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A Project Report
On

**“Effect Of Heat Treatment On The Mechanical And Corrosion Properties
Of 6061 Aluminium Alloy”**

Submitted in partial fulfillment of the requirements as a part of the curriculum,

Bachelors of Engineering in Mechanical Engineering

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CERTIFICATE

Certified that the project work entitled “**Effect Of Heat Treatment On The Mechanical And Corrosion Properties Of 6061 Aluminium Alloy**” is presented by **Mr. Arpit Pande, Mr. Krishna Rishi, Mr. Kundan Kumar Gaurav, Mr. Ved Raj**, bonafide students of **CMR Institute of Technology** in partial fulfillment of the requirements as a part of the curriculum, **Bachelors of Engineering in Mechanical Engineering**, of **Visvesvaraya Technological University, Belagavi** during the year **2019-20**. It is certified that all correction/suggestion indicated for Internal Assessment have been incorporated in the report deposited in the departmental library. The project report has been approved as it satisfies the academic requirements in respect of the project work prescribed for the bachelor of engineering degree.

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1.

2.

ABSTRACT

Heat treatment is a controlled process which is used to alter the microstructure (without changing the product shape) of metals and alloys such as aluminium to impart properties which benefit the working life of a component. Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation etc. Aluminium is corrosion resistant in its pure state. Aluminium alloys which are light weight and strong do not possess the corrosion resistance of pure metal. Hence they are treated to prevent deterioration. Aluminium alloy's lightweight performance delivers great benefit in transport applications such as aerospace, cars etc. Although generally more expensive than ferrous metal, nonferrous metal and alloys have numerous important applications because of properties such as high thermal conductivity, low density and ease of fabrication.

The change in microstructure of the material when heat treated can influence the mechanical properties and the microstructure of the aluminium alloy. Study and compare the following mechanical properties by performing following tests:

Corrosion Test, Tensile Test and Hardness Test.

The aim is to study these effects to design products according to prevailing conditions to ensure failure free operation.

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1. INTRODUCTION

1.1 ALUMINIUM ALLOY

Aluminum is the most widely available metallic element (about 8%) in the solid portion of the earth's crust; but it always exists in a combined form, usually a hydrated oxide, of which bauxite is the principal ore. Thermodynamically, metallic aluminum is very active and seeks to return to the natural oxidized state through the process of corrosion. The activity of aluminum can be appreciated when one considers that fine aluminum powder undergoing rapid chemical oxidation is the primary fuel in modern aerospace rockets.

An aluminum alloy is a composition consisting mainly of aluminium to which other elements have been added. The alloy is made by mixing together the elements when aluminum is molten (liquid), which cools to form a homogeneous solid solution. The other elements may make up as much as 15 percent of the alloy by mass. Added elements include iron, copper, magnesium, silicon, and zinc. The addition of elements to the aluminum gives the alloy improved strength, workability, corrosion resistance, electrical conductivity, and/or density, compared with the pure metallic element. Aluminum alloys tend to be lightweight and corrosion resistant.

Aluminum offers a wide range of properties that can be engineered precisely to the demands of specific applications through the choice of alloy, temper, and fabrication process. In most applications, two or more key characteristics of aluminum come prominently into play for example, light weight combined with strength in airplanes, railroad cars, trucks, and other transportation equipment. High resistance to corrosion and high thermal conductivity are important in equipment for the chemical and petroleum industries; these properties combine with non-toxicity for food processing equipment. Attractive appearance together with high resistance to weathering and low maintenance requirements have led to extensive use in buildings of all types. High reflectivity, excellent weathering characteristics, and light weight are all important in roofing materials. Light weight contributes to low handling and shipping costs, whatever the application.

1.2 DIFFERENT GRADES OF ALUMINIUM ALLOY

Alloys have common names, but they may be identified using a four-digit number. The first digit of the number identifies the class or series of alloy.

- ◆ **1xxx** - Commercially pure aluminum also has a four-digit numerical identifier. Series 1xxx alloys are made of 99 percent or higher purity aluminum.
- ◆ **2xxx** - The principal alloying element in the 2xxx series is copper. Heat treating these alloys improves their strength. These alloys are strong and tough, but not as corrosion resistant as other aluminum alloys, so they are usually painted or coated for use. The most common aircraft alloy is 2024. Alloy 2024-T351 is among the hardest of the aluminum alloys.
- ◆ **3xxx** - The main alloying element in this series is manganese, usually with a smaller amount of magnesium. The most popular alloy from this series is 3003, which is workable and

moderately strong. 3003 is used to make cooking utensils. Alloy 3004 is one of the alloys used to make aluminum cans for beverages.

- ◆ **4xxx** - Silicon is added to aluminum to make 4xxx alloys. This lowers the melting point of the metal without making it brittle. This series is used to make welding wire. Alloy 4043 is used to make filler alloys for welding cars and structural elements.
- ◆ **5xxx** - The principal alloying element in the 5xxx series is magnesium. These alloys are strong, weldable, and resist marine corrosion. The 5xxx alloys are used to make pressure vessels and storage tanks and for various marine applications. Alloy 5182 is used to make the lid of aluminum beverage cans. So, aluminum cans actually consist of at least two alloys!
- ◆ **6xxx** - Silicon and magnesium are present in 6xxx alloys. The elements combine to form magnesium silicide. These alloys are formable, weldable, and heat treatable. They have good corrosion resistance and moderate strength. The most common alloy in this series is 6061, which is used to make truck and boat frames. Extrusion products from the 6xxx series are used in architecture and to make the iPhone 6.
- ◆ **7xxx** - Zinc is the principal alloying element in the series starting with the number 7. The resulting alloy is heat-treatable and very strong. Important alloys are 7050 and 7075, both used to construct aircraft.
- ◆ **8xxx** - These are aluminum alloys made with other elements. Examples include 8500, 8510, and 8520.
- ◆ **9xxx** - Presently, the series starting with the number 9 is unused.

Aluminum Association series	Types of alloy composition	Strengthening method
1xxx	Al	Cold work
2xxx	Al-Cu-Mg(1-2.5%)	Heat treat
2xxx	Al0Cu-Mg-Si(3-6%)	Heat treat
3xxx	Al-Mn-Mg	Cold work
4xxx	Al-Si	Cold work(some heat treat)
5xxx	Al-Mg(1-2.5%Mg)	Cold work
5xxx	Al-Mg-Mn(3-6%Mg)	Cold work
6xxx	Al-Mg-Si	Heat treat
7xxx	Al-Zn-Mg	Heat treat
7xxx	Al-Zn-Mg-Cu	Heat treat
8xxx	Al-Li-Cu-Mg	Heat treat

Fig. 1 Wrought aluminum alloy series designations

1.3 MEANING OF XXXX IN ALUMINIUM GRADES

We shall first consider the 4-digit wrought aluminum alloy identification system.

The first digit (Xxxx) indicates the principal alloying element, which has been added to the aluminum alloy and is often used to describe the aluminum alloy series, i.e., 1000 series, 2000 series, 3000 series, up to 8000 series. The second single digit (xXxx), if different from 0, indicates a modification of the specific alloy, and the third and fourth digits (xxXX) are arbitrary numbers given to identify a specific alloy in the series. Example: In alloy 5183, the number 5 indicates that it is of the magnesium alloy series, the 1 indicates that it is the 1st modification to the original alloy 5083, and the 83 identifies it in the 5xxx series.

1.4 6061 ALUMINIUM ALLOY

6061 is a precipitation-hardened aluminum alloy, containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S", it was developed in 1935. It has good mechanical properties, exhibits good weldability, and is very commonly extruded (second in popularity only to 6063). It is one of the most common alloys of aluminum for general-purpose use.

It is commonly available in pre-tempered grades such as 6061-O (annealed), tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T651 (solutionized, stress-relieved stretched and artificially aged).

Fig. depicts the pseudo-binary phase diagram for the 6061 Al system: binary means that two phases may simultaneously coexist and pseudo means that there are more than two elements that constitute the two phases.

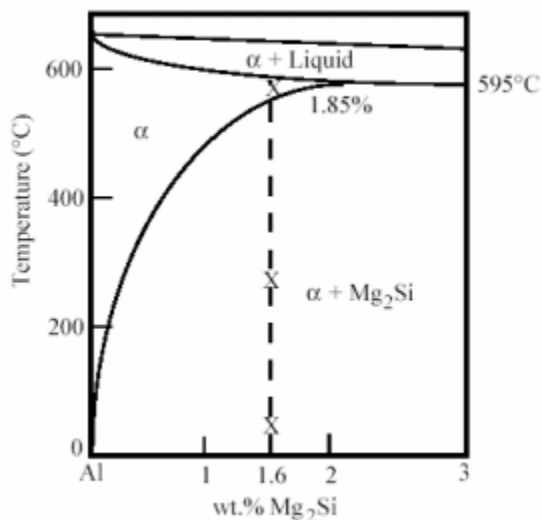


Fig. 2 Pseudo-binary phase diagram for the 6061 Al system

1.5 CHEMICAL COMPOSITION

(6061 Aluminum Alloy Composition by Mass %)

Al 95.85 - 98.56

Mg 0.8 - 1.2

Si 0.40 - 0.8

Fe 0.0 - 0.7

Cu 0.15 - 0.40
Cr 0.04 - 0.35
Zn 0.0 - 0.25
Ti 0.0 - 0.25
Mn 0.0 - 0.15
Remainder 0.05 each, 0.15 total

1.6 PROPERTIES OF A6061

Physical properties:

Density (ρ) 2.70 g/cm

Mechanical properties:

Young's modulus (E) 68.9 GPa (9,990 ksi)

Tensile strength (σ_t) 124–290 MPa (18.0– 42.1 ksi)

Elongation (ϵ) at break 12–25%

Poisson's ratio (ν) 0.33

Thermal properties:

Melting temperature (T_m) 585 °C (1,085 °F)

Thermal conductivity (k) 151–202 W/(m·K)

Linear thermal expansion coefficient (α) $2.32 \times 10^{-5} \text{ K}^{-1}$

Specific heat capacity (c) 897 J/(kg·K)

Electrical properties:

Volume resistivity (ρ) 32.5–39.2 nOhm.m

The mechanical properties of 6061 depend greatly on the temper, or heat treatment, of the material. Young's Modulus is 69 GPa (10,000 ksi) regardless of temper.

1.7 BASIC ALUMINIUM HEAT TREATMENT DESIGNATIONS

- ◆ **F, As-Fabricated** - This is applied to products shaped by cold working, hot working, or casting processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits. No special control has been performed to the heat treatment or strain hardening after the shaping process such as casting, hot working, or cold working.
- ◆ **O, Annealed** - O applies to wrought products that are annealed to obtain lowest strength temper and to cast products that are annealed to improve ductility and dimensional stability. The O maybe followed by a digit other than zero. This is the lowest strength, highest ductility temper.
- ◆ **H, Strain-Hardened** - (applied to wrought products only) This indicates products that have been strengthened by strain hardening, with or without supplementary thermal treatment to produce some reduction in strength. The H is always followed by two or more digits. Used for products that have been strengthened by strain hardening, with or without subsequent heat treatment. The designation is followed by two or more numbers as discussed below.

- ◆ **W, Solution Heat-Treated** - This is an unstable temper applicable only to alloys whose strength naturally (spontaneously) changes at room temperature over a duration of months or even years after solution heat treatment. The designation is specific only when the period of natural aging is indicated (for example, W 1/ 2 h). This is seldom encountered because it is an unstable temper that applies only to alloys that spontaneously age at ambient temperature after heat treatment.
- ◆ **T, Solution Heat-Treated** - This applies to alloys whose strength is stable within a few weeks of solution heat treatment. The T is always followed by one or more digits. Used for products that have been strengthened by heat treatment, with or without subsequent strain hardening. The designation is followed by one or more numbers as discussed below.

1.8 HEAT TREATING T TEMPER CODES

- ◆ **T1** - Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.
- ◆ **T2** - Cooled from an elevated temperature shaping process, cold worked, and naturally aged to a substantially stable condition.
- ◆ **T3** - Solution heat treated, cold worked, and naturally aged to a substantially stable condition.
- ◆ **T4** - Solution heat treated, and naturally aged to a substantially stable condition.
- ◆ **T5** - Cooled from an elevated temperature shaping process then artificially aged.
- ◆ **T6** - Solution heat treated then artificially aged.
- ◆ **T7** - Solution heat treated then overaged/stabilized.
- ◆ **T8** - Solution heat treated, cold worked, then artificially aged.
- ◆ **T9** - Solution heat treated, artificially aged, then cold worked.
- ◆ **T10** - Cooled from an elevated temperature shaping process, cold worked, then artificially aged.

1.9 TYPES OF 6061 ALUMINIUM ALLOY

1.9.1 A6061-O

Annealed 6061 (6061-O temper) has maximum ultimate tensile strength no more than 150 MPa (22 ksi), and maximum yield strength no more than 83 MPa (12 ksi) or 110 MPa (16ksi). The material has elongation (stretch before ultimate failure) of 10–18%. To obtain the annealed condition, the alloy is typically heated at 415 °C for 2-3 hours.

1.9.2 A6061-T4

T4 temper 6061 has an ultimate tensile strength of at least 180 MPa (26 ksi) or 210 MPa (30 ksi) and yield strength of at least 110 MPa (16 ksi). It has elongation of 10-16%.

1.9.3 A6061-T6

T6 temper 6061 has been treated to provide the maximum precipitation hardening (and therefore maximum yield strength) for a 6061 aluminum alloy. It has an ultimate tensile strength of at least 290 MPa (42 ksi) and yield strength of at least 240 MPa (35 ksi). More typical values are 310 MPa (45 ksi) and 270 MPa (39 ksi), respectively.[10] In thicknesses of 6.35 mm (0.250 in) or less, it has elongation of 8% or more; in thicker sections, it has elongation of 10%. T651 temper has similar mechanical properties. The typical value for thermal conductivity for 6061-T6 at 25 °C (77 °F) is around 152 W/m K. A material data sheet defines the fatigue limit under cyclic load as 97 MPa (14 ksi) for 500,000,000 completely reversed cycles using a standard RR Moore test machine and specimen. Note that aluminum does not exhibit a well defined "knee" on its S-n graph, so there is some debate as to how many cycles equates to "infinite life". Also note the actual value of fatigue limit for an application can be dramatically affected by the conventional de-rating factors of loading, gradient, and surface finish.

1.10 USES

A6061 is commonly used for:

- ◆ construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft than commercial or military aircraft.
- ◆ yacht construction, including small utility boats.
- ◆ automotive parts, such as the chassis of the Audi A8.
- ◆ Flashlights
- ◆ aluminum cans for the packaging of
- ◆ food and beverages.
- ◆ Scuba tanks and other high pressure gas
- ◆ storage cylinders (post 1995)

A6061-T6 is used for:

- ◆ bicycle frames and components.
- ◆ many fly fishing reels.
- ◆ the Pioneer plaque was made of this alloy.
- ◆ the secondary chambers and baffle systems in firearm sound suppressors (primarily pistol suppressors for reduced weight and improved mechanical functionality),
- ◆ The upper and lower receivers of many non mil-spec AR-15 rifle variants.
- ◆ Many aluminum docks and gangways are constructed with 6061-T6 extrusions, and welded into place.
- ◆ Material used in some ultra-high vacuum (UHV) chambers
- ◆ Many parts for remote controlled model aircraft, notably helicopter rotor components.
- ◆ Large amateur radio antennas.

2. LITERATURE SURVEY

2.1 MICROSTRUCTURE

Different aluminum heat treatments control the size and dispersion of Mg_2Si precipitates in the material. Grain boundary sizes also change, but do not have as important of an impact on strength as the precipitates. Grain sizes can change orders of magnitude based upon stress and can have grains as small as a few hundred nanometers, but are typically a few micrometers to hundreds of micrometers in diameter. Iron, manganese, and chromium secondary phases ($Fe_2Si_2Al_9$, $(Fe, Mn, Cr)_3SiAl_{12}$) often form as inclusions in the material.

Grain sizes in aluminum alloys are heavily dependent upon the processing techniques and heat treatment. Different cross-sections of material which has been stressed can cause order of magnitude differences in grain size. Some specially processed aluminum alloys have grain diameters which are hundreds of nanometers, but most range from a few micrometers to hundreds of micrometers.

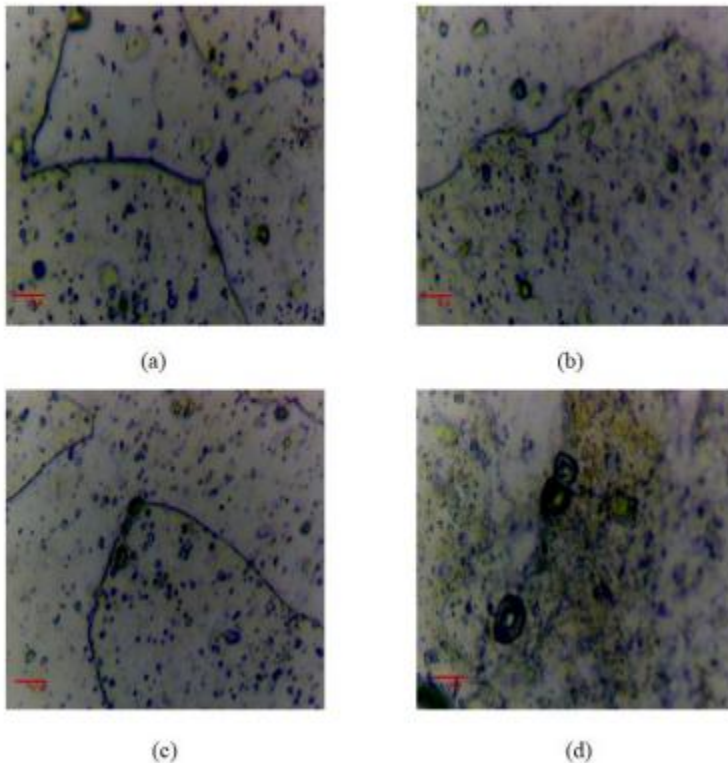


Fig. 3 Microstructure evaluation at 50x resolution of Al alloy sample quenched in (a) Brine solution (b) Water (c) Alcohol (d) Air

2.2 HEAT TREATMENT

Heat treatment in its broadest sense refers to any of the heating and cooling operations that are performed for the purpose of changing the mechanical properties, the metallurgical structure, or the residual stress state of a metallic product. When the term is applied to aluminum alloys, however, its use frequently is restricted to the specific operations employed to increase strength and hardness of the precipitation-hardenable wrought and cast alloys. These usually are referred to as the "heat-treatable" alloys to distinguish them from those alloys in which no significant strengthening can be achieved by heating and cooling. The latter, generally referred to as "non-heat-treatable" alloys, depend primarily on cold work to increase strength. All alloys can be cold worked to increase strength. This has little effect on their resistance to corrosion but decreases properties such as elongation, forming and toughness. Excessive cold working can cause banded slip planes in the metals. These planes are in a higher thermodynamic state and can be more susceptible to corrosion. Also they contain numerous dislocations that act as sites for localized precipitation leading to localized corrosion. Heating to decrease strength and increase ductility (annealing) is used with alloys of both types; metallurgical reactions may vary with type of alloy and with degree of softening desired. Except for the low temperature stabilization treatment sometimes, given for 5xxx series alloys, complete or partial annealing treatments are the only ones used for non-heat-treatable alloys.

2.2.1 PRECIPITATION HARDENING

The basic requirement of a precipitation hardening alloy system is that the solid solubility limit should be decreased by decreasing the temperature. During the precipitation hardening, the aluminum alloy 6061-T6 was heated up at high temperature and subsequently cooled by quenching it into the water or some other cooling medium. The rapid cooling suppresses the separation of the θ -phase so that the alloy exists at the low temperature under an unstable supersaturated state. If, however, after quenching, the alloy is allowed to 'age' for a sufficient amount of time, the second phase precipitates out.

Solutionizing, is the first step in the precipitation-hardening process where the alloy is heated above the solvus temperature and soaked there until a homogeneous solid solution (α) is produced. The θ precipitates are dissolved in this step and any segregation present in the original alloy is reduced.

Aging aluminum 6061 is done between 350 to 500 degrees Fahrenheit, and depending on thickness and other factors—the parts stay in the oven for 12-24 hours.

Following this aging, the parts are now at a T6 condition. In general, T6 is the most common temper for aluminum, and because 6061 aluminum is often used in heavy-duty structures, the strength and limited formability of metal at that temper is important.

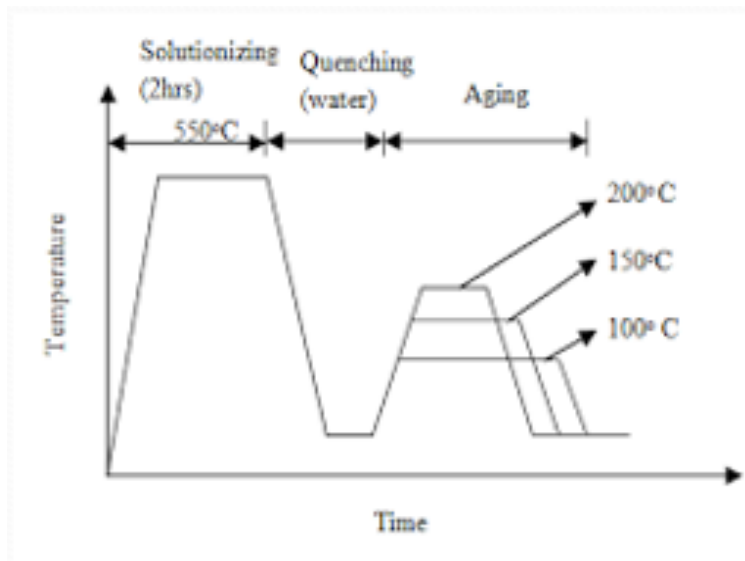
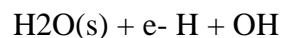


Fig. 4 Age hardening treatment of Al 6061 alloy

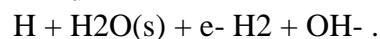
2.3 CORROSION

Aluminum, as indicated by its position in the electromotive force (emf) series, is a thermodynamically reactive metal; among structural metals, only beryllium and magnesium are more reactive. Aluminum owes its excellent corrosion resistance to the barrier oxide film that is bonded strongly to its surface. The conditions for thermodynamic stability of the oxide film are expressed by the Pourbaix (potential versus pH) diagram. As shown by this diagram, aluminum is passive (is protected by its oxide film) in the pH range of about 4 to 8.5. The limits of this range, however, vary somewhat with temperature, with the specific form of oxide film present, and with the presence of substances that can form soluble complexes or insoluble salts with aluminum. Beyond the limits of its passive range, aluminum corrodes in aqueous solutions because its oxides are soluble in many acids and bases, yielding Al^{3+} ions in acids and AlO_2^- (aluminate) ions in bases. There are, however, instances when corrosion does not occur outside the passive range, for example, when the oxide film is insoluble or when the film is maintained by the oxidizing nature of the solution.

The mechanism of corrosion of aluminum and aluminum alloys in neutral solutions is based on the dissolution of aluminum atoms from the active sites or flawed regions of the naturally formed barrier film. It represents an irreversible coupled reaction, the anodic part of which is the metal dissolution and the cathodic counterpart is the reduction of water or oxygen to OH^- , according to the cathodic reactions:



And



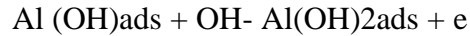
In oxygen rich solutions (naturally aerated or oxygen saturated), the cathodic part occurs through oxygen reduction:



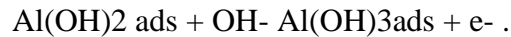
Where (s) refers to the electrode surface.

The anodic reactions are:

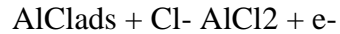




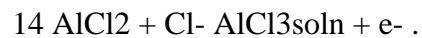
And



The formation of the adsorbed Al(OH)_3 , which transforms into $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ in neutral media, leads to the observed passivity. The presence of Cl^- ions in neutral solutions leads to reactions of the type:



And



And thus $\text{Al(s)} + 3 \text{Cl}^- \rightarrow \text{AlCl}_3 + e^-$

AlCl_3 goes into the solution and hydrolyzes therein, leaving bare active sites available for attack. This explains the observed increase in the rate of corrosion in the presence of Cl^- . In the case of Al-Cu, the presence of Cu on the material surface leads to an increase in the ratio of cathodic area and the formation of highly active galvanic couples which lead to an increase in the corrosion rate. The oxide film is naturally self-renewing and accidental abrasion or other mechanical damage of the surface film is rapidly repaired. The barrier film formed on Al and Al alloys is of duplex nature. It consists of an adherent, compact and stable inner layer of oxide film covered with a porous, less stable outer layer which is more susceptible to corrosion. At lower and higher pH, aluminum is more likely to corrode but by no means always does so. For example, aluminum is quite resistant to concentrated nitric acid. When aluminum is exposed to alkaline conditions, corrosion may occur, and when the oxide film is perforated locally, accelerated attack occurs because aluminum is attacked more rapidly than its oxide under alkaline conditions. The result is pitting. In acidic conditions, the oxide is more rapidly attacked than aluminum, and more general attack should result. The conditions that promote corrosion of aluminum and its alloys, therefore, must be those that continuously abrade the film mechanically or promote conditions that locally degrade the protective oxide film and minimize the availability of oxygen to rebuild it. The acidity or alkalinity of the environment significantly affects the corrosion behavior of aluminum alloys.

2.4 TENSILE

In physics, tension is described as the pulling force transmitted axially by the means of a string, a cable, chain, or similar one-dimensional continuous object, or by each end of a rod, truss member, or similar three-dimensional object; tension might also be described as the action-reaction pair of forces acting at each end of said elements. Tension could be the opposite of compression.

At the atomic level, when atoms or molecules are pulled apart from each other and gain potential energy with a restoring force still existing, the restoring force might create what is also called tension. Each end of a string or rod under such tension could pull on the object it is attached to, in order to restore the string/rod to its relaxed length.

In physics, tension, as a transmitted force, as an action-reaction pair of forces, or as a restoring force, may be a force and has the units of force measured in newtons (or sometimes pounds-force). The ends of a string or other object transmitting tension will exert forces on the objects to which the string or rod is connected, in the direction of the string at the point of attachment.

These forces due to tension are also called "passive forces". There are two basic possibilities for systems of objects held by strings: either acceleration is zero and the system is therefore in equilibrium, or there is acceleration, and therefore a net force is present in the system.

2.4.1 TENSION IN ONE DIRECTION

Tension in a string is a scalar quantity (i.e. non-negative). Zero tension is slack. A string or rope is often idealized as one dimension, having length but being massless with zero cross section. If there are no bends in the string, as occur with vibrations or pulleys, then tension is a constant along the string, equal to the magnitude of the forces applied by the ends of the string. By Newton's third law, these are the same forces exerted on the ends of the string by the objects to which the ends are attached. If the string curves around one or more pulleys, it will still have constant tension along its length in the idealized situation that the pulleys are massless and frictionless. A vibrating string vibrates with a set of frequencies that depend on the string's tension. These frequencies can be derived from Newton's laws of motion. Each microscopic segment of the string pulls on and is pulled upon by its neighboring segments, with a force equal to the tension at that position along the string.

If the string has curvature, then the two pulls on a segment by its two neighbors will not add to zero, and there will be a net force on that segment of the string, causing an acceleration. This net force is a restoring force, and the motion of the string can include transverse waves that solve the equation central to Sturm–Liouville theory:

$$-\frac{d}{dx} \left[\tau(x) \frac{d\rho(x)}{dx} \right] + v(x)\rho(x) = \omega^2 \sigma(x)\rho(x)$$

where $v(x)$ is the force constant per unit length [units force per area] and ω^2 are the eigenvalues for resonances of transverse displacement $\rho(x)$ on the string, with solutions that include the various harmonics on a stringed instrument.

2.5 HARDNESS

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation. More simply put, when using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material.

The determination of the Rockwell hardness of a material involves the application of a minor load followed by a major load. The minor load establishes the zero position. The major load is applied, then removed while still maintaining the minor load. The depth of penetration from the zero datum is measured from a dial, on which a harder material gives a higher number. That is, the penetration depth and hardness are inversely proportional. The chief advantage of Rockwell hardness is its ability to display hardness values directly, thus obviating tedious calculations involved in other hardness measurement techniques.

The equation for Rockwell Hardness is $HR = N - \frac{d}{s}$, where d is the depth (from the zero load point), and N and s are scale factors that depend on the scale of the test being used (see following section).

It is typically used in engineering and metallurgy. Its commercial popularity arises from its speed, reliability, robustness, resolution and small area of indentation.

Legacy Rockwell hardness testers operation steps:

1. Load an initial force: Rockwell hardness test initial test force is 10 kgf (98 N; 22 lbf); superficial Rockwell hardness test initial test force is 3 kgf (29 N; 6.6 lbf).
2. Load main load: reference below form / table 'Scales and values'.
3. Leave the main load for a "dwell time" sufficient for indentation to come to a halt.
4. Release load; the Rockwell value will typically display on a dial or screen automatically.

In order to get a reliable reading the thickness of the test-piece should be at least 10 times the depth of the indentation. Also, readings should be taken from a flat perpendicular surface, because convex surfaces give lower readings. A correction factor can be used if the hardness of a convex surface is to be measured.

3. EXPERIMENTAL ANALYSIS

3.1 CORROSION TEST

3.1.1 SAMPLE PREPARATION

- ◆ Cut out 3 samples of 30*30 mm each from aluminium sheet.
- ◆ Grind the samples with the help of sandpapers of different grit as follows;
220 μ m, 400 μ m, 600 μ m, 800 μ m, 1000 μ m.
- ◆ Polish the sample using the alumina paste on the metallurgical polishing machine.



Fig. 5 Polishing machine



Fig. 6 Polishing process

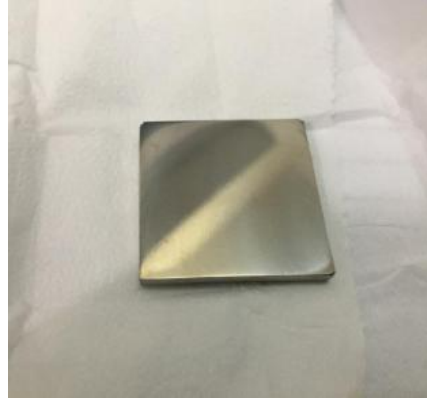


Fig. 7 Corrosion sample

3.1.2 ELECTROCHEMICAL POLARISATION TEST

Tafel polarization experiments were performed in 3.5 % NaCl solution under freely aerated condition at ambient temperature (30°C) using a potentiostat (Versastat II, Princeton Applied Research, USA). The tests were performed in a three electrode flat cell (PAR, USA) with a platinum electrode as counter electrode and a saturated calomel electrode (SCE) as reference electrode. Samples were polished to 1 micron surface finish (alumina paste) and an area of 1 X 1cm² was exposed to the solution in the flat cell. Before performing Tafel polarization experiment, free corrosion potential (FCP) was monitored for 1 hour. Exposure of the sample surface to the solution for 1 hour before applying external potential allowed the chemistry of the electrical double layer (EDL) on the surface to stabilize. Corrosion rate was calculated from the corrosion current density (i_{corr}) obtained from the Tafel polarization curves.



Fig. 8 Corrosion test setup

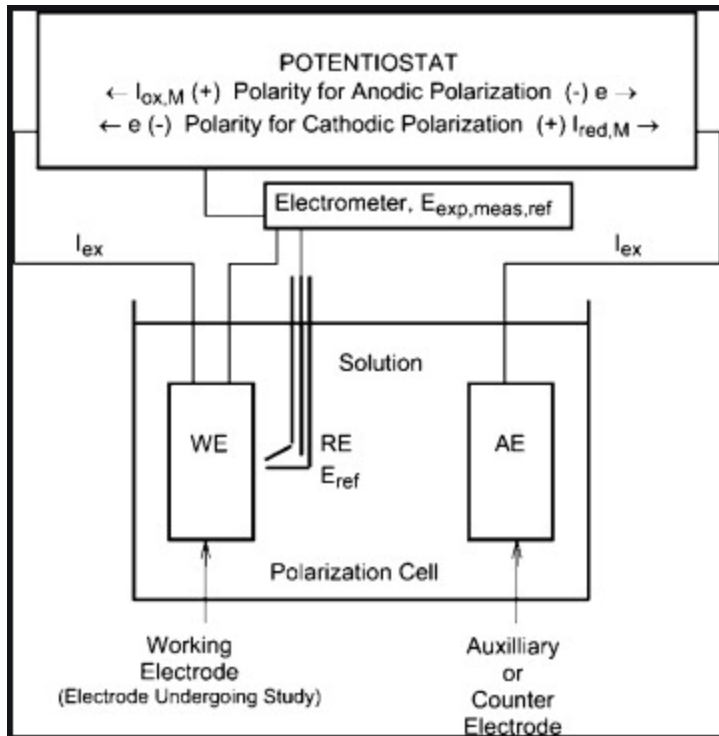


Fig. 9 Corrosion test process

3.1.3 WEIGHT LOSS MEASUREMENTS

Weight loss experiments were performed by immersion test (ASTM- G31-72) in freely aerated 3.5 % NaCl solution. The test panels of 30 X 30 X 5 mm³ dimensions were prepared to a surface finish of 120 grit (SiC paper). The panels were immersed in the solution in separate beakers for total duration of 49 days at room temperature (30°C). Each sample was exposed to the solution, for repeatability purpose. After the immersion test, the panels were cleaned with Clarke's solution of the following composition: 1000 ml hydrochloric acid (HCl, specific gravity 1.835) + 20 g antimony trioxide (Sb₂O₃) + 50 g stannous chloride (SnCl₂) (ASTM G-1-03). Cleaning was performed in steps such that a constant weight indicated complete removal of the rust from the surface of the sample. The corrosion rate was calculated from the weight loss measurements by using the following equation (ASTM G-1-03).

$$\text{Corrosion rate} = (K \cdot W) / (A \cdot T \cdot D)$$

where K = a constant, 3.45 X 10⁶, for corrosion rate calculated in mils per year (mpy),

W = mass loss in g, A = area in cm², T = time of exposure in hours (= 1176 hours),

D = density in g/cm³ (~7.8 g/cc for steels)

3.1.4 RESULT

Corrosion potential is a mixed potential (also an open-circuit potential or rest potential) at which the rate of anodic dissolution of the electrode equals the rate of cathodic reactions and there is no net current flowing in or out of the electrode. Corrosion current is the dissolution current at the corrosion potential.

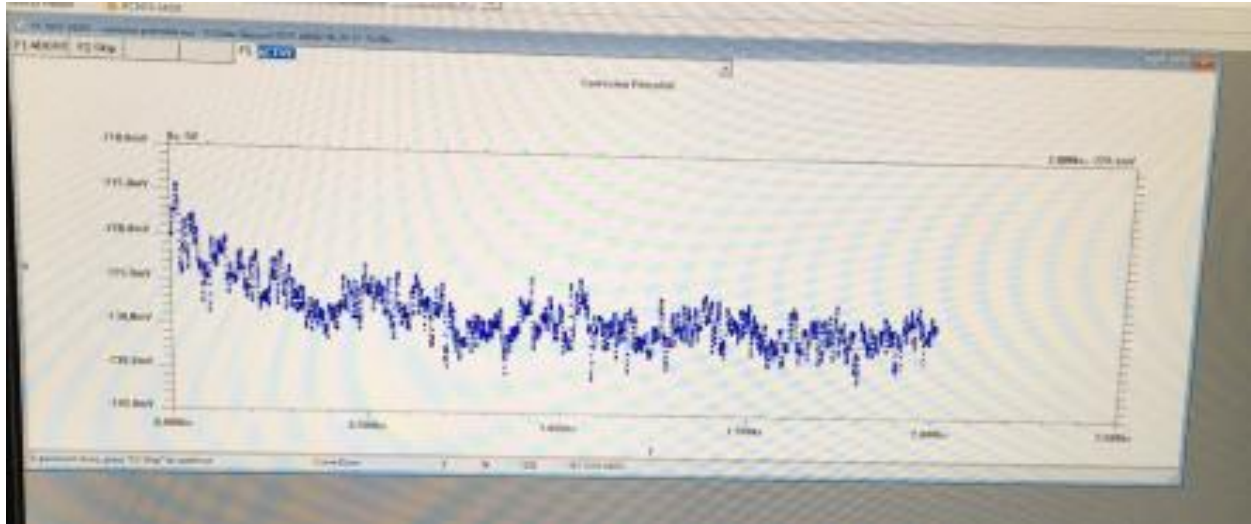


Fig. 10 Potential vs time graph

3.2 TENSILE TEST

3.2.1 SAMPLE PREPARATION

- ◆ Prepare 6 samples for tensile test.
- ◆ These samples are prepared according to ASTM E8 standard.
- ◆ Perform heat treatment on 3 samples and keep 3 samples without heat treatment.
- ◆ Perform the tensile test on all of the 6 samples and compare the properties of the heat treated samples and the other samples.



Fig. 11 Tensile sample

3.2.2 TEST PROCESS

The most common testing machine used in tensile testing is the universal testing machine. This type of machine has two crossheads; one is adjusted for the length of the specimen and the other is driven to apply tension to the test specimen. There are two types: hydraulic powered and electromagnetically powered machines.

The machine must have the proper capabilities for the test specimen being tested. There are four main parameters: force capacity, speed, precision and accuracy. Force capacity refers to the fact that the machine must be able to generate enough force to fracture the specimen. The machine must be able to apply the force quickly or slowly enough to properly mimic the actual application. Finally, the machine must be able to accurately and precisely measure the gauge length and forces applied; for instance, a large machine that is designed to measure long elongations may not work with a brittle material that experiences short elongations prior to fracturing.

Alignment of the test specimen in the testing machine is critical, because if the specimen is misaligned, either at an angle or offset to one side, the machine will exert a bending force on the specimen. This is especially bad for brittle materials, because it will dramatically skew the results. This situation can be minimized by using spherical seats or U-joints between the grips and the test machine. If the initial portion of the stress-strain curve is curved and not linear, it indicates the specimen is misaligned in the testing machine.

The strain measurements are most commonly measured with an extensometer, but strain gauges are also frequently used on small test specimen or when Poisson's ratio is being measured. Newer test machines have digital time, force, and elongation measurement systems consisting of electronic sensors connected to a data collection device (often a computer) and software to manipulate and output the data. However, analog machines continue to meet and exceed ASTM, NIST, and ASM metal tensile testing accuracy requirements, continuing to be used today.

The test process involves placing the test specimen in the testing machine and slowly extending it until it fractures. During this process, the elongation of the gauge section is recorded against the applied force. The data is manipulated so that it is not specific to the geometry of the test sample. The elongation measurement is used to calculate the engineering strain, ϵ , using the following equation:

$$\epsilon = \Delta L / L_0$$

where ΔL is the change in gauge length, L_0 is the initial gauge length, and L is the final length. The force measurement is used to calculate the engineering stress, σ , using the following equation:

$$\sigma = F_n / A$$

where F is the tensile force and A is the nominal cross-section of the specimen. The machine does these calculations as the force increases, so that the data points can be graphed into a stress-strain curve.

All the tensile tests were conducted on 25 kN servo hydraulic universal testing machine (model AMT-SC) at 5mm/min crosshead speed. With grain refinement, more and more grains that are

nearby are turned to have a different orientation. This makes it difficult for a dislocation to cross between grains, and travel and accumulate. Accumulation of dislocations is precursors to crack initiation and failure. Grain refinement introduces more and more grains boundaries and this halts the movement of dislocations thereby delaying failure and improving the strength of a material. This phenomenon works up to a certain grain size below or above which the strength starts to drop with further alteration in grain size as observable from ultimate tensile strength.

Hall Petch equation interpretation:

$$\sigma_0 = \sigma_i + k/\sqrt{D}$$

Above equation indicates that the strength of a metal is equal to the frictional stress (σ) plus a factor (k) times the inverse of the square root of the grain size (D). Reducing the grain size will cause the material to become stronger. If scales pertaining to 50x resolutions are read it is clearly visible that grain size is minimum for Brine solution and maximum for air. This is also verified when UTM test is performed on the heat treated samples.

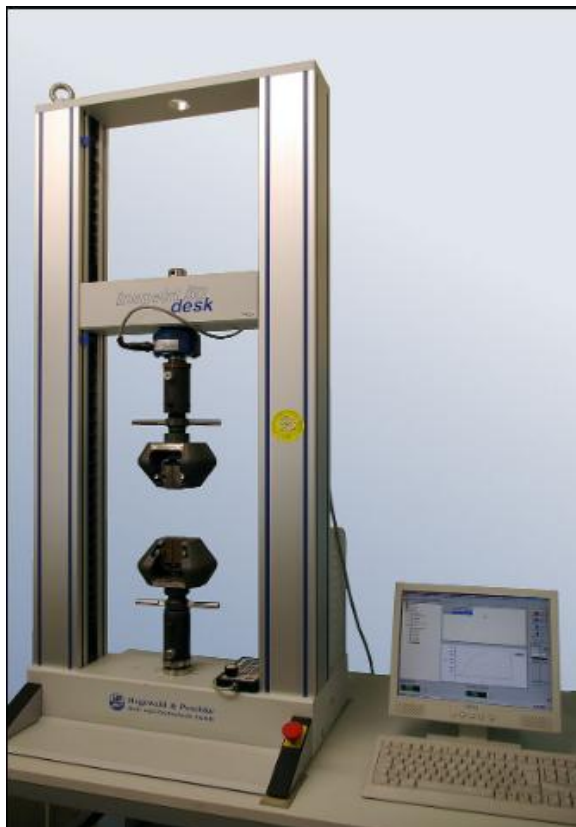


Fig. 12 Universal testing machine (UTM)

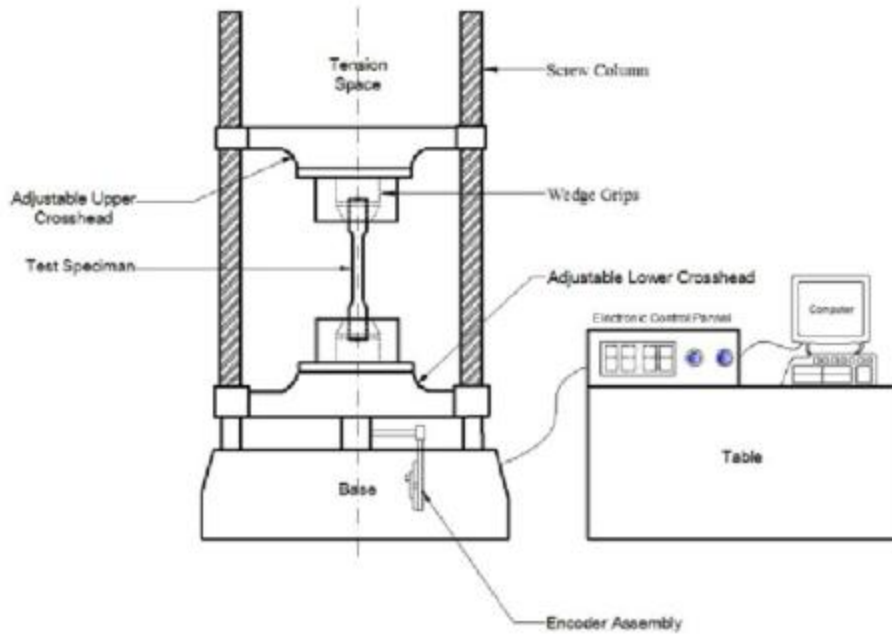


Fig. 13 Tensile testing

3.2.3 RESULT

The following is obtained after the completion of tensile test on A6061 alloy samples.

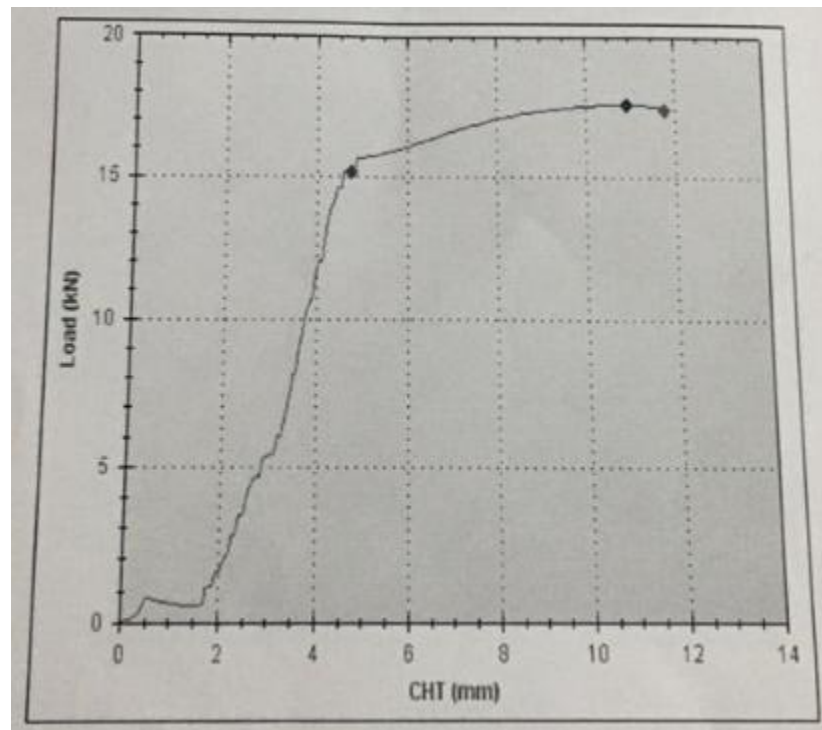


Fig. 14 Load vs Cross-head travel graph of untreated samples

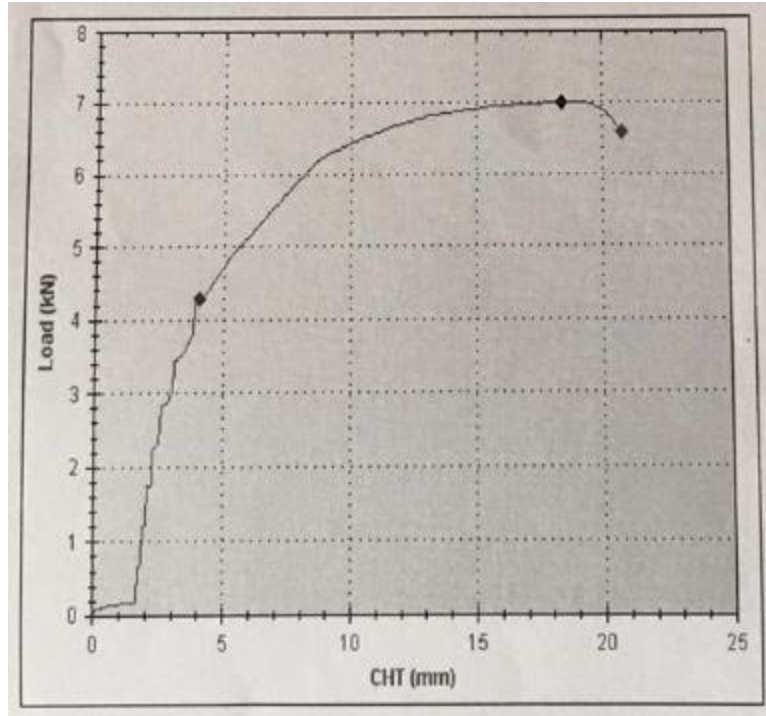


Fig. 15 Load vs Cross-head travel graph of heat treated samples

3.3 HARDNESS TEST

3.3.1 SAMPLE PREPARATION

- ◆ Prepare 6 samples for hardness test.
- ◆ These samples are prepared according to ASTM E18 standard.
- ◆ Perform heat treatment on 3 samples and keep 3 samples without heat treatment.
- ◆ Perform the impact test on all of the 6 samples and compare the properties of the heat treated samples and the other samples.

3.3.2 TEST PROCESS

The Rockwell hardness test method, as defined in ASTM E-18, is the most commonly used hardness test method. You should obtain a copy of this standard, read and understand the standard completely before attempting a Rockwell test.

The Rockwell test is generally easier to perform, and more accurate than other types of hardness testing methods. The Rockwell test method is used on all metals, except in condition where the test metal structure or surface conditions would introduce too much variations; where the indentations would be too large for the application; or where the sample size or sample shape prohibits its use.

The Rockwell method measures the permanent depth of indentation produced by a force/load on

an indenter. First, a preliminary test force (commonly referred to as preload or minor load) is applied to a sample using a diamond or ball indenter. This preload breaks through the surface to reduce the effects of surface finish. After holding the preliminary test force for a specified dwell time, the baseline depth of indentation is measured.

After the preload, an additional load, call the major load, is added to reach the total required test load. This force is held for a predetermined amount of time (dwell time) to allow for elastic recovery. This major load is then released, returning to the preliminary load. After holding the preliminary test force for a specified dwell time, the final depth of indentation is measured. The Rockwell hardness value is derived from the difference in the baseline and final depth measurements. This distance is converted to a hardness number. The preliminary test force is removed and the indenter is removed from the test specimen.

Rockwell hardness test machine was used for the hardness test. The procedure for this test is follow: the indenter (1/16-inch diameter steel sphere) is pressed into the sample by an accurately controlled test force (100 kgf). The force is maintained for a specific dwell time, normally 10 seconds. After the dwell time is complete, the indenter is removed leaving a round indent in the sample. The size of the indent is determined optically by measuring two diagonals of the round indent using either a portable microscope or one that is integrated with the load application device. The Rockwell hardness number is a function of the test force divided by the curved surface area of the indent. The indentation is considered to be spherical with a radius equal to half the diameter of the ball. The average of the two diagonals is used calculate the Rockwell hardness.



Fig. 16 Rockwell hardness tester

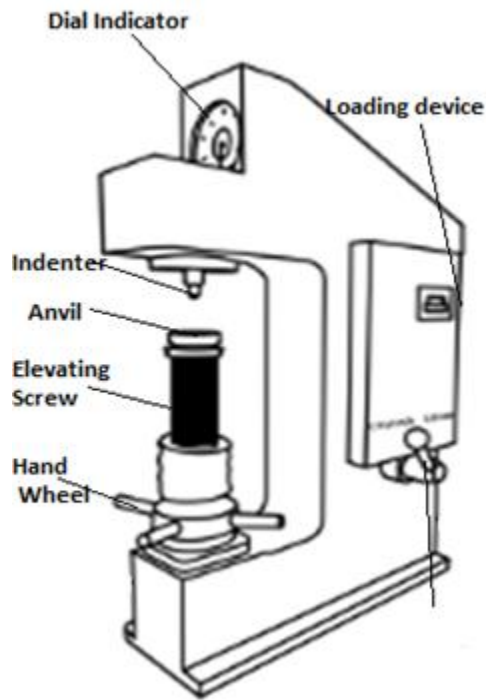


Fig. 17 Hardness testing

3.3.3 RESULT

The following table is obtained after the completion of hardness test on A6061 alloy samples.

Reading	Rockwell Hardness number (RHN) [Scale B]	
	Untreated samples	Heat treated samples
1	51	17
2	56	17
3	56	24
4	51	25
5	58	25
6	57	23
7	57	18
8	57	24
9	57	28
10	56	18

4. CONCLUSION

Materials can be hardened by inhibiting the motion of crystal defects called dislocations. In pure metals, the presence of defects (such as vacancies, interstitials, dislocations and grain boundaries) can enhance the strength. In two-phase alloys, additional stress is needed to enable the dislocation to intersect the second-phase particles. A finely dispersed precipitate may, therefore, strengthen the material. This phenomenon is termed precipitation hardening. The distribution of precipitates affects the hardness, yield strength, ultimate tensile strength and toughness. The hardness and yield strength are greater when the precipitates are small and finely dispersed in α matrix than when the precipitates are large and not finely scattered. Therefore, to gain hardness, the specimen should be heat treated to produce a fine dispersion of small precipitates. It has been found that rapid solidification process and heat treatment eliminate the formation of micro segregation, and significantly improved some mechanical properties. Grain Refinement plays a significant role in predicting the ultimate tensile strength of heat treated Al alloy. Finer grains accumulate during grain refinement and impede the movement of dislocation by introducing several grain boundaries to the dislocation due to which it has to change its orientation every time it passes through the new grain and also the grain area the dislocation has to travel is more for fine grain arrangement due to which its effect is considerably reduced and the amount of energy to produce the required deformation also increases.

5. DECLARATION

We, students of Eighth Semester, B.E, Mechanical Engineering, CMR Institute of Technology, declare that the project work titled **“Effect Of Heat Treatment On The Mechanical And Corrosion Properties Of 6061 Aluminium Alloy”** has been carried out by us and submitted in partial fulfillment of the course requirements for the award of degree in **Bachelor of Engineering in Mechanical Engineering** of **Visvesvaraya Technological University, Belagavi**, during the academic year 2017-2018.

Arpit Pande Krishna Rishi Kundan Kumar Gaurav Ved Raj
1CR16ME0201CR16ME0381CR16ME0391CR16ME088

Place: Bengaluru

Date:

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