Improvement on Wear Resistance of 316 Austenitic Stainless Steel by High Temperature Nitriding Technique

By

MOHD KHAIRUL MUNIR B KAMARUZAMAN

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfillment of requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

JUNE 2010

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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DR PATTHI BIN HUSSAIN

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JUNE 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MR MOHD KHAIRUL MUNIR BIN KAMARUZAMAN)

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Bismillahirrahmanirrahim.

Alhamdulillah, with the help of His Almighty, I eventually succeed in completing my research project within time given.

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ABSTRACT

The purpose of this project is to study on wear resistance of 316L Austenitic Stainless steel and makes an improvement on it by applying high temperature nitriding technique. Wear resistance of current stainless steel in market indeed is not sufficient to sustain this kind of heavy loads. Thus, wear resistance of stainless steel needs to be improved in order to overcome this problem. The process of high-temperature nitriding is investigated as a method of intensifying diffusion saturation with nitrogen for some high-alloy steels of the Ferritic and austenitic types. High-strength austenitic stainless steels can be produced by **replacing carbon with nitrogen [1, 2].** High temperature nitriding using Gas nitriding is a case-hardening process whereby nitrogen is introduced into the surface of a solid ferrous alloy by holding the metal at extremely high temperature of 1200°C in contact with a nitrogenous gas. In order to achieve this, the samples are prepared as per received and nitrided one. For nitriding process, the sample undergo the heat treatment for 3 hours and 5 hours duration in the tube furnace under the temperature of 1200°C with the nitrogen is supplied through it. Both nitrided and as received sample then undergo several testing such as hardness testing and scratch resistance testing. The difference result yield from the testing then compared between the as received and nitrided one. For the hardness test, it is proved that the hardness increases up to 26% after undergoing the nitriding method on the sample. So do for the scratch resistance testing result. The result showed that hardness is improved as the depth of penetration for nitrided one is shallower compared to the as received one.

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CHAPTER 1
INTRODUCTION

1. BACKGROUND

1.1 Stainless Steel

Stainless Steel is a common name for metal alloys that consist of 10.5% or more Chromium (Cr) and more than 50% Iron (Fe) [1][7]. Although it is called "stainless", a better term for it is "highly stain resistant". The chromium content in stainless steel alloys is what generally prevents corrosion. Pure iron, the primary element of stainless steel, is extracted from its natural state as iron ore, it is unstable by itself, and naturally wants to corrode (rust). The chromium helps to procrastinate nature's attempts to combine the pure iron with oxygen and water to form rust.

The chromium works by reacting with oxygen to form a tough, adherent, invisible, passive layer of chromium oxide film on the steel surface. If damaged mechanically or chemically, this film is self healing as long as it has enough oxygen. Because oxygen is necessary for the reaction, liquids and other foodstuffs stored for a prolonged time in stainless can prevent oxygen contact and thus promote corrosion, as can prolonged contact with household cleaners such as bleach. Generally, an increase of chromium content improves the corrosion resistance of stainless steels. The addition of nickel is used to raise the general corrosion resistance required in more aggressive usage or conditions. The presence of molybdenum (Mo) improves the localized corrosion resistance, such as against pitting (scarring).

Other alloying metals are also used to improve the structure and properties of stainless steels, such as Titanium, Vanadium and Copper. Non metal additions typically include natural elements such as Carbon & Nitrogen, as well as Silicon. High-carbon stainless steel contains a minimum of 0.3% carbon [1]. The higher the carbon content, the less formable and the tougher the steel becomes. Its hardness makes it suitable for things such as cutting edges, and other high-wear applications like plow blades. Carbon thus helps makes the edge easier to sharpen, and helps retain a sharp edge longer.

1.1.1 Stainless Steel - Mechanical Properties

The mechanical properties of stainless steels are almost always requirements of the product specifications used to purchase the product. For flat rolled products the properties usually specified are tensile strength, yield stress (or proof stress), elongation and Brinell or Rockwell hardness [1][7]. Much less frequently there are requirements for impact resistance, either Charpy or Izod. Bar, tube, pipe, fittings etc. also usually require at least tensile strength and yield stress. These properties give a guarantee that the material in question has been correctly produced, and are also used by engineers to calculate the working loads or pressures that the product can safely carry in service.

1.1.2 Typical Properties

Typical mechanical properties of annealed materials are as in the graph of Figure 1.1 Note that the high cold work hardening rate of the austenitic grades in particular results in actual properties of some commercial products being significantly higher than these values. The yield stress (usually measured as 0.2% proof stress) is particularly increased by even quite minor amounts of cold work [8]. More details of the work hardening of stainless steels are given in the section of this handbook on fabrication.

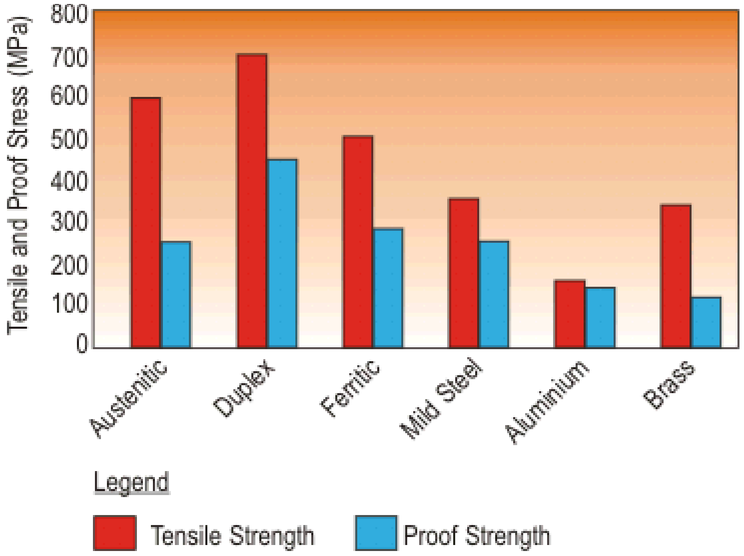


Figure 1.1: Typical Tensile Properties of Annealed Materials [2].

1.1.3 Yield Strength

An unusual feature of annealed austenitic stainless steels is that the yield strength is a very low proportion of the tensile strength, typically only 40-45%. The comparable figure for a mild steel is about 65-70% [7]. As indicated above a small amount of cold work greatly increases the yield (much more so than the tensile strength), so the yield also increases to a higher proportion of tensile. Only a few % of cold work will increase the yield by 200 or 300MPa, and in severely cold worked material like spring temper wire or strip, the yield is usually about 80-95% of the tensile strength[1][7].

As engineering design calculations are frequently made on yield criterion the low yield strength of austenitic stainless steels may well mean that their design load cannot be higher than that of mild steel, despite the tensile strength being substantially higher. Design stresses for various grades and temperatures are given in Australian Standard AS1210 "Unfired Pressure Vessels".

1.1.4 Ductility

The other mechanical property of note is the ductility, usually measured by %

elongation during a tensile test. This shows the amount of deformation a piece of metal will withstand before it fractures. Austenitic stainless steels have exceptionally high elongations, usually about 60-70% for annealed products, as shown in figure 1.2. It is the combination of high work hardening rate and high elongation that permits the severe fabrication operations which are routinely carried out, such as deep drawing of kitchen sinks and laundry troughs.

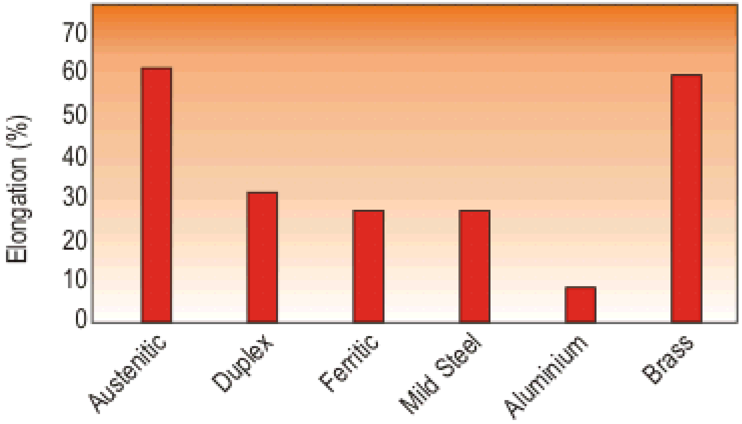


Figure 1.2: Typical elongations of annealed materials [2].

1.1.5 Hardness

Hardness (measured by Brinell, Rockwell or Vickers machines) is another value for the strength of a material. Hardness is usually defined as resistance to penetration, so these test machines measure the depth to which a very hard indenter is forced into a material under the action of a known force [6]. Each machine has a different shaped indenter and a different force application system, so conversion between hardness scales is not generally very accurate. Although conversion tables have been produced these conversions are only approximate, and should not be used to determine conformance to standards.

It is also sometimes convenient to do a hardness test and then convert the result to tensile strength. Although the conversions for carbon and low alloy steels are fairly reliable, those for stainless steels are much less so.

The next most widely used grades are the ferritic steels such as AISI 410 followed by the molybdenum-alloyed steels AISI 316 and AISI 316L. Together these grades make up over 80% of the total tonnage of stainless steels. Stainless steels with their excellent corrosion properties have a very broad application range. This extends to Chemical plants, Dairy and Food processing industries, Nuclear power plants, Heat exchangers, Laboratory benches and Equipments.

1.2 Austenitic Stainless Steel

Austenitic stainless steel is a type of non-magnetic stainless steels that contain nickel and chromium sufficient to develop and retain the austenitic phase at room temperature [1,6]. It cannot be hardened by normal heat-treatment but do work harden. Austenitic stainless steel, also known as the 300 series, is the most common and abundantly used steel. It contains 0.15% carbon and 16% chromium, along with other elements like nickel, nitrogen and manganese [1]. It is ductile and also highly resistant to corrosion. Type 304 and 316 are the most commonly used type of stainless steel. It is the classic 18/8 stainless steel. This type of stainless steel is used for making shafts, pumps, etc.

Austenitic stainless steels have high ductility, low yield stress and relatively high ultimate tensile strength, when compare to typical carbon steel [1]. Austenitic steels have a F.C.C atomic structure which provides more planes for the flow of dislocations, combined with the low level of interstitial elements (elements that lock the dislocation chain), gives this material its good ductility. This also explains why this material has no clearly defined yield point, which is why its yield stress is always expressed as a proof stress. Austenitic steels have excellent toughness down to true absolute (-273°C), with no steep ductile to brittle transition [1, 2].

1.2.1. 316 Austenitic Stainless Steel

1.2.1.1 General Properties

Alloys 316 (UNS S31600), 316L (S31603), and 317L (S31703) are molybdenum-bearing austenitic stainless steels which are more resistant to general corrosion and pitting/crevice corrosion than the conventional chromium-nickel austenitic stainless steels such as Alloy 304 [16]. These alloys also offer higher creep, stress-to-rupture, and tensile strength at elevated temperature. Alloy 317L containing 3 to 4% molybdenum is preferred to Alloys 316 or 316L which contain 2 to 3% molybdenum in applications requiring enhanced pitting and general corrosion resistance.

In addition to excellent corrosion resistance and strength properties, the Alloys 316, 316L, and 317L Cr-Ni-Mo alloys also provide the excellent fabricability and formability which are typical of the austenitic stainless steels.

1.2.1.2 Composition

The chemical compositions which represented by ASTM A240 and ASME SA-240 specifications are indicated in the table below.

Table 1.1: Austenitic stainless steel composition table [16]

	Percentage by Weight (maximum unless range is specified)		
Element	**Alloy 316**	**Alloy 316L**	**Alloy 317L**
Carbon	0.08	0.030	0.030
Manganese	2.00	2.00	2.00
Silicon	0.75	0.75	0.75
Chromium	16.00 18.00	16.00 18.00	18.00 20.00
Nickel	10.00 14.00	10.00 14.00	11.00 15.00
Molybdenum	2.00 3.00	2.00 3.00	3.00 4.00
Phosphorus	0.045	0.045	0.045

Sulfur	0.030	0.030	0.030
Nitrogen	0.10	0.10	0.10
Iron	Balance	Balance	Balance

1.2.1.3 Resistance to Corrosion

Alloys 316, 316L, and 317L are more resistant to atmospheric and other mild types of corrosion than the 18-8 stainless steels. Alloys 316 and 317L are considerably more resistant than any of the other chromium-nickel types to solutions of sulfuric acid. At temperatures as high as 120°F (38°C), both types have excellent resistance to higher concentrations [16]. Service tests are usually desirable as operating conditions and acid contaminants may significantly affect corrosion rate. Where condensation of sulfur-bearing gases occurs, these alloys are much more resistant than other types of stainless steels. In such applications, however, the acid concentration has a marked influence on the rate of attack and should be carefully determined.

Generally, the Alloy 316 and 316L grades can be considered to perform equally well for a given environment. The same is true for Alloy 317L. A notable exception is in environments sufficiently corrosive to cause intergranular corrosion of welds and heat-affected zones on susceptible alloys. In such media, the Alloy 316L and 317L grades are preferred for the welded condition since low carbon levels enhance resistance to intergranular corrosion.

1.2.1.4 Physical Properties

a) Structure

When properly annealed, Alloys 316 and 317L are primarily austenitic. Small quantities of ferrite may or may not be present. When slowly cooled or held in the temperature range 800 to 1500°F (427 to 816°C), carbides are precipitated and the structure consists of austenite plus carbides [16].

b) Melting Range: 2450 to 2630°F (1390 to 1440°C)

c) Density: 0.29 lb/in^3 (8.027 g/cm^3)

d) Modulus of Elasticity in Tension: 29 x 10^6 psi (200 Gpa)

e) Modulus of Shear: 11.9 x 10^6 psi (82 Gpa)

Table 1.2: Coefficient of Linear Thermal Expansion austenitic stainless steel

Temperature Range		**Coefficients**	
°F	**°C**	**in/in/°F**	**cm/cm/°C**
68 - 212	20 - 100	9.2 x 10^{-6}	16.5 x 10^{-6}
68 - 932	20 - 500	10.1 x 10^{-6}	18.2 x 10^{-6}
68 - 1832	20 - 1000	10.8 x 10^{-6}	19.5 x 10^{-6}

1.2.1.5 Thermal Conductivity

Table 1.3: Thermal conductivity of austenitic stainless steel

Temperature Range		**Btu•in/hr•ft^2•°F**	**W/m•K**
°F	**°C**		
68 - 212	20 - 100	100.8	14.6

The overall heat transfer coefficient of metals is determined by factors in addition to thermal conductivity of the metal. The ability of the 18-8 stainless grades to maintain clean surfaces often allows better heat transfer than other metals having higher thermal conductivity.

1.2.1.6 Specific Heat

Table 1.4: Specific heat of austenitic stainless steel

°F	°C	Btu/lb•°F	Jkg•K
68	20	0.108	450
200	93	0.116	485

1.2.1.7 Electrical Resistivity

Table 1.5: Electrical resistivity of austenitic stainless steel

Alloy	**Value at 68°F (20°C)**	
	Microhm-in.	**Microhm-cm.**
316	29.1	74.0
317	31.1	79.0

1.2.1.8 Mechanical Properties

Minimum mechanical properties for annealed Alloys 316, 316L and 317L austenitic stainless steel plate as required by ASTM specifications A240 and ASME specification SA-240 are shown below.

Table 1.6: Mechanical properties of austenitic stainless steel

Property	**Minimum Mechanical Properties Required by ASTM A240 and ASME SA-240**		
	Alloy 316 (S31600)	**Alloy 316L (S31603)**	**Alloy 317L (S31703)**
Yield Strength 0.2% Offset psi (MPa)	30,000 (205)	25,000 (170)	30,000 (205)
Ultimate Tensile Strength	75,000 (515)	70,000 (485)	75,000 (515)

psi (MPa)			
Percent Elongation in 2 in. or 51 mm.	40.0	40.0	40.0
Hardness Max. Brinell (R_B)	217 (95)	217 (95)	217 (95)

1.2.1.9 Fatigue Strength

The fatigue strength or endurance limit is the maximum stress below which material is unlikely to fail in 10 million cycles in air environment. For austenitic stainless steels as a group, the fatigue strength is typically about 35 percent of the tensile strength. Substantial variability in service results is experienced since additional variables such as corrosive conditions, form of stress and mean value, surface roughness, and other factors affect fatigue properties. For this reason, no definitive endurance limit values can be given which are representative of all operating conditions.

1.2.1.10 Heat Treatment

Annealing

The austenitic stainless steels are provided in the mill annealed condition ready for use. Heat treatment may be necessary during or after fabrication to remove the effects of cold forming or to dissolve precipitated chromium carbides resulting from thermal exposures. For the Alloys 316 and 317L the solution anneal is accomplished by heating in the 1900 to 2150°F (1040 to 1175°C) temperature range followed by air cooling or a water quench, depending on section thickness. Cooling should be sufficiently rapid through the 1500 to 800°F (816 to 427°C) range to avoid reprecipitation of chromium carbides and provide optimum corrosion resistance. In every case, the metal should be cooled from the annealing temperature to black heat in less than three minutes.

1.2.2 Wear in Stainless Steel

Wear is defined as the undesired cumulative change in dimensions brought about by the gradual removal of discrete particles from contacting surfaces in motion, due to predominantly to mechanical action [5]. Wear is, in fact not a single process but a number of different process that may take place independently or in combination. It is related to surface interactions and more specifically the removal of material from a surface as a result of mechanical action.[5] The need for mechanical action, in the form of contact due to relative motion, is an important distinction between mechanical wear and other processes with similar outcomes.

Under normal operating parameters, the property changes during usage normally occur in three different stages as follows:

- Primary or early stage or run-in period, where rate of change can be high.
- Secondary or mid-age process where a steady rate of aging process is maintained. Most of the useful or working life of the component is comprised in this stage.
- Tertiary or old-age stage, where a high rate of aging leads to rapid failure.

With increasing severity of environmental conditions such as higher temperatures, strain rates, stress and sliding velocities, the secondary stage is shortened and the primary stage tends to merge with the tertiary stage, thus drastically reducing the working life. Surface engineering processes are used to minimize wear and extend working life of material. [4][5]

The mechanism of wear is very complex and the theoretical treatment without the use of rather sweeping simplifications is not possible. The real area of contact between two solid surfaces compared with the apparent area of contact is invariably very small, being limited to points of contact between surface asperities. The load applied to the surfaces will be transferred through these points of contact and the localized forces can be very large. The material intrinsic surface properties such as hardness, strength, ductility, work hardening etc. are very important factors for wear resistance, but other factors like surface finish, lubrication, load, speed, corrosion, temperature and properties of the opposing surface etc. are equally important.

In addition, the categories of fretting wear and impact wear [3, 4, 5] have been recognized by wear specialists. Erosion and cavitations are sometimes considered to be categories of wear as well.

Wear is one of the mechanical failures that always happen on stainless steels. It damages the surface of steels as a result of relative motion with respect to another substance. There are five major subcategories of wear, [5] including:-

a) adhesive wear
b) abrasive wear
c) corrosive wear
d) surface fatigue wear
e) deformation wear

In addition, the categories of fretting wear and impact wear [3, 4, 5] have been recognized by wear specialists. Erosion and cavitations are sometimes considered to be categories of wear as well. For stainless steel, wear can cause geometrical changes both on a macro and micro-scale. On macro-scale, the nature of the contact between two bodies changes, effecting the distribution of stress and load across the contact region.

1.3 Problem Statement

Austenitic stainless steels are known for their excellent corrosion resistance. However their hardness and wear resistance are relatively low. The large wear in abrasively stressed part leads to short life times that could be prolonged with improved tribological properties.

1.4 Objective

The objectives of this project is to study on wear resistance of 316 Austenitic Stainless steel and makes an improvement on it by applying high temperature nitriding technique.

1.5 Scope of Work

The scope of work includes understanding the definition of stainless steel and its worldwide uses in industries. It also involves studying its types, behaviors and properties, weaknesses and the way to improve it. Another scope of study is to understand the characteristic of Austenitic Stainless Steel and how the material properties, especially wear resistance of material can be improved by applying a special technique called High Temperature Nitriding. And of course it is important to study the concept of applying nitrogen to steel first.

CHAPTER 2

LITERATURE REVIEW

2. NITRIDING PROCESS: LITERATURE REVIEW

2.1 History of Nitriding Process

Nitriding technique is not a new method in industries as it has already been discovered few centuries ago. **Dr. Adolph Fry** in the early 1900's [17] found that nitrogen and iron had an affinity to one another, much the same way that aluminum and iron contact under heat can cause soldering to occur in die casting dies. From his work in 1906 he developed the iron-nitrogen equilibrium diagram. This diagram is still valid today. If heat is applied to both iron and a nitrogen gas, the nitrogen will diffuse in the surface of the steel and along with this create a structural change in the surface of the steel affecting the hardness. This increase, it was noted, went from 282 to 470 Brinell Hardness in steel containing 0.39% carbon and 2.88 % chromium.

From this began the development of extremely high surface hardness steels called "Nitralloy" steels. These steels provided high resistance to decomposition along with being stable to temperatures up to 1800 degrees F. Dr. Fry also investigated the effect of adding other alloys such as vanadium, tungsten, manganese, molybdenum, and titanium and discovered that all of these elements would also produce stable high nitrogen content nitrides.

At the same time in New Jersey, **Adolph Machlet** while working for American Gas Company in Elizabeth, was also studying absorption of nitrogen into iron under heat conditions [17]. He applied for his patents somewhat earlier than Fry. He consequently received his patent long before Fry on June 24, 1913. Sad to say no commercial benefits were recognized by US industries at the time, however, Dr. Jeffries in Essen Germany saw otherwise and pushed for America to further develop it.

In 1927 at an SME convention in Chicago a good friend of Fry, Pierre Aubert presented both the research and practical applications for it that were being used in Europe. These included, railway steel, machine tools, along with other applications in both the auto and aviation industries. Here are some of the benefits explained at the time:

- High surface hardness with practically no distortion
- Core material properites did not change
- Higher wear resistance than those acheived at the time with other surface treatments
- Tempering did not negate the hardness advantages
- No shelf life aging since parts were free of internal stress
- Corrosion resistance

These benefits still hold true today, however, the techniques for creating the diffusion have advanced and improved.

Work continued and in 1928, McQuaid and Ketchum both metallurgists at Timken - Detroit Axle Co. presented yet another paper using the work of Fry and Machlet as their pivot point along with some of their own investigative work into practical applications and costs.

Next in 1929, Robert Sergeson from Central Alloy Steel Corp. in Canton, Ohio did work that was published with regard to the effect of varying the aluminum content of the nitralloy along with the effect of nickel.

It was not until V.O. Homberg and J.P. Walsted at MIT that any work was done on the effect of varied temperature on the physical properties of the nitriding steels, equipment preheat-treatment, and decarburization effects on nitrided steel. In their work, the initial comments were made regarding the phenomena of "white layer" and its effects on component performance.

Dr. Carl F. Floe an Associate Professor at MIT continued the study of the "white layer" (epsilon) effect and supported discussions of various methods to change the composition and reducing or changing this thin hard layer. His work today is known as the "The Floe Process" [17].

All of this early pioneering work in the field of nitriding ranging from process control, evaluation of metallurgical results, alloy steel developments, and most others still are gospel in today's processing environments.

This early work led the way for the 1930 Plasma Ion Nitriding or "Glow Discharge Technique" as it is also known. The jump start for this technology was the desire to be able to shorten cycle times, reduce distortion and improve upon the metallurgical problems and properties associated with nitriding.

Continuing development, refinement, and modern day capabilities have progressed carbonitriding from the early liquid, gas, and plasma to controlled atmosphere methods. Now in the early 21st Century comes automated ferritic nitrocarburizing.

2.2. Nitriding: Background

Stainless steel nowadays is widely used not only in moderate industries but also in heavy industries such as oil and gas field. Stainless steel is well-known of its resistant to corrosion and pitting. Furthermore, its nice appearance makes it most preferred in making households things like cutleries. However, in oil and gas, heavy duty tasks carried out need the equipment to withstand massive workloads and pressures. When exposing to this situation for a long periods of time, the current equipment can no longer withstands the loads and then fails. Wear resistance of current stainless steel in market indeed is not sufficient to sustain this kind of heavy loads. Thus, wear resistance of stainless steel needs to be improved in order to overcome this problem. One of the methods of improvement is by applying nitriding method.

Nitriding is widely used in various branches of machines construction. It is used for surface hardening of broad variety of machine parts in very different applications and also to increase service life of machineries. In industries, stainless steel can immensely benefit from additions of nitrogen, since nitrogen improves the mechanical properties as well as the corrosion resistance. Favoured for component that subjected to heavy loading, nitriding imparts high surface hardness which promotes high resistance to wear, scuffing, galling and seizure. Thus, it is well documented that in austenitic steels of intentionally low nickel content, nitrogen serves to increase the yield strength, the ultimate tensile strength, and the ductility, as well as the resistance to pitting corrosion, crevice corrosion, and **wear** [6].

The process of high-temperature nitriding is investigated as a method of intensifying diffusion saturation with nitrogen for some high-alloy steels of the ferritic and austenitic types. High-strength austenitic stainless steels can be produced by **replacing carbon with nitrogen [1, 2].** Nitrogen has greater solid-solubility than carbon, is a strong austenite stabilizer, potent interstitial solid-solution strengtheners, and improves pitting corrosion resistance and wears resistance [2, 3].

An austenitic stainless steel should be considered high-nitrogen if it contains more nitrogen than can be retained in the material by processing at atmospheric pressure. For most alloys, this limit is approximately 0.4 wt. % [3]. This kind of process describes melting and processing technologies that applicable to high-nitrogen steels and the effects of interstitial nitrogen on a variety of material properties. Nitrided case-hardened steels exhibit high surface hardness values at elevated temperature as well as improved corrosion resistance under alkaline conditions (except in the case of stainless steel) [3].

Benefits of nitriding:-

- High surface hardness values
- Increase wear resistance and antigalling properties
- Improvement in fatigue life
- Improvement of corrosion resistance
- High surface hardness, resistance to temperatures up to at least the nitriding temperature
- Low distortion and movement due to low processing temperatures

2.3 Types of Nitriding Process

The processes are named after the medium used to donate nitrogen. The three main methods used are: **gas nitriding, salt bath nitriding, and plasma nitriding.**

2.3.1 Gas nitriding

In gas nitriding the donor is nitrogen rich gas usually ammonia (NH_3), which is why it is sometimes known as ammonia nitriding. When ammonia comes into contact with the heated work piece it disassociates into nitrogen and hydrogen [18]. The nitrogen then diffuses from the surface into the core of the material. This process has been around for nearly a century though only in the last few decades has there been a concentrated effort to investigate the thermodynamics and kinetics involved. Recent developments have lead to a process that can be accurately controlled. The thickness and phase constitution of the resulting nitriding layers can be selected and the process optimized for the particular properties required. The advantages of gas nitriding over the other variants are:

- All round nitriding effect (can be a disadvantage in some cases, compare with plasma nitriding)
- Large batch sizes possible - the limiting factor being furnace size and gas flow

- With modern computer control of the atmosphere the nitriding results can be tightly controlled
- Relatively cheap equipment cost - especially compared with plasma

The disadvantages of gas nitriding are:

- Reaction kinetics heavily influenced by surface condition - an oily surface or one contaminated with cutting fluids for example will deliver poor results
- Surface activation is sometimes required to successfully treat steels with a high chromium content - compare sputtering during plasma nitriding
- Ammonia as nitriding medium - though not especially toxic it can be harmful when inhaled in large quantities. Also, care must be taken when heating in the presence of oxygen to reduce the risk of explosion

2.3.2 Salt bath nitriding

In salt bath nitriding the nitrogen donating medium is a nitrogen containing salt such as cyanide salt. The salts used also donate carbon to the workpiece surface making salt bath a nitrocarburizing process. The temperature used is typical of all nitrocarburizing processes: 550–590 °C (1,022–1,094 °F) [18]. The advantages of salt nitriding are:

- Quick processing time - usually in the order of 4 hours or so to achieve
- Simple operation - heat the salt and workpieces to temperature and submerge until the duration has expired

The disadvantages are:

- The salts used are highly toxic - Disposal of salts are controlled by stringent environmental laws in western countries and has increased the costs involved in using salt baths. This is one of the most significant reasons the process has fallen out of favor in the last decade or so.
- Only one process possible with a particular salt type - since the nitrogen potential is set by the salt, only one type of process is possible

2.3.3 Plasma nitriding

Plasma nitriding, also known as ion nitriding, plasma ion nitriding or glow-discharge nitriding is an industrial surface hardening treatment for metallic materials. There are hot plasmas typified by plasma jets used for metal cutting, welding, cladding or spraying. There are also cold plasmas, usually generated inside vacuum chambers, at low pressure regimes. Here the high temperature characteristics of the ionized gases are not used, but the electronic properties become more useful. Thus an ionized gas like nitrogen in such a low pressure regime becomes much more reactive.

Usually steels, alloy steels etc. are very beneficially treated with plasma nitriding. Plasma nitriding advantage is related to the close control of the nitrided microstructure, allowing nitriding with or without compound layer formation. Not only the performance of metal parts gets enhanced but working lifespan gets boosted. So does the strain limit, and the fatigue strength of the metals being treated. A plasma nitrided part is usually ready for use. It calls for no machining, or polishing or any other post-nitriding operations. Thus the process is user-friendly, saves energy since it works fastest, and causes little or no distortion. This process was invented by Dr. Bernhardt Berghaus of Germany [18] who later settled in Zurich to escape persecution of his community by the Nazis in 1939. It was only after his death in late 1960s that the process was acquired by Klockner group and popularized world over. Plasma nitriding is often coupled with physical vapor deposition (PVD) process and labeled Duplex Treatment, to avail of immensely enhanced benefits. Many users prefer to have a plasma oxidation step combined at the last phase of processing to generate a smooth jetblack layer of oxides which is very resistant to not only wear but corrosion.

2.4. High Temperature nitriding with Gas Nitriding

High temperature nitriding using Gas nitriding is a case-hardening process whereby nitrogen is introduced into the surface of a solid ferrous alloy by holding the metal at extremely high temperature of 1200°C in contact with a nitrogenous gas. In this gas nitriding the donor is nitrogen rich gas from nitrogen tank. Since nitrogen as an interstitial atom is a potent solid solution strengthener, nitrogen contributes to high yield strength and improves the creep property and ductility as well as the corrosion resistance, so that it compensates for the nickel content. Moreover, nitrogen contributes to the quantitative control of the chromium carbides precipitates formed during tempering, so that it influences the corrosion resistance.

The advantages of high temperature gas nitriding over the other variants are:

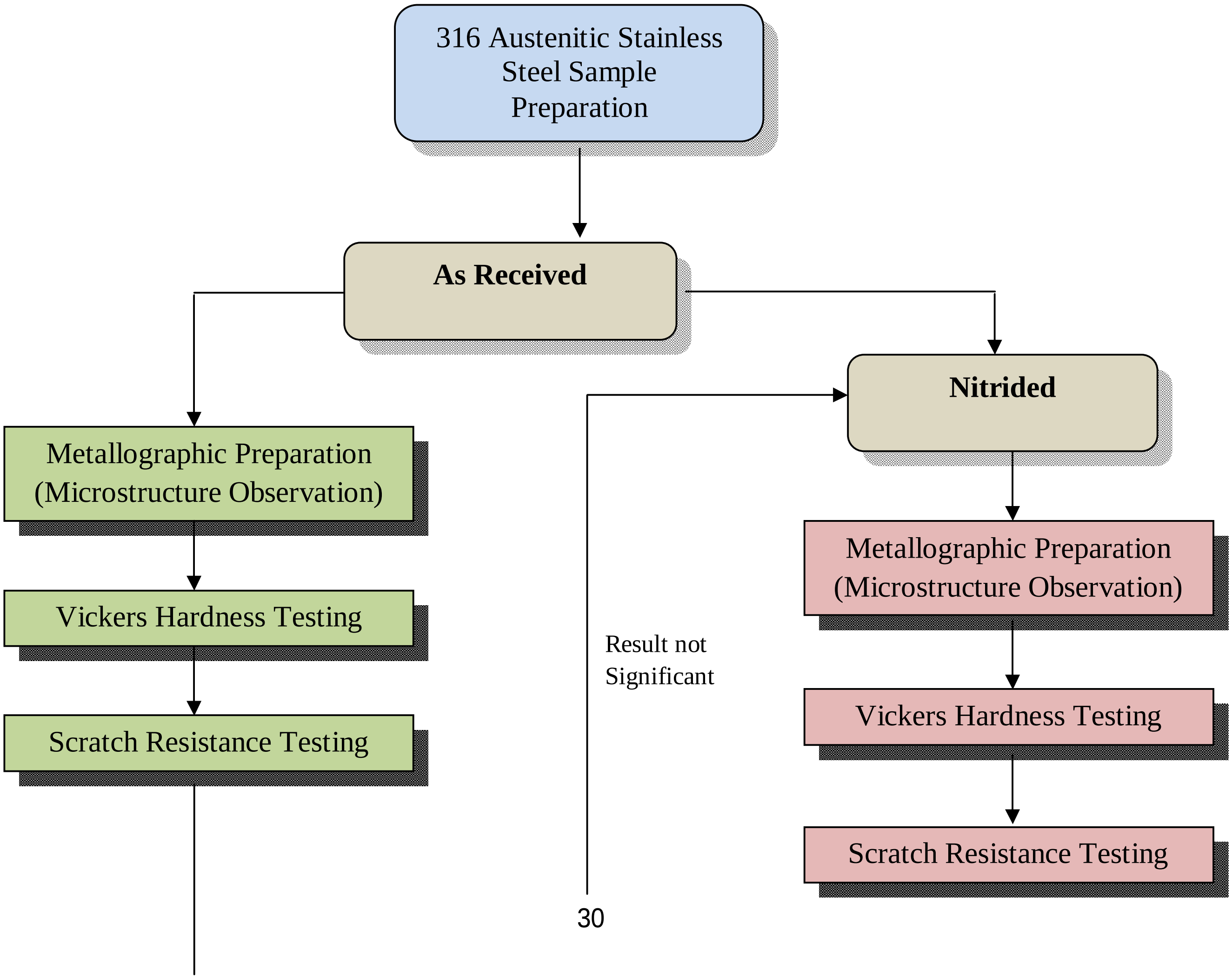
- All round nitriding effect (can be a disadvantage in some cases, compare with plasma nitriding)
- Large batch sizes possible - the limiting factor being furnace size and gas flow
- With modern computer control of the atmosphere the nitriding results can be tightly controlled
- Relatively cheap equipment cost - especially compared with plasma

CHAPTER 3

METHODOLOGY

3.1 Methodology: Project works flow

Figure 3.1 shows the flow of project work that consists of several steps and procedures.



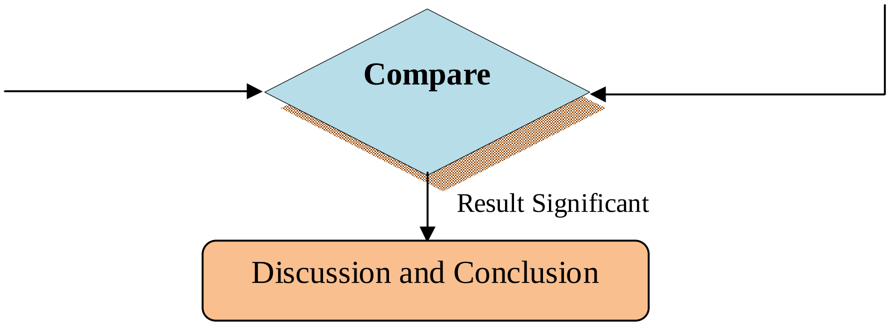
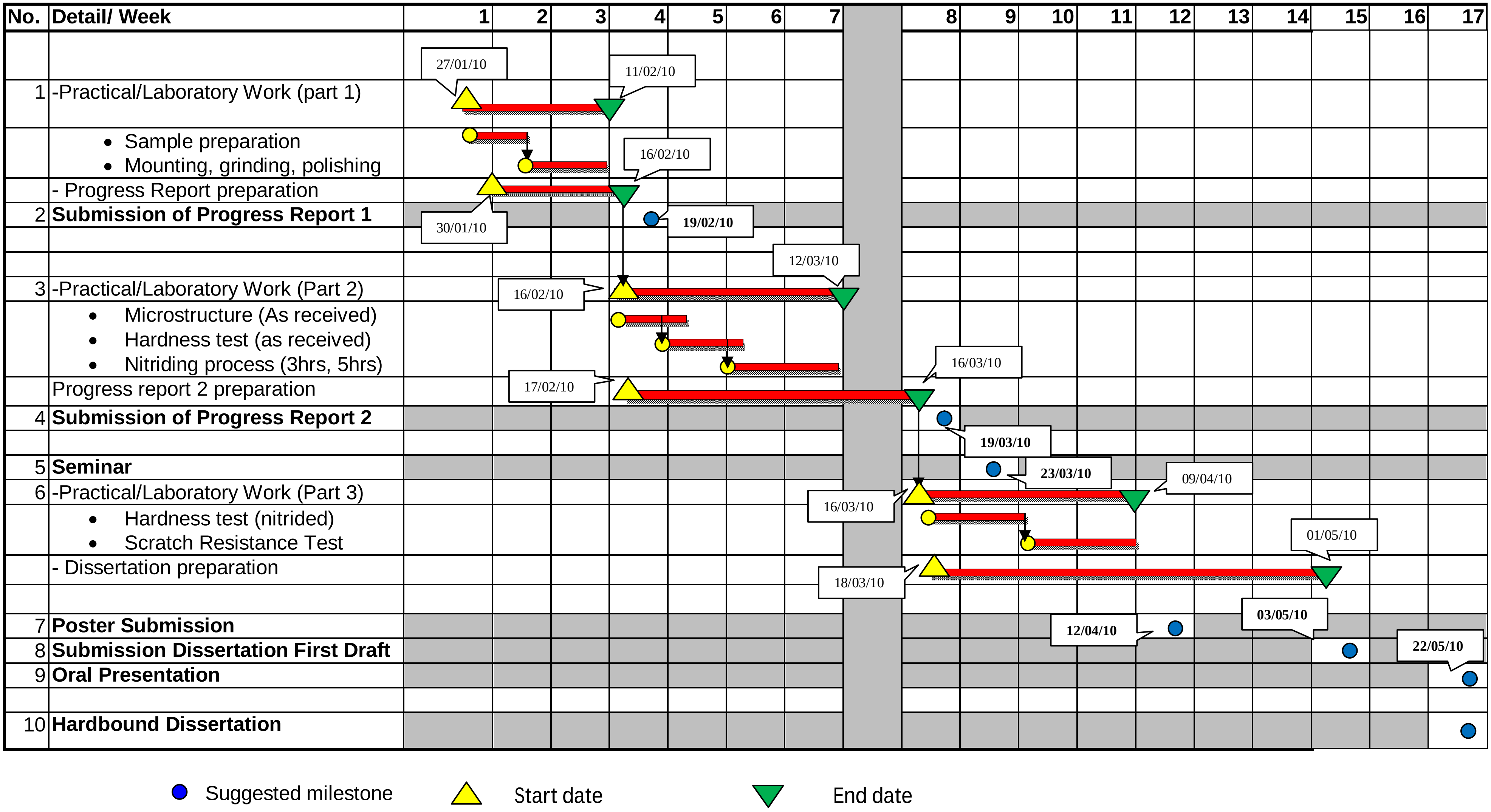


Figure 3.1: Project work flow

3.2 Gantt Chart for FYP II



3.3. Metallographic Sample Preparation for Grains Observation

Metallographic sample preparation is done to observe the grains of the 316L Austenitic Stainless Steel before nitriding process. The grains and grain boundaries is observed using Optical microscope (OM).The result then compared with the grains analysis of nitride 316 Austenitic stainless steel.

3.3.1 Sectioning

Sectioning is a step in sample preparation where the specimen is cut in to the desired shape. This step involves cutting action that can change the microstructure due to heating and work hardening. The degree of damage varies with techniques used and type of sample material. Commonly used cutting method is abrasive cutter. Other methods are diamond cutter, hand saw and hacksaw.

3.3.2 Mounting

Mounting is a step in specimen preparation where the specimen in encapsulated in polymeric matrix. The purpose of mounting is to provide protection for the specimen and ease handling during microscopic examination.

3.3.3 Grinding

The purpose of grinding is to remove damage introduced by previous operation such due to heating or work hardening. Instead of that it is also remove the saw marks and clean the encapsulent and specimen surfaces. The goal of grinding is a plane surface with minimal damage.

Grinding is performed on SIC abrasive paper that mounted on a motor driven wheel. Grinding is done in wet medium with water as lubrication. Grinding sequence [7] follows a series of descending grain size from 120, 320, 600, 800 and 1200 grit.

3.3.4 Polishing

The purpose of polishing is to produce scratch free surface with mirror-like finish. Washing and cleaning between steps are critical. Polishing involve two steps which are the rough polishing and fine polishing. Rough polishing is performed using diamond paste on a wheel covered with Naples cloth. It is involve diamond suspension size range from 6 – 3 μm. For fine polishing, it is performed using 1μm grain diamond suspension on a wheel covered with napped cloth or polishing cloth.

3.3.5 Etching

Etching is functioned to make the microstructure of the 316L Austenitic Stainless Steel under microscope inspection. This process involves chemical reaction between the sample and etchant under controlled condition. For 316L Austenitic Stainless Steel, the etchant that used in etching the sample is Vilella's reagent [1, 6]. The compositions of Vilella's reagent are 50% glycerol, 33.3% Hydrochloric Acid (HCl) and 16.6% Nitric Acid (HNO_3).

3.4. Hardness Test

Hardness test is done to compare the difference in hardness between as received austenitic stainless steel and the nitrided one. For this testing, Vickers Hardness Tester is used. The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 300 gf. The full load is applied for 10 seconds.

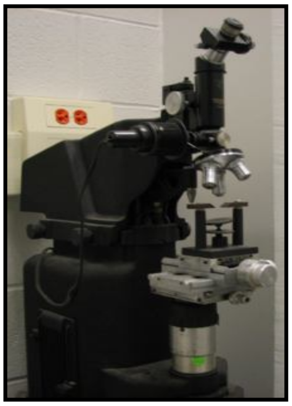


Figure 3.2: Vickers Hardness Tester

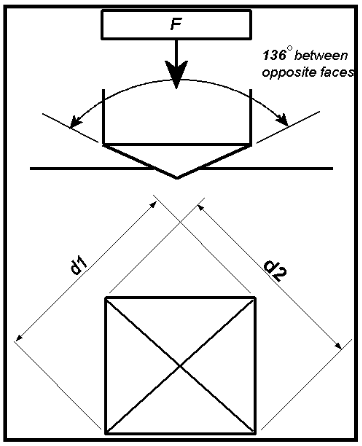


Figure 3.3: Testing method

The hardness then calculated using the following formula:

$$HV = \frac{2F\sin\frac{136^o}{2}}{d^2} \qquad HV = 1.854\frac{F}{d^2}\ \text{approximately}$$

[14]

The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

The testing is obtained on the cross section of the stainless steel plate to see whether the hardness varies from outer surface through inner of the steel after the nitriding process.

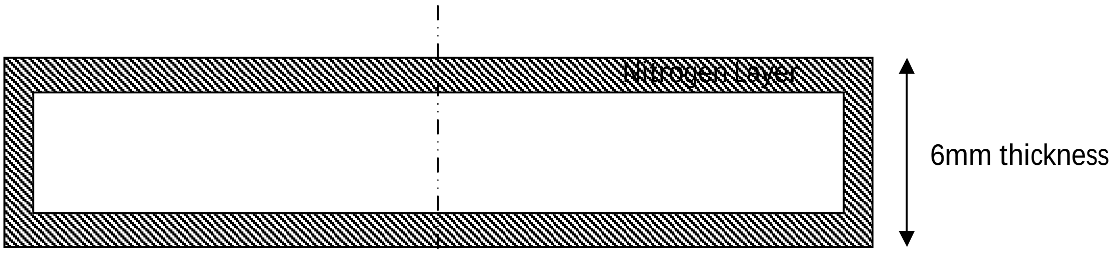


Figure 3.4: Cross-section of the nitrided stainless steel plate

3.5. High Temperature Nitriding

3.5.1. Equipment

1. Gas Nitriding Furnace
2. Flow meter (to control flow)
3. Nitrogen
4. Austenitic Stainless Steel plate (cut into pieces)
5. Conical flask (to determine gas flow)
6. Acetone (to clean the sample)

3.5.2. Equipment Layout

Fig.3.5: Nitrogen tank (supply nitrogen)

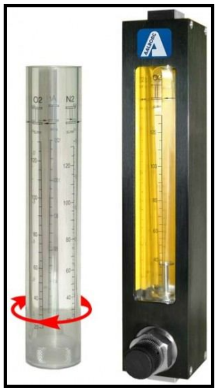


Fig.3.6: Flow meter

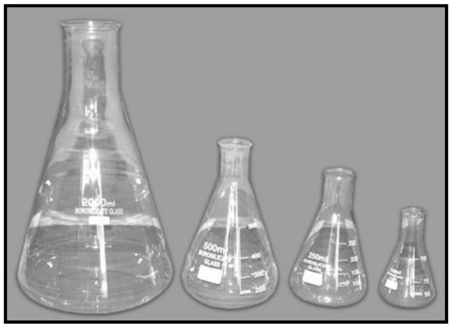


Fig 3.8: Conical Flask

Fig 3.7: Tube Furnace

3.5.3. Nitriding procedure

First run: 5 hours duration

1. First, tube furnace is cleaned from any contaminants and debris
2. Then, the equipment is set in the mean of connecting the furnace with nitrogen tank at one side and let another side to vent the nitrogen flow into the conical flask.
3. The sample of the Austenitic stainless steel plate then is inserted into the furnace.
4. Later, the furnace is switched on and set right before flowing the nitrogen into the furnace.
5. Furnace Setting:
    - Cycle 1, Segment I, ramp rate, target 1200°C, rate 6.0°C/min
    - Segment II, dwell, duration 5hours (300 min + 3min allowance)
    - Segment III, cooling target 30°C, rate 10.0°C/min
    - Segment IV, anti-dwell
6. The air in the furnace then purged with nitrogen flow for about 15 minutes.
7. Flow meter is calibrated to ensure the right flow of nitrogen into the furnace.
8. Observation is made on the appearance of gas bubble in water-contained conical flask to ensure the nitrogen is flowing through the furnace.
9. After that, the valve is closed to stop the nitrogen flow into the furnace. The sample is then heated up to 1200°C for 200 minutes (estimated 3 hours).
10. When the temperature reaches 1200°C, the valve is opened to flow the nitrogen into the furnace. The process is maintained for 300 minutes (5 hours) with additional time 10 minutes.
11. Later, the furnace is opened and the samples are taken out carefully.

    CAUTION: Wear the safety helmet and safety glove during the process of taking out the sample from hot furnace.
12. The sample then immediately quenched in the water for a few seconds.
13. Proceed to the wear testing.

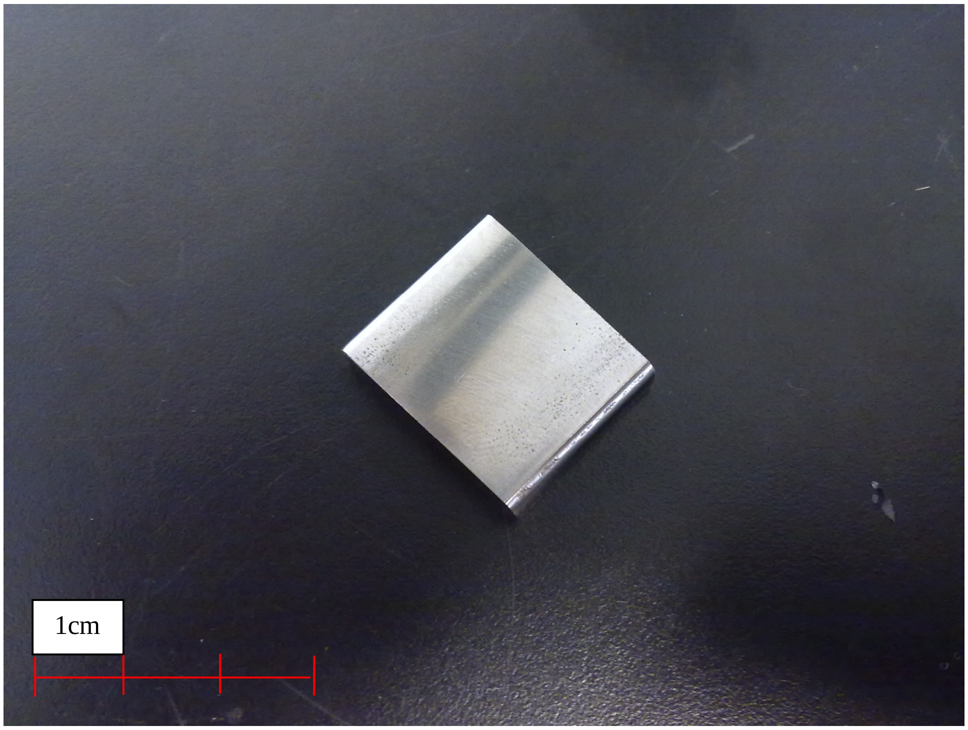


Fig.3.9: Sample of Austenitic Stainless Steel Plate (As Received)

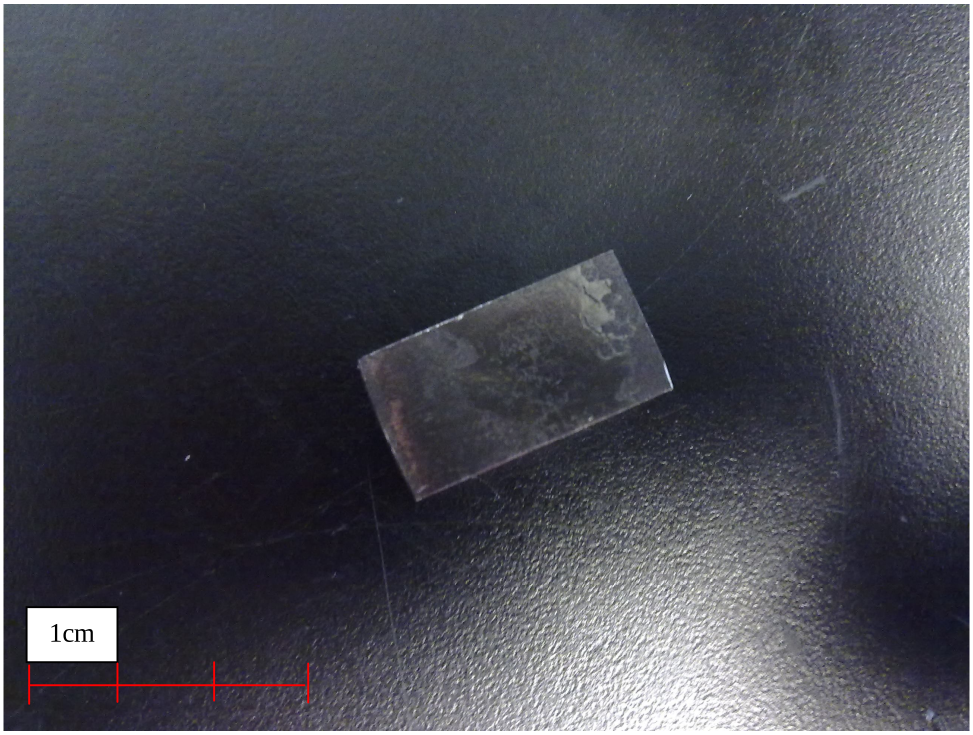


Fig.3.10: Sample of Austenitic Stainless Steel Plate (After Nitriding)

CHAPTER 4

RESULT AND DISCUSSION

4.1. Result and Discussion

4.1.1. Result: Microstructure

After undergoing the metallographic preparation, we proceed to the study on the microstructure of non-nitrided 316L austenitic stainless steel. Figure 4.1 and 4.2 show the result that we yield from Optical Microscope:-

4.1.1.1 Non-nitrided

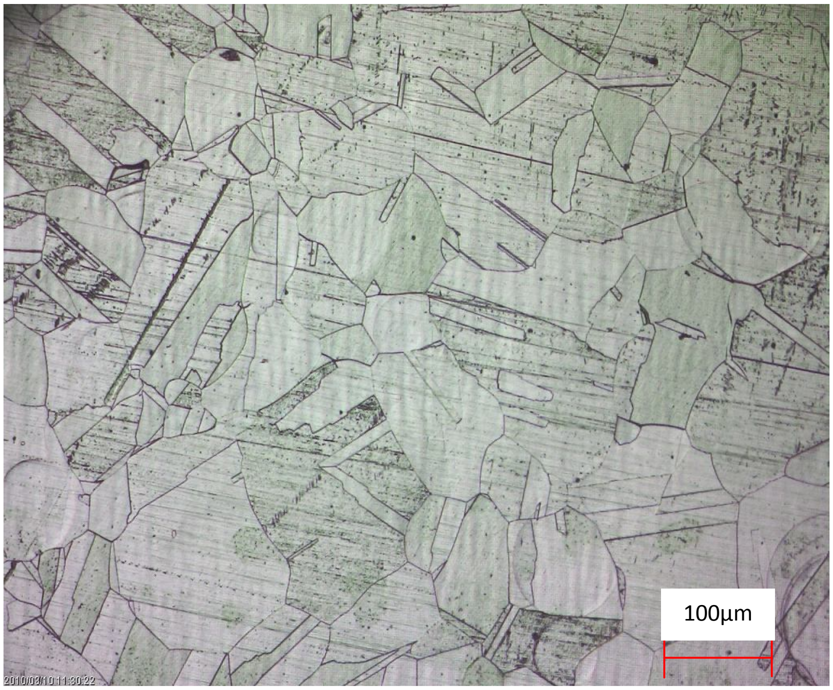


Fig 4.1: Microstructure of 316 Austenitic Stainless steel; as received sample

4.1.1.2 Nitrided

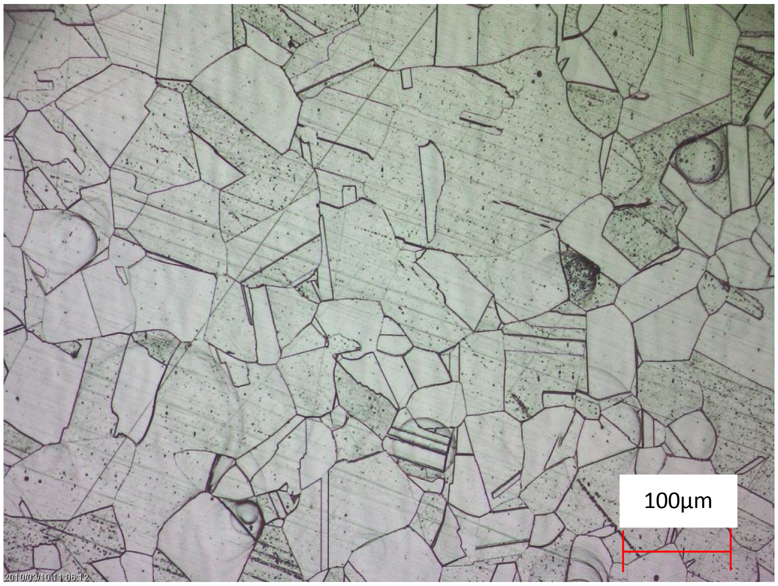
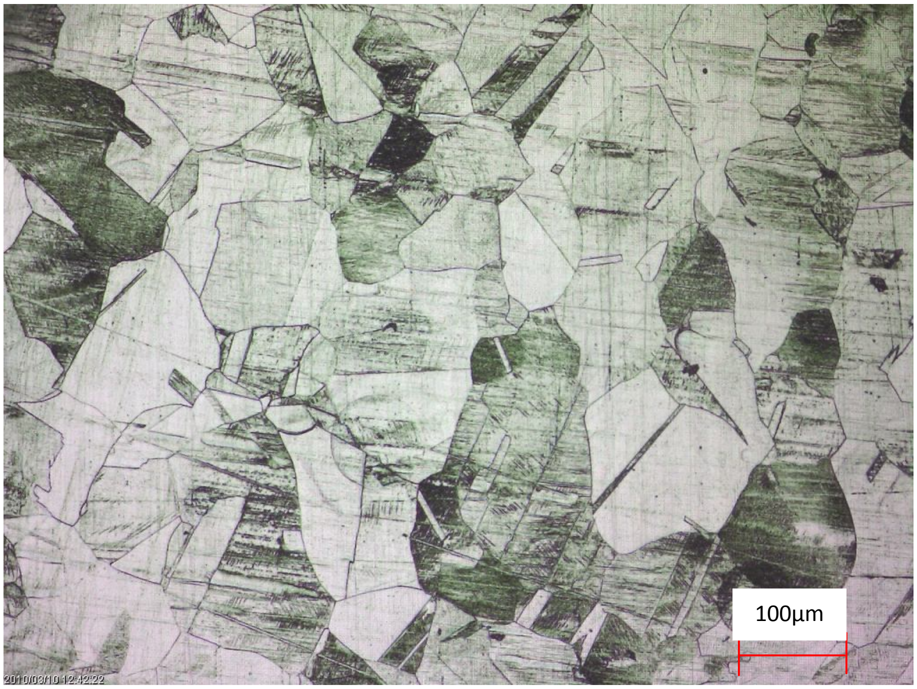


Fig 4.2a: Microstructure of 316 Austenitic Stainless steel; Nitrided (3 Hours)
Fig 4.2b: Left side view



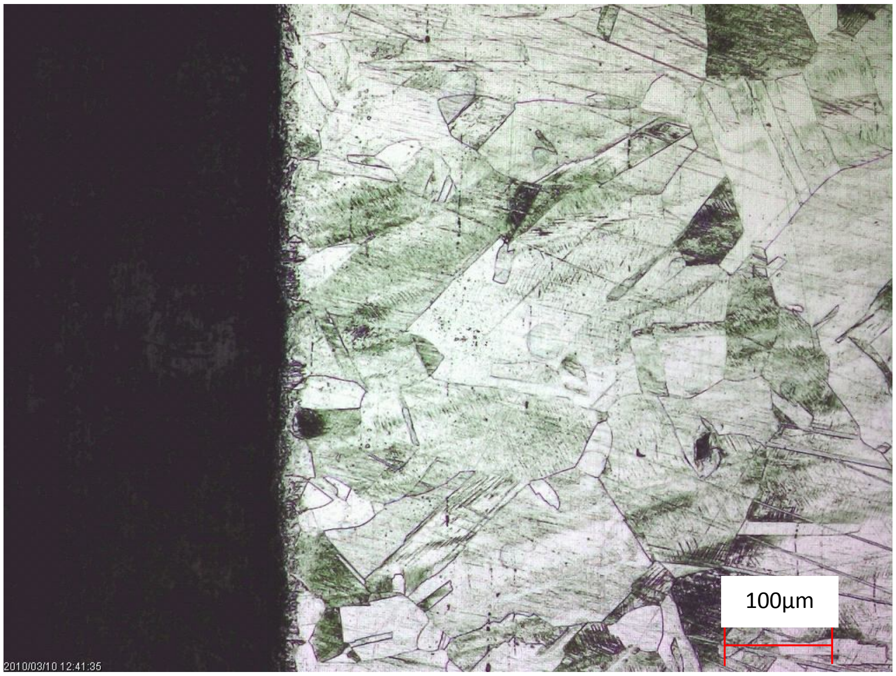


Fig 4.3a: Microstructure of 316 Austenitic Stainless steel: Nitrided (5 Hours)
Fig 4.3b: left side view

4.1.2 Discussion: Microstructure

4.1.2.1. non-nitrided

From the image, the bond zone of several µm widths consists of a mixture of stainless steel and low carbon steel. Each component metal is composed of small crystal grains size. Many of the grains contain annealing twins. The dark region indicates the presence of chromium in material.

It is observed that the stainless steel had the anticipated austenitic structure with a grain size of estimated 10–20 microns. Austenitic grains, in turn, are divided into sub grains by dislocation walls with different size ranging.

Theoretically, Austenitic steels have a Face Centered Cubic (F.C.C) atomic structure which provides more planes for the flow of dislocations, combined with the low level of interstitial elements (elements that lock the dislocation chain), gives this material its good ductility. This also explains why this material has no clearly defined yield point, which is why its yield stress is always expressed as a proof stress.

4.1.2.2 Nitrided

For the 3 hours and 5 hours durations, it is observed there is a little bit changes in microstructures compared to as received. The microstructures become darker and the grains become closer and more compact to each other. the dark thin layer of the outmost surface was identified as a mixture of martensite and the precipitates, and its appearance was considered to result from the affinity between chromium and carbon/nitrogen. The subsequent white layer approximately 90 µm deep contained the austenite, and the dark interior matrix indicates that austenite and martensite coexisted as in the case of the treated specimen, as shown in figure 4.2 and 4.3. The white layer that was formed was attributed to the nitrogen permeation from the surface to the interior due to the high temperature gas nitriding.

The case was taken as the zone of high hardness, which is a dark band that is fairly clearly differentiated from the core with the clearly recognizable structure of the base metal and fine nitride inclusions (Fig. 4.2 & 4.3). It does not include the wide solid solution of nitrogen located underneath the high-strength zone of the diffusion coating. The case depth increases with the nitriding temperature, reaching a maximum at 1200°C and remains unchanged . This variation of case depth with temperature can be explained by the reduced activity of the gaseous phase at 900-1000°C due to increasing dissociation of ammonia and the decreasing amount of atomic nitrogen entering into the surface (D. Kogan and V. N. Bukarev). With increasing temperature, the diffusion of nitrogen is accelerated, which reduces the thickness of the high-nitrogen zone.

4.1.3. Result: Vickers Hardness Test

Load: 300 gram force (gf)

Table 4.1: Hardness data

Duration (hours)	**0**	**3**	**5**
Thickness (mm)	**Hardness (HV)**		
0.6	256.0	304.7	321.5
1.2	255.9	304.4	331.8
1.8	253.3	288.9	321.7
2.4	244.0	268.3	300.5
3.0	244.2	268.4	300.0
3.6	244.0	266.2	286.2
4.2	244.8	269.0	279.0
4.8	250.0	279.9	300.9
5.4	259.0	307.1	327.1
5.8	259.0	307.2	327.2

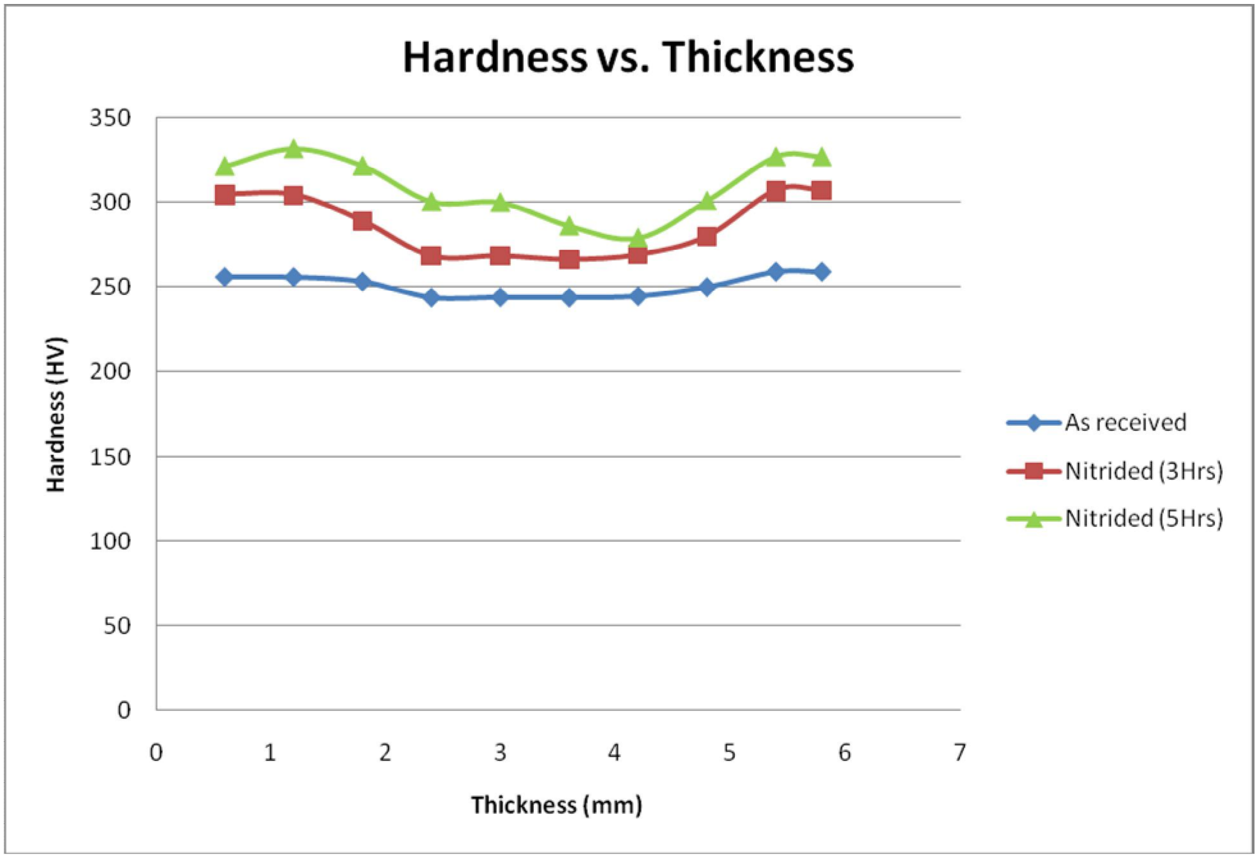


Fig 4.4: Hardness vs thickness graph

4.1.4 Discussion: Hardness Test

Based on the plotted graph in figure 4.1, this high temperature nitriding technique definitely improves the hardness of the austenitic stainless steel as the plot shows the difference in hardness between nitrided austenitic stainless steel and non-nitrided one. As receive, the standard hardness for non-nitrided stainless steel is 260HV and the test gives the result within the range of the standard one. After undergoing nitriding process, the hardness test on the nitrided one shows tremendous increase in hardness. The hardness is improved in the outer surface of the plate and the hardness then deteriorates through inner of the plate. This is because the nitrided layer covers most outer surface and nitrogen only diffuse into certain depth of the plate thickness. Specifically, the primary reason for the hardness drop was the occurrence of martensite caused by the nitrogen permeation that induced the phase changes, and this tendency was associated with the austenite layer. The nitrogen solid solution strengthening at the surface promotes the increase in hardness afforded by the precipitates.

- Average thickness for as received:

$$= \frac{\mathbf{256.0 + 255.9 + 253.3 + 244.0 + 244.2 + 244.0 + 244.8 + 250.0 + 259.0 + 259.0}}{\mathbf{10}}$$

= 251

- Average thickness for 3 hours:-

$$= \frac{\mathbf{304.7 + 304.4 + 288.9 + 268.3 + 268.4 + 266.2 + 269.0 + 279.9 + 307.1 + 307.2}}{\mathbf{10}}$$

= 286

- Average thickness for 5 hours:-

$$= \frac{\mathbf{321.5 + 331.8 + 321.7 + 300.5 + 300.0 + 286.2 + 279.0 + 300.9 + 327.1 + 327.2}}{\mathbf{10}}$$

= 309

- For 3 hours nitriding compared to as received:-

$$\text{Percentage increase in hardness (\%)} = \frac{(286 - 251)}{251} \times 100\% = \mathbf{13.9\%}$$

- For 5 hours nitriding compared to as received:-

$$\text{Percentage increase in hardness (\%)} = \frac{(309 - 251)}{251} \times 100\% = \mathbf{23\%}$$

Based on the calculation made, percentage of hardness increases up to 23 percent subject to nitriding under 5 hours duration. This is proved that hardness can be improved by this technique. After all, this significant change indicates that the steel is really been improved by nitriding process in term of its hardness. This is because after going through nitriding process, the steel is well-coated by a nitrogen layer and several amount of the nitrogen has been diffused into the stainless steel and as a result, it improves the hardness of the stainless steel a bit. Direct measurements of the hardness in the process of nitriding and during subsequent cooling showed that the hardness of the nitrided case develops primarily during cooling after completion of the nitriding process.

4.1.5. Result: Scratch Resistance Test

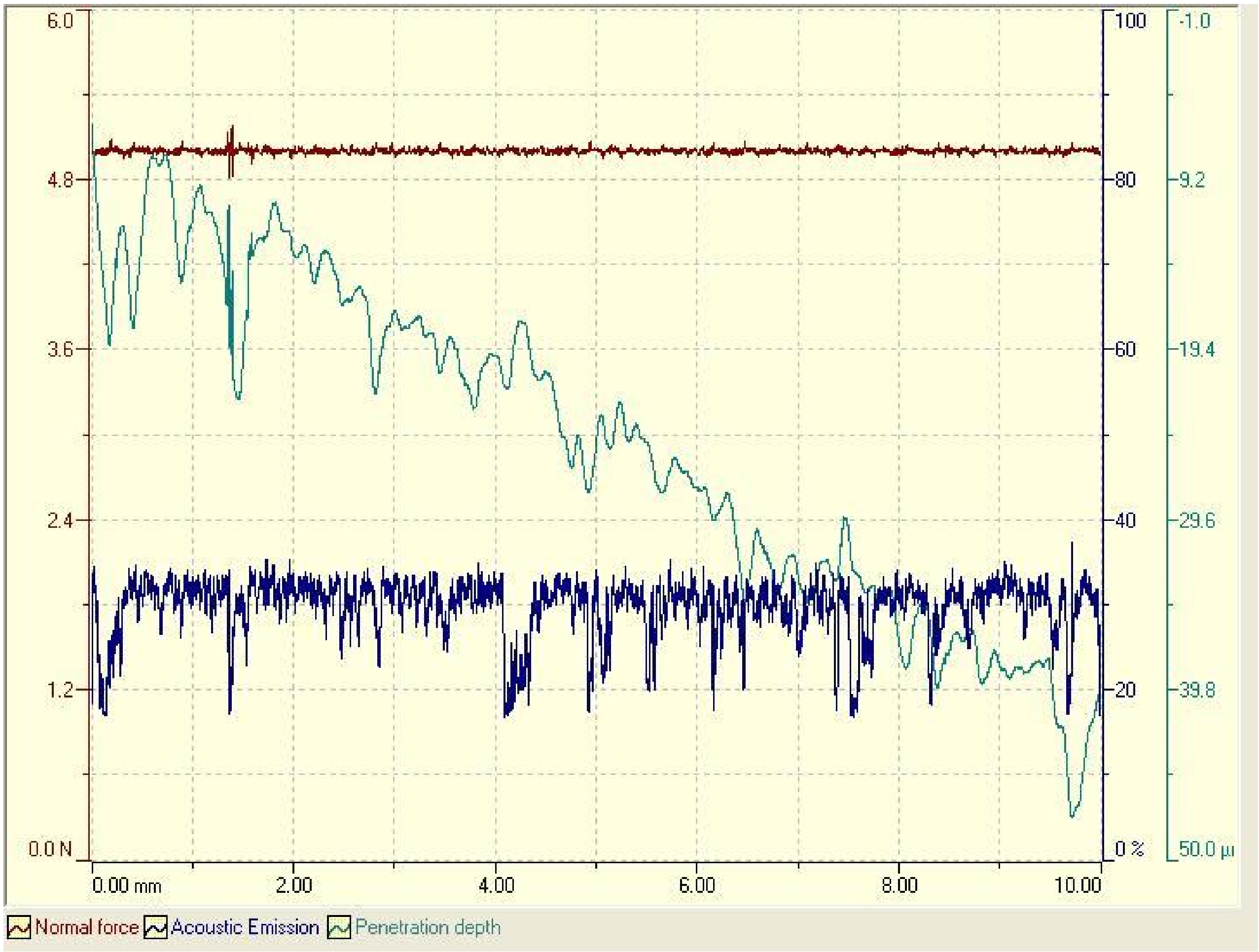


Figure 4.5: Depth of penetration trending (as received)

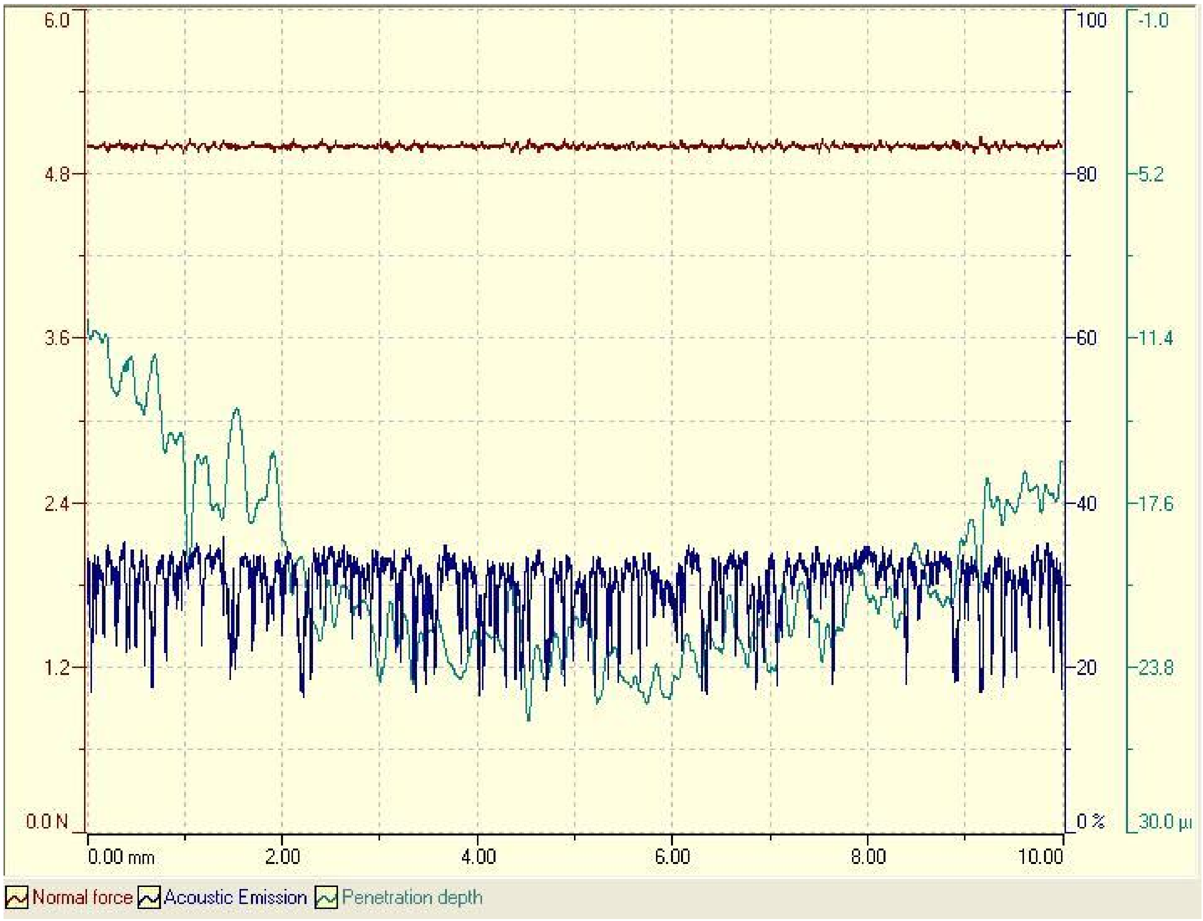
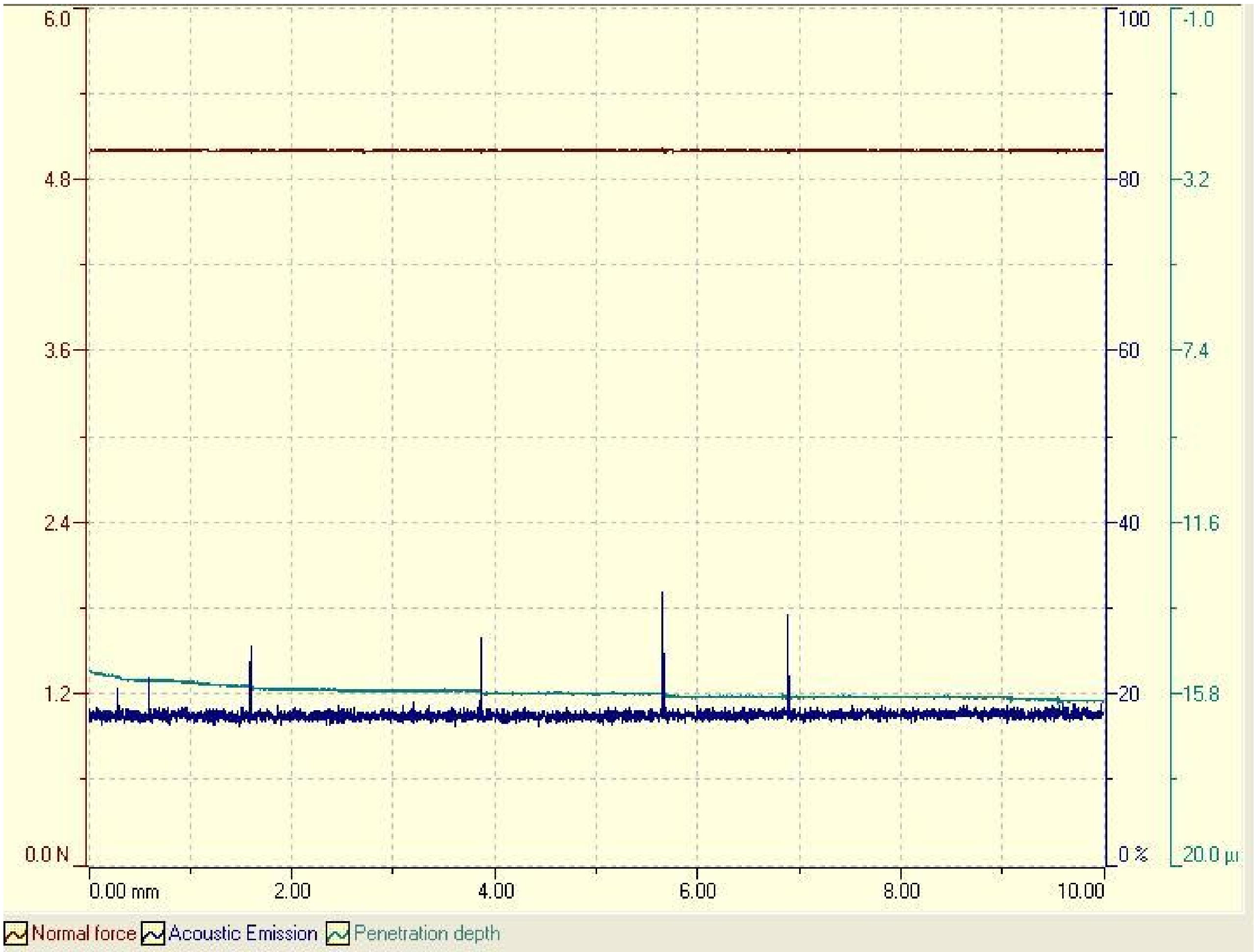


Figure 4.6: Depth of penetration trending (3 Hours)



Graph 4.7: Depth of penetration trending (5 Hours)

4.1.6 Scratch Resistance Test

For this test, the same amount of load is applied which is 5N. The scratch is made for 10mm length with the rate of 2.02 mm/min. After undergoing the test, for as received, graph 4.1, 4.2 and 4.3 show the depth of penetration is quite significant when the maximum depth is about to reach 50 µm. For the 3 hours duration nitrided sample, it the scratch penetrate less than the as received one. The maximum depth of penetration is about 30µm. For the 5 hours nitrided sample, the depth of penetration is around 15µm which is the lowest among 3. This means the hardness is improved a lot comparing the as received and the nitrided one.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion and Recommendation

5.1.1 Conclusion

Based on the significant result from the experiment, wear resistance of 316-austenitic stainless steel can be improved by applying high temperature nitriding method. Nitriding involves the diffusion of nitrogen into the surface layers of low carbon steel at elevated temperature. The formation of nitrides in the nitrided layer provides the increased hardness. Nitriding steels offer many advantages like a much higher surface hardness is obtainable when compared with case-hardening steels and they are extremely resistant to abrasion and have high fatigue strength. Principal reasons for nitriding are:

- To obtain high surface hardness
- To increase wear resistance and antigalling properties
- To improve fatigue life
- To improve corrosion resistance
- To obtain a surface that is resistant to the softening effect of heat at temperatures up to the nitriding temperature.

After undergoing the experiment on high temperature gas nitriding, this method is proved by doing the hardness test where the hardness increases about 26% from as received. Scratch resistance test also proves that the depth of penetration for the nitrided one is shallower than as received. Direct measurements of the hardness in the process of nitriding and during subsequent cooling showed that the hardness of the nitrided case develops primarily during cooling after completion of the nitriding process.

5.12. Recommendation

For this process to be more efficient, sufficient concentration of nitrogen is needed to turn an iron-chromium stainless steel into an austenite. Rapid cooling (quenching) from temperatures around 1200°C is necessary to obtain the metastable austenite at ambient temperature. Another one is, increase the duration of nitriding to increase the hardness of the steel. Prior to heat treatment. all hardenable steels must be hardened and tempered before being nitrided. The tempering temperature must be high enough to guarantee structural stability at the nitriding temperature: the minimum tempering temperature is usually at least 30°C (50°F) higher than the maximum temperature to be used in nitriding.

In certain alloys, such as series 4100 and 4300 steels, hardness of the nitrided case is modified appreciable by core hardness: that is, a decrease in core hardness results in a decrease in case hardness. Consequently, in order to obtain maximum case hardness, these steels are usually provided with maximum core hardness by being tempered at the minimum allowable tempering temperature.

After hardening and tempering, and before nitriding, parts should be thoroughly cleaned. Most pans can be successfully nitrided immediately after vapor degreasing. However, some machine-finishing processes such as buffing, finish grinding, lapping, and burnishing may produce surfaces that retard nitriding and result in uneven case depth and distortion. There are several methods by which the surfaces of parts finished by such methods may be successfully conditioned before nitriding.

One method consists of vapor degreasing pans and then abrasive cleaning them with aluminum oxide grit or other abrasives such as garnet, or silicon carbide, immediately prior to nitriding. Any residual grit must be brushed off before pans are loaded into the furnace. Pans should be handled with clean gloves.

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APPENDICES

Appendix A:

Metallographic Sample Preparation

&

Test Method for Wear testing with a Pin-on-Disk

Figure A1: Abrasive cutter used to cut sample

Figure A2: Mounting machine

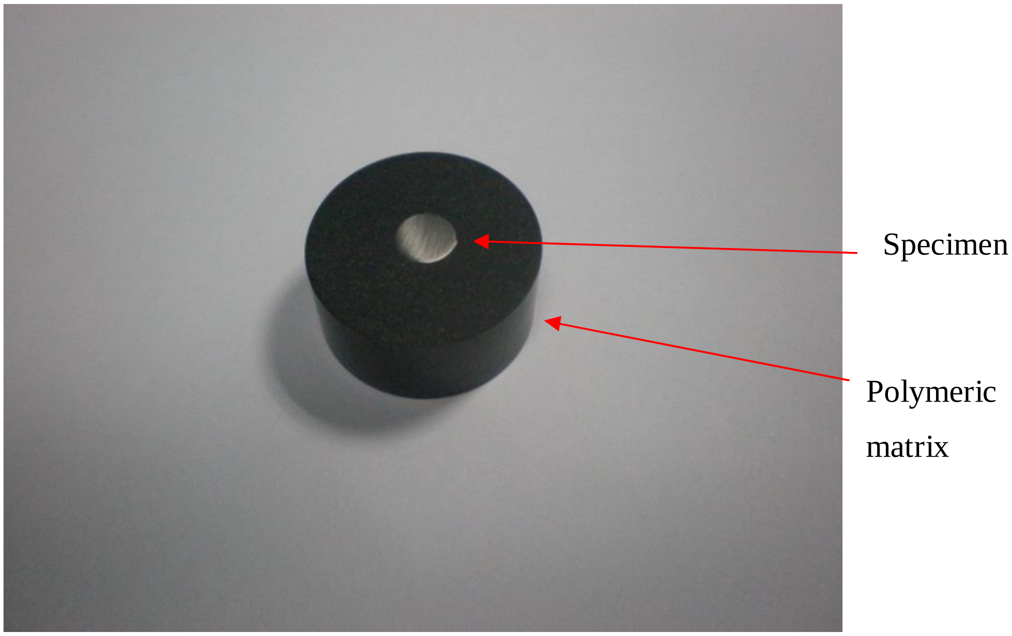


Figure A3: Finished mounted specimen

Figure A4: Grinding machine

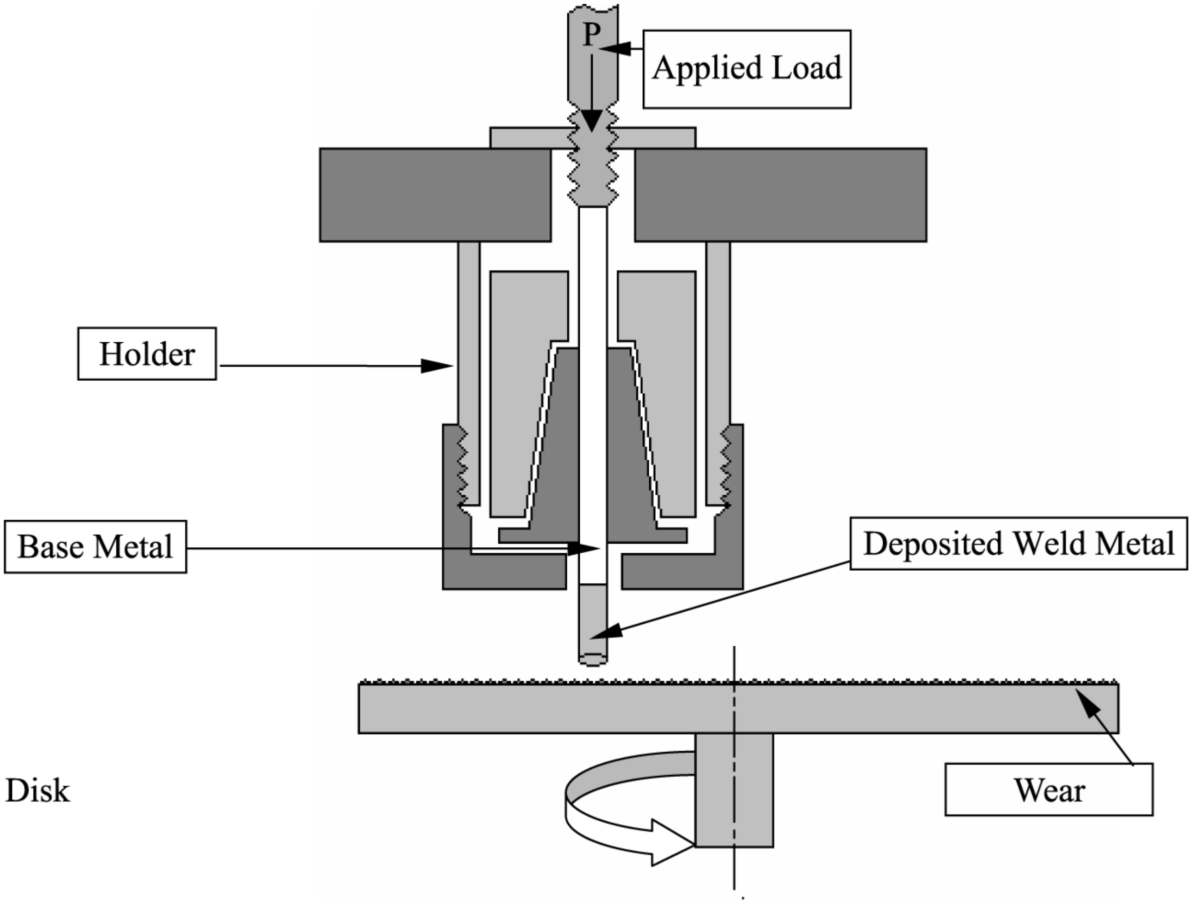


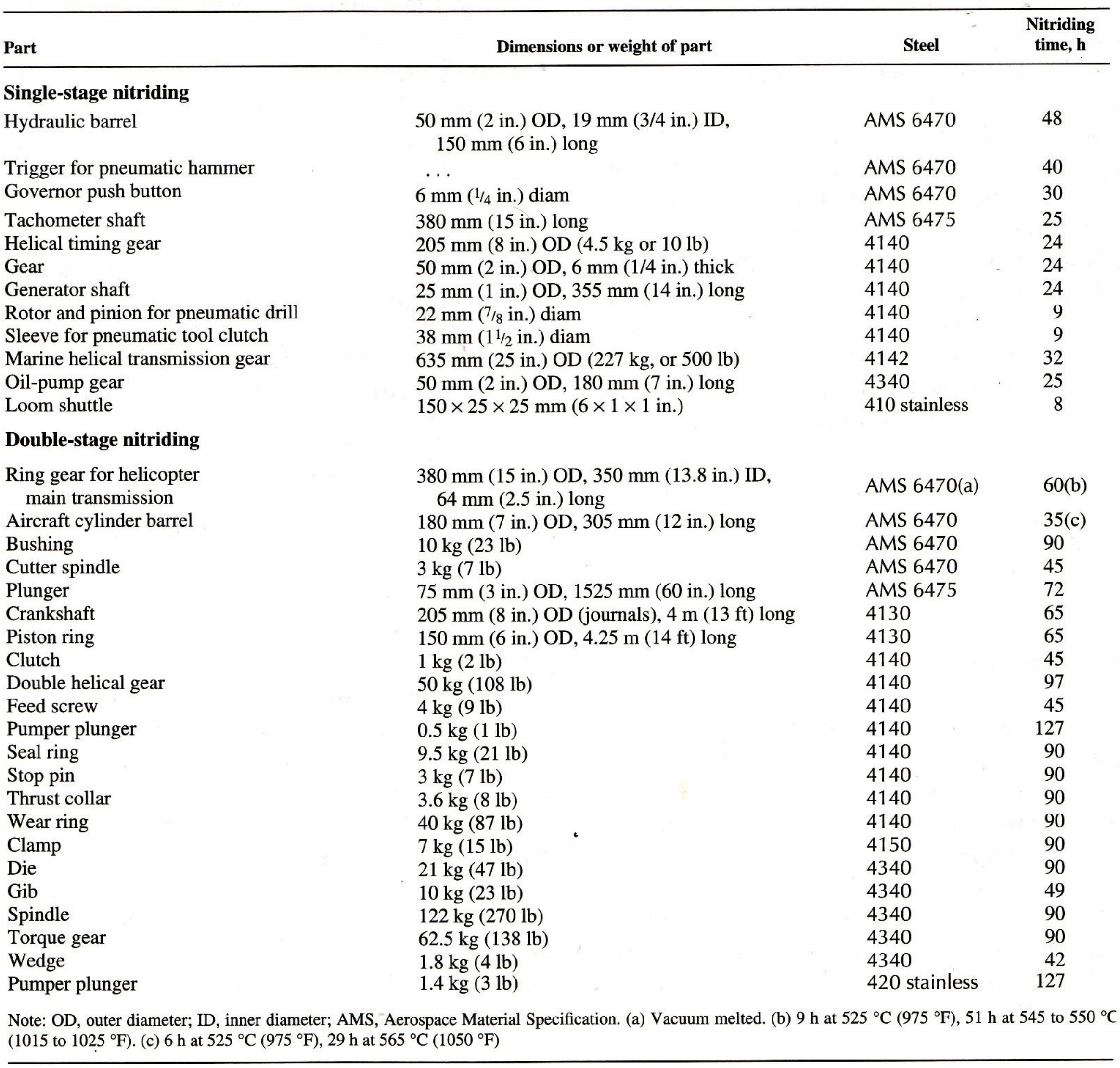
Figure A5: Pin-on-Disk Test Apparatus

Appendix B:
Austenitic Stainless steel data, applications & procedure

Table B1: Chemical composition of Austenitic Stainless Steel

Chemical Composition (%)											
No	**Grade**	**DIN**	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Others**
1	301	1.4310 - X10CrNi18-8	< 0.15	< 2.00	< 2.00	< 0.045	< 0.03	16 - 19	0	6 - 9.5	N = 0.12 - 0.22
2	302	NA	< 0.15	< 1.00	< 2.00	< 0.045	< 0.03	17 - 19	0	8 -10	N < 0.1
3	303	1.4305 - X8CrNiS18-9	< 0.10	< 1.00	< 2.00	< 0.045	< 0.15 - 0.35	17 - 19	0	8 -10	Cu < 1; N < 0.11
4	304	1.4301 - X5rNi18-10	< 0.07	< 1.00	< 2.00	< 0.045	< 0.015	17 - 19.5	0	8 - 10.5	N < 0.11
5	304L	1.4306 - X2CrNi19-11	< 0.030	< 1.00	< 2.00	< 0.045	< 0.015	18 - 20	0	10 - 12	N < 0.11
6	316	1.4401 - X5CrNiMo17-12-2	< 0.07	< 1.00	< 2.00	< 0.045	< 0.015	16.5 - 18.5	2 - 2.5	10 -13	N < 0.11
7	316L	1.4404 - X2CrNiMo17-12-2	< 0.03	< 1.00	< 2.00	< 0.045	< 0.015	16.5 - 18.5	2 - 2.5	10 - 13	N < 0.11
8	316L	1.4435 - X2CrNiMo18-14-3	< 0.03	< 1.00	< 2.00	< 0.045	< 0.015	17 - 19	2.5 - 3	12.5 - 15	N < 0.11
9	316L-Ultra	1.4435	< 0.03	< 0.60	< 2.00	< 0.040	< 0.015	17 - 18.5	2.5 - 3	13 - 15	NA
10	316L (Medical)	1.4441 - X2CrNiMo18-15-3	< 0.03	< 1.00	< 2.00	< 0.025	< 0.010	17 - 19	2.5 - 3.2	13 - 15.5	N < 0.1; Cu < 0.1
11	316Ti	1.4571 - X6CrNiMoTi17-12-2	< 0.08	< 1.00	< 2.00	< 0.045	< 0.015	16.5 - 18.5	2 - 2.5	10.5 - 13.5	5x%C<Ti<0.7
12	316LS	NA	< 0.03	< 1.00	< 2.00	< 0.045	0.12 - 0.18	16.5 - 18.5	2 - 2.5	11 - 14	Cu 1 - 2
13	316LS-PXQ	1.4427So	< 0.03	< 1.00	< 2.00	< 0.045	0.10 - 0.13	16.5 - 18.5	2 - 2.8	12 - 14	NA
14	316L - PM	1.4435 PM	< 0.03	< 1.00	< 2.00	< 0.045	0.015 - 0.03	17 - 19	2.5 - 3	12.5 - 15	N < 0.11
15	316L - Ugima	1.4435 Ugima	< 0.03	< 1.00	< 2.00	< 0.045	< 0.03	17 - 18.5	2.5 - 3	12.5 - 15	NA
16	904L	1.4539 - X1NiCrMoCu25-20-5	< 0.02	< 0.70	< 2.00	< 0.030	< 0.010	19 - 21	04-May	24 - 26	Cu = 1.2 - 2.0

Table B2: Nitriding applications and procedures



Part	Dimensions or weight of part	Steel	Nitriding time, h
Single-stage nitriding			
Hydraulic barrel	50 mm (2 in.) OD, 19 mm (3/4 in.) ID, 150 mm (6 in.) long	AMS 6470	48
Trigger for pneumatic hammer	. . .	AMS 6470	40
Governor push button	6 mm (1/4 in.) diam	AMS 6470	30
Tachometer shaft	380 mm (15 in.) long	AMS 6475	25
Helical timing gear	205 mm (8 in.) OD (4.5 kg or 10 lb)	4140	24
Gear	50 mm (2 in.) OD, 6 mm (1/4 in.) thick	4140	24
Generator shaft	25 mm (1 in.) OD, 355 mm (14 in.) long	4140	24
Rotor and pinion for pneumatic drill	22 mm (7/8 in.) diam	4140	9
Sleeve for pneumatic tool clutch	38 mm (1 1/2 in.) diam	4140	9
Marine helical transmission gear	635 mm (25 in.) OD (227 kg, or 500 lb)	4142	32
Oil-pump gear	50 mm (2 in.) OD, 180 mm (7 in.) long	4340	25
Loom shuttle	150 × 25 × 25 mm (6 × 1 × 1 in.)	410 stainless	8
Double-stage nitriding			
Ring gear for helicopter main transmission	380 mm (15 in.) OD, 350 mm (13.8 in.) ID, 64 mm (2.5 in.) long	AMS 6470(a)	60(b)
Aircraft cylinder barrel	180 mm (7 in.) OD, 305 mm (12 in.) long	AMS 6470	35(c)
Bushing	10 kg (23 lb)	AMS 6470	90
Cutter spindle	3 kg (7 lb)	AMS 6470	45
Plunger	75 mm (3 in.) OD, 1525 mm (60 in.) long	AMS 6475	72
Crankshaft	205 mm (8 in.) OD (journals), 4 m (13 ft) long	4130	65
Piston ring	150 mm (6 in.) OD, 4.25 m (14 ft) long	4130	65
Clutch	1 kg (2 lb)	4140	45
Double helical gear	50 kg (108 lb)	4140	97
Feed screw	4 kg (9 lb)	4140	45
Pumper plunger	0.5 kg (1 lb)	4140	127
Seal ring	9.5 kg (21 lb)	4140	90
Stop pin	3 kg (7 lb)	4140	90
Thrust collar	3.6 kg (8 lb)	4140	90
Wear ring	40 kg (87 lb)	4140	90
Clamp	7 kg (15 lb)	4150	90
Die	21 kg (47 lb)	4340	90
Gib	10 kg (23 lb)	4340	49
Spindle	122 kg (270 lb)	4340	90
Torque gear	62.5 kg (138 lb)	4340	90
Wedge	1.8 kg (4 lb)	4340	42
Pumper plunger	1.4 kg (3 lb)	420 stainless	127

Note: OD, outer diameter; ID, inner diameter; AMS, Aerospace Material Specification. (a) Vacuum melted. (b) 9 h at 525 °C (975 °F), 51 h at 545 to 550 °C (1015 to 1025 °F). (c) 6 h at 525 °C (975 °F), 29 h at 565 °C (1050 °F)

Table B3: Nitriding requirement table

Part	Requirement	Material and process originally used	Resultant problem	Solution
Gear	Good wear surface and fatigue properties	Carburized 3310 steel 0.4 to 0.6 mm (0.017 to 0.025 in.) case	Difficulty in obtaining satisfactory case to meet a reliability requirement	AMS 6470 substituted for 3310 and double-stage nitrided for 25 h
High-speed pinion (on gear motor)	Provide teeth with minimum (equivalent) hardness of 50 HRC	8620 steel gas carburized at 900 °C (1650 °F) to 0.5 mm (0.02 in.) case, direct quenched from 845 °C (1550 °F), and tempered at 205 °C (400 °F)	Distortion in teeth and bore caused high rejection rate	4140 steel, substituted for 8620, was heat treated to 255 HB; parts were rough machined, finish machined, nitrided(a)
Bushings (for conveyor rollers handling abrasive alkaline material)	High surface hardness for abrasion resistance; resistance to alkaline corrosion	Carburized bushings	Service life of bushings was short because of scoring	Substitution of Nitralloy 135 type G (resulfurized) heat treated to 269 HB and nitrided(b)
Spur gears (in train of power gears; 10-pitch, tip modified)	Sustain continuous Hertz stress of 1035 MPa (150 ksi) (overload of 1550 MPa, or 225 ksi), continuous Lewis stress of 275 MPa (40 ksi) (overload of 725 MPa, or 105 ksi)(c)	Carburized AMS 6260	Gears failed because of inadequate scuff resistance, also suffered property losses at high operating temperatures	Substitution of material of Hll type, hardened and multiple tempered (3 h + 3 h) to 48 to 52 HRC, then double-stage nitrided(d)

Note: AMS, Aerospace Material Specification. (a) Single-stage nitrided at 510 °C (950 °F) for 38 h. Cost increased 5%, but rejection rate dropped to zero. (b) Single-stage nitrided at 510 °C (950 °F) for 38 h. Case depth was 0.46 mm (0.018 in.), and hardness was 94 HR15-N; parts had three times the service life of carburized parts. (c) Must withstand operating temperatures to 290 °C (550 °F). (d) 15 h at 515 °C (960 °F) (15 to 25% dissociation); then 525 °C (980 °F) (80 to 83% dissociation). Effective case depth (to 60 HRC), 0.25 to 0.4 mm (0.010 to 0.015 in.); case hardness, 67 to 72 HRC (converted from Rockwell 15-N scale)