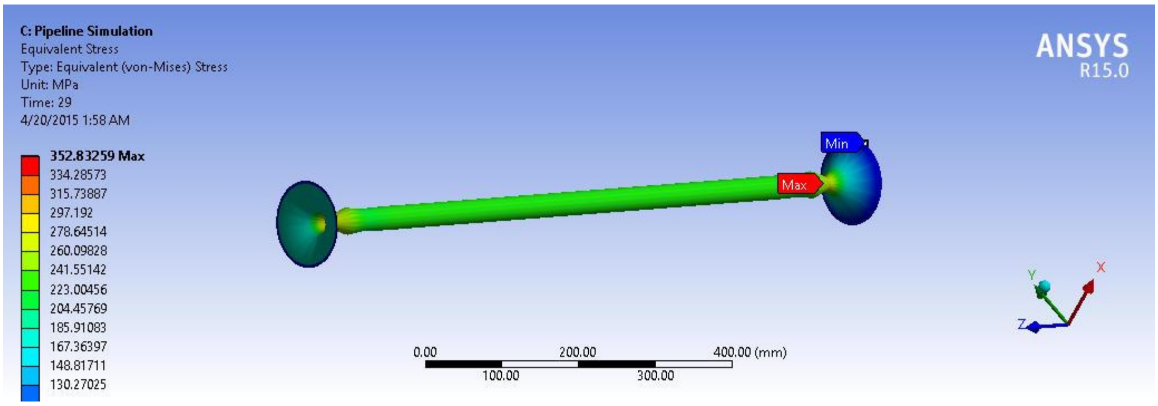

Figure 4. 12 Corroded Bare Failure

Nickel chromium coated AISI 1040 fails at a yield stress of 372.86 Mpa which is at a depth of 2940m.

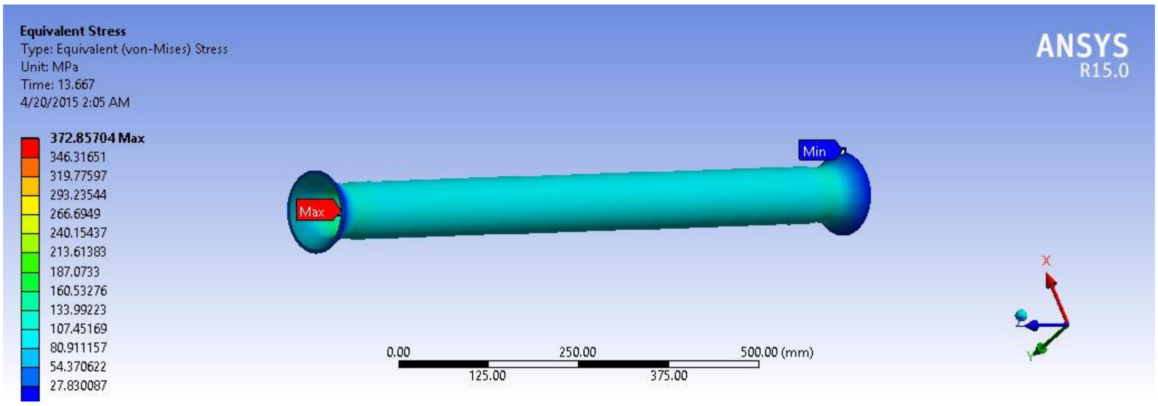

Figure 4. 13 Nickel Chromium Failure

Corroded Nickel Chromium fails at 365.88Mpa at a depth of 2920m

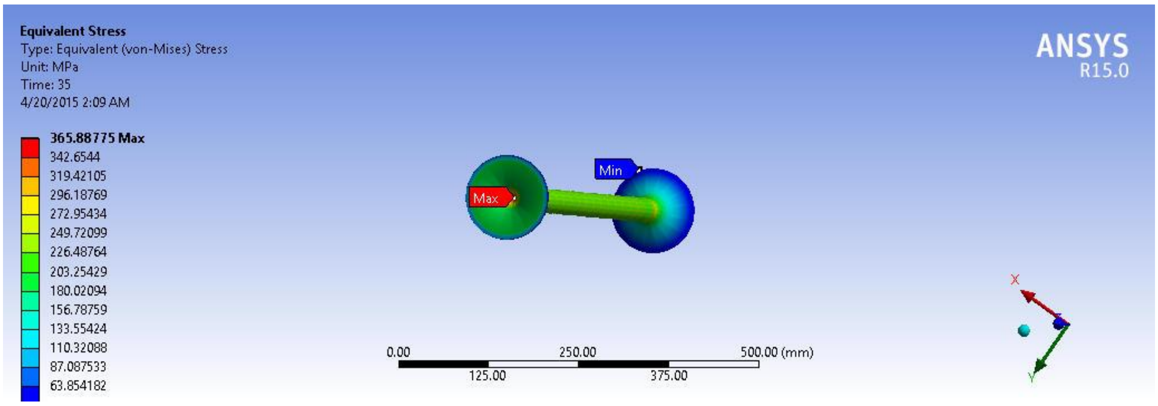

Figure 4. 14 Corroded Nickel Chromium Failure

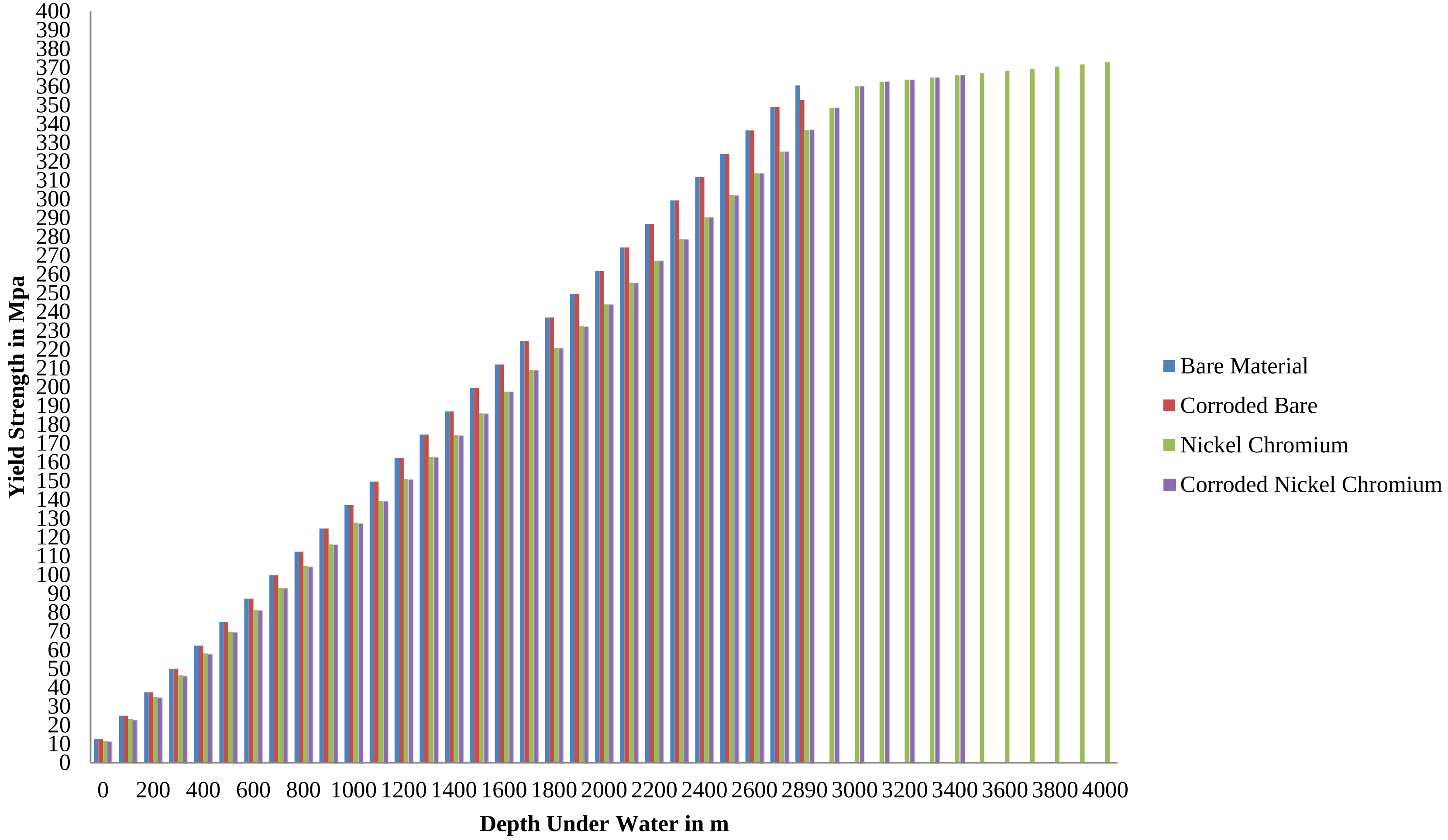

Figure 4. 15 Comparison of results

5. RESULTS AND DISCUSSION

Based upon the experimental testing performed the results are tabulated below.

Table 5. 1 Results and Percentage variation from Experimental Testing

Material	**Tensile Strength MPa**	**Yield Strength MPa**	**Impact Strength KN**	**Hardness**
AISI 1040	574.01	360	400.912	33.166
Corroded AISI 1040	568.01 (-1.04%)	352 (-2.22%)	357.605 (-10.80%)	29.622 (-10.68%)
Nickel Chromium Plated Specimen	577.569 (+0.62%)	372 (+3.33)	516.195 (+28.755)	32.9 (-0.8%)
Corroded Nickel Chromium Plated Specimen	572.721 (-0.22%)	365 (+1.38)	376.175 (-6.17%)	36.33 (+9.53%)

From the above results it can be determined that 20 microns of nickel chromium composite coating has improved the mechanical properties of the substrate material. Chromium being brittle in nature has induced brittleness while tensile testing and increased the impact energy during impact testing. The corrosion rate of bare material was determined to be 2.5mm per year and after electroplating the rate was abridged to 0.436mm per year.

The results of experimental testing were used as inputs for imitation. The models conditions were based on the deepest underwater pipeline in red sea [12]. The simulation pipe specimen is considered to be made of AISI 1040 and a part of under construction project. Assumptions are made to simulate deep water conditions with varying external pressure and temperature. The internal pressure of the pipeline is neglected.

As per the simulated results the AISI 1040 pipeline fails at a depth of 2830m with an external pressure of 28.3Mpa whereas the corroded specimen fails at a depth of 2800m at an external pressure of 28Mpa. After the electroplating process the specimen fails at a depth of 2940m at an external pressure of 29.4 Mpa. The coating has increase the depth of usage to another 110m. The blemished electroplated specimen fails at a depth of 2920m at an external pressure of 29.2Mpa. From the results obtained we know that the electroplating has reduced the corrosion rate of the bare material.

In order to determine the actual efficiency of the coating further more tests are to be done as per accepted international standards. If these tests provide promising results electroplated coatings can be used in the near future. The use of computational techniques helps the user to determine the effect of the coating without huge investments.

Nickel Chromium coating has provided successful test results during the primary testing and further investment can be provided for this composite mixture. More over the coating process used in these experiments are electrodeposition the use of thermal arc spray coating would certainly provide better results than that of electroplated. This experiment can further be continued by varying the thickness of both the coating materials or by adding a third like copper. Experimental testing has shown that copper nickel chromium coating specimens provide greater strength than the nickel chromium coated. Dichromous Chromium coated as a passive layer around nickel is supposed to provide better results in terms of strength, impact energy and hardness.

6. SIMULATION REPORT

Project

First Saved	Saturday, April 11, 2015
Last Saved	Monday, April 20, 2015
Product Version	15.0.7 Release
Save Project Before Solution	No
Save Project After Solution	No

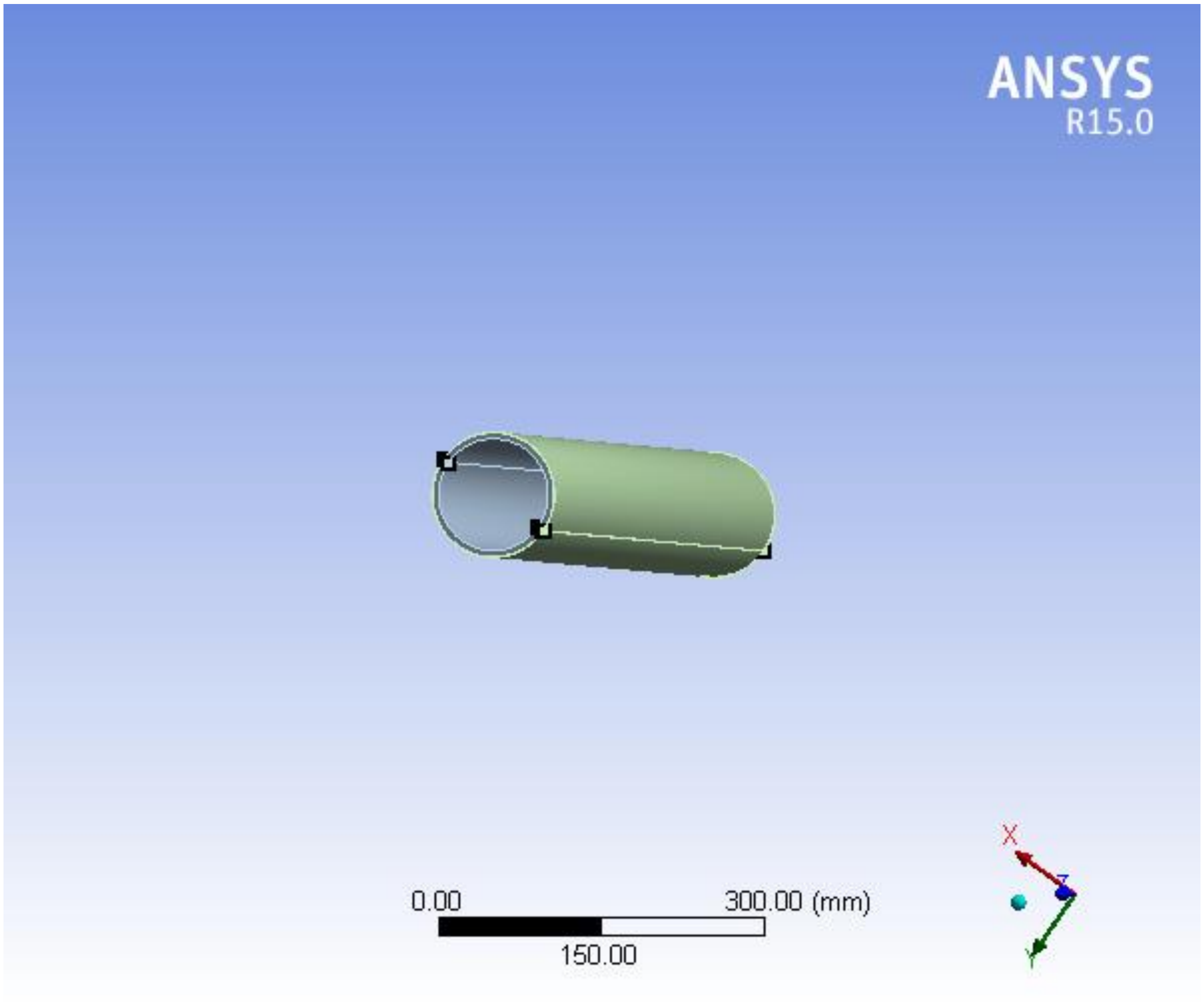

Figure 6. 1 Bare Specimen

Units

Table 6. 1 Units

Unit System	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (C4)

Geometry

Table 6. 2 Geometry Details

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\My Files\References\Project\Corrosion\Ansys testing\4 inch pipeline.IGS
Type	Iges
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	114.3 mm
Length Y	114.3 mm
Length Z	1000. mm
Properties	
Volume	1.8992e+006 mm³
Mass	14.899 kg
Scale Factor Value	1.
Statistics	
Bodies	1
Active Bodies	1

Nodes	2320
Elements	320
Mesh Metric	None
Basic Geometry Options	
Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	No
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\500025641\AppData\Local\Temp
Analysis Type	3-D

Mixed Import Resolution	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

Table 6. 3 Geometry Parts

Object Name	*Part 1*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Stiffness Behavior	Flexible
Coordinate System	Default Coordinate System
Reference Temperature	By Environment
Material	
Assignment	AISI 1040 Oil Quenched
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Length X	114.3 mm
Length Y	114.3 mm

Length Z	1000. mm
Properties	
Volume	1.8992e+006 mm^3
Mass	14.899 kg
Centroid X	2.2362e-009 mm
Centroid Y	-2.2777e-010 mm
Centroid Z	2.468 mm
Moment of Inertia Ip1	1.2644e+006 kg·mm^2
Moment of Inertia Ip2	1.2644e+006 kg·mm^2
Moment of Inertia Ip3	43717 kg·mm^2
Statistics	
Nodes	2320
Elements	320
Mesh Metric	None

Coordinate Systems

Table 6. 4 Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.

Origin	
Origin X	0. mm
Origin Y	0. mm
Origin Z	0. mm
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Mesh

Table 6. 5 Meshing Details

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium

Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	162.070 mm
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	Yes
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes

Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	2320
Elements	320
Mesh Metric	None

Table 6. 6 Mesh Controls

Object Name	*Body Sizing*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Type	Element Size
Element Size	50. mm

Behavior	Soft

Static Structural (C5)

Table 6. 7 Static Structural Analysis

Object Name	*Static Structural (C5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

Table 6. 8 Analysis settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	41.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled

Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes

Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	D:\My Files\References\Project\Corrosion\Ansys testing\pipeline simulation\pipeline small testing files\dp0\SYS-4\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	nmm

Table 6. 9 Loads

<table>
<tr><td>Object Name</td><td><i>Fixed Support</i></td><td><i>Internal pressure</i></td><td><i>Ext pressure</i></td><td><i>Thermal Condition</i></td></tr>
<tr><td>State</td><td>Fully Defined</td><td>Suppressed</td><td colspan="2">Fully Defined</td></tr>
<tr><td colspan="5">Scope</td></tr>
<tr><td>Scoping Method</td><td colspan="4">Geometry Selection</td></tr>
<tr><td>Geometry</td><td colspan="3">2 Faces</td><td>1 Body</td></tr>
<tr><td colspan="5">Definition</td></tr>
<tr><td>Type</td><td>Fixed Support</td><td colspan="2">Pressure</td><td>Thermal Condition</td></tr>
<tr><td>Suppressed</td><td>No</td><td>Yes</td><td colspan="2">No</td></tr>
<tr><td>Define By</td><td></td><td colspan="2">Normal To</td><td></td></tr>
<tr><td>Magnitude</td><td></td><td>5. MPa (ramped)</td><td colspan="2">Tabular Data</td></tr>
<tr><td colspan="5">Tabular Data</td></tr>
<tr><td>Independent Variable</td><td colspan="2"></td><td colspan="2">Time</td></tr>
</table>

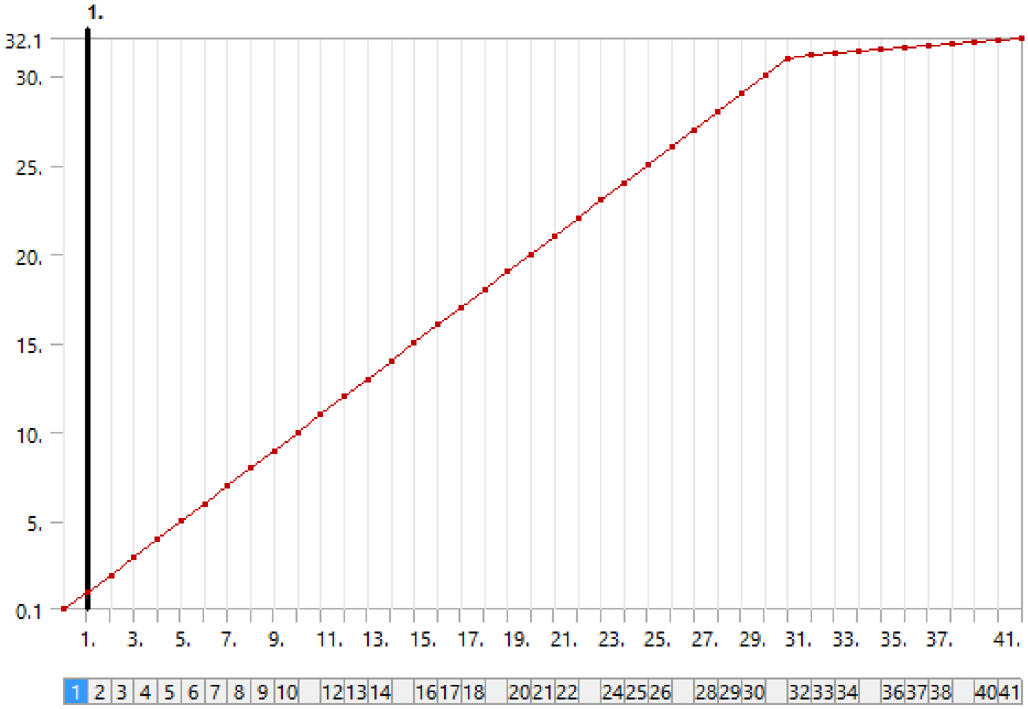

Figure 6. 2 External Pressure

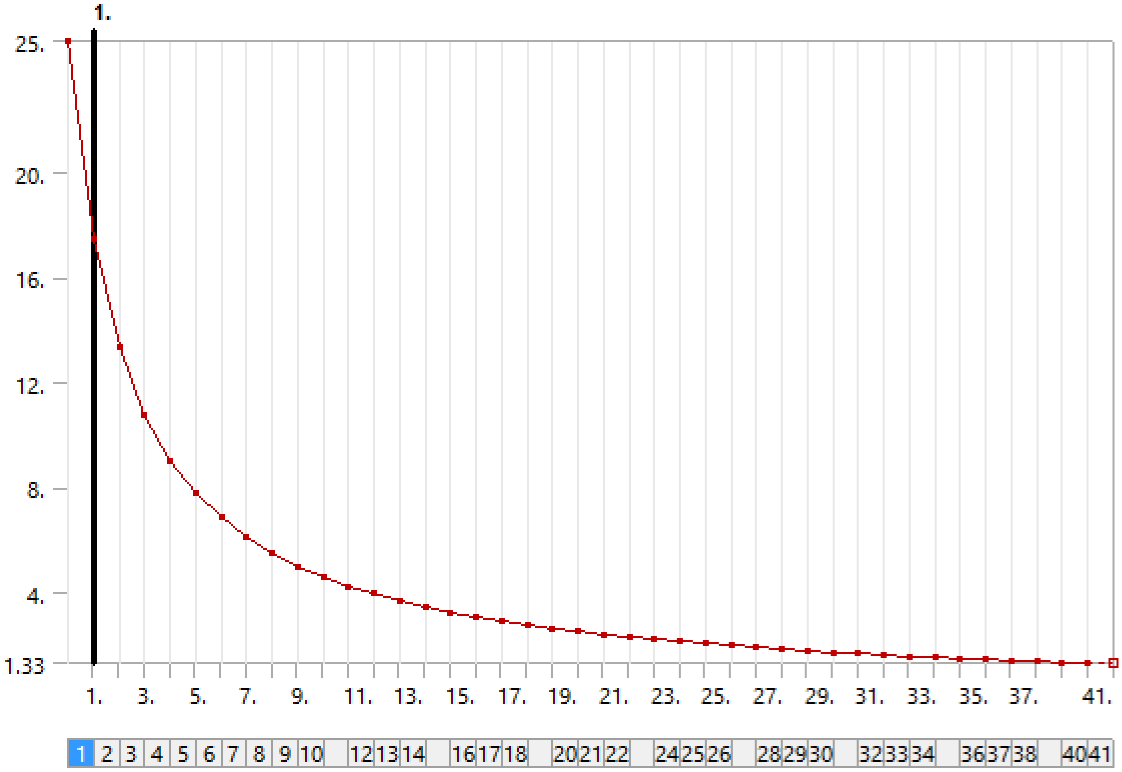

Figure 6. 3 Thermal Condition

Table 6. 10 Thermal Conditions

Steps	Time [s]	Temperature [°C]
1	0.	25.
	1.	17.47
2	2.	13.35
3	3.	10.782
4	4.	9.049
5	5.	7.7963
6	6.	6.848
7	7.	6.1055
8	8.	5.508
9	9.	5.0174
10	10.	4.606
11	11.	4.2584
12	12.	3.959
13	13.	3.6989
14	14.	3.4709
15	15.	3.2694
16	16.	3.09
17	17.	2.924
18	18.	2.7843
19	19.	2.6531

20	20.	2.5338
21	21.	2.424
22	22.	2.324
23	23.	2.2324
24	24.	2.1472
25	25.	2.0684
26	26.	1.995
27	27.	1.926
28	28.	1.863
29	29.	1.8034
30	30.	1.7474
31	31.	1.69
32	32.	1.64
33	33.	1.59
34	34.	1.55
35	35.	1.51
36	36.	1.47
37	37.	1.43
38	38.	1.39
39	39.	1.36
40	40.	1.33
41	41.	= 1.33

Table 6. 11 Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

Table 6. 12 Results

Object Name	*Equivalent Elastic Strain*	*Equivalent Stress*	*Total Deformation*	*Directional Deformation*
State	Solved			
Scope				
Scoping Method	Geometry Selection			

Geometry	All Bodies			
Definition				
Type	Equivalent Elastic Strain	Equivalent (von-Mises) Stress	Total Deformation	Directional Deformation
By	Time			
Display Time	Last	34. s	Last	
Calculate Time History	Yes			
Identifier				
Suppressed	No			
Orientation				Y Axis
Coordinate System				Global Coordinate System
Integration Point Results				
Display Option	Averaged			
Average Across Bodies	No			
Results				
Minimum	5.6728e-004 mm/mm	95.152 MPa	0. mm	-0.10148 mm
Maximum	2.1687e-003 mm/mm	360.31 MPa	0.10155 mm	0.10148 mm
Minimum Value Over Time				
Minimum	1.6783e-005 mm/mm	3.2925 MPa	0. mm	-0.10148 mm

Maximum	5.6728e-004 mm/mm	111.29 MPa	0. mm	-3.0025e-003 mm
Maximum Value Over Time				
Minimum	6.4163e-005 mm/mm	12.468 MPa	3.0046e-003 mm	3.0024e-003 mm
Maximum	2.1687e-003 mm/mm	421.4 MPa	0.10155 mm	0.10148 mm
Information				
Time	41. s	34. s	41. s	
Load Step	41	34	41	
Sub step	1			
Iteration Number	41	34	41	

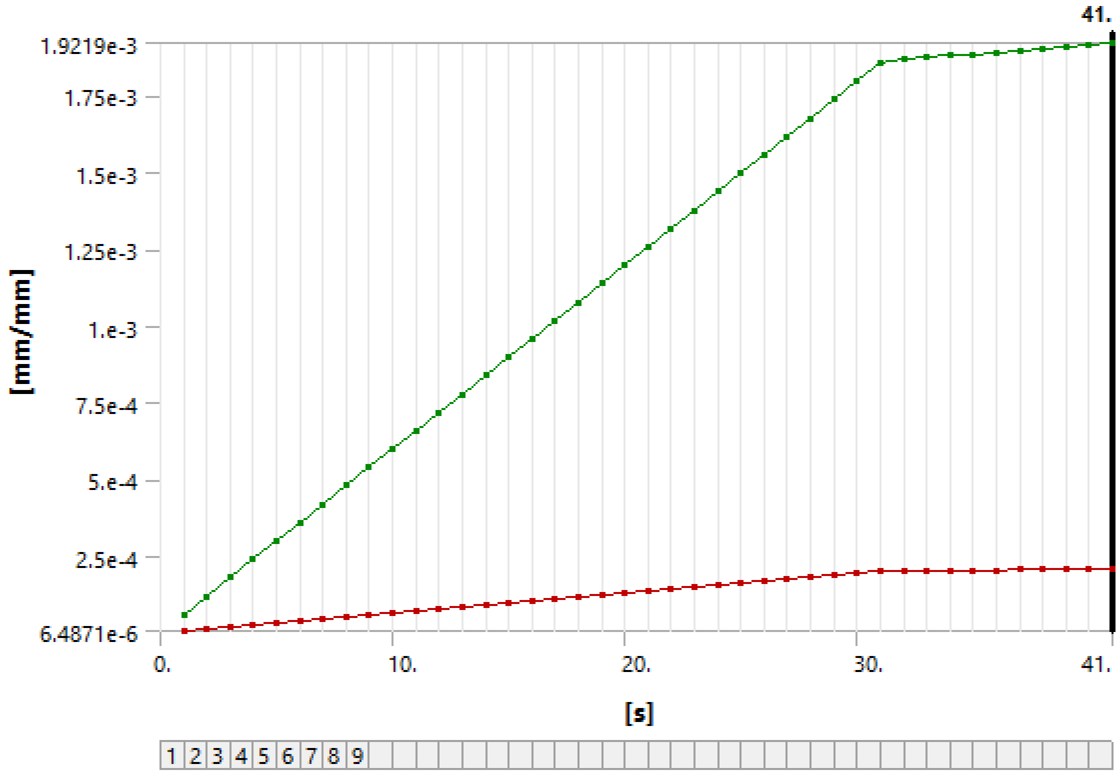

Figure 6. 4 Elastic Strain

Table 6. 13 Elastic Strain

Time [s]	Minimum [mm/mm]	Maximum [mm/mm]
1.	1.6783e-005	6.4163e-005
2.	3.3567e-005	1.2833e-004
3.	5.035e-005	1.9249e-004
4.	6.7133e-005	2.5665e-004
5.	8.3917e-005	3.2081e-004
6.	1.007e-004	3.8498e-004
7.	1.1748e-004	4.4914e-004
8.	1.3427e-004	5.133e-004

9.	1.5105e-004	5.7746e-004
10.	1.6783e-004	6.4163e-004
11.	1.8462e-004	7.0579e-004
12.	2.014e-004	7.6995e-004
13.	2.1818e-004	8.3412e-004
14.	2.3497e-004	8.9828e-004
15.	2.5175e-004	9.6244e-004
16.	2.6853e-004	1.0266e-003
17.	2.8532e-004	1.0908e-003
18.	3.021e-004	1.1549e-003
19.	3.1888e-004	1.2191e-003
20.	3.3567e-004	1.2833e-003
21.	3.5245e-004	1.3474e-003
22.	3.6923e-004	1.4116e-003
23.	3.8602e-004	1.4757e-003
24.	4.028e-004	1.5399e-003
25.	4.1958e-004	1.6041e-003
26.	4.3637e-004	1.6682e-003
27.	4.5315e-004	1.7324e-003
28.	4.6993e-004	1.7966e-003
29.	4.7497e-004	1.8158e-003
30.	4.7665e-004	1.8222e-003

31.	4.7833e-004	1.8286e-003
32.	4.8e-004	1.8351e-003
33.	4.8168e-004	1.8415e-003
34.	4.8504e-004	1.8543e-003
35.	4.8672e-004	1.8607e-003
36.	5.5889e-004	2.1366e-003
37.	5.6056e-004	2.143e-003
38.	5.6224e-004	2.1495e-003
39.	5.6392e-004	2.1559e-003
40.	5.656e-004	2.1623e-003
41.	5.6728e-004	2.1687e-003

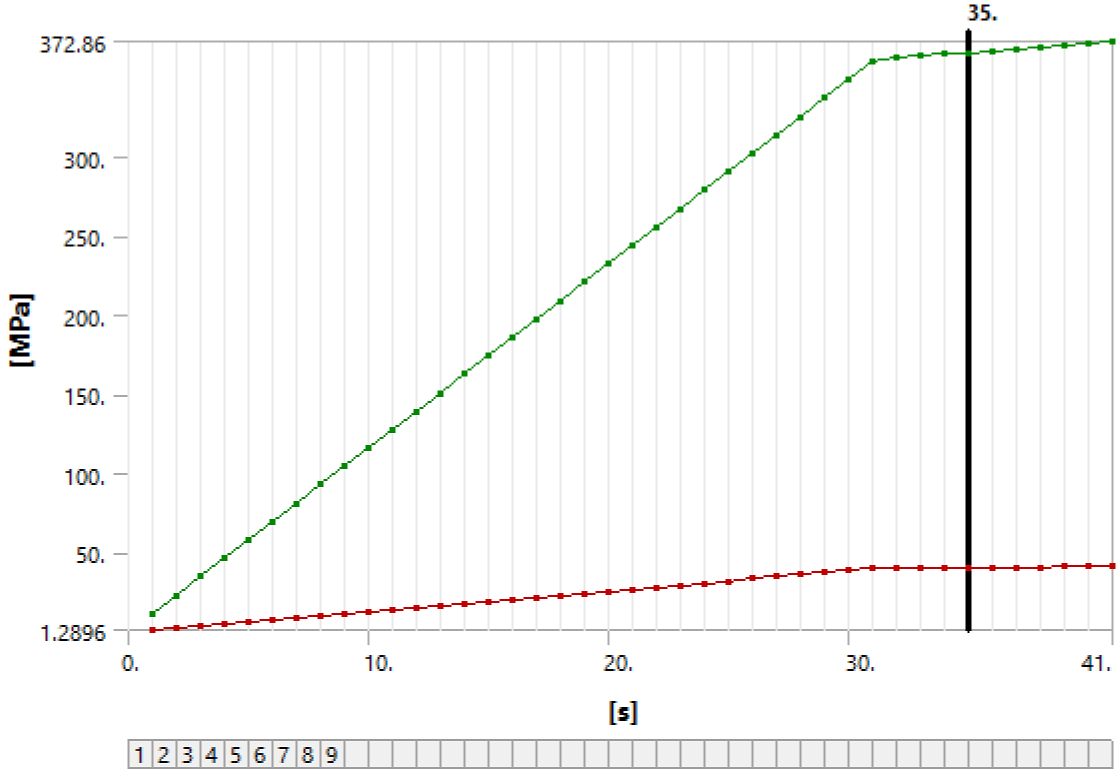

Figure 6. 5 Equivalent stress

Table 6. 14 Equivalent stress

Time [s]	Minimum [MPa]	Maximum [MPa]
1.	3.2925	12.468
2.	6.5849	24.935
3.	9.8774	37.403
4.	13.17	49.87
5.	16.462	62.338
6.	19.755	74.805
7.	23.047	87.273
8.	26.34	99.741
9.	29.632	112.21
10.	32.925	124.68
11.	36.217	137.14
12.	39.509	149.61
13.	42.802	162.08
14.	46.094	174.55
15.	49.387	187.01
16.	52.679	199.48
17.	55.972	211.95
18.	59.264	224.42
19.	62.557	236.88
20.	65.849	249.35

21.	69.142	261.82
22.	72.434	274.29
23.	75.727	286.75
24.	79.019	299.22
25.	82.311	311.69
26.	85.604	324.16
27.	88.896	336.62
28.	92.189	349.09
29.	93.177	352.83
30.	93.506	354.08
31.	93.835	355.33
32.	94.164	356.57
33.	94.494	357.82
34.	95.152	360.31

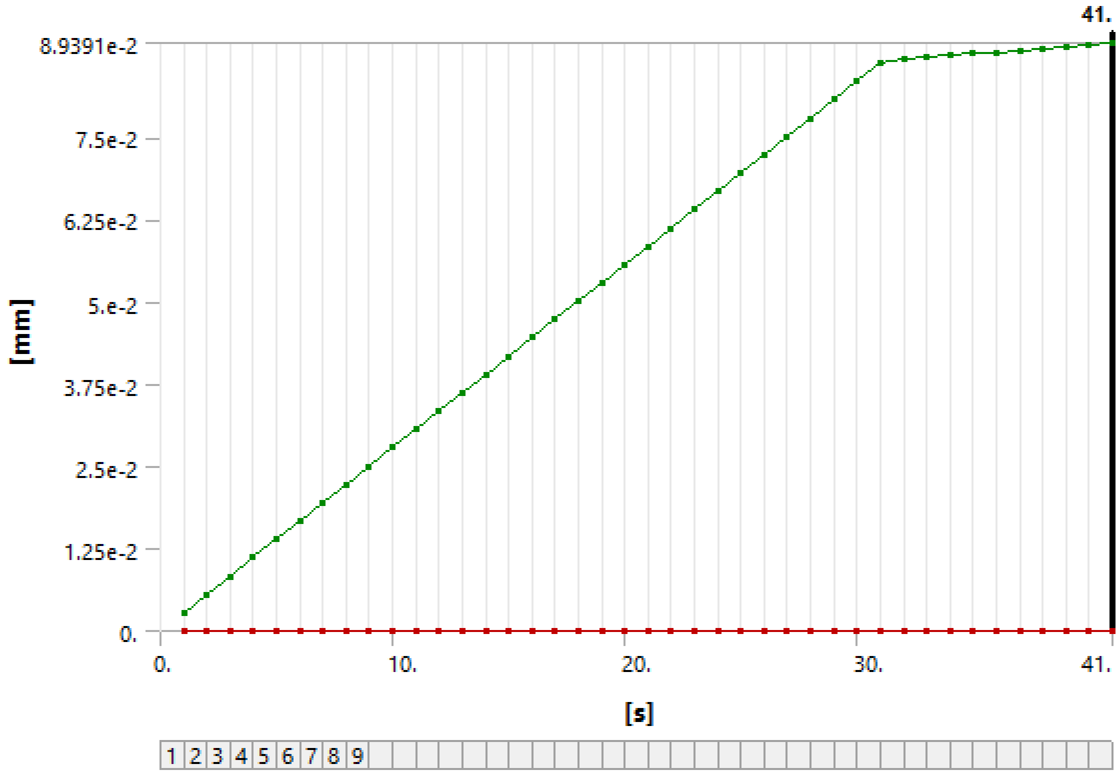

Figure 6. 6 deformation

Table 6. 15 Deformation

Time [s]	Minimum [mm]	Maximum [mm]
1.	0.	3.0046e-003
2.		6.0091e-003
3.		9.0137e-003
4.		1.2018e-002
5.		1.5023e-002
6.		1.8027e-002
7.		2.1032e-002
8.		2.4037e-002

9.		2.7041e-002
10.		3.0046e-002
11.		3.305e-002
12.		3.6055e-002
13.		3.9059e-002
14.		4.2064e-002
15.		4.5069e-002
16.		4.8073e-002
17.		5.1078e-002
18.		5.4082e-002
19.		5.7087e-002
20.		6.0091e-002
21.		6.3096e-002
22.		6.6101e-002
23.		6.9105e-002
24.		7.211e-002
25.		7.5114e-002
26.		7.8119e-002
27.		8.1124e-002
28.		8.4128e-002
29.		8.5029e-002
30.		8.533e-002

31.		8.563e-002
32.		8.5931e-002
33.		8.6231e-002
34.		8.6832e-002
35.		8.7133e-002
36.		0.10005
37.		0.10035
38.		0.10065
39.		0.10095
40.		0.10125
41.		0.10155

Material Data

AISI 1040 Oil Quenched

Table 6. 16 Material data

Density	7.845e-006 kg mm^-3

Table 6. 17 Isotropic elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	2.e+005	0.29	1.5873e+005	77519

Table 6. 18 Yield strength

Tensile Yield Strength MPa
360

Table 6. 19 Ultimate Tensile Strength

Tensile Ultimate Strength MPa
571

Project Report Coated Specimen

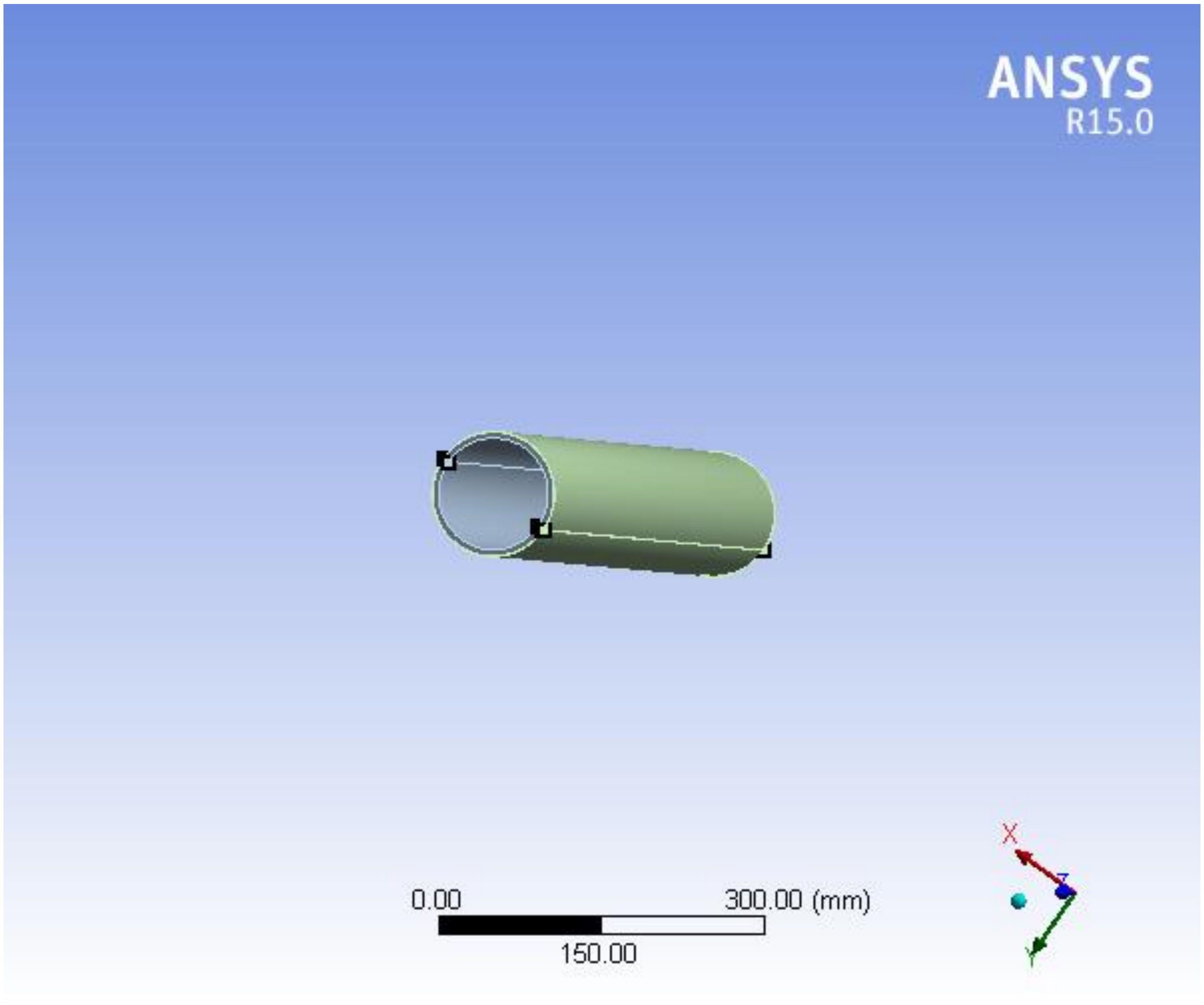

Figure 6. 7 Coated Specimen

Table 6. 20 units

Unit System	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (D4)

Geometry

Table 6. 21 Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\My Files\References\Project\Corrosion\Ansys testing\pipeline simulation\pipeline small testing files\dp0\SYS-5\DM\SYS-5.agdb
Type	Design Modeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	115.3 mm
Length Y	115.3 mm
Length Z	1000. mm
Properties	

Volume	2.0798e+006 mm³
Mass	16.197 kg
Scale Factor Value	1.
Statistics	
Bodies	2
Active Bodies	2
Nodes	4640
Elements	640
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No

Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\500025641\AppData\Local\Temp
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

Table 6. 22 Geometry Parts

Object Name	*Solid*	*Solid*
State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	
Definition		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default Coordinate System	
Reference Temperature	By Environment	
Material		
Assignment	AISI 1040 Oil Quenched	Chromium for Project 2

Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
Bounding Box		
Length X	114.3 mm	115.3 mm
Length Y	114.3 mm	115.3 mm
Length Z	1000. mm	
Properties		
Volume	1.8992e+006 mm³	1.8058e+005 mm³
Mass	14.899 kg	1.2984 kg
Centroid X	4.1329e-012 mm	2.1161e-012 mm
Centroid Y	1.3522e-002 mm	1.4274e-002 mm
Centroid Z	-6.2496e-013 mm	-6.2177e-012 mm
Moment of Inertia Ip1	1.2576e+006 kg·mm²	1.0964e+005 kg·mm²
Moment of Inertia Ip2	1.2576e+006 kg·mm²	1.0964e+005 kg·mm²
Moment of Inertia Ip3	43739 kg·mm²	4230.9 kg·mm²
Statistics		
Nodes	2320	
Elements	320	
Mesh Metric	None	

Table 6. 23 Coordinate systems

Object Name	*Global Coordinate System*

State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. mm
Origin Y	0. mm
Origin Z	0. mm
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Connections

Table 6. 24 Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

Table 6. 25 Contacts

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.533 mm
Use Range	No
Face/Face	Yes
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies

Table 6. 26 Contact regions

Object Name	*Contact Region*
State	Fully Defined

Scope	
Scoping Method	Geometry Selection
Contact	2 Faces
Target	2 Faces
Contact Bodies	Solid
Target Bodies	Solid
Definition	
Type	Bonded
Scope Mode	Automatic
Behavior	Program Controlled
Trim Contact	Program Controlled
Trim Tolerance	2.533 mm
Suppressed	No
Advanced	
Formulation	Program Controlled
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Pinball Region	Program Controlled
Geometric Modification	

Contact Geometry Correction	None

Mesh

Table 6. 27 Meshing

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	162.070 mm
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272

Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	Yes
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default

Statistics	
Nodes	4640
Elements	640
Mesh Metric	None

Table 6. 28 Mesh Controls

Object Name	*Face Sizing*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	12 Faces
Definition	
Suppressed	No
Type	Element Size
Element Size	50. mm
Behavior	Soft

Static Structural (D5)

Table 6. 29 Static Structural

Object Name	*Static Structural (D5)*
State	Solved
Definition	
Physics Type	Structural

Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

Table 6. 30 Analysis settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	41.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full	No

Solve	
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	D:\My Files\References\Project\Corrosion\Ansys testing\pipeline simulation\pipeline small testing files\dp0\SYS-5\MECH\
Future Analysis	None

Scratch Solver Files Directory	
Save MAPDL db.	No
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	mm

Table 6. 31 Loads

Object Name	*Fixed Support*	*Internal pressure*	*Ext pressure*	*Thermal Condition*
State	Fully Defined	Suppressed	Fully Defined	
Scope				
Scoping Method	Geometry Selection			
Geometry	2 Faces			1 Body
Definition				
Type	Fixed Support	Pressure		Thermal Condition
Suppressed	No	Yes	No	
Define By		Normal To		
Magnitude		5. MPa (ramped)	Tabular Data	
Tabular Data				
Independent Variable			Time	

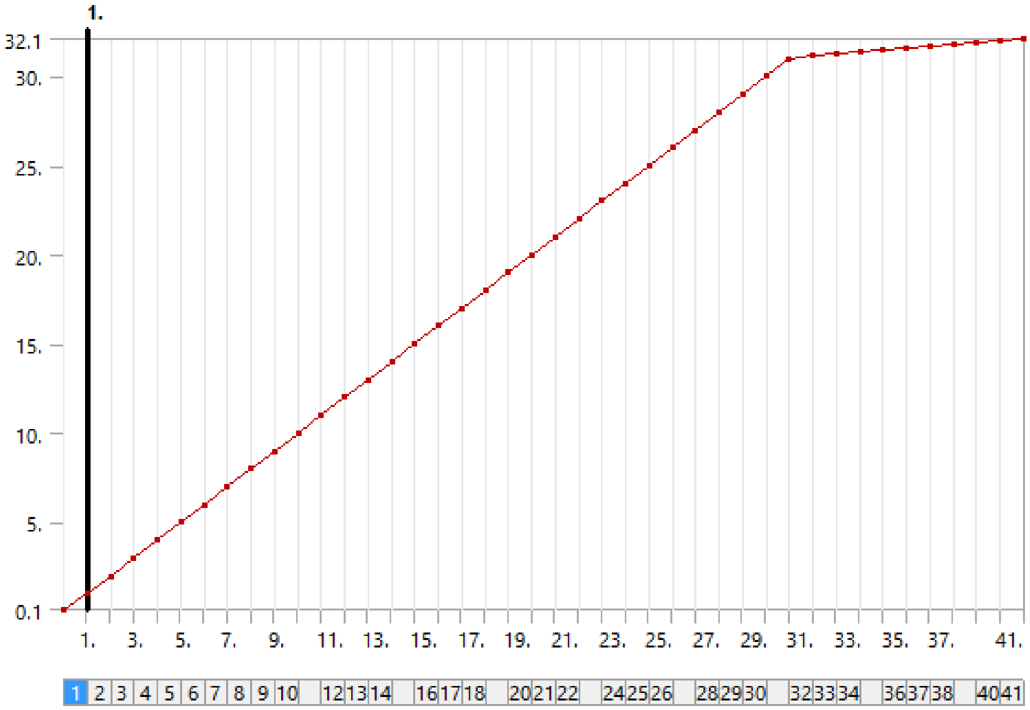

Figure 6. 8 External Pressure

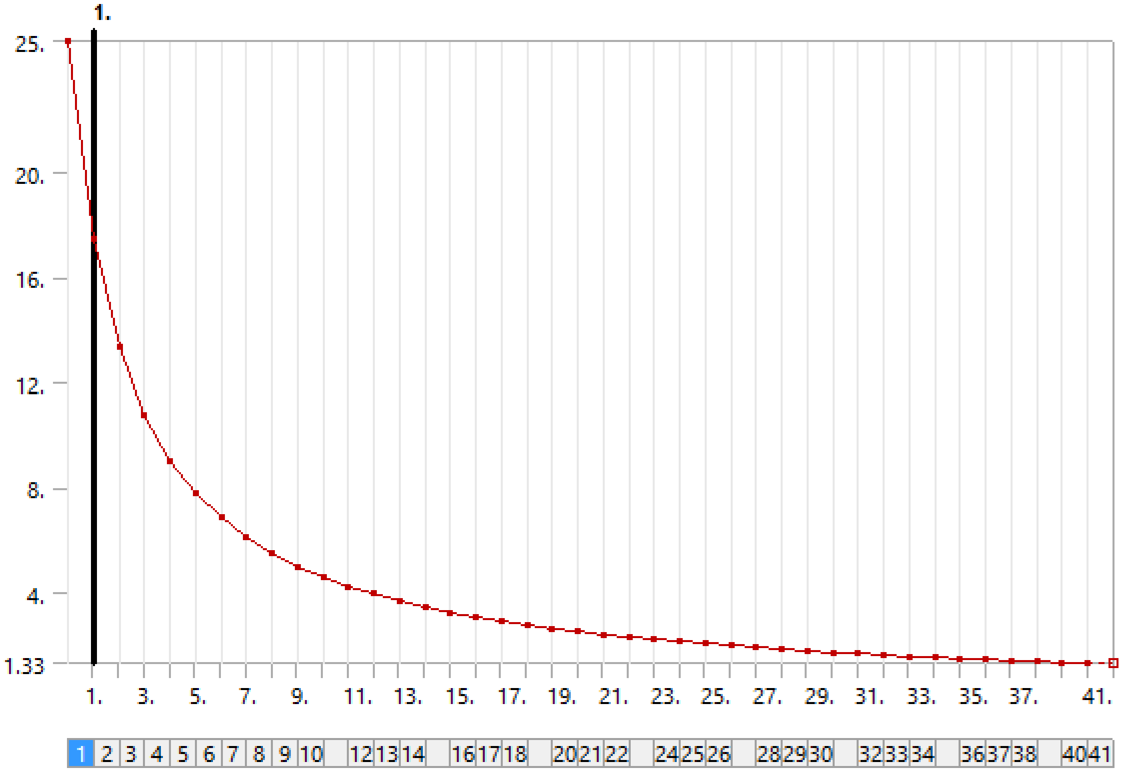

Figure 6. 9 Water Temperature

Table 6. 32 Thermal Condition

Steps	Time [s]	Temperature [°C]
1	0.	25.
	1.	17.47
2	2.	13.35
3	3.	10.782
4	4.	9.049
5	5.	7.7963
6	6.	6.848
7	7.	6.1055
8	8.	5.508
9	9.	5.0174
10	10.	4.606
11	11.	4.2584
12	12.	3.959
13	13.	3.6989
14	14.	3.4709
15	15.	3.2694
16	16.	3.09
17	17.	2.924
18	18.	2.7843
19	19.	2.6531

20	20.	2.5338
21	21.	2.424
22	22.	2.324
23	23.	2.2324
24	24.	2.1472
25	25.	2.0684
26	26.	1.995
27	27.	1.926
28	28.	1.863
29	29.	1.8034
30	30.	1.7474
31	31.	1.69
32	32.	1.64
33	33.	1.59
34	34.	1.55
35	35.	1.51
36	36.	1.47
37	37.	1.43
38	38.	1.39
39	39.	1.36
40	40.	1.33
41	41.	= 1.33

Solution (D6)

Table 6. 33 Solution

Object Name	*Solution (D6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done

Table 6. 34 Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes

Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

Table 6. 35 Results

Object Name	*Equivalent Elastic Strain*	*Equivalent Stress*	*Total Deformation*
State	Solved		
Scope			
Scoping Method	Geometry Selection		
Geometry	All Bodies		
Definition			
Type	Equivalent Elastic Strain	Equivalent (von-Mises) Stress	Total Deformation
By	Time		
Display Time	Last	35. s	Last
Calculate Time History	Yes		
Identifier			
Suppressed	No		
Integration Point Results			
Display Option	Averaged		
Average Across Bodies	No		
Results			

Minimum	2.0823e-004 mm/mm	40.621 MPa	0. mm
Maximum	1.9219e-003 mm/mm	365.89 MPa	8.9391e-002 mm
Minimum Occurs On	Solid		
Maximum Occurs On	Solid		
Minimum Value Over Time			
Minimum	6.4871e-006 mm/mm	1.2896 MPa	0. mm
Maximum	2.0823e-004 mm/mm	41.395 MPa	0. mm
Maximum Value Over Time			
Minimum	5.9872e-005 mm/mm	11.615 MPa	2.7848e-003 mm
Maximum	1.9219e-003 mm/mm	372.86 MPa	8.9391e-002 mm
Information			
Time	41. s	35. s	41. s
Load Step	41	35	41
Sub step	1		
Iteration Number	41	35	41

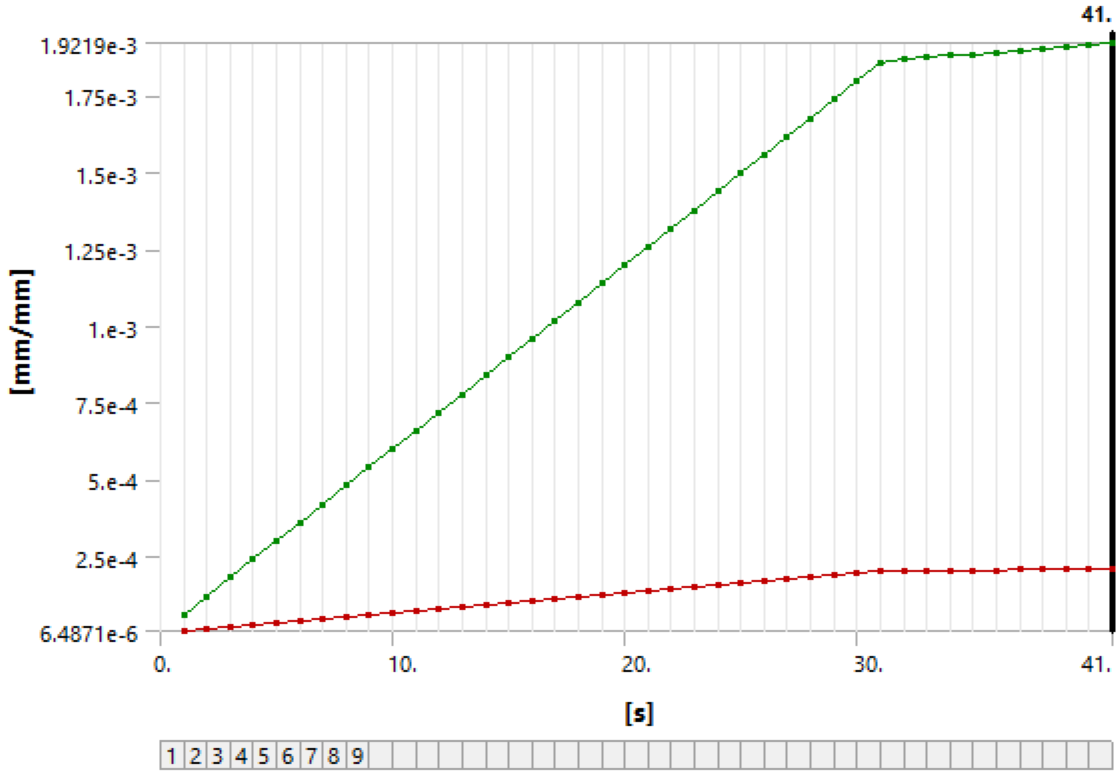

Figure 6. 10 Elastic Strain

Table 6. 36 Elastic Strain

Time [s]	Minimum [mm/mm]	Maximum [mm/mm]
1.	6.4871e-006	5.9872e-005
2.	1.2974e-005	1.1974e-004
3.	1.9461e-005	1.7962e-004
4.	2.5948e-005	2.3949e-004
5.	3.2435e-005	2.9936e-004
6.	3.8922e-005	3.5923e-004
7.	4.5409e-005	4.1911e-004
8.	5.1896e-005	4.7898e-004

9.	5.8384e-005	5.3885e-004
10.	6.4871e-005	5.9872e-004
11.	7.1358e-005	6.5859e-004
12.	7.7845e-005	7.1847e-004
13.	8.4332e-005	7.7834e-004
14.	9.0819e-005	8.3821e-004
15.	9.7306e-005	8.9808e-004
16.	1.0379e-004	9.5796e-004
17.	1.1028e-004	1.0178e-003
18.	1.1677e-004	1.0777e-003
19.	1.2325e-004	1.1376e-003
20.	1.2974e-004	1.1974e-003
21.	1.3623e-004	1.2573e-003
22.	1.4272e-004	1.3172e-003
23.	1.492e-004	1.3771e-003
24.	1.5569e-004	1.4369e-003
25.	1.6218e-004	1.4968e-003
26.	1.6866e-004	1.5567e-003
27.	1.7515e-004	1.6165e-003
28.	1.8164e-004	1.6764e-003
29.	1.8812e-004	1.7363e-003
30.	1.9461e-004	1.7962e-003

31.	2.011e-004	1.856e-003
32.	2.024e-004	1.868e-003
33.	2.0304e-004	1.874e-003
34.	2.0369e-004	1.88e-003
35.	2.0434e-004	1.886e-003
36.	2.0499e-004	1.892e-003
37.	2.0564e-004	1.8979e-003
38.	2.0629e-004	1.9039e-003
39.	2.0694e-004	1.9099e-003
40.	2.0759e-004	1.9159e-003
41.	2.0823e-004	1.9219e-003

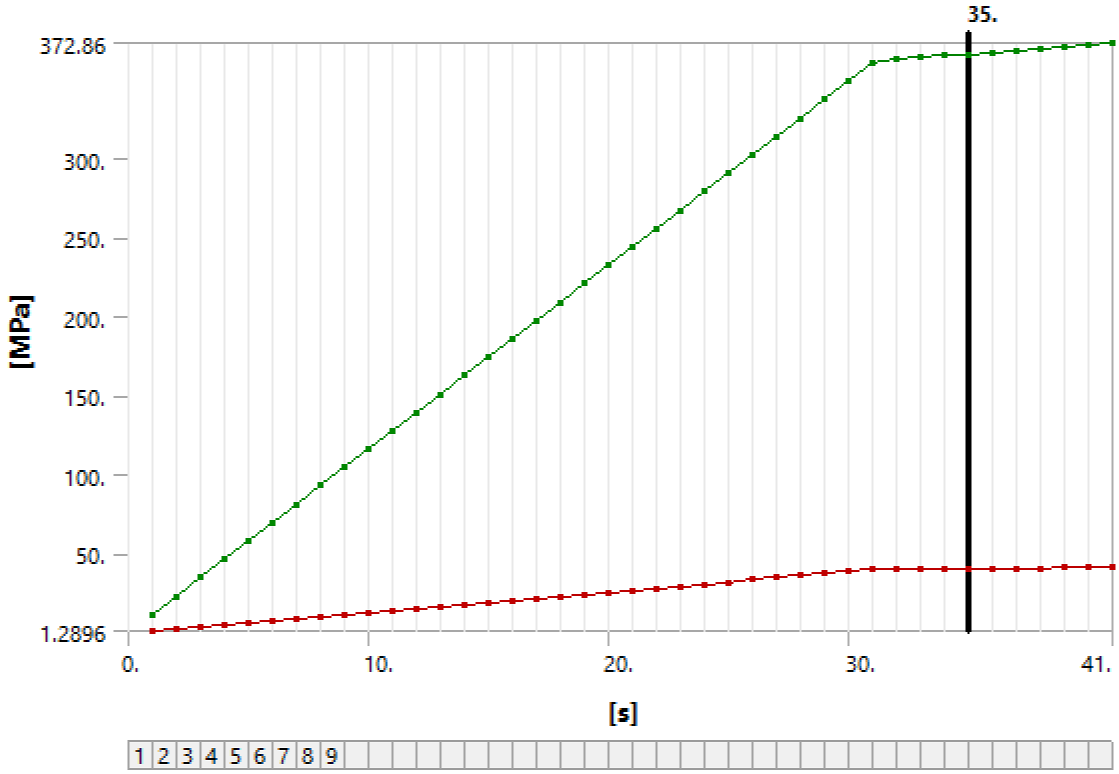

Figure 6. 11 Equivalent stress

Table 6. 37 Equivalent stress

Time [s]	Minimum [MPa]	Maximum [MPa]
1.	1.2896	11.615
2.	2.5791	23.231
3.	3.8687	34.846
4.	5.1582	46.462
5.	6.4478	58.077
6.	7.7373	69.693
7.	9.0269	81.308
8.	10.316	92.924

9.	11.606	104.54
10.	12.896	116.15
11.	14.185	127.77
12.	15.475	139.39
13.	16.764	151.
14.	18.054	162.62
15.	19.343	174.23
16.	20.633	185.85
17.	21.922	197.46
18.	23.212	209.08
19.	24.501	220.69
20.	25.791	232.31
21.	27.081	243.93
22.	28.37	255.54
23.	29.66	267.16
24.	30.949	278.77
25.	32.239	290.39
26.	33.528	302.
27.	34.818	313.62
28.	36.107	325.23
29.	37.397	336.85
30.	38.687	348.46

31.	39.976	360.08
32.	40.234	362.4
33.	40.363	363.56
34.	40.492	364.73
35.	40.621	365.89
36.	40.75	367.05
37.	40.879	368.21
38.	41.008	369.37
39.	41.137	370.53
40.	41.266	371.7
41.	41.395	372.86

FIGURE 6
Model (D4) > Static Structural (D5) > Solution (D6) > Total Deformation

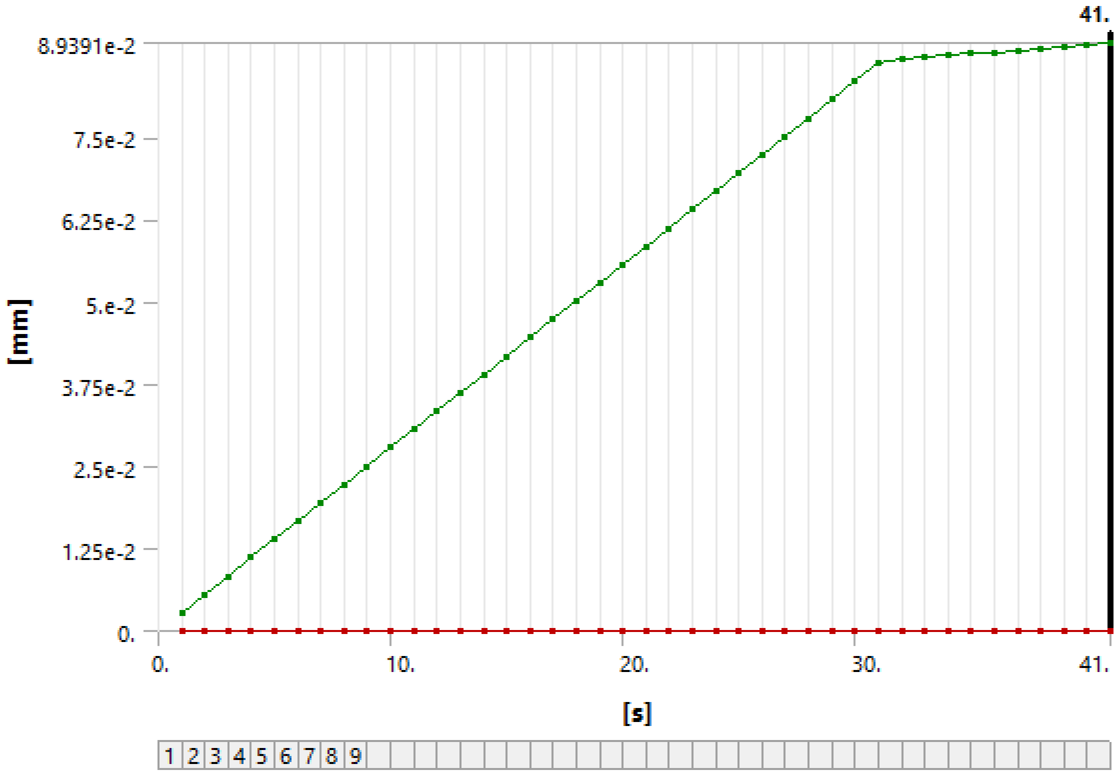

Figure 6. 12 Deformation

Table 6. 38 Deformation

Time [s]	Minimum [mm]	Maximum [mm]
1.	0.	2.7848e-003
2.		5.5695e-003
3.		8.3543e-003
4.		1.1139e-002
5.		1.3924e-002
6.		1.6709e-002
7.		1.9493e-002
8.		2.2278e-002

9.		2.5063e-002
10.		2.7848e-002
11.		3.0632e-002
12.		3.3417e-002
13.		3.6202e-002
14.		3.8987e-002
15.		4.1771e-002
16.		4.4556e-002
17.		4.7341e-002
18.		5.0126e-002
19.		5.291e-002
20.		5.5695e-002
21.		5.848e-002
22.		6.1265e-002
23.		6.4049e-002
24.		6.6834e-002
25.		6.9619e-002
26.		7.2404e-002
27.		7.5188e-002
28.		7.7973e-002
29.		8.0758e-002
30.		8.3543e-002

31.		8.6327e-002
32.		8.6884e-002
33.		8.7163e-002
34.		8.7441e-002
35.		8.772e-002
36.		8.7998e-002
37.		8.8277e-002
38.		8.8555e-002
39.		8.8834e-002
40.		8.9112e-002
41.		8.9391e-002

Material Data

AISI 1040 Oil Quenched

Table 6. 39 Material Data

Density	7.845e-006 kg mm^-3

Table 6. 40 Isentropic Elastic

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	2.e+005	0.29	1.5873e+005	77519

Table 6. 41 Yield Strength

Tensile Yield Strength MPa
360

Table 6. 42 Ultimate Tensile Strength

Tensile Ultimate Strength MPa
571

Nickel Chromium

Table 6. 43 Coating density

Density	7.79e-006 kg mm^-3

Table 6. 44 Material inputs

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	2.e+005	0.21	1.1494e+005	82645

Table 6. 45 Yield Strength

Tensile Yield Strength MPa
135

Table 6. 46 Tensile Ultimate Strength

Tensile Ultimate Strength MPa
279

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