Flywheel: Jurnal Teknik Mesin Untirta Vol. 10, Issue 1, April 2024, page 47 -53

FLYWHEEL: JURNAL TEKNIK MESIN UNTIRTA

Homepagejurnal: http://jurnal.untirta.ac.id/index.php/jwl

Failure Analysis of Landing Gear Material

Asmadi Lubay[1], Reny Afriany[1], Bahrul Ilmi[1], Yeny Pusvyta[1]*

[1] *Departemen of Mechanical Engineering, IBA University, 11750, Palembang, Indonesia*

*Corresponding author: *renyafriany911@gmail.com*

ARTICLE INFO

Received 05/01/2012
revision 04/04/2021
accepted 19/05/2021
Available online 29/05/2021

ABSTRACT

The electroplating process of ferrous and non-ferrous metals has advantages such as; as a protector against corrosion, improving appearance and increasing hardness, for example in coating: Cr, Cd and Ni. However, the coating process with Cd on AISI 4340 steel can result in metal embrittlement which leads to delayed brittle failure. This damage is very dangerous because there is no previous indication on the metal surface. In addition, fracture can occur at stresses much lower than the tensile stress of the material. From the results of this study, it is known that the non-uniformity of the thickness of the Cd layer formed results in stress concentration which further forms strain, this factor triggers the initial crack. The embrittlement by hydrogen comes from the electroplating bath that uses conventional cyanide coupled with brighteners. In addition, the very hard nature of AISI 4340 steel contributes to the embrittlement. The embrittlement of the material by hydrogen is caused by the presence of elemental sulphur which is cathodic poisons that segregate at the grain boundaries. Hardness will decrease the higher the baking temperature and the longer the baking time. The best condition to prevent embrittlement is if the baking process is carried out for at least 48 hours at a temperature of 250°C. The fracture surface by hydrogen embrittlement is in the form of intergranular crack, which indicates that the fracture is brittle.

Keywords: *Electroplating, Embrittlement, AISI 4340 steel, Hydrogen, Intergranular crack*

1. INTRODUCTION

1.1. Background

In the manufacturing industry, it is sometimes necessary for metals to have a combination of properties of several types of metals, for example, metals that have high hardness but are resistant to corrosion. To resolve this, one method is to use the Cd electroplating method on steel. In addition to protecting the steel from corrosion, it can also increase the surface hardness of the steel. However, the inhomogeneous electroplating process on the surface is one indication of the weakness of the steel. In addition, the process temperature and duration of electroplating must be balanced to obtain the optimal results we want. The electroplating process on ferrous material components has the following objectives:

1) Protection of materials from corrosion processes for example; Zn, Cu, Ni, Cr and Cd on steel.
2) Improving the appearance components, for example; Cu, Zn, Cr on Ni steel, Ag and Au on brass
3) Serves as a stop off in heat treatment for example Cu on steel to prevent decarburisation, for bronze on steel to prevent denitridisation.
4) However, the coating process with Cd on AISI 4340 steel can result in embrittlement of the material which leads to delayed brittle failure. This event is very dangerous as the component can fracture suddenly without any prior indication. Therefore, testing and analysis are required to study the brittle fracture mechanism.

1.2. Problem Formulation

This study was conducted with variations of the baking process with different temperatures and different time durations. The baking process is carried out on workpieces that have been coated with Cadmium which are shiny and not porous using the coating process specifications. The object used in this study is AISI 4340 steel which is used for aircraft **landing gear** components to study the symptoms of material embrittlement that lead to delayed brittle failure, fracture shape analysis is carried out, while mechanical testing is carried out to determine the effect of temperature and baking time:

1) Tensile Testing
2) Endurance limit testing and
3) Hardness testing

The discussion in this study is not only supported by test result data but also approached with several literature studies.

1.3. Research Objectives

1) To determine the mechanism of delayed damage to steel material electrolytically coated with Cadmium.
2) To determine the effect of temperature and baking time on the durability of materials that experience embrittlement due to the presence of hydrogen in the material.
3) To determine the elements that are very influential on the material embrittlement phenomenon.

2. LITERATURE REVIEW

2.1. Types of Cracks Caused by Environment

Material damage in the form of cracks can be caused by; the environment, the chemical composition of the material, the load received and the time factor. Cracking caused by the environment is a case that occurs in many industries, especially for high-strength alloy steel. Specifically, metal damage caused by the environment are:

1) Stress corrosion cracking.
2) Metal induced embrittlement
3) Fatique corrosion (corrosion fatique)
4) Embrittlement by hydrogen (hydrogen embrittlement)

For high strength steel, the fracture model by the four factors mentioned above is difficult to distinguish because it has a similar fracture form, namely intergranular fracture along the austenite grain boundary. Some unexpected sources of failure that can lead to embrittlement include:

a. Internal hydrogen coming from pickling process, coating embrittlement and so on.
b. Fluxes and manufacturing processes
c. Chemical elements or impurities contaminated on the surface or in the crevices of the workpiece.
d. or in the crevices of the workpiece.
e. Caused by elements such as Cl, S from insulating materials, concrete and so on.
f. H2S gas from anaerobic bacteria and MoS2 lubricants and water vapour.

2.2. AISI 4340 High Strength Steel Material

Many alloys used in the aircraft industry and engine construction are embrittled by hydrogen, such alloys include: steel, aluminium, titanium and Ni alloys. AISI 4340 high strength steel is widely used for aircraft *landing gear*. The material has high strength and has good corrosion and wear resistance after undergoing a coating process with cadmium. The strength of steel is an important parameter that affects the brittle nature of the material. The tendency to hydrogen embrittlement increases with high material strength. AISI 4340 steel subjected to immersion and curing in 3.5% NaCl solution at room temperature, will deteriorate rapidly if the tempering temperature is reduced and the strength is increased. However, this relationship is observed for high strength steels because steels with yield strength below 700 MPa usually have no effect on hydrogen embrittlement. For corrosion and wear resistance, the landing gear components have been cadmium plated. The failure was due to hydrogen embrittlement and the hydrogen source from the Cd plating process.

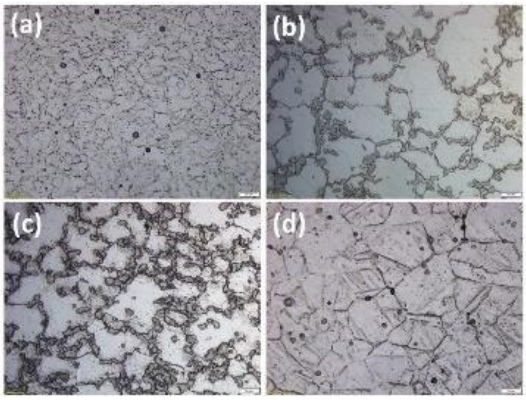

Figure 1. Micro structure of AISI 4340 Steel (a) Without treatment.
(b) Holding time 40 min. (c) Holding time 80 min.
(d) Holding time 120 min

2.3. N-219 Landing Gear

According to the definition of the American Aviation Agency (FAA) or the Federation of Avitation Administration. Currently also adopted by the Indonesian Civil Avitation Safety Regulation (CASR). Aircraft is a device used in aviation. The aircraft category for its flight certification in this case is an aircraft. The N-219 aircraft is a twin-engine multi-purpose aircraft designed to operate in remote areas. Used to carry passengers and cargo, the aircraft is built to meet the requirements designed to have the largest cabin volume in its class and flexible doors that ensure that the aircraft is multi-functional.

Figure 2. Landing Gear

Landing gear is the main support for an aircraft when parking, taxiing, taking off or landing. The most common type of landing gear consists of three wheels; two main wheels and a third wheel in the front or rear position of the aircraft. Landing gear that uses the rear wheel is called Conventional wheel. If the third wheel is housed in the nose of the aircraft this is called the Nose Wheel and the design is called Tricycle gear, Nose Wheel or Tail Wheel that can be steered makes the aircraft controllable when operating on the ground.

2.4. Hydrogen Release Process (Baking)

To achieve a low hydrogen concentration and reduce the possibility of damage, the baking process is carried out after the component undergoes a coating process (electroplating). Specifications for the baking process depend on the material and its use as well as the nature of the coating surface. In the aircraft industry, components coated with Cd are generally baked for 24 hours at 190 ^{0C}. To determine the effectiveness of the baking process, several tests are carried out, among others by using the barnacle electrode method, with this method it is possible to measure the diffusing hydrogen and monitor the efficiency of the baking process. The barnacle electrode technique is based on the electrochemical hydrogen permease method, if hydrogen is in the component then this part will function as an anode in the electrochemical cell. With this method hydrogen will be oxidised so that it can diffuse to the surface where the oxide current is related to the hydrogen content. Another method of measuring hydrogen content is by using the LECO RM-2 total hydrogen determination system, which uses the inert gas fusion technique to determine the total hydrogen concentration in the sample. Although the baking process results in the recovery of lost ductility, the treatment does not eliminate the tendency for delayed embrittlement, especially for high strength materials.

3. RESEARCH METHODOLOGY

The material is AISI 4340 steel with chemical composition:

C= 0.388 % Cu= 0.186 % Si = 0.300 % Cr = 0.877 %
Mn= 0.555 % Ni = 1.812 %P = 0.140 %Mo = 0.267 %

Subsequent coating with Copper (Cd) to prevent decarburisation during the heat treatment process.

The allowable copper layer thickness is 25-75 microns so that the process time ranges from 2-3 hours. Copper plating is carried out according to standard PS-0-35-3301, then dried. The copper plating process is carried out with:

Solution:

$Cu(CN)_2$ = 30 gr/l NaCn = 40 gr/lNa_2CO_3 = 15 gr/l

Current= 3 A/dm^2 Tegangan = 4 Volt

Temperature = 60^0 C PH =12

Anode = Cu

Then the heat treatment process is carried out with the aim of increasing the hardness and tensile strength so that it meets the requirements as a Landing gear component, the minimum tensile strength requirements are 1800-1900 MPa and hardness 51-54 HRC. The heat treatment process is carried out at a temperature of 830 ^{0C}holding time 55 minutes, then quenched in oil media and then the tempering process at temp. 200 ^{0C}holding time 60 min.

The coating process with Cadmium bright from a conventional cyanide bath containing brighteners was carried out as follows:

Larutan: NaCN = 90 gr/l

Na_2CO_3 = 30 gr/l

Cd = 21 gr/l

PH = 13;

Fo = 300 ppm

Anoda = Pb – Sn

Furthermore, the baking process was carried out at temp. 190 $^{0\,C}$ with time variations of 15 hours, 24 hours, 45 hours, 72 hours and 100 hours. Testing for embrittlement by hydrogen was carried out to ASTM F 519 standards with endurance testing. The fracture surfaces of the notched tensile specimens were examined with an optical microscope. Endurance testing is carried out for 200 hours (8 days) without breaking. The calculation method to obtain the test load was obtained:

Tensile strength $\sigma = 220$ kg/mm^2 = 2200 MPa

Cross-sectional area = 38.5 mm^2.

75% x 2200 = 1650 Mpa = 1650 N/mm^2.

Load obtained = 1650 N/mm^2 x 38.5 mm^2 = 63528 N = 63352.8 kg

Load used for endurance limit (63352.8 kg /13.2) – 108 = 373 kg

4. RESULTS AND DISCUSSION

Table 1. Cadmium layer thickness

Layer location	L1 (mikron)	L2 (mikron)	L3 (mikron)	L average
1	18	19	20	
2	19	18	17	
3	14	12	11	
4	18	19	20	
5	17	18	20	
6	19	21	22	
7	16	18	19	18
8	17	17	18	
9	22	19	21	
10	18	21	17	
11	19	20	17	
12	12	14	15	
13	15	15	16	
14	19	18	20	

The standard used for the coating process is PS 20-0-35-3000 with Cd bright coating type and using electroplating bath of cyanide bath containing brighteners. At the location around the notch, it is difficult to obtain a good coating considering that the depth and radius of the notch are very small and the notch depth = 1,245 mm. In general, in most locations, the cadmium layer is obtained with the same thickness. In the unequal thickness section, the Cadmium layer is formed at the location around the notch, this indication will affect the location of crack propagation.

4.1. Endurance Test Result

The difficulty of knowing the hydrogen content in a component poses a problem for estimating the life of the component, therefore Endurance testing (Endurance limit) is used to test the hypothesis that the damage is caused by hydrogen embrittlement considering that a fairly low hydrogen content has an effect on delayed brittle damage under static tensile loads with a very slow strain rate. Here hydrogen diffusion is important as it takes time to increase the hydrogen concentration at a triaxial stress location. This can cause damage to the material, where the crack initiation comes from the base of the point at the maximum triaxial stress region.

Table 2. Endurance test results

TEST ITEM	BAKING	FRACTURE TIME	TEST RESULTS
1	15 hours 190 ^{0}C	1 hours 10 minutes 4 hours 23 minutes 5 hours 11 minutes	Failed Failed Failed
2	24 Hours 190 ^{0}C	12 hours 13 minutes 26 hours 52 minutes 10 hours 21 minutes	Failed Failed Failed
3	48 Hours 190 ^{0}C	25 hours 12 minutes 20 hours 41 minutes 40 hours 33 minutes	Failed Failed Failed
4	72 Hours 190 ^{0}C	85 hours 22 minutes 100 hours 12 minutes 90 hours 11 minutes	Failed Failed Failed
5	100 Hours 190 ^{0}C	185 hours 55 minutes 100 hours 34 minutes 250 hours 48 minutes	Failed Failed Failed
6	15 Hours 250 ^{0}C	35 hours 54 minutes 62 hours 24 minutes 43 hours 14 minutes	Failed Failed Failed
7	24 Hours 250 ^{0}C	60 hours 38 minutes 73 hours 56 minutes 54 hours 41 minutes	Failed Failed Failed
8	48 Hours 250 ^{0}C	341 hours 10 minutes 347 hours 05 minutes 348 hours 21 minutes	Not Failed Not Failed Not Failed
9	72 Hours 250 ^{0}C	349 hours 20 minutes 338 hours 16 minutes 339 hours 25 minutes	Not Failed Not Failed Not Failed
10	100 Hours 250 ^{0}C	359 hours12 minutes 338 hours 03 minutes 340 hours 32 minutes	Not Failed Not Failed Not Failed
11	Non Baking	08 minutes 1 hours 03 minutes 2 hours 10 minutes	Failed Failed Failed

From Table 2 it can be seen that the test specimens that did not get the baking process broke up in a relatively short testing time, some even took only 8 min. This means that there is a certain amount of hydrogen from the electroplating process trapped in the material that can embrittle the crystal lattice (according to the theory of hydrogen content of 1 - 2 ppm can cause hydrogen embrittlement). By doing the baking process after electroplating, it is expected that the hydrogen trapped in the material can come out. The longer the baking time for the same temperature and the higher the baking temperature for the same time can cause the test material to fail (break) in a longer period of time, this is because more hydrogen diffuses out of the material during the baking process. The mechanism of the entry of hydrogen atoms can be seen in the chemical reaction below:

$$H_2O + e \rightarrow H_{ads} + OH^-$$

$$H_{ads} + H_{ads} \rightarrow H_2$$

$$H_{ads} + H_2O + e \rightarrow H_2 + OH^-$$

A material that undergoes the electroplating process is declared not to experience the effects of hydrogen embrittlement, namely if in endurance testing the material does not experience fracture for more than 200 hours of testing[2], this requirement is met by test specimens no. 8, 9 and 10 respectively: 8, 9 and 10 respectively, which were subjected to baking for 48 hours, 72 hours and 100 hours at a temperature of 250 ^{0C}. Removing hydrogen from the material requires a longer time and a higher temperature than that required for materials coated with Cadmium which are dull (not shiny). The higher temperature can increase the frequency of hydrogen jumps thus increasing the mobility of hydrogen to exit the material.

4.2. Hardness Test Rest

Table 3. Hardness Test Results

TEST ITEMS	HV-1	HV-2	HV-3	HV-Rata^2	Baking
1	616	635	629	627	15 hours 190^0 C
2	541	539	545	542	24 hours 190^0 C
3	537	540	541	539	48 hours 190^0 C
4	516	523	512	514	72 hours 190^0 C
5	492	495	497	495	100 hours 190^0 C
6	535	530	533	533	15 hours 250^0 C
7	510	513	511	511	24 hours 250^0 C
8	489	488	493	490	48 hours 250^0 C
9	485	481	479	482	72 hours 250^0 C
10	461	460	464	462	100 hours 250^0 C
11	647	643	641	644	Not Baking

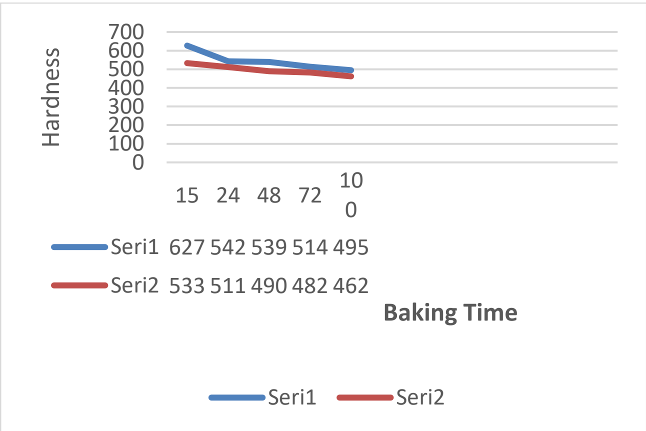

Figure 4. Hardness vs Baking Time

The effect of hydrogen embriltlement in steel is that the ductility of the steel is reduced. However, it can be restored by the baking process. The hardness test data shows that the longer the baking time (for the same temperature) and the higher the baking temperature (for the same time), the hardness of the material will decrease, which means that the brittleness of the material decreases, which also means that material damage (due to internal hydrogen) will occur over a longer period of time. The decrease in hardness as the baking temperature gets higher, leads to a limitation of the baking temperature used, this is because even though the embrittlement effect is reduced, the material becomes less hard. So that as a result the component does not function anymore, besides that the diffusivity of hydrogen in the austenite phase is much lower and the solubility of hydrogen in the austenite phase is much higher than in the ferrite phase so that the release of hydrogen at temperatures above the transformation temperature is relatively ineffective when compared to the release of hydrogen below the transformation temperature. The decrease in hardness due to temperature baking is not due to changes in microstructure because the baking temperature is only 190°C - 250°C below the transformation temperature.

4.3. Fracture Surface

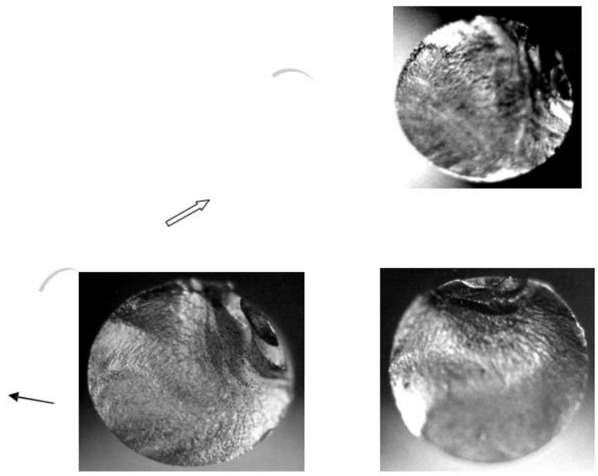

Figure 5. Broken Surface of Test Item

The heat treatment process carried out on the test specimen produces a tempered martensite phase, this result is as expected so that the material has a high enough strength to be used as an aircraft landing gear component, although materials with high strength tend to be more susceptible to hydrogen embrittlement if they get a coating process.

Macrofractography observations show that the fracture is brittle as indicated by the flat shape of the fracture structure. The brittle fracture is caused by internal hydrogen entering the material during the coating process with Cd. In Figure 5 it can be seen that the crack starts from the arrow which then increases in size and propagates to the outside of the grain surface. The final fracture occurs because the remaining cross section is no longer able to withstand further load.

Generally, the initial crack starts from the notch area where there is an imperfect cadmium layer. The result of the cadmium layer is uneven thickness, especially in the notch area. The occurrence of the initial crack starts from the notch area where there are surface defects in the form of micro cracks. In the area of micro cracks, there are imperfections in the Cd layer. In addition, there is a concentration of stress that can cause strain localisation so that it can lead to the onset of an initial crack. In steels containing internal hydrogen, fracture can occur at stresses much lower than the tensile stress.

From the results of microfractography observations, it can be seen that the shape of the fracture that occurs is intergranular where this fracture model occurs in all test specimens. This fracture is caused by the load in endurance testing with a very slow strain rate / static loading. Most of the grains show an eleavage shape (only a few are dimple shape), this indicates that the fracture is brittle.

After obtaining microfractography photos, qualitative and quantitative analyses were carried out on the cracks to determine the cause of material fracture using EDAX. The results of EDAX examination at three crack locations on three test specimens. It turns out that in the crack section there is an element S (sulfur) as much as 0.14% while outside the crack location no element S was found. So the cause of intergranular fracture at the grain boundary is the segregation of element S to the grain boundary where the element is a cathodic poison or negative catalyst in the hydrogen recombination reaction which can slow down the rate of hydrogen atoms combining to form hydrogen molecules, as a result it can prolong the existence of hydrogen atoms. The S element is thought to come from the brighteners solution during the electroplating process, hence the electroplating process using a conventional cyanide type bath which also contributes to the presence of internal hydrogen in the material because the electroplating bath contains CN- ions which can act as **cathodic poisons**.

With the presence of the element S at the grain boundaries, there are a number of hydrogen atoms trapped at the grain boundaries where the interaction of the dissolved hydrogen with the grain boundaries can reduce the **cohesive** strength of the **lattice**. This theory presented by **Troiano** and modified by **Oriani** is known as the **Decohesion theory**. Internal hydrogen will result in lattice dilation and internal strain energy due to the segregation of hydrogen towards the grain boundaries leading to localised reduction in boundary decohesian stress.

5. CONCLUSIONS

1) To prevent damage due to hydrogen embrittlement, the material must be baked for 48 hours at a temperature of 250^0 C.
2) Embrittlement of material by hydrogen is obtained from electroplating baths that use conventional cyanide coupled with brighteners.
3) Embrittlement by hydrogen is also due to the presence of elemental sulphur which is cathodic poisons that segregate to the grain boundaries.
4) Hardness will decrease if the baking temperature is higher and the baking time is longer.

REFERENCES

[1] SP.Lynch, *Failure of structure and component by environmentally assisted cracking*, Aeronetical Reseach laboratory Defence Science and Technology Organisation Department of Defence, Melbourne, Australia, Engineering Failure Analysis, Vol.1, 1994.

[2] RA. Oriani, *Hydrogen in Metals*, Proceeding of conference on Fundamental Aspect of Stress Corrosion Cracking, Steahle, Ferty, Van Rooyen, eds, NACF, 1967.

[3] CA, Zapffs and CE.Sims, *Hydrogen embrittlement, Internal Stress and Defects in steel*, Trans ASME 145, 1941.

[4] CG. Interante, *Basic Aspect of the problem of hydrogen in steel*, National Bureau of standard , Washington DC, 1982.

[5] PG. Bastient, The phenomena of cracking and fracture of steel in the presence of hydrogen, New York pp 311-341.

[6] MG.Fontana, *Corrosion Engineering*, third edition, Mc Graw-Hill Book company, 1986.