CASTING AND METALLURGICAL ANALYSIS OF ALUMINIUM-6061

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Abstract: *Aluminium alloys are most extensively used Non-ferrous materials in aircraft and automobile industries. Among the aluminium alloys 6000 series are mostly suitable one by virtue its versability is heat treatment and extrusion capabilities. In the present study the influence of various alloying elements in Al 6061 is undertaken keeping in view the mechanical and metallurgical aspects. Experiments are carried by taguchi philosophy of design experiments. L8 orthogonal array is adapted in selection of compositions of alloying elements for casting specimens and testing is carried to study the mechanical and micro structural properties.*

Keywords: *Al6061, L8 array.*

1. INTRODUCTION

A non-ferrous metal is a metal, which does not contain appreciable amount of ferrous. Non-ferrous metals are used in many engineering applications because of desirable properties such as low weight (e.g., aluminum), higher conductivity (e.g., copper) non-magnetic property or resistance to corrosion (e.g., zinc). An Important non-ferrous metals include aluminium, copper, lead, nickel, chromium, manganese, magnesium, titanium and zinc, and alloys such as brass. Precious metals such as gold, silver and platinum are also non-ferrous. They are usually obtained through minerals such as sulfides, carbonates, and silicates. Non-ferrous metals are usually refined through electrolysis. Alloying additions improve the properties when added in appropriate quantities.

Key Properties: Typical properties of aluminium alloy 6061 include: Medium to high strength, Good toughness, Good surface finish, Excellent corrosion resistance to atmospheric conditions, Good corrosion resistance to sea water, Can be anodized, Good weldability and brazability, Good workability, Widely available.

2. WORK MATERIAL AND METHODOLOGY

The versatility of aluminium makes it the most widely used metal after steel. Aluminium alloy 6061 is one of the most extensively used of the 6000 series aluminium alloys. It is a versatile heat treatable extruded alloy with medium to high strength capabilities. Chemical and mechanical properties are summarised in tables 1 and 2.

Table 1: Composition of Al6061

Component	Amount(wt. %)
Aluminium	Balance
Magnesium	0.8-1.2
Silicon	0.4-0.8
Iron	Max. 0.7
Copper	0.15-0.40
Zinc	Max. 0.25
Titanium	Max. 0.15
Manganese	Max. 0.15
Chromium	0.04-0.35
Others	0.05

Table 2: Mechanical Properties of Al6061

Density	2.70 g/cm³
Modulus of Elasticity	70-80 GPa
Poisson's Ratio	0.33
Thermal Conductivity	173 W/m K
Ultimate Tensile Strength	230-310GPa

A: Experimental Design of Taguchi:

- Taguchi has designed a number of orthogonal arrays to aid in the development of experiments
- These arrays are essentially balanced fractional factorial designs.
- He suggests using two array matrices for each designed experiment.
- The inner array is used to study the effects of the design parameters we wish to study.
- An outer array is used to model the noise factors that may impact the performance of the product in the field.

L8 Orthogonal array: Orthogonal Arrays (often referred to Taguchi Methods) are often employed in industrial experiments to study the effect of several control factors. Popularized by G. Taguchi. Other Taguchi contributions include:

- Model of the Engineering Design Process
- Robust Design Principle
- Efforts to push quality upstream into the engineering design process

An orthogonal array is a type of experiment where the columns for the independent variables are "orthogonal" to one another. To define an orthogonal array, one must identify:

1. Number of factors to be studied
2. Levels for each factor
3. The specific 2-factor interactions to be estimated
4. The special difficulties that would be encountered in running the experiment. We know that with two-level full factorial experiments, we can estimate variable interactions. When two-level fractional factorial designs are used, we begin to confound our interactions, and often lose the ability to obtain unconfused estimates of main and interaction effects. We have also seen that if the generators are chosen carefully then knowledge of lower order interactions can be obtained under that assumption that higher order interactions are negligible. Orthogonal array testing is a black box testing technique, which is a systematic, statistical way of software testing. It is used when the number of inputs to the system is relatively small, but too large to allow for exhaustive testing of every possible input to the systems. It is particularly effective in finding errors associated with faulty logic within computer software. Orthogonal arrays can be applied in user interface testing, system testing, regression testing and performance testing. The permutations of factor levels comprising a single treatment are so chosen that their responses are uncorrelated and hence each treatment gives a unique piece of information. The net effect of organizing the experiment in such treatments is that the same piece of information is gathered in the minimum number of experiments. The following castings of different compositions were made by using Taguchi method with L8 Orthogonal Array is shown in Table 3.

Table 3: L8 Array

S. NO	P1 (Mg)	P2 (Si)	P3 (Cu)	P4 (Zn)	P5 (Mn)	P6 (Fe)	P7 (Cr)
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

3 CASTING PROCESS

Casting is one of the earliest metal shaping materials known to human beings. Metal casting involves pouring molten metal into a mould containing a cavity of the desired shape to produce a metal product. The casting is then removed from the mould and excess metal is removed, often using shot blasting, grinding or welding processes. The product may then undergo a range of processes such as heat treatment, polishing and surface coating or finishing. The solidified object is called Casting and the process is called Founding.

Different casting techniques have been designed to overcome specific casting problems or to optimize the process for specific metals, product designs and scales or other operational considerations such as automation. All casing processes use a mould, either permanent or temporary, which is a 'negative' of the desired shape. Once the metal is poured and has solidified it forms the 'positive' shape of the desired product. Processes differ in the number of stages that are required to produce the final casting. The numbers 1 & 2 in L8 Orthogonal Array indicates the maximum and minimum % composition of the Alloying elements as shown in Table 4.

Table 4: % Composition of the Alloying Elements

Component	Amount (wt. %) 1 - 2
Aluminium	Balance
Magnesium	0.8 - 1.2
Silicon	0.4 - 0.8
Copper	0.15 - 0.4
Zinc	0.05 - 0.25
Manganese	0.05 - 0.15
Iron	0.05 - 0.7
Chromium	0.04 - 0.35

4. EXPERIMENTAL DETAILS

4.1 Preparation Of Al 6061 Alloy

Melting was carried out in induction furnace. The molten metal was poured into the mould prepared from sand, and allowed to solidify, the ingots obtained after solidification were then machined to the required dimensions.

Pattern: A cylindrical pattern is used in present casting in which the pattern is made of Cast iron. Different composition castings details as follows.

Design Philosophy: L8 orthogonal array is selected for experimentation and composition of alloying elements for all 8 trails prepared by die-casting as the cylindrical pattern of cast iron metal, by pump the molten metal at 700^{0}_{c} . The prepared ingots was used for preparation of the specimens for metallurgical and mechanical properties, after finishing the casting. The specimen for mechanical testing is shown in Table 5.

Melting:Required amount of Al, Cu, Si, Mn, Cr, Mg and Zn is weighed in an electronic balance and kept in induction furnace for heating, melting. Melting was done by an induction furnace, which can heat up to 1000°C. The furnace is heated to a temperature of 700 °C. Slag was removed from the top after complete melting. Pouring: Molten

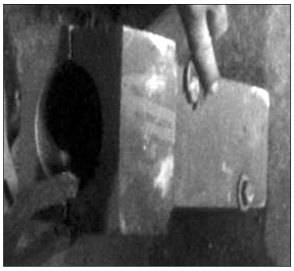


Fig 4.1. Die Pattern Used Preparation

Fig 4.2. Specimen Using Die Casting

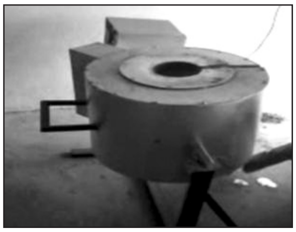


Fig 4.3. Melting of Al Alloy

Fig 4.4. Molten Metal in furnace

Table 5: Composition of Specimen (1-8)

SPECIMEN		1	2	3	4	5	6	7	8
S.NO	M/L	%	%	%	%	%	%	%	%
1	Mg	0.8	0.8	0.8	0.8	1.2	1.2	1.2	1.2
2	Si	0.4	0.4	0.8	0.8	0.4	0.4	0.8	0.8
3	Cu	0.15	0.15	0.4	0.4	0.4	0.4	0.15	0.15
4	Zn	0.05	0.25	0.05	0.25	0.05	0.25	0.05	0.25
5	Mn	0.05	0.15	0.05	0.15	0.15	0.05	0.15	0.05
6	Fe	0.05	0.7	0.7	0.05	0.05	0.7	0.7	0.05
7	Cr	0.04	0.35	0.35	0.04	0.35	0.04	0.04	0.35

composition was poured into a die by using a crucible. Solidification: Aluminium alloy was allowed to solidify inside the die. Once solidified, the casting was removed from die by opening the ejector pins. Cleaning: All operations such as the removal of sand, scale and excess metal from the casting, burned-on sand and scale are removed to improve the surface appearance of the casting. Excess metal, in the form of fins, wires, parting line fins and gates are removed. Visual inspection of the casting for defects and general quality test is performed. Machining: The specimens are properly machined using lathe. Initially the job is fixed to the three-way chuck. Turning: Referring to the fig 4.9, the part is rotated while a single point cutting tool is moved parallel to the axis of rotation. The starting material is a work piece generated by casting. Facing: Referring to fig 4.10, facing in the context of turning work involves moving the cutting tool at right angles to the axis of rotation of the rotating work piece. This can be performed by the operation of the cross-slide, if one is fitted, as distinct from the longitudinal feed (turning).

Fig 4.5. Pouring of Liquid Metal

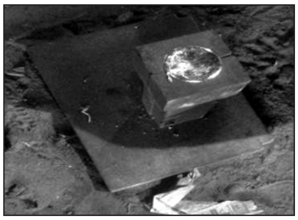


Fig 4.6. Castings after Solidification

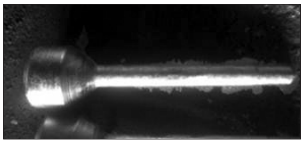


Fig 4.7. Visual Inspection

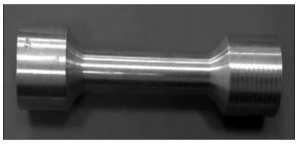


Fig 4.8. Turning

5 RESULTS AND DISCUSSIONS

5.1 Microstructure of the Specimens:

5.1.1 Specimen 1

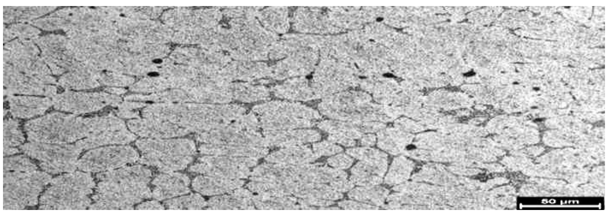


Fig 5.1. Microstructure of Specimen-1 with 200X

The figure shows the microstructure of specimen 1 with 200X magnification for the following composition, 94%Al-0.92%Mg-0.6% Cu-0.86%Zn-1.67%Si-0.5%Cr-0.95%Fe0.5%Mn The mechanical and metallurgical properties are following,

1. Grain orientation is not uniform because the material is not heat treatable.
2. The dark region constitutes of alloying elements, which are Copper, Magnesium, Silicon, Chromium, Zinc, Iron, manganese and white portion is aluminium.

5.1.2 Specimen 2

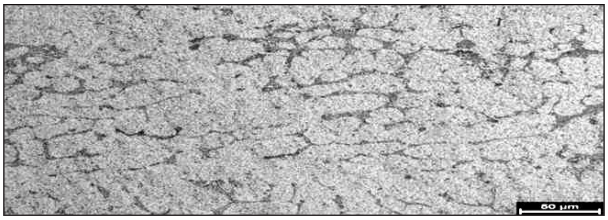


Fig 5.2. Microstructure of Specimen 2 with 200X

The above figure shows the microstructure of specimen 2 with 200X magnification for the following composition, 94.53% -Al, 0.64%- Mg, 0.7%- Cu, 0.53%- Zn, 1.65%- Si, 0.4%- Cr, 0.35%Mn, 1.2%-Fe. The mechanical and metallurgical properties are following,

1. The darker regions formed are alloying elements in the form of flakes. The white region in the matrix is due to the presence of aluminium.
2. which increases the ductility of the material thereby decreasing the strength and hardness.

5.1.3 Specimen 3

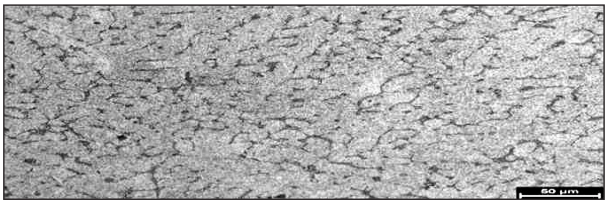


Fig 5.3. Microstructure of Specimen 3 with 200X

The above figure shows the microstructure of specimen 3 with 200X magnification for the following composition, 94.57%-Al, 0.73%- Mg, 0.67% Cu, 0.33%- Zn, 2% Si, 0.4% Cr, 0.20%-Cr, 1.1%-Fe. The mechanical and metallurgical properties are following,

1. Alloying elements are discontinuous and dispersed randomly through the aluminium alloy matrix.
2. The alloying elements are non-uniform in size and are irregularly shaped.
3. The dark region constitutes of alloying elements, which are Copper, Magnesium, Silicon, Chromium, Zinc and white portion is of Aluminium.

5.1.4 Specimen 4

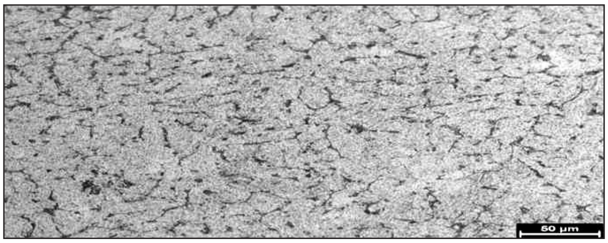


Fig 5.4. Microstructure of Specimen 4 with 200X

The above figure shows the microstructure of specimen 4 with 200 X magnification for the following composition, 94.69%- Al, 0.73%- Mg, 0.64%- Cu, 0.5%- Zn, 1.95%- Si, 0.06%- Cr, 0.89%- Fe, 0.21%-Mn. The mechanical and metallurgical properties are following,

1. The alloying elements forming the dark portion in the microstructure are continuous throughout the alloy.
2. Alloying elements are non-uniform in size and are shapeless.

5.1.5 Specimen 5

Fig 5.5. Microstructure of Specimen-5 with 100X

The figure gives the microstructure of specimen 5 with magnification that is 100 X 95.65%- Al, 0.2%- Mg, 1.54%-Si, 0.83%- Cu, 0.33% - Zn, 0.18%- Cr, 0.24% -Mn, 1.03%-Fe, The mechanical and metallurgical properties are following,

1. White regions in the structure are formed by aluminium whereas darker regions by the alloying elements. Micro structure obtained is brighter than any other because of higher amount of aluminium in it.
2. It is observed that with the addition of Manganese hardness has been increased.
3. It can be found that melting point of alloy is high because of absence of silicon.

5.1.6 Specimen 6

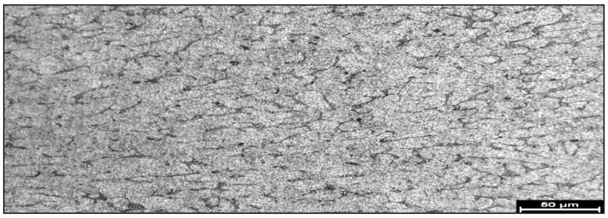


Fig 5.6. Microstructure of Specimen 6 with 200X

The above figure shows the microstructure of specimen 6 with 200 magnification for the following composition, 93.54%- Al, 0.79%- Mg, 0.95%- Cu, 1.5%- Si, 0.55%- Zn, 1%- Cr, 0.31% Mn, 1.27%-Fe, The mechanical and metallurgical properties are following, (1) Grains are oriented uniformly. (2) In this microstructure, Grain Boundaries are clearly visible. (3) Grains structures are in the form of bars.

5.1.7 Specimen 7

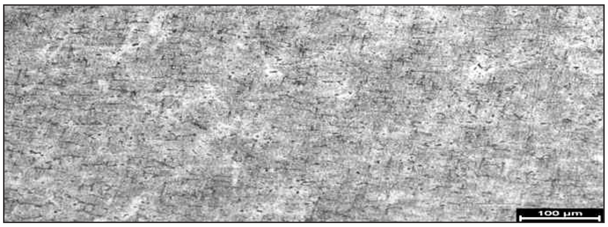


Fig 5.7. Microstructure of Specimen-7 with 100X

The above figure shows the microstructure of specimen 7 with 100X magnification for the following composition, 94.24%- Al, 0.95%- Mg, 0.61%- Cu, 2.29%- Si, 0.38%- Zn,0.2 %- Cr, 0.4% Mn, 0.84%-Fe, The mechanical and metallurgical properties are following, Figure shows that the microstructure of 6061 aluminium alloy of specimen contains Mg, Si (black spots) and Fe, Mn, Al (grey) particles. Optical microscopic examination of the composite reveals the presence of reinforcement particles in the form of clusters. From Figure, it is found that the discontinuous Cr, Zn reinforcement phase being non-uniform in size and irregularly shaped are dispersed randomly through the aluminium alloy.

5.1.8 Specimen 8

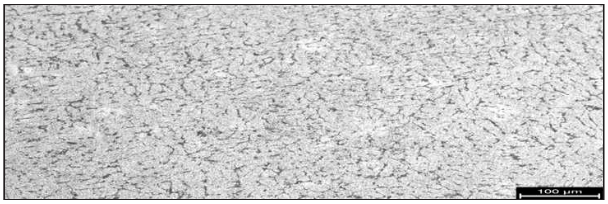


Fig 5.8. Microstructure of Specimen-8 with 100X

The above figure shows the microstructure of specimen 8 with 200 magnification for the following composition, 93.86%- Al, 1.25%- Mg, 0.64%- Cu, 2.04%- Si, 0.51%- Zn,0.52%- Cr, 0.13% Mn, 1.05%-Fe.

5.2 Tensile Strength of the Specimen

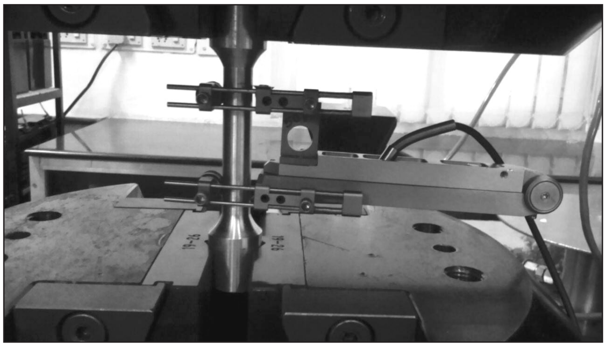
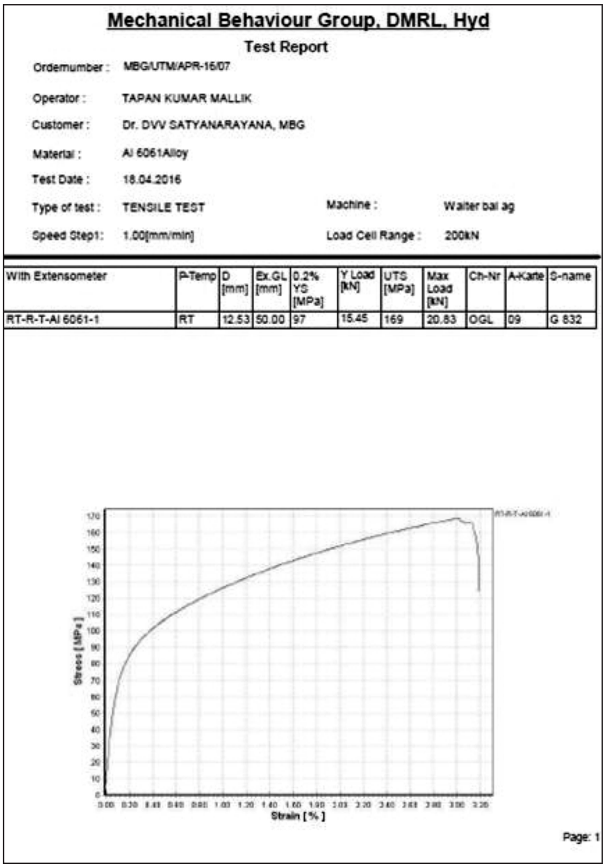


Fig 5.9. Testing for Ultimate Tensile Strength

5.2.1 Specimen 1



Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

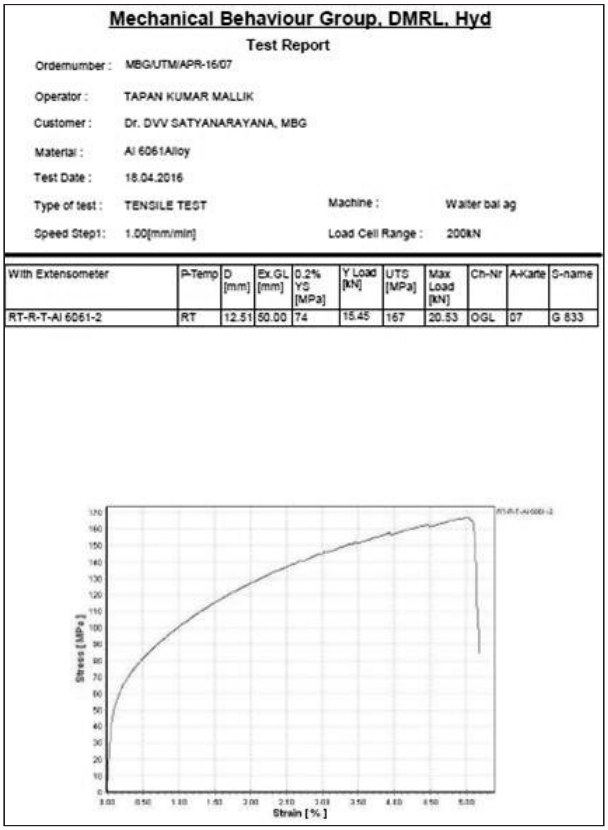
Type of test : TENSILE TEST Machine : Walter bai ag

Speed Step1: 1.00[mm/min] Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-1	RT	12.53	50.00	97	15.45	169	20.83	OGL	09	G 832

Fig 5.10. Stress-Strain Graph for Specimen - 1

5.2.2 Specimen 2



Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

Type of test : TENSILE TEST Machine : Walter bai ag

Speed Step1: 1.00[mm/min] Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-2	RT	12.51	50.00	74	15.45	167	20.53	OGL	07	G 833

Fig 5.11. Stress-Strain Graph for Specimen - 2

5.2.3 Specimen 3

Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

Type of test : TENSILE TEST   Machine : Walter bai ag

Speed Step1: 1.00[mm/min]   Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-3	RT	12.43	50.00	72	15.45	153	18.53	05	08	G 834

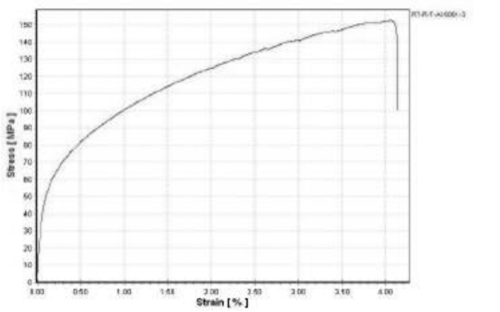


Fig 5.12. Stress-Strain Graph for Specimen-3

5.2.4 Specimen 4

Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

Type of test : TENSILE TEST   Machine : Walter bai ag

Speed Step1: 1.00[mm/min]   Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-4	RT	12.44	50.00	74	15.45	129	15.69	OGL	05	G 835

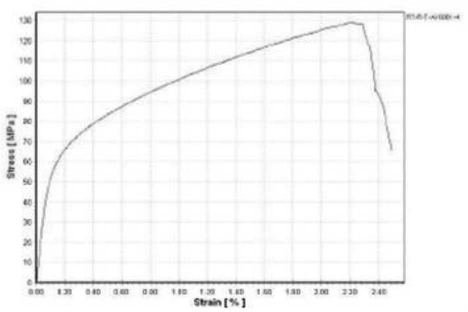


Fig 5.13. Stress-Strain Graph for Specimen-4

5.2.5 Specimen 5

Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

Type of test : TENSILE TEST   Machine : Walter bai ag

Speed Step1: 1.00[mm/min]   Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-5	RT	12.40	50.00	68	15.45	140	16.95	05	10	G 836

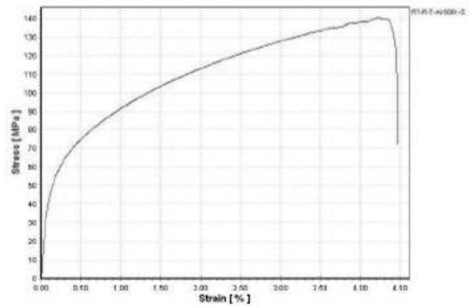


Fig 5.14. Stress-Strain Graph for Specimen-5

5.2.6 Specimen 6

Mechanical Behaviour Group, DMRL, Hyd

Test Report

Ordernumber : MBG/UTM/APR-16/07

Operator : TAPAN KUMAR MALLIK

Customer : Dr. DVV SATYANARAYANA, MBG

Material : Al 6061Alloy

Test Date : 18.04.2016

Type of test : TENSILE TEST   Machine : Walter bai ag

Speed Step1: 1.00[mm/min]   Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-6	RT	12.49	50.00	91	15.45	171	21.00	03	05	G 837

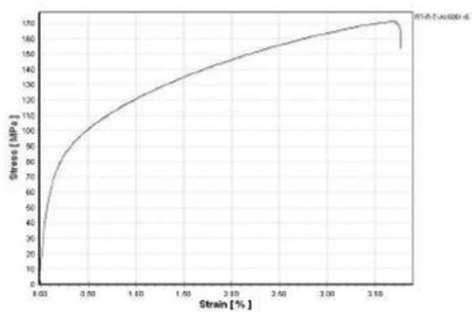
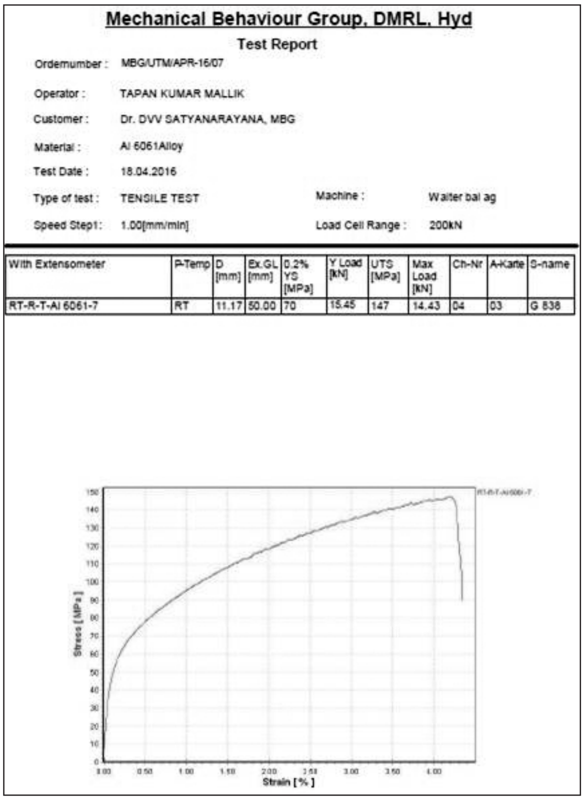


Fig 5.15. Stress-Strain Graph for Specimen-6

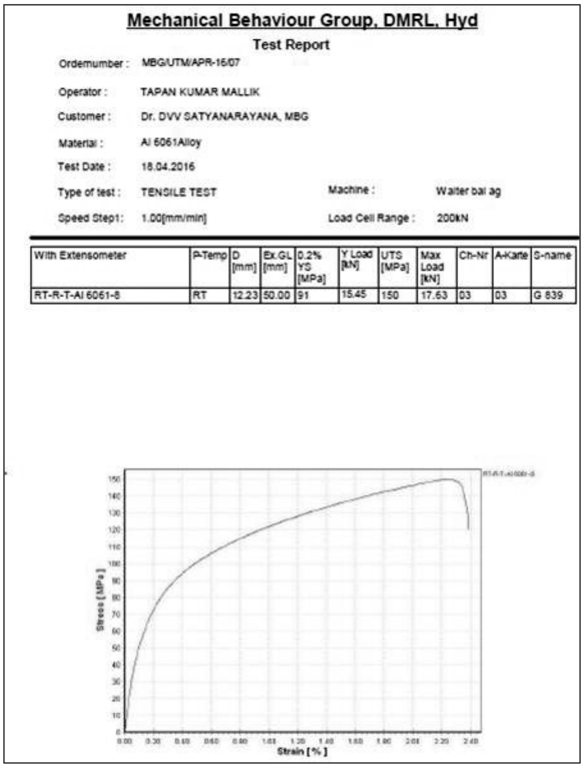
5.2.7 Specimen 7


Mechanical Behaviour Group, DMRL, Hyd
Test Report
Ordernumber : MBG/UTM/APR-16/07
Operator : TAPAN KUMAR MALLIK
Customer : Dr. DVV SATYANARAYANA, MBG
Material : Al 6061Alloy
Test Date : 18.04.2016
Type of test : TENSILE TEST Machine : Walter bai ag
Speed Step1: 1.00[mm/min] Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-7	RT	11.17	50.00	70	15.45	147	14.43	04	03	G 838

Fig 5.16: Stress-Strain Graph for Specimen-7

5.2.8 Specimen 8


Mechanical Behaviour Group, DMRL, Hyd
Test Report
Ordernumber : MBG/UTM/APR-16/07
Operator : TAPAN KUMAR MALLIK
Customer : Dr. DVV SATYANARAYANA, MBG
Material : Al 6061Alloy
Test Date : 18.04.2016
Type of test : TENSILE TEST Machine : Walter bai ag
Speed Step1: 1.00[mm/min] Load Cell Range : 200kN

With Extensometer	P-Temp	D [mm]	Ex.GL [mm]	0.2% YS [MPa]	Y Load [kN]	UTS [MPa]	Max Load [kN]	Ch-Nr	A-Karte	S-name
RT-R-T-Al 6061-8	RT	12.23	50.00	91	15.45	150	17.63	03	03	G 839

Fig 5. 17. Stress-Strain Graph for Specimen-8

5.3 Impact strength

Table 6: Impact Strength

SPECIMEN NUMBER	IMPACT STRENGTH
1	4 JOULES
2	4 JOULES
3	4 JOULES
4	4 JOULES
5	7 JOULES
6	3 JOULES
7	3 JOULES
8	3 JOULES

6. CONCLUSIONS

In this present study, the metallurgical and mechanical properties of (optimized alloy composition by Taguchi method) Al-606 alloy are determined. The main results and conclusions of this present study is summarized as below:

Specimen 6 with the following composition is found to be the best because of its mechanical and metallurgical properties.

93.54%- Al, 0.79%- Mg, 0.95%- Cu, 1.5%- Si, 0.55%- Zn, 1%- Cr, 0.31% Mn, 1.27%-Fe,

The Maximum Ultimate Tensile Strength is found to be 171Mpa for Specimen 6. The maximum Impact strength is found to be 7 joules for Specimen 5. Hence, these compositions of specimen 6 and specimen 5 has more applications than aluminium 6061 alloy. Generally, alkaline is added to enhance the corrosive resistance of aluminium alloy, which is not necessary for this material.

From metallurgical point of view, grains structure, grains boundaries are clearly shown by optical microscope and composition of the materials through XRF Analysis.

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