Study On The Effect Of Nitriding Temperature Towards Wear Resistance Of Duplex Stainless Steel

by

Muhammad Khairul Nizam bin Zulfikri Gopinath

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

(Associate Professor Dr. Patthi bin Hussain)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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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.

MUHAMMAD KHAIRUL NIZAM BIN ZULFIKRI GOPINATH

ABSTRACT

This report basically discusses the research or review done and basic understanding of the chosen topic, which is **Study On The Effect Of Nitriding Temperature Towards Wear Resistance Of Duplex Stainless Steel.** In industry, duplex stainless steel has been used due to good corrosion resistance, high fatigue resistance, high wear resistance and high mechanical strength. It is also brittle. The nitriding process has been chosen as the heat treatment process that can enhance the mechanical properties of the duplex stainless steel. The sample undergoes constant 6 hour of nitriding process in the tube furnace with different temperature which are 1100°C, 1050°C and 1000°C. High temperature gas nitriding (HTGN) has been used in this project. All the parameters for the nitriding process such as temperature and time must be setup on the horizontal tube furnace. Optical microscopy, as well as glancing angle X-Ray diffraction (XRD) has been used to study the nitrided surfaces. For wear test, pin on disc method has been chosen as the method to analyze the wear resistance of each sample. The result from the wear test is measured by determining the weight loss as function of sliding distance. In order to perform this project, all the steps for the experimental work must be understood. The nitriding process is the key factor for the project. It is to determine whether the nitriding temperature can affect the wear resistance of the stainless steel. The weight losses of the sample are increased in the wear test as the temperature of nitriding for the sample increase. The nitrogen diffuses into the steel better when the temperature is high. It improves the wear resistance of the duplex stainless steel.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

The basic idea of this project is more on experimental work. The process of nitriding will be the main keyword for this project. The variation of nitriding temperature will be analysed whether it has significant effect towards the wear resistance of stainless steel. The nitriding process is required to improve wear, corrosion and fatigue properties of the materials. The process targets surface modifications of the steel. Each sample undergoes constant 6 hour of nitriding process in the tube furnace with three different temperatures which are 1100°C, 1050°C and 1000°C.

Before the nitriding process, the stainless steel undergoes microstructure studies by using optical microscope and scanning electron microscope (SEM). This process is to observe the grain structure of the steel. Using the optical microscope, the sample is going through 100 times magnification while using the scanning electron microscope (SEM), the sample is going through 1000 and 3000 times magnifications. The weight of each sample before and after nitriding will be taken to show the weight difference.

After nitriding process, each sample will undergo wear resistance test. During this test, load applied to the sample is about 25N and the speed of the disc is about 1000 revolution per minute. The test is to distinguish the weight loss after wear resistance test between each sample and the raw material. Furthermore, the test is to show whether the wear resistance of each sample increase or not after nitriding process.

The X-ray Diffraction (XRD) is used to analyze the compound of the sample.

1.2 Problem Statement

In industry, duplex stainless steel has been used due to good corrosion resistance, high fatigue resistance, high wear resistance and high mechanical strength. It is also brittle. The nitriding process functions as gas diffusion treatments for enhancing the surface wear properties of steels. The high temperature of gas nitriding will be used to enhance the wear resistance of the steel. Besides, the variation of nitriding temperature towards the steel is to be identified and investigated whether it has significant effect on wear resistance. The nitriding time for each sample is constant for six hours.

1.3 Objective and Scope of Study

Objectives of this project are

- To study the effect of nitriding temperatures towards Duplex Stainless Steel (LDX 2101) in term of wear resistance.
- To determine the weight loss of each nitrided steel that varies with temperature after undergo wear test.

Basically, the scope of study for this project is in the form of laboratory experiments. All the process before conducting the gas nitriding process should be perform accordingly such as cutting, grinding and polishing the samples. The high temperature of gas nitriding will be used to each sample with different temperature and constant six hours of the process. The conventional high temperature gas nitriding process (HTGN) will be conducted in the horizontal tube furnace with three different temperatures. The process will follow strictly according to the ASTM A355 standard specifications. For the wear test, the DUCOM multi specimen tester will be used to analyze the weight loss for every sample.

Therefore, the mechanical properties of the steel in term of wear resistance are expected to be improved.

CHAPTER 2

LITERATURE REVIEW

2.1 Stainless Steel

In metallurgy, stainless steel, also known as inox steel or inox from French "inoxydable", is defined as a steel alloy with a minimum of 10.5 or 11% chromium content by mass [1]. Stainless steel does not stain, corrode, or rust as easily as ordinary steel, but it is not stain-proof [2]. It is also called corrosion-resistant steel or CRES when the alloy type and grade are not detailed, particularly in the aviation industry [3]. There are different grades and surface finishes of stainless steel to suit the environment the alloy must endure. Stainless steel is used where both the properties of steel and resistance to corrosion are required.

Stainless steel differs from carbon steel by the amount of chromium present. Unprotected carbon steel rusts readily when exposed to air and moisture. This iron oxide film (the rust) is active and accelerates corrosion by forming more iron oxide. Stainless steels contain sufficient chromium to form a passive film of chromium oxide, which prevents further surface corrosion and blocks corrosion from spreading into the metal's internal structure.

Stainless steel's resistance to corrosion and staining, low maintenance and familiar mineralogy make it an ideal material for many applications. The alloy is milled into coils, sheets, plates, bars, wire, and tubing to be used in cookware, cutlery, hardware, surgical instruments, major appliances, industrial equipment (for example, in sugar refineries) and as an automotive and aerospace structural alloy and construction material in large buildings.

Storage tanks and tankers used to transport orange juice and other food are often made of stainless steel, because of its corrosion resistance and antibacterial properties. This also influences its use in commercial kitchens and food processing plants, as it can be steam-cleaned and sterilized and does not need paint or other surface finishes.

There are over 150 grades of stainless steel with five major types which are commonly used in industry. The five types of stainless steel that mostly used are ferritic, austenitic, martensitic, duplex stainless steel (ferritic-austenitic) and precipitation hardening stainless steel.

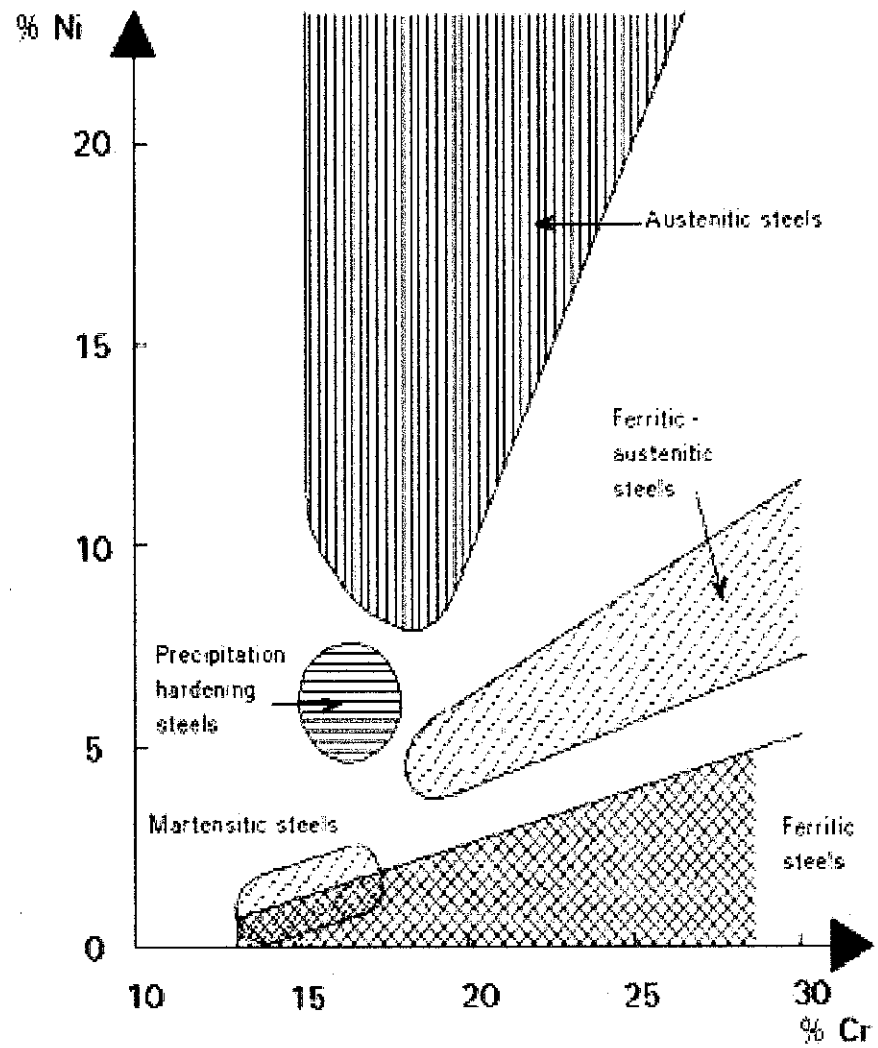

Figure 2.1: Types of stainless steels with percentage of nickel (Ni) and chromium (Cr)

2.1.1 Duplex Stainless Steel

Duplex stainless steels (DSS) have a mixed microstructure consisting of ferrite (body-centered cubic) and austenite (face-centered cubic) phases [4]. When duplex stainless steels have the optimum phase balance, which is usually approximately equal proportions of ferrite and austenite phases, they exhibit higher resistance to stress corrosion cracking and higher strength than austenitic stainless steels. Taking advantages of these positive factors, duplex stainless steels are widely used in the oil and gas, petrochemical, pulp and paper, and pollution control industries.

The duplex stainless steels (DSS) are an intermediate class between ferritic and austenitic stainless steels. Thus, these steels have the combined characteristic of both families. DSS are more resistant to stress corrosion but not quite as resistant as the ferritic ones; toughness is better than that of the ferritic steels but not as good as that of the austenitic. However, the strength of DSS is greater than that of austenitic ones. DSS were developed in the 1940s, but were not commercially produced until 1970s [5]. Due to the optimum compromise between mechanical properties, corrosion resistance and economical advantages compared with austenitic stainless steels, DSS have increased their applications.

The duplex stainless steels are family of grades, which range in performance depending on their alloy content. The development of duplex stainless steel has continued and modern duplex stainless steels can be divided into five groups:

- Lean duplex steels, low-alloyed
- Standard duplex steels, normal-alloyed
- 25 chromium such as Alloy 255 with Pitting Resistance Equivalent Number (PREN) less than 40
- Super duplex steels, high-alloyed
- Hyper duplex steels, very high-alloyed

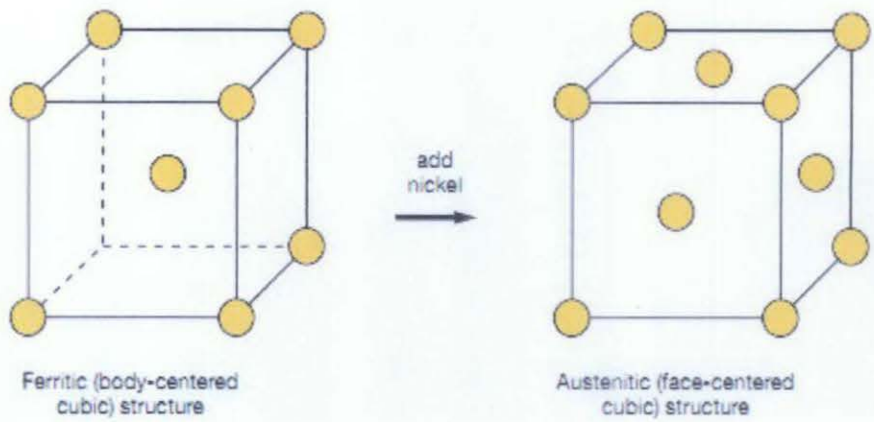

Figure 2.2: By adding nickel, the crystallographic structure changes from body-centered cubic (BCC) to face-centered cubic (FCC) [8]

Ferritic stainless steels contain little or no nickel, duplex stainless steels contain low to intermediate amount of nickel such as 1.5 to 7%, and the 300-series austenitic stainless steels, contain at least 6% nickel. The addition of nickel delays the formation of detrimental intermetallic phases in austenitic stainless steels but is far less effective than nitrogen in delaying their formation in duplex stainless steel [7].

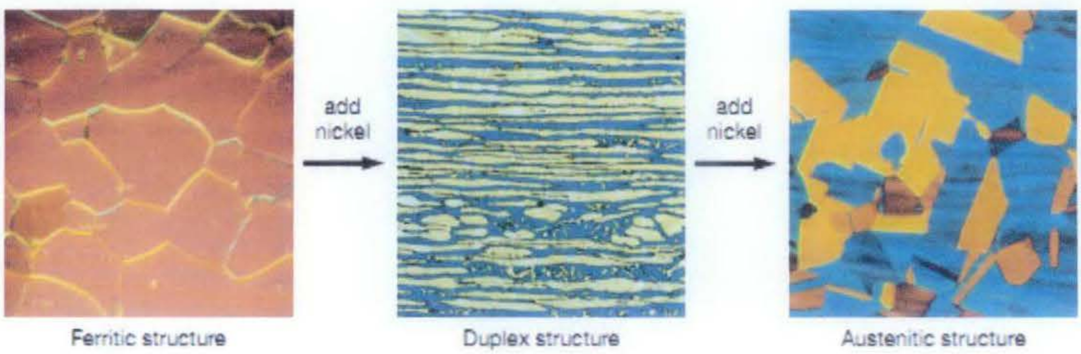

Figure 2.3: Increasing the nickel content changes the microstructure of stainless steel from ferritic (left), duplex (middle) and austenitic (right) [8]

The face-centered cubic structure is responsible for excellent toughness of austenitic stainless steels. Its presence in about half of the microstructure of duplex grades greatly increases their toughness relative to ferritic stainless steel [7].

2.1.2 LDX 2101

For this project, type of LDX 2101 is used. There are several types of duplex stainless steel including LDX 2101, Duplex 2205 and Duplex 2507. LDX 2101 is a lean duplex stainless steel designed for general purpose use. Like other duplex stainless steels, LDX 2101 provides both superior strength and chloride stress corrosion cracking resistance compared to 300 series stainless steels. The use of manganese ensures proper ferrite-austenite phase balance, while allowing a reduction in nickel content. As a result, LDX 2101 is priced competitively with 304/304L and 306/316L stainless steels [8].

The combination of a duplex structure and high nitrogen content provide significantly higher strength levels than 306/316L stainless steel. Often a lighter gauge of LDX 2101 can be utilized, while maintaining the same strength as a 300 series fabrication. The resultant weight savings can dramatically reduce the material and fabrication costs of a component.

Table 2.1: Tensile Properties Cold Rolled Plate and Sheet>1/4"

Alloy	Ultimate Tensile Strength, ksi (Min)	0.2% Yield Strength, ksi (Min)	Elongation, Percent (Min)	Hardness, Brinell (Max)
LDX 2101	94	65	30	290
304/304L	75	30	40	201
316/316L	75	30	40	217
2205	95	65	25	293
2304	87	58	25	290
AL 2003™	95	65	25	293

Source: ASTM A 240

There are many applications that used the LDX 2101 such as chemical process pressure vessels, piping and heat exchangers, storage tanks, water treatment, pulp and paper mill equipment and water heater tanks [8]. Some of the features of LDX 2101 are:

- High resistance to chloride stress corrosion cracking (SCC)
- High strength
- Chloride pitting and crevice corrosion comparable to type 316L stainless
- Good general corrosion resistance
- Good machinability and weldability
- Good erosion resistance
- Good fatigue resistance
- High energy absorption
- Low thermal expansion
- High wear resistance

Those features are related to the microstructure of duplex stainless steel which consists of ferritic and austenitic steels.

Table 2.2: Chemical composition of LDX 2101 [8]

Alloy	Min	Max
Chromium (Cr)	21.0	22.0
Nickel (Ni)	1.35	1.70
Manganese (Mn)	4.00	6.00
Molybdenum (Mo)	0.10	0.80
Nitrogen (N)	0.20	0.25
Carbon (C)	–	0.040
Silicon (Si)	–	1.00
Copper (Cu)	0.10	0.80
Phosphorus (P)	–	0.040
Sulfur (S)	–	0.030
Iron (Fe)	Balance	

2.2 Nitriding

Nitriding is a very common process of heat treatment. The main aim of this process is to obtain a nitrided layer which improves the wear resistance of steel [9]. Nitriding process is a case hardening process that depends on the absorption of nitrogen into the steel. All machining, stress relieving, as well as hardening and tempering are normally carried out before nitriding.

The parts are heated in a special container through which ammonia gas is allowed to pass. The ammonia splits into hydrogen and nitrogen and the nitrogen reacts with the steel penetrating the surface to form nitrides. Nitriding steels offer many advantages: a much higher surface hardness is obtainable when compared with case-hardening steels; they are extremely resistant to abrasion and have high fatigue strength.

Nitriding diffuses nitrogen into the surface of steel to improve mechanical properties to the material. There are several advantages that nitriding can offer to the stainless steel. It is predominantly used on the steel but also in titanium, aluminium and molybdenum. With nitriding, the steel can:

- increase wear resistance
- improve fatigue life
- improve the corrosion resistance
- improve the strength
- improve resistance to stress corrosion cracking (SCC)

2.2.1 Gas Nitriding Process

The gas nitriding divided into two types of process which are single stage and double stage nitriding. When ammonia comes into contact with the heated work piece it disassociates into nitrogen and hydrogen. The nitrogen then diffuses from the surface into the core of the material. It develops a very hard case in a component at relatively low temperature without the need of quenching.

Low temperature gas nitriding is done partially dissociated ammonia or in a mixture of ammonia and nitrogen. Oxygen or air is needed to activate the process [10]. Either single stage or double stage process employed when nitriding with anhydrous ammonia. The equation below shows the ammonia decomposition in the nitriding reaction.

$$2NH3 \rightarrow N^{+} + N^{+} + 3H_2$$

The single stage process produces a brittle; nitrogen-rich layer that known as white nitride layer at the surface of the nitrided case. For the second stage, the process is same with the first stage but differ in term of time or temperature. The purpose for second stage is to reduce the depth of the white layer produced on the surface of the case [11]. The external ammonia dissociator is necessary for obtaining the required higher second stage dissociation.

2.2.2 High Temperature Gas Nitriding

High temperature gas nitriding (HTGN) focus on nitrogen atom that absorbed into the surface of steel. Then, it diffuses into the near surface region [12]. The comparison has been made between the high and low temperature gas nitriding that showed quite different condition where intense chromium nitride precipitation occurs and greatly increasing the hardness of the steel.

According to research on duplex stainless steel, after the high temperature gas nitriding, the steel showed an austenitic surface layer that contains high nitrogen content in solid solution. Solution nitriding is a simple and powerful technique to obtain high nitrogen stainless steel without requiring special equipment.

High treatment temperature allows dissolving high nitrogen content in the steel without inducing nitride formation. The growth rate of the nitrided layer can be increased by increasing the nitriding temperature [13]. It has been known that the addition of nitrogen towards the austenitic steel has many advantages including the tensile strength increase, pitting corrosion resistance improve and the nitrogen itself harmless to the human body.

The high temperature gas nitriding (HTGN) is different from conventional gas nitriding where the HTGN is performed in nitrogen gas (N_2) atmosphere which is neither explosive neither toxic while the ammonia-hydrogen (NH_3-H_2) mixture is used. The nitrogen diffuses interstitially which is in between the atom or crystalline structure of the atom to form solid solution inside it. So, the surface of the steel increases due to that condition [14].

2.3 Wear

Wear is erosion or sideways displacement of material from it is "derivative" and original position on a solid surface performed by the action of another surface. Wear is related to interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface [15]. The need for relative motion between two surfaces and initial mechanical contact between asperities is an important distinction between mechanical wear compared to other processes with similar outcomes [16].

The definition of wear includes loss of dimension from plastic deformation if it is originated at the interface between two sliding surfaces. However, plastic deformation such as yield stress is excluded from the wear definition if it does not incorporates a relative sliding motion and contact against another surface despite the possibility for material removal because it lacks the relative sliding action of another surface.

The complex nature of wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes [17]. There are several types of wear which are:

- Adhesive wear
- Abrasive wear
- Surface fatigue
- Fretting wear
- Erosive wear

Wear can also be defined as a process where interaction between two surfaces or bounding faces of solids within the working environment results in dimensional loss of one solid, with or without any actual decoupling and loss of material. Aspects of the working environment which affect wear include loads and features such as unidirectional sliding, reciprocating, rolling, and impact loads, speed, temperature, but also different types of counter-bodies such as solid, liquid or gas and type of contact ranging between single phase or multiphase, in which the last multiphase may combine liquid with solid particles and gas bubbles.

2.3.1 Wear Test

Wear characteristics are more to system properties rather than material properties. Contact type, the operating conditions, environment, the material characteristics of the test material and the mating material are the main factors for operating wear mechanism.

There is a range of test available for wear resistance testing. The two common tests are lubricated rolling and sliding wear where for lubricated rolling, the roller is made from the metal matrix composites (MMC) test material and the cylinder is made from cast iron. As for sliding test, there is a stationary test block which is MMC and a rotating steel ring. The wear test is done at specific applied normal load and rotational speed.

The pin-on-disk method will be used to analyze the wear characteristic of the nitride duplex stainless steel. Wear resistance is determines by using DUCOM Multi Specimen Tester. It was performed according to ASTM Standard G99. This type of apparatus offers far better control of experimental conditions and become increasingly used in preference to other tribometers.

Figure 2.4: DUCOM Multi Specimen Tester

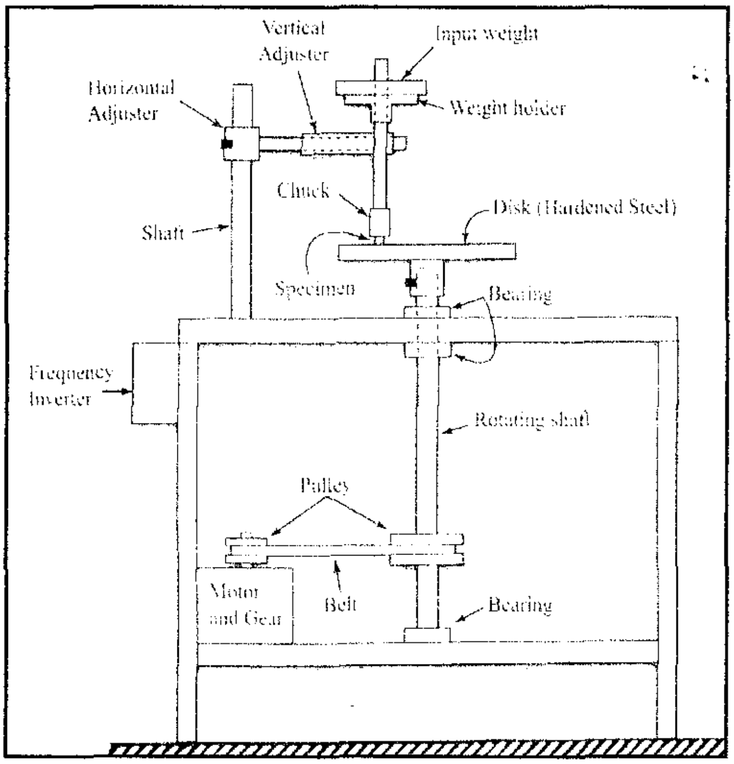

Figure 2.5: Schematic diagram of the pin-on-disk apparatus

The details regarding the pin-on-disk type wear testing apparatus can be referred to Figure 2.5. When using this machine, user can set the parameters by key in the values. The result from the test is measured by determining the weight loss as function of sliding distance [18].

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

Literature reviews

- Study on the previous research such as nitriding concept, microstructure and wear resistance test.

Sample preparations

- Raw material of LDX 2101 duplex stainless steel undergoes cutting process using EDM wire cut to specific size.
- Grinding, polishing and etching are used to determine the early microstructure.

Determine the microstructure of the sample

- Microstructure studies on the sample using the optical microscope (OM) and scanning electron microscope (SEM)

Conduct nitriding process

- Perform gas nitriding at three different temperatures with and constant six hours in the horizontal tube furnace.
- Weight of samples before and after nitriding are to be taken.

Conduct the wear test

- Cut the sample into specific size to undergo wear resistance test after nitriding.
- Weight loss after wear test to be analyzed.

Result compilation and comparison

- Observe the samples composition and microstructure using X-ray Diffraction (XRD) and Field Emission Scanning Elctron Micrsoscope (FESEM).
- Plot the graph for the weight loss for all sample after undergo wear test

Conclusion and recommendations

- Recommendations and suggestion to the project for improvement.
- Conclude finding of the project

3.2 Project Activities

In completing this project, there are few steps and procedures will be taken to ensure that the objectives of the project are fulfilled.

3.2.1 Research Methodology

- Identifying real problem and project objectives
- Revision of the crystal structure and phase (LDX 2101 of duplex stainless steels)
- Get familiar with stainless steel (specially LDX 2101 of DSS) and the types in industry
- Survey any related info and literature review using journals, books, magazine and internet

3.2.2 Project Procedures

(1) Get the substrate material – determine the dimension and shape for the sample (20mm length x 20mm width)

(2) Microstructure observation and confirmation before nitriding,

i. Sample selection (LDX 2101 duplex stainless steel)

ii. Sample preparation:

- Sectioning – Sample is cut into small size.
- Grinding – Surface damages introduced by previous operation are removed.

Figure 3.1: Grinding and polishing machine

- Polishing – To produce scratch-free surface with mirror-image finish

Figure 3.2: 1 micron DIAMAT Polycrystalline Diamond for polishing

- Etching – To make the microstructure of the surface under microscope inspection will be visible. For LDX 2101 of D.S.S, the etching agent is Fry Reagent. After etching the sample, ensure the sample surface is washed with water to remove any contaminant. Then wash with ethanol and dry properly to avoid any water to be in surface when observing the microstructure.

Figure 3.3: Fry Reagent

(3) Perform HTGN process

a) Tube furnace is used and connected with the nitrogen supply, flow meter and cone flask. Cone flask filled up with water with the intention that the bubble can be observed as a way to confirm the flow of nitrogen besides using the flow meter.

Figure 3.4: Nitrogen supply

Figure 3.5: Flowmeter

Figure 3.6: Cone flask

b) A specific temperature and time to perform nitriding are decided.

c) For this project, the nitriding temperature is divided to three different temperatures at 1000°C, 1050°C and 1100°C while time interval is constant for six hours.

d) The HTGN is performed as in procedures below :

   i. Carried out in Carbolite Horizontal Tube Furnace

Figure 3.7: Carbolite Horizontal Tube Furnace

ii. Sample is cleaned using acetone

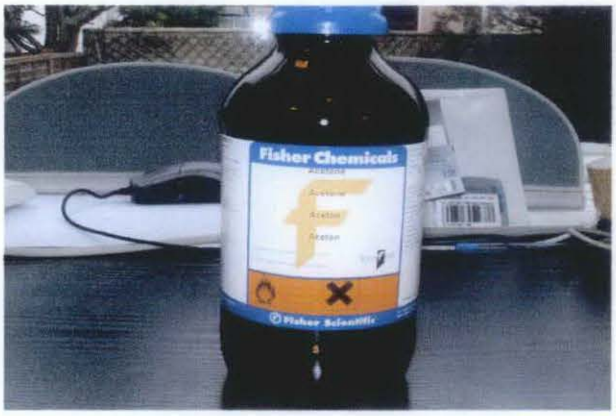

Figure 3.8: Acetone

iii. The sample is placed in alumina boat and inserted into the heating zone

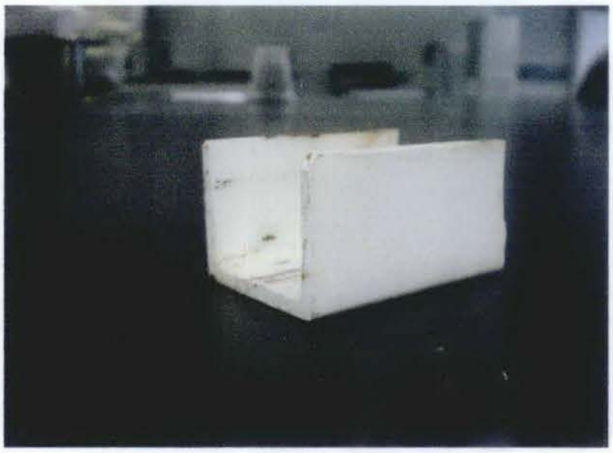

Figure 3.9: Alumina Boat

iv. Air in furnace is purging with nitrogen for 15 minutes and at a flow rate of $1000cm^3/min$ to prevent oxidation of the samples.

v. Heating at 15°C/min started immediately after the purging completed.

vi. The required parameters such as time and temperatures are set.

vii. Turn on the heater and the furnace is heated to temperature of 1000°C for six hours and nitrogen will be introduce into furnace with flow rate of $1000cm^3/min$

viii. After six hours, the nitride sample is let to be cool by slow cooling.

ix. The tube furnace opened, personal protection equip ment (PPE) must be wear. The procedure is repeated for temperatures of 1050°C and 1100°C.

x. Analysis and compile the result of the data.

(4) Perform wear test process

i. The raw sample is cut into the size for the wear test (12mm x 6mm).

ii. The sample is weighted before the test

iii. The sample is put inside the sample holder.

Figure 3.10: Sample holder for wear test.

iv. The disc is placed inside the wear machine.

v. The load is setup with 2.5 kg and 1000 rpm rotating speed.

vi. Time is set for 6 minutes.

vii. The machine is run.

viii. After finished, the sample is weighted.

ix. The procedures are repeated using the 1000°C, 1050°C and 1100°C nitrided samples.

x. The weight loss of each sample is analysed.

Table 3.1: DUCOM Multi Specimen Tester Parameters

Variables	**Unit**	**Values**
Load	Kg	2.5
Rotating speed	RPM	1000
Time	Minute	6
Temperature	°C	Room temperature (24)
Geometry	-	Rectangular
Atmosphere	-	Relative Humidity: 70% Atmospheric pressure: 1atm
Material used	-	1) Test specimens (LDX 2101 duplex stainless steel) 2) Disk Material Hardened steel (LDX 2101 duplex stainless steel)
Surface finish	-	Machined surface finish
Type of lubricant	-	Dry

3.2 Hardware and Tools

3.2.1 Raw Materials

- Duplex stainless steel types of LDX 2101

3.2.2 Tools

- Wire cut EDM
- Grinder and emery paper
- Polisher and 1 micron diamond paste
- Fry reagent
- Optical microscope
- X-Ray Diffractiometer (XRD)
- Scanning Electron Microscope (SEM)
- Horizontal tube furnace
- DUCOM Multi Specimen Tester

Table 3.2: Detail of equipment use

Equipment / Tool	Description
Scanning Electron Microscopy (SEM)	Creates high magnified images by using electron instead of light waves.
X-Ray Diffractiometer (XRD)	The identification of crystalline compounds by their diffraction pattern.
Optical microscopy	The use of visible light to magnify the sample.
DUCOM Multi Specimen Tester	Perform pin on disc method for wear test.

Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project work continue : Grinding, polishing and etching														
Start nitriding process														
Progress report preparation														
Fabrication for wear test: Disc (turning) and Sample (EDM)														
Submission of Progress Report 1									Δ					
Perform Wear Test on fabricated samples														
Analysis using XRD and FESEM														
Result gathering														
Poster Exhibition											Δ			
Submission of Dissertation final draft														Δ
Oral presentation														Δ
Submission of Dissertation (hard bound)											7 days after oral presentation			

Δ Key milestone

☐ Completed activities

Figure 3.11: Gantt chart

CHAPTER 4

RESULT AND DISCUSSION

4.1 Nitriding Process

Table 4.1: The weight of each sample (before and after nitriding).

Sample	Temperature (°C)	Weight before nitriding (g)	Weight after nitriding (g)	Weight difference (g)
1	1000°C	17.583	17.622	0.014
2	1050°C	17.486	17.509	0.023
3	1100°C	17.484	17.498	0.039

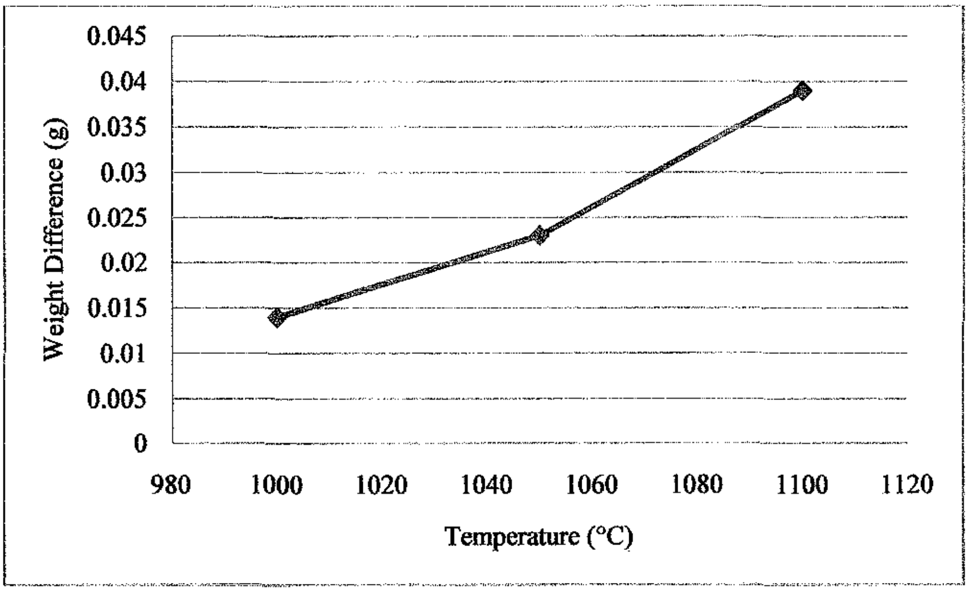

Figure 4.1: The temperature (°C) versus weight difference in gram.

The nitrogen diffusion is greatly influenced by the temperature. Based on the Figure 4.1, the graph shows that weight difference increased when the temperature increased in gas nitriding process. The calculation is from the weight before subtracting weight after nitriding. Nitrogen diffuse into the steel is better when the temperature is high, so, it increases the weight of the steel. It has been known that the addition of nitrogen during nitriding process greatly influence the weight of the steel. The growth rate of the nitrided layer can be increased by increasing the nitriding temperature [13].

4.2 Wear Test

Table 4.2: The weight of each sample (before and after wear test).

Sample	Weight before wear test (g)	Weight after wear test (g)	Weight loss (g)
1000°C	3.0143	2.8136	0.2007
1050°C	3.0973	2.9164	0.1809
1100°C	3.0607	2.9008	0.1599

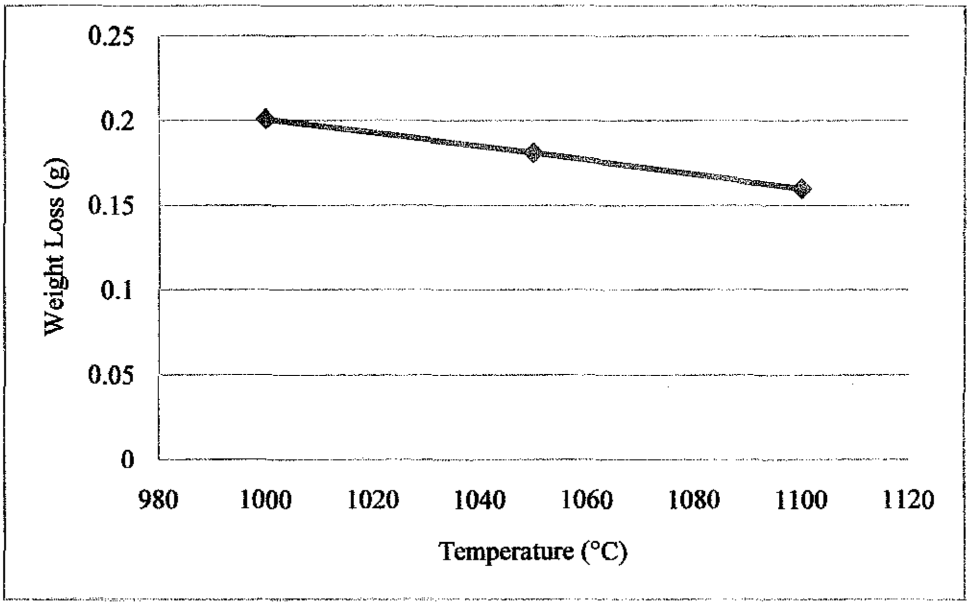

Figure 4.2: The temperature (°C) versus weight loss in gram

Based on the Figure 4.2, the graph shows that weight loss decreased when the temperature increased in wear test process. The calculation is from the weight before subtracting weight after wear test. Nitrogen diffuse into the steel is better when the temperature is high, so, it increases the wear resistance of the steel. Based on the result on Yun-tao Xi, *et.al* in their experiment, the weight loss of after 30 minutes wear test are 4.33 mg, 0.13 mg and 0.21 mg for the untreated sample, the 350 °C and 550 °C nitrided samples respectively [19]. It shows that the temperature for nitriding plays important role in term of wear resistance of the steel.

4.3 Wear Resistance Analysis

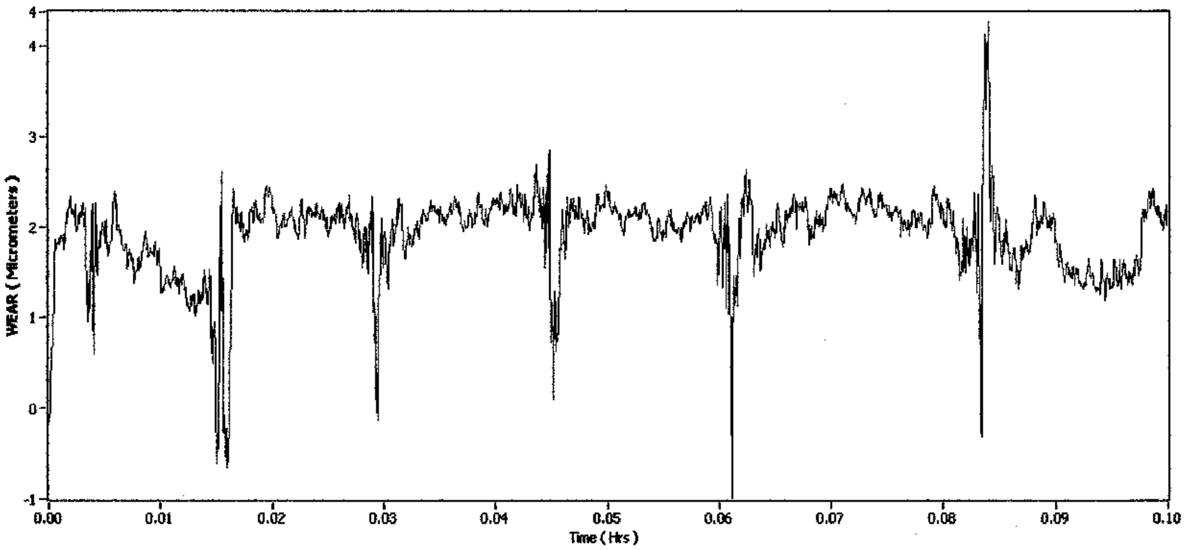

Figure 4.3: Wear resistance graph of the raw material.

Based on Figure 4.3, it is approximately that wear displacement about 2.3 micrometers for 0.1 hour or 6 minutes of wear test. The graph is for the wear test on the raw material of LDX 2101 duplex stainless steel. The weight loss for raw material of LDX 2101 duplex stainless steel after undergo wear test is 0.2312 g.

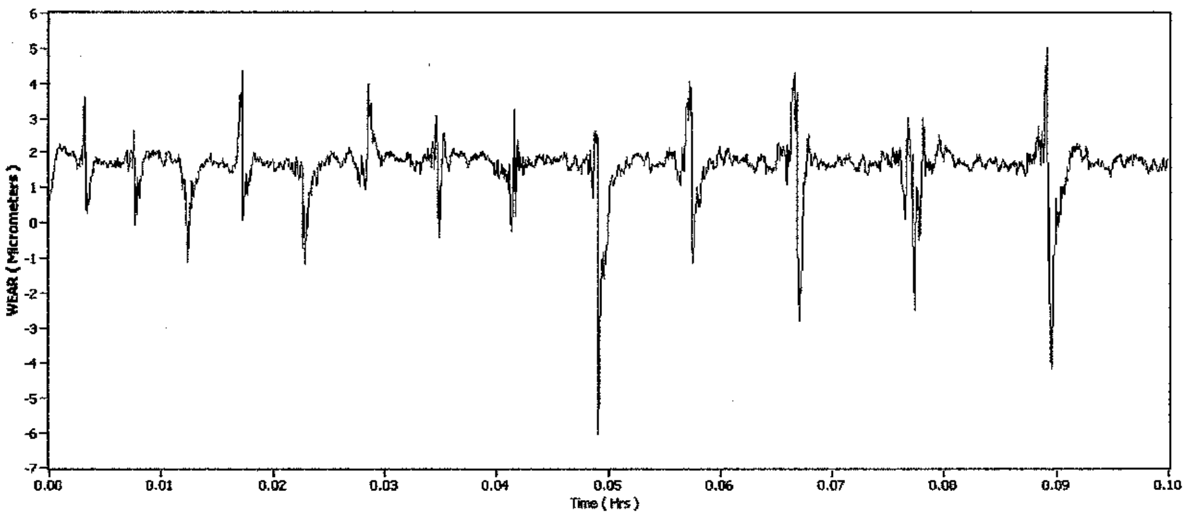

Figure 4.4: Wear resistance graph of the 1000°C nitrided sample.

Based on Figure 4.4, it is approximately that wear displacement about 2.0 micrometers for 0.1 hour or 6 minutes of wear test. The graph is for the wear test on the raw material of LDX 2101 duplex stainless steel. The weight loss for 1000°C nitrided steel after undergo wear test is 0.2007 g.

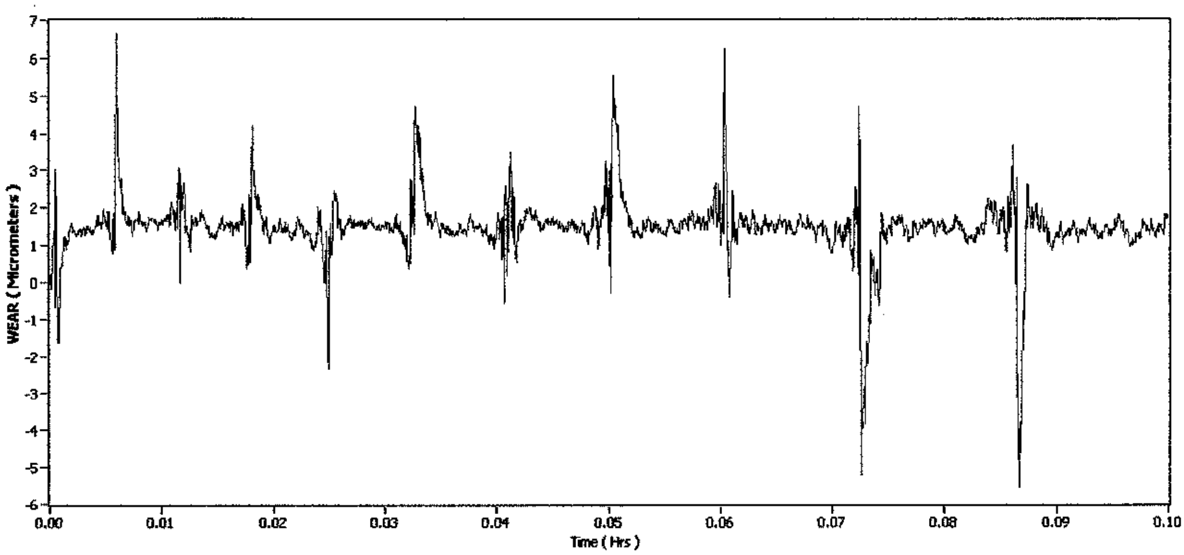

Figure 4.5: Wear resistance graph of the 1050°C nitrided sample.

Based on Figure 4.5, it is approximately that wear displacement about 1.8 micrometers for 0.1 hour or 6 minutes of wear test. The graph is for the wear test on the raw material of LDX 2101 duplex stainless steel. The weight loss for 1050°C nitrided steel after undergo wear test is 0.1809g.

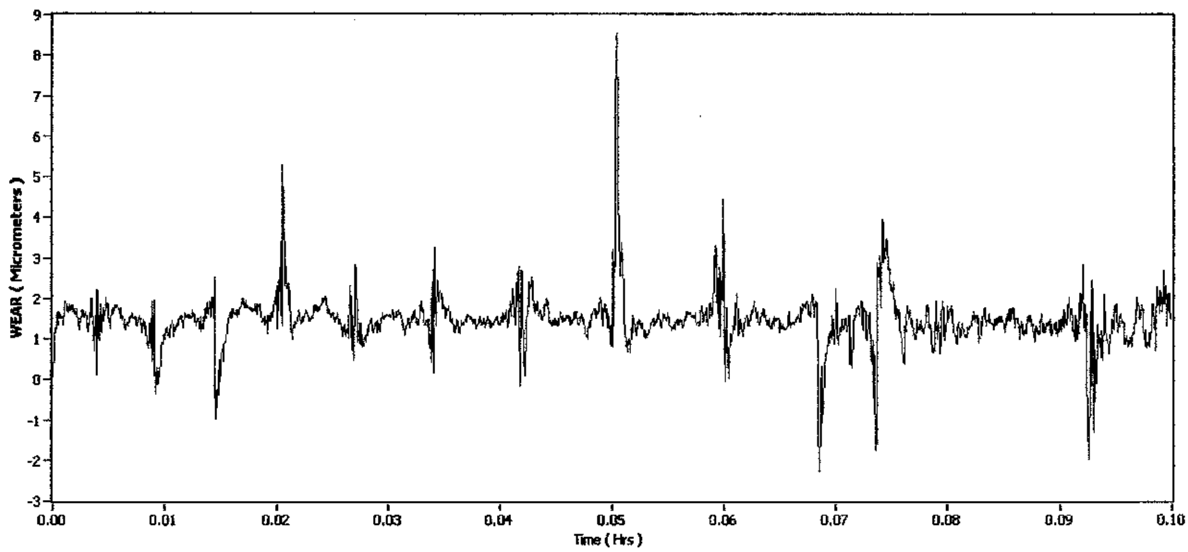

Figure 4.6: Wear resistance graph of the 1100°C nitrided sample.

Based on Figure 4.6, it is approximately that wear displacement about 1.5 micrometers for 0.1 hour or 6 minutes of wear test. The graph is for the wear test on the raw material of LDX 2101 duplex stainless steel. The weight loss for 1100°C nitrided steel after undergo wear test is 0.1599 g.

Based on the four graphs, it shows that the wear resistance of the LDX 2101 increased with the temperature of nitriding process. The graph shows the reduction of wear displacement from approximately 2.3 micrometers, 2.0 micrometers, 1.8 micrometers and 1.5 micrometers for the raw, 1000°C, 1050°C and 1100°C sample respectively.

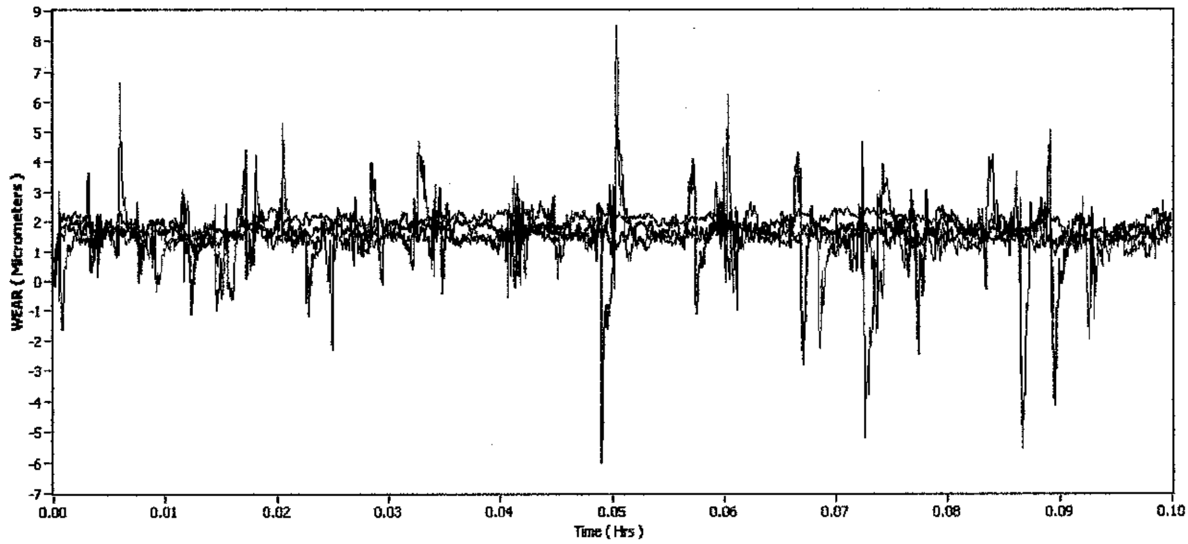

Figure 4.7: Comparison of wear resistance graph for all samples.

4.5 XRD Result

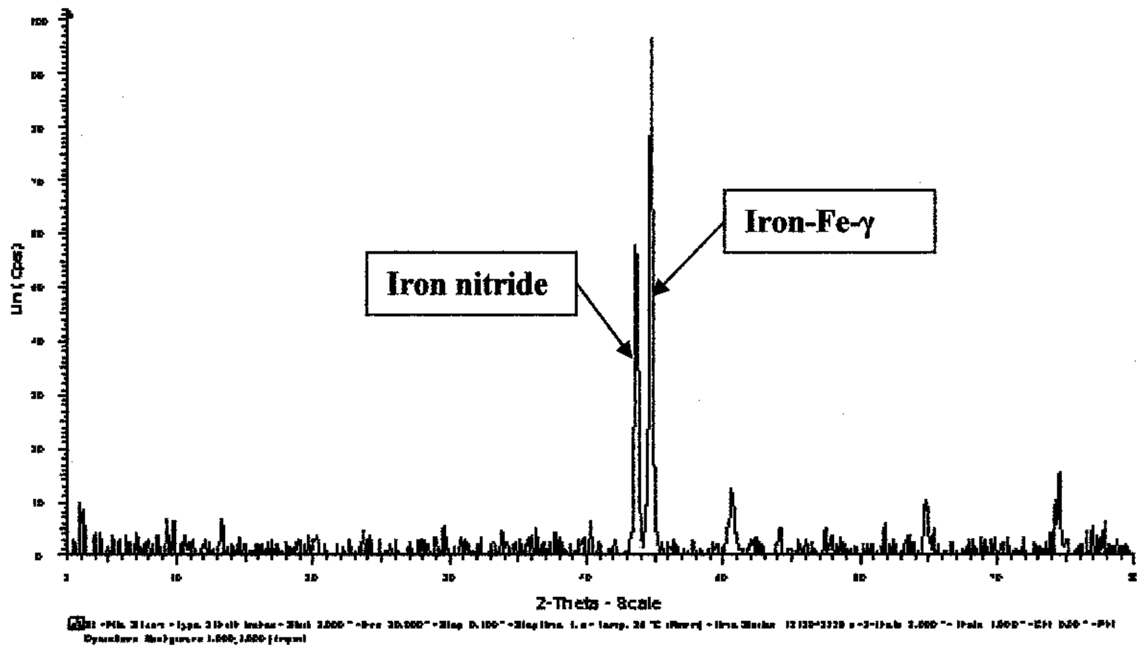

Figure 4.8: XRD result for raw sample

As found in the XRD result of Figure 4.8, there is a less presence of nitrogen compounds in the raw specimen. The high presence of nitrogen compound can lead to the increment of the wear resistance.

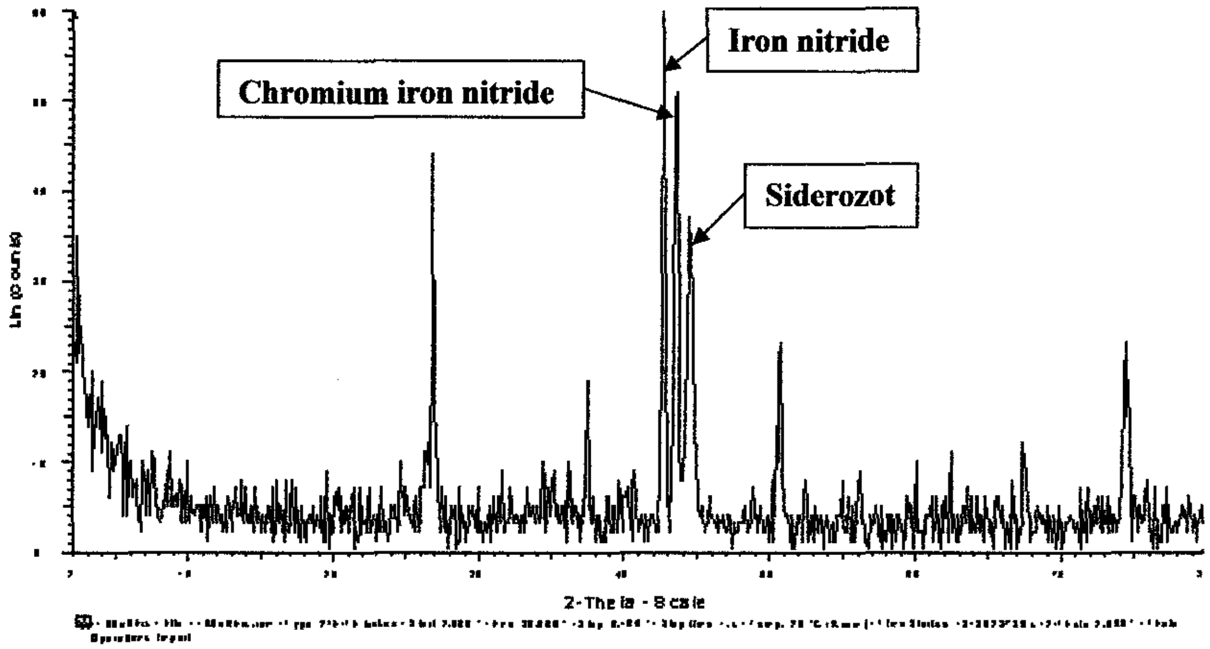

Figure 4.9: XRD result for nitrided sample

From the Figure 4.9 XRD analysis, the phase formations of nitrides were obtained. From the XRD pattern, it was observed that iron nitrides are formed at the peaks with nitrogen formation. The formation of Cr-Ni-Fe-C elements such as siderozot, iron nitride and chromium iron nitride in nitrided sample improves the wear resistance of the material.

CHAPTER 5

CONCLUSION

As conclusions, the high temperature of gas nitriding process greatly influences the diffusion of nitrogen into the LDX 2101 duplex stainless steel. From the analysis of the weight difference, the 1100°C sample was the highest weight difference followed by the 1050°C and 1000°C samples, respectively. The increment is 0.039 g for 1100°C sample, 0.023 g for 1050°C sample and 0.1599 g for 1000°C sample.

The highest weight loss after undergoing wear test is 1000°C sample with the difference of 0.2007 g. It follows by 1050°C sample with the difference of 0.1809 g and then 1100°C sample with the difference of 0.1599 g. The wear test analysis shows that the higher temperatures of the sample undergo the nitriding process, the higher wear resistance and less weight loss of the steel.

The presence of nitrogen compound inside the sample on the XRD analysis lead to the increment of wear resistance of the steel. As the comparison between the raw sample with the nitrided sample, it showed the formation Cr-Ni-Fe-C element on the nitrided sample.

RECOMMENDATION

There are a few recommendation proposed to improve this project. The range of nitriding temperature shall be expanded to the higher range. The higher range of temperature in the nitriding process can lead to the precise and accurate interpretation towards the wear behaviour of the steel. Besides, the effect of other parameter such as time interval and rate of purging for nitriding process shall be investigated to determine the optimum condition to evaluate the surface modification of the steel. Perhaps, in the future, the comparison study on the different method to enhance the wear resistance of the steel can be done. Finally, it is recommended that to run the high temperature gas nitriding using the new stainless steel with different grade to confirm whether it is applicable to be used the method.

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