UNIVERSITI TEKNIKAL MALAYSIA MELAKA

MECHANICAL AND THERMAL PROPERTIES OF INTERMETALLIC Ni_3Al FOR AUTOMOTIVE BODY APPLICATIONS

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering (Engineering Materials) with Honours,

by

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FACULTY OF MANUFACTURING ENGINEERING

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfillment of the requirements for the Bachelor Degree of Manufacturing Engineering (Engineering Materials) with Honours. The member of the supervisory committee is as follow:

……………………………………………….

(PROF. MADYA DR. T. JOSEPH SAHAYA ANAND)

ABSTRACT

This project describes the study of the mechanical and thermal property of Ni_3Al to be applied on automotive body. Ni_3Al is an intermetallic compound which has a unique property with temperature. It is a material which is lighter and 5 times stronger than stainless steel as temperature approaches 800^{o}C. However, this material is expensive and is not common in the industries. Through this study, hardness test as mechanical property, and corrosion test is done on non-heat treated Ni_3Al, and annealed Ni_3Al specimens. Annealing is done at temperature 300^{o}C, 500^{o}C, and 700^{o}C; soaked for 1 hour, and let cool at furnace for 24 hours. The material composition before and after annealing, is then analyzed with X-ray Dispersive (XRD) and Energy Dispersive X-ray (EDX) analysis. The results showed that Ni_3Al have highest Vickers hardness value of 554 HV when it is non-heat treated. Ni_3Al's hardness drops as it had undergoes annealing process. Results also showed highest polarization resistance when Ni_3Al is annealed at temperature 300^{o}C which is 4154.95 Ω cm^2. It also exhibit passivation behavior. On the other hand, XRD confirmed the composition of Ni_3Al. EDX also had confirmed the elements of the material used in this project and it shows no other element exist other than Ni and Al even after annealing process. At the end of this project, it is found that Ni_3Al is a promising material to be applied on automotive body as its hardness and corrosion resistivity is higher than current automotive material. However, due to its cost, Ni_3Al may only be applied on high end automotive body such as BMW, Mercedes, Audi, and so on.

ABSTRAK

Projek ini membentangkan kajian sifat mekanikal dan termal Ni_3Al untuk diapplikasikan dalam badan automotif. N_3Al adalah sejenis sebatian yang mempunyai sifat unik terhadap suhu. Ia adala sejenis bahan yang lebih ringan dan 5 kali lebih kuat daripada besi tahan karat apabila suhunya mencapai 800 ^{o}C. Bagaimanapun, bahan ini mahal dan tidak biasa digunakan dalam industri. Daripada kajian ini, kekerasan sebagai sifat mechanical, dan ujian karat dikaji ke atas Ni_3Al yang tidak dirawat dan dirawat. Rawatan suhu dijalankan pada suhu 300^{o}C, 500^{o}C, dan 700^{o}C; selama 1 jam, dan disejukkan dalam relau selama 24 jam. Composisi bahan sebelum dan selepas rawatan akan dikenal pasti dengan analisis Pengagihan X-Ray (XRD) dan Peleraian Tenaga X-Ray (EDX). Hasil kajian menunjukkan bahawa Ni_3Al mempunyai kekerasan Vickers setinggi 554 HV dan kekerasannya berkurang apabila rawatan suhu dijalankan. Hasil kajian juga menunjukkan bahawa Ni_3Al mempunyai ketahanan pola tertinggi apabila dirawat pada suhu 300 ^{o}C iaitu 4154.95 Ω cm^2. XRD dalam project ini telah mengenalpasti komposisi bahan yang digunakan adalah Ni_3Al, dan EDX pula mengenalpasti elemen yang wujud dalam bahan project ini adalah hanya Ni dan Al walaupun setelah dirawat. Pada akhir project ini, Ni_3Al memberikan hasil yang baik di mana kekerasan dan ketahanan karatnya adalah lebih baik daripada bahan badan automotif masa kini. Tetapi, harganya adalah mahal menjadikan Ni_3Al mungkin hanya boleh diapplikasikan dalam kereta berjenama seperti BMW, Mercedes, Audi, dan lain-lain.

DEDICATION

I dedicated this report to my project supervisor, Prof. Madya Dr. T. Joseph Sahaya Anand and my fellow friends who are doing similar study. Also to Mr. Ganesh, a postgraduate who guided us thoughout our project. Without their patience, understanding, and support, the completion of this work would not have been possible.

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LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
CNC	-	Computer Numerical Control
CS	-	Combustion Synthesized
EDX	-	Energy Dispersive X-ray
FEM	-	Finite Element Method
FKP	-	Faculty of Manufacturing Engineering
HSLA	-	High Strength Low Alloy
HSS	-	High Strength Steel
ISO	-	International Organization for Standardization
LCD	-	Liquid Crystal Display
ORNL	-	Oak Ridge National Laboratory
RE	-	Reactively Extruded
Rp	-	Polarization Resistance
RP	-	Reactively Pressed
SEM	-	Scanning Electron Microscopes
UK	-	United Kingdom
UTeM	-	Universiti Teknikal Malaysia Melaka
UTM	-	Universal Testing Machine
XRD	-	X-Ray Diffraction

CHAPTER 1

INTRODUCTION

This section contains the introduction of the mechanical and thermal properties of Ni_3Al for car body application, problem statement, objectives, scope, and importance of study of this project.

1.1 Introduction

Current materials that are used to construct automotive body consist of many different type; aluminum, magnesium, high strength steel, composites, polymer, etc. The main material that used to construct automotive body is high strength steel. High strength steel is preferred because of it is cheap, and yet be able to give an excellent properties like high hardness, yield strength, ultimate tensile strength, etc.

This project is to study whether Ni_3Al can be able to replace the flaws that current automotive body materials are facing, or not. Ni_3Al is an intermetallic which has very high melting temperature and unique properties. As Ni_3Al is subjected to increase in temperature, its mechanical properties improves. It is six times stronger than stainless steel and its strength doubles when temperature reaches 800^{o}C compared to room temperature.

In this project, focus is given to mechanical and thermal properties of Ni_3Al. Four tests will be conducted to determine the mechanical properties of Ni_3Al. They are tensile test, hardness test, fatigue test, and impact test. Ni_3Al thermal property is done by heat treating Ni_3Al samples at temperature ranging from 300^{o}C to 700^{o}C. Then same test are conducted on the heat treated samples.

1.2 Background of problems

One of the problem that current car body material faces is the weight of the material. The material that is used in current days is mainly high strength steel with an average density of 7.87g/cc compared to aluminum which is 2.69g/cc. When the weight of the car is higher, inertia of the car is higher, and friction between tires and ground also increased. These lead to more fuel consumption in order to move the car forward. If aluminum is used instead, the cost of the car will be very high due to the price of aluminum.

Another problem that car body faces is its resistance to corrosion. Cars are usually protected by a tough layer of paint. If these paints are exposed to acidic liquid, it will be degraded. This degradation will cause the some of the acidic liquid contact with metallic material which were protected by the paint. At the end, corrosion happens, and in the worst situation, corrosion will spread to the whole car structure. The source of acidic liquid might come from acidic rain or bird's droppings.

Accidents may happen anytime anywhere on road. Thus choosing a material that will reduce the impact of collision is crucial. The material of the car body should be hard and strength to absorb impacts.

1.3 Objectives

The objectives of this project are:

1. To compare the mechanical property, thermal property, and chemical property of Ni_3Al with current automotive body material
2. To analyze whether Ni_3Al is a suitable material to replace current automotive body material.

1.4 Scope

Two related tests are chosen for this project, which are hardness test and corrosion test on Ni_3Al material. This project includes how the samples are prepared based on American Society for Testing and Materials (ASTM) testing standards. This project also includes annealing process as thermal property to the prepared samples, and then evaluating their mechanical and chemical property. The Ni_3Al crystallography structure is confirmed by using X-ray Diffraction (XRD) analysis. The composition of the material before and after heat treatment will be confirmed by Energy Dispersive X-ray (EDX) analysis. At the end, the obtained data will be compared to current automotive body material and conclusion will be drawn whether Ni_3Al is suitable to be applied on automotive body system.

1.5 Importance of Study

This project is important to explore other type applications of Ni_3Al. Ni_3Al nowadays are only applied on manufacturing industries where it is used as binder for tungsten and chromium, and mainly on high temperature rollers. Due to this, Ni_3Al material is not widely manufactured, and thus have very expensive price. If this project proves that Ni_3Al can be used in automotive body application, then there will be investors to invest on mass production of this material. This will reduce the cost of Ni_3Al, and increases its availability in future. Hence, there will be more applications of Ni_3Al material in future.

CHAPTER 2

LITERATURE REVIEW

2.1 Ni_3Al Intermetallic Compound

Intermetallic compounds are a broad class of metals resulting from the combination of various elements including nickel aluminides (such as NiAl, Ni_3Al and Ni_5Al_3), titanium aluminide, niobium aluminide, iron aluminide, iron silicide, and various other silicides. Each of them has a unique set of properties [James, K.W. (2004)]. According to John, E. (1998), intrinsic Ni_3Al have an increasing property like strength and hardness with increase in temperature. However, its bigger flaw is it is brittle and is not easy to shape. In 1982, Oak Ridge National Laboratory (ORNL), led by C.T. Liu, discovered a way to make this desirable material ductile by adding Boron. The result is a material (IC-221M) lighter and six times stronger than stainless steel. John, E. (1998) also stated that Ni_3Al is a very promising material which someday might be the main material for automobile's engine. **Figure 2.1** shows Al-Ni phase diagram.

2.1.1 Structure

Nickel aluminides are intermetallic materials that have long been considered potentially useful because of their ordered crystal structure, they are very strong and hard and melt only at very high temperatures [Carolyn, K. (1995)]. Ni_3Al have an $L1_2$ (cP4) crystal structure (**Figure 2.2**), a derivative of the face-centered cubic (fcc) crystal structure which is similar to bcc iron with high crystal symmetries and having favorable system {(1 1 0) <1 1 1>}. This unit cell contains four atoms, i.e., the same number as fcc. The Ni_3Al atoms occupy face-centered positions and the aluminum or silicon atoms occupy the corners of the unit cell [John, W (2001), Chakraborty et al. (2001)]. This crystal structure have give rise to a very strong and hard material. It is six times stronger than stainless steel, and it will become harder as temperature rises. At 800^0C Ni_3Al is twice as strong as it is at room temperature [Carolyn, K. (1995), John, E. (1998)]. Besides, Ni_3Al have melting temperature as high as 1395^oC [Chaman, L. (1994)].

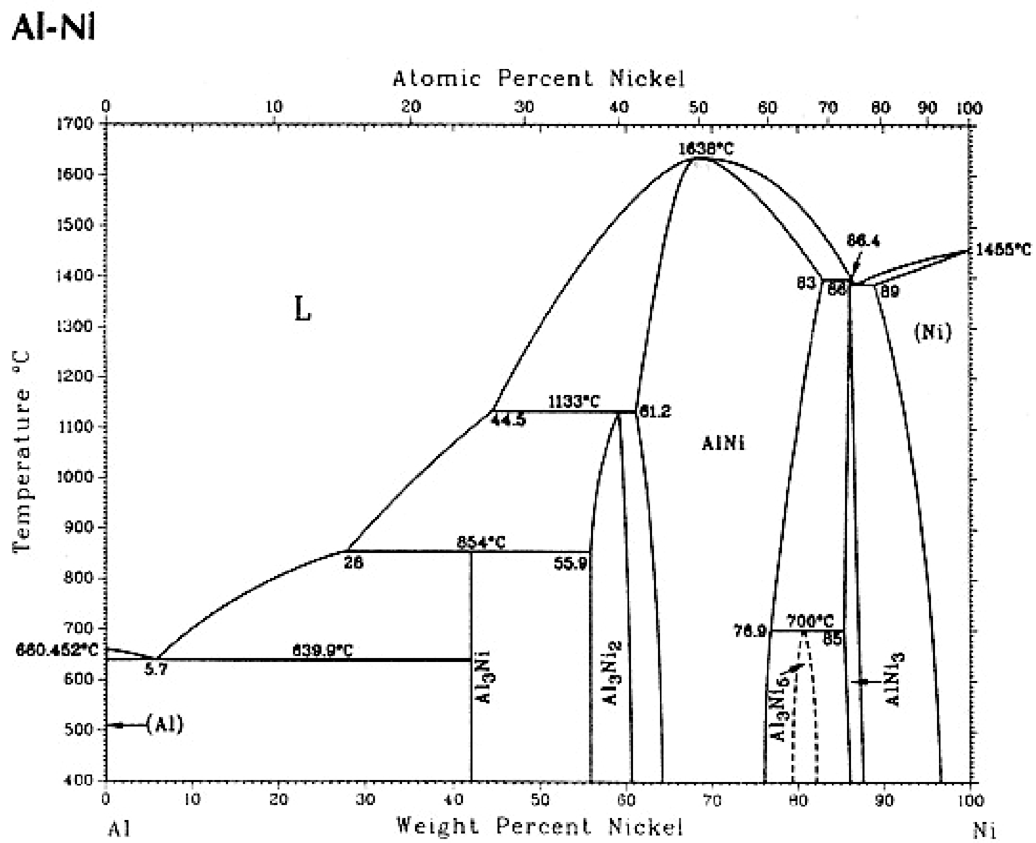

Figure 2.1: Al-Ni Phase diagram

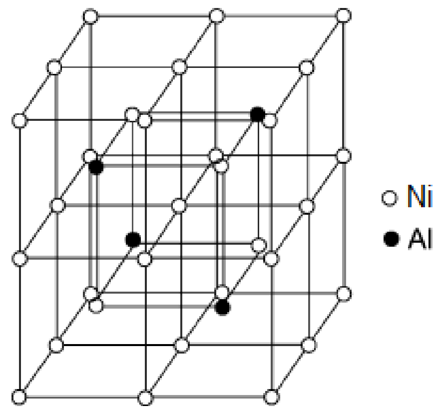

Figure 2.2: Ni_3Al Crystal structure

2.1.2 Processing

In a conventional melting process, nickel aluminide is obtained by melting nickel and loading aluminum into the molten nickel melt stock. This process requires heating the melt stock to a temperature of 1600°C prior to the addition of aluminum. Melting of aluminum is generally not preferred since molten aluminum can seep through the crucible as the temperature is raised to 800°C or higher and damage the induction coil with serious safety issues to the furnace and the operators. The addition of aluminum to the molten nickel melt stock can raise the temperature of the crucible by several hundred degrees and will also result in oxidation of aluminum and some other alloying elements [Deev,i S.C., and Sikka, V.K. (1995)].

Melting of Ni,Al-based intermetallic alloys was successfully accomplished by the Exo-Melt™ process by modifying the furnace-loading sequence to initiate the highly exothermic NiAl reaction to form superheated NiAl liquid initially. In contrast to the Exo-Melt™ process, the conventional melting practice of adding aluminum to molten nickel increased the temperature of the bath from 1600 to 2300°C and a vapor cloud formed due to the oxidation of alloying elements. The Exo-Melt™ process results in power savings of 47% over conventional melting practices, and the process has been used to melt and cast a total of 8000 kg of Ni&Al-based alloy [Deev,i S.C., and Sikka, V.K. (1996)]. Time required to melt and pour the intermetallic by the Exo-Melt^{TM} process can be reduced by 50% as opposed to a conventional process. All of these resulted in substantial savings in energy and a reduction in processing cost. [Deev,i S.C., and Sikka, V.K. (1995)].

2.1.3 Properties of Ni_3Al

The physical properties of Ni_3Al alloy designated IC-221M are given by **Table 2.1** by James, K.W. (2004).

In year 2005, a detailed study of the high-temperature oxidation behavior of powder processed Ni_3Al (combustion synthesized (CS), reactively pressed (RP), and reactively extruded (RE)) in air at two different temperatures (1000 and 1200 °C) for 400 h was carried out. The results indicated that Ni_3Al alloys processed using RE showed superior high-temperature oxidation resistance compared to either RP or CS-Ni_3Al at both 1000 and 1200 °C. The oxide scales resulting from the high-temperature oxidation of Ni_3Al consisted of an internal layer of Al_2O_3 (major phase in the case of RE and RP), intermediate layer of $NiAl_2O_4$, and an external scale of NiO (major phase in the case of CS-Ni_3Al at 1000 and 1200 °C) [Moussa, S.O., and Morsi, K. (2006)].

The stress corrosion cracking resistance of ductile nickel aluminide, Ni_3Al+*B*, was evaluated by conducting experiments in solutions with varying pH and ionic concentration. The results demonstrate that the ductility of this material is greatly reduced and the fracture mode changes from ductile transgranular to brittle intergranular cracking when environmental conditions are favorable for hydrogen absorption during the steady state regardless of the solution composition and pH. The results also indicate that, in the absence of cathodic polarization, this material exhibits ductile behavior during free corrosion in solutions of neutral and alkaline pH [Richard, E.R. (1995)].

Table 2.1: Properties of Ni_3Al alloy IC-221M

Property	Temperature (°C)							
	Room	200	400	600	800	900	1000	1100
Density (g/cm^3)	7.86	—	—	—	—	—	—	—
Hardness (R_C)	30	—	—	—	—	—	—	—
Microhardness (dph)	260	270	280	290	280	230	120	—
Modulus (GPa)	200	190	174	160	148	139	126	114
Mean coeff. of thermal expansion (10^{-6}/°C)	12.77[a]	13.08[b]	13.72[b]	14.33[b]	15.17[b]	15.78[b]	16.57[b]	—
Thermal conductivity (W/m · K)	11.9	13.9	16.7	20.3	25.2	27.5	30.2	—
0.2% Tensile yield strength (MPa)	555	570	590	610	680	600	400	200
Ultimate tensile strength (MPa)	770	800	850	850	820	675	500	200
Total tensile elongation (%)	14	14	17	18	5	5	7	10
10^2 h rupture strength (MPa)	—	—	—	—	—	—	—	—
10^3 h rupture strength (MPa)	—	—	—	—	—	—	—	—
10^3 h rupture strength (MPa)	—	—	—	—	—	—	—	—
Charpy impact toughness (J)	40	40	40	35	15	10	—	—
Fatigue 10^6 cycle life (MPa)	—	—	—	630[c]	—	—	—	—
Fatigue 10^7 cycle life (MPa)	—	—	—	550[c]	—	—	—	—

[a] Room temperature to 100°C (212°F).
[b] Room temperature to specified temperature.
[c] Data at 650°C (1202°F) for investment-cast test bars.

In year 1992, the effect of casting temperature on the fatigue properties of cast nickel aluminide alloys had been conducted. The results of high cycle fatigue tests at 650 °C on several cast Ni_3Al alloys are reported and compared with cast IN-713C. These alloys include IC-221M and several variations to the IC-221M composition. The results show that IC-221M cast at the highest temperature has the best fatigue strength, exceeding that for IN-713C. In these alloys, crack initiation occurs at shrinkage microporosity and the effect of casting temperature on porosity is related to the observed differences in fatigue lives [Brian, G., and Vinod, K.S. (1992)]

2.1.4 Ni_3Al Applications

An early, exclusive license for a specific application with Cummins Engine Company was finalized in 1985 for the use of the nickel aluminide alloys for turbo charges in diesel engines. However, problems with weight and performance have shifted the focus of the program from nickel aluminides to titanium aluminides. Another application of nickel aluminides being evaluated is for centrifugal cast furnace rolls Sandusky International at year 1993. At year 1992, GM Delphi Saginaw Steering Systems investigated the use of nickel aluminides for trays and assemblies in carburizing heat-treating furnaces. At year 1996, United Defense LP had taken the license for commercialization of nickel aluminides. More than 22,960kg of nickel aluminides had been melted [Norman et al. (1997)].

Due to unique properties of Ni_3Al, it had been used in industry to replace conventional furnace rolls. This had solve the blistering problem on conventional furnace roll in industries. Ni_3Al also being evaluated as statically cast die blocks for hot forging process to increase life because of its yield strength at 850^oC and its resistance to oxidation, which is better than cast stainless steels [James, K.W. (2004)].

2.2 Automotive body material

Automotive such as car is taken as an example in this project. **Table 2.2** shows comparison of materials properties that used to construct a car body. It can be noted that HSS is the main material to construct current car body