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Evaluation Of Surface Roughness And Mechanical Properties Of Recycled Metal Matrix Composite Materials

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ABSTRACT

This study focuses on evaluating the surface roughness and mechanical properties of recycled metal matrix composite (MMC) materials developed from copper and aluminum 6061 alloys. The copper-based MMC was fabricated using 94% copper, 2% silicon carbide (SiC), 2% lead, and 1% fly ash, while the aluminum-based MMC consisted of 96% aluminum 6061, 2% SiC, 1% lead, and 1% fly ash. These composites were produced using the stir casting method to ensure uniform dispersion of reinforcements. The primary objective was to assess the potential of using recycled materials and industrial waste to enhance mechanical performance while promoting sustainable manufacturing practices. Surface roughness was analyzed using a stylus profilometer, and mechanical properties including tensile strength, hardness, and impact resistancewere tested according to ASTM standards. Results indicated that the inclusion of SiC and fly ash significantly improved hardness and wear resistance, while lead enhanced machinability. Aluminum-based MMCs demonstrated superior strength-to-weight ratios, whereas copper-based composites showed enhanced thermal conductivity and damping capacity. The findings suggest that recycled MMCs with tailored compositions offer a promising, eco-friendly alternative for structural and industrial applications

Keywords: Copper and Aluminum 6061 alloy, Stir casting, Stylus Profilemeter, Lathe Machine, Impact test, Compressive & Tensile strength.

1. INTRODUCTION:

1.1 Surface Roughness

Surface roughness or simply roughness is the quality of a surface of not being smooth and it is hence linked to human perception of the surface texture. From a mathematical perspective it is related to the spatial variability structure of surfaces, and inherently it is a multiscale property. It has different interpretations and definitions depending on the disciplines considered.

In surface metrology, surface roughness is a component of surface finish (surface texture). It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. Roughness is typically assumed to be the high-frequency, short-wavelength component of a measured surface. However, in practice it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose.

The profile roughness parameters are included in BS EN ISO 4287:2000 British standard, identical with the ISO 4287:1997 standard.The standard is based on the ″M″ (mean line) system. There are many different roughness parameters in use, but is by far the most common, though this is often for historical reasons and not for particularas the early roughness meters could only measure Some parameters are used only in certain industries or within certain countries.

1.2 Classification of Surface Roughness

Surface roughness refers to the texture of a surface and the fine irregularities present on it. It is typically characterized by the deviations from an ideal smooth surface and is classified based on the nature of these deviations. The main types of surface roughness include:

1.2. 1. Waviness

Larger, more widely spaced irregularities caused by machine vibrations, heat treatment, or stress.

Typically measured over a longer surface length compared to roughness.

The measurement of the waviness can be done with a variety of instruments, including both surface finish profilometers and roundness instruments. The nature of these instruments is continually progressing and now includes both stylus-based contact instruments as well as optical & laser-based non-contact instruments.

1.2.2. Roughness

Small, closely spaced surface irregularities caused by machining processes like grinding, milling, or turning.

Typically measured using parameters like Ra (average roughness), Rz (mean peak-to-valley height), and Rq(root mean square roughness).

Surface roughness is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth.

1.2.3. Lay (Directionality)

The predominant pattern or direction of surface texture, often determined by the machining method.

Common lay patterns include circular, radial, cross-hatched, or isotropic.

Lay is generally produced by the manufacturing process and can be parallel, perpendicular, circular, crosshatched, radial, multi-directional, or isotropic (non-directional).

1.2.4. Flaws

Irregularities such as cracks, scratches, or pits caused by defects in the manufacturing process, material defects, or handling damage.

Any scratches, cracks, holes, depressions, seams, tears, or inclusions can be called a flaw. Although some flaws relate to surface texture, they also affect surface integrity.

1.3 Measurement of Surface Roughness:

Contact Methods: Stylus Profilometer.

The contact method involves the dragging of a diamond stylus whose tip dimension is such that it can penetrate the detailed geometry of the surface. The stylus is mounted onto an arm with a transducer at the other end. Any change in height of the stylus due to the surface features corresponds to a change in the signal detected and amplified by the transducer and the subsequent electronics. The most common type of transducer is based on the inductance principle and offers a large range-to-resolution as well as being of robust construction.

Non-Contact Methods: Laser Scanning, Optical Interferrometer.

Optical interferometers work on the principle of exposing the surface to be characterized to monochromatic or white light and observing the interference fringes produced using an optical flat tilted through a small angle. The fringe patterns are produced by splitting the light beam and the interference patterns are produced due to interference between reflections from the tilted optical flat and the surface to be measured. The fringe patterns are analyzed by a computer program incorporating the appropriate algorithms to give an unfiltered representation of the surface. The data may be statistically processed and filtered to provide parametric values.

Profilometer:

It is a metrology instrument for topographical characterization of a product's uppermost layers. It is a multipoint form of measurement that considers a material's primary form and the sub-micron (µm) textural variations of its surface, which are typically characterized as dimensional fractality and surface roughness.

It can be used to measure the surface roughness of a product, mechanical component, or other surface.

A surface profilometer or profilometer uses high-precision data acquisition components to measure the distinct features of a product substrate on nano-, micro-, and macroscales. This is carried out through contact or non-contact methods.

Applications of a Surface Profilometer:

These measurement principles are regularly used for process control applications, particularly to assess the ongoing performance of mechanically mating surfaces such as shafts and bearings. Gradual wearing can exponentially reduce the efficacy of a device due to friction-induced defects and a reduction of lubricating agents.

The surface profiles of sensitive optical lenses are also routinely assessed to monitor batch-to-batch consistency for optics of varying scales.

Surface profilometers or profilometers have eliminated the uncertainties associated with the arbitrary assessment of product surface topographies, and enabled previously unforeseen levels of precision in sectors where surface interactivity is a critical indicator of product performance.

Fig 1. Profilometer surface roughness tester.

2. SPECIMENS:

Copper and aluminum are two widely used metals in various industries due to their distinct properties, versatility, and applicability in different engineering fields.

2.1 Aluminum Alloy (6061): Aluminum (Al) is a lightweight, silvery-white metal known for its low density, resistance to corrosion, and high strength-to-weight ratio. These properties make aluminum ideal for use in applications where weight reduction is critical, such as in the aerospace, automotive, and packaging industries. Aluminum also exhibits excellent corrosion resistance due to the formation of a protective oxide layer on its surface.

It is highly recyclable and used in a variety of forms, including sheets, foils, and extrusions.

Table 1 Properties of Aluminum Alloy.

Young' Modulus	5GPa
Poisson's ratio	0.33
Density (kg/m^3)	2700
UTS	296.4 MPa
Strength Coefficient	562.5
Strain hardness (n)	0.5487
Yield Strength	155 MPa
% reduction at fracture	45.8

2.2 Copper alloy:

Copper alloys are mixtures of copper with other metals like zinc, tin, and nickel, designed to enhance specific properties beyond those of pure copper, such as strength, hardness, and corrosion resistance. The most well-known examples are brass (copper and zinc) and bronze (copper and tin), which are used in applications ranging from plumbing and musical instruments to ship hardware and electrical components.

Table 2 Properties of Copper Alloy

Melting Point	1084^0
Boiling Point	2562^0 C
Density	8.96 g/cm^3 (at 25^{0}C)
Specific heat	385 J/Kg K
Thermal Conductivity	398 W/m K (at 25^{0}C)
Hardness	62 Hv
Tensile Strength	255-313 N/mm^2

Fig 2 Al-6061 specimen

Fig 3 copper specimen

2.3 Measurement of Surface Roughness:

Surface roughness is measured using a profilometer or laser scanner. The measurement can be done manually or digitally.

Contact-based methods

Stylus measurement

A diamond stylus is dragged across the surface, and the vertical displacements are recorded.

Profilometer

A profilometer with a diamond stylus is moved over the surface to capture the roughness.

Non-contact methods

Optical profilometry: Uses light reflected from the surface to analyze surface roughness.

White light interferometer: An optical method that uses high precision microscopes to scan the surface.

Laser scanning confocal microscope: An optical method that uses a laser to scan the surface.

Applications:

Surface roughness measurements are used in industry to assess microelectromechanical systems and detect defects in LED arrays and photovoltaic devices.

Automotive:

The roughness of engine parts like piston rings and cylinder walls affects lubrication and wear.

Fig 4 Surface roughness readings

3. RESULTS AND DISCUSSION

After joining of materials using casting process, each sample was separately tested and determined the tensile strength, compressive strength, impact strength, and hardness average values.

The results in various tests were discussed below,

Ultimate Tensile Strength:

The yield and tensile strength of the samples are assessed and demonstrated.

Figures 4.1,4.2 and 4.3 demonstrate the photographic view of the samples of Al 6061 alloy and copper alloy before and after test respectively.

Fig 5 (a) Al-6061Before Testing

Fig 6 (b) Al-6061 after Testing

Fig 7 (a) Copper before Testing

Fig 8 (b) Copper after Testing

3.1. CALCULATIONS-Al-6061:

Ultimate Tensile Strength Test:

Dimensions Of A Specimen:

Length= 220mm, Breadth=18mm,

Thickness=14mm

For Copper (sample-1):

From UTM machine:

Breaking load=32KN = 32000N

Cross sectional area = 18*14 = 252mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area

= 32 * 10^3 / (252mm^2)

= 126.98N/mm^2

For Al-6061(sample-1):

From UTM machine:

Breaking load=19KN = 19000N

Cross sectional area = 18*14 = 252mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area = 19 * 10^3 / (252mm^2) = 70.370N/mm^2

Ultimate Tensile Strength Test:

Dimensions of A Specimen:

Length= 220mm

Breadth=18mm

Thickness=14mm

For Copper (sample-2):

From UTM machine:

Breaking load=32.8KN = 32800N

Cross sectional area = 18*14 = 252mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area

= 32.8 * 10^3 / (252mm^2)

= 130.15N/mm^2

For Al-6061(sample-2):

From UTM machine:

Breaking load=18.5KN = 18500N

Cross sectional area = 18*14 = 252mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area

= 18.5 * 10^3 / (252mm^2)

= 73.41N/mm^2

Average value of Al-6061:

70.370 + 73.412 / 2 = 71.891N/mm^2

Average value of copper:

126.98 + 130.15/ 2 = 128.565N/mm^2

Yield Strength Test:

Dimensions Of A Specimen:

Length= 220mm

Breadth=18mm

Thickness=14mm

For copper (Sample-1):

From UTM machine:

Cross sectional area = 18*14 = 252mm^2

Yield load=17KN=17000N

Tensile strength of Al-6061 = Yield load / cross sectional area

= 17 * 10^3 / (252mm^2)

= 67.460N/mm^2

For copper (Sample-2):

From UTM machine:

Cross sectional area = 18*14 = 252mm^2

Yield load=17.9KN= 17900N

Tensile strength of Al-6061 = Breaking load / cross sectional area

= 17.9 * 10^3 / (252mm^2)

= 71.031N/mm^2

Average value of copper:

67.460 + 71.031 / 2 = 69.245N/mm^2

Yield Strength Test:

Dimensions of A Specimen:

Length= 220mm

Breadth=18mm

Thickness=14mm

For Al-6061(Sample-1):

From UTM machine:

Cross sectional area = 18*14 = 252mm^2

Yield load=5KN=5000N

Tensile strength of Al-6061 = Yield load / cross sectional area

= 5* 10^3 / (252mm^2)

= 7.407N/mm^2

For Al-6061 (Sample-2):

From UTM machine:

Cross sectional area = 18*14 = 252mm^2

Yield load=4.8KN= 4800N

Tensile strength of Al-6061 = Breaking load / cross sectional area

= 4.8 * 10^3 / (252mm^2)

= 19.04N/mm^2

Average value of copper:

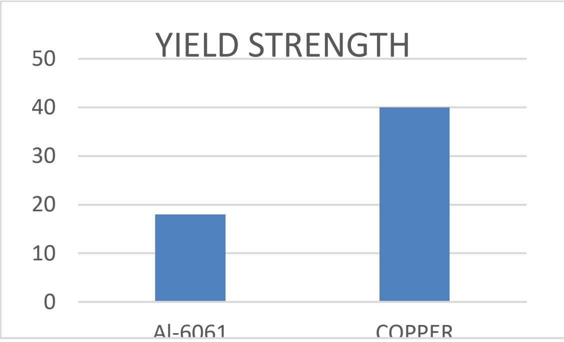
7.407 + 19.04 / 2 = 13.22N/mm^2

Table 3 Tensile and Yield strength of samples

SAMPLES	ULTIMATE TENSILE STRENGTH N/mm^2	YIELD STRENGTH N/mm^2
Al-6061	71.891	13.22
COPPER	128.565	69.24

In the below graph Al-6061 have low yield strength compare to the copper. Copper have high yield strength compare to Al-6061. The below graph shows yield strength increase gradually.

Yield Strength V/S Type of Specimen



GRAPH 1. : Chart representing variation in tensile strength with type of specimen:

In the below graph Al-6061 have low tensile strength compare to the copper. Copper have high tensile strength compare to Al-6061. The below graph shows tensile strength increase gradually.

Tensile Strength V/S Type Of Specimen

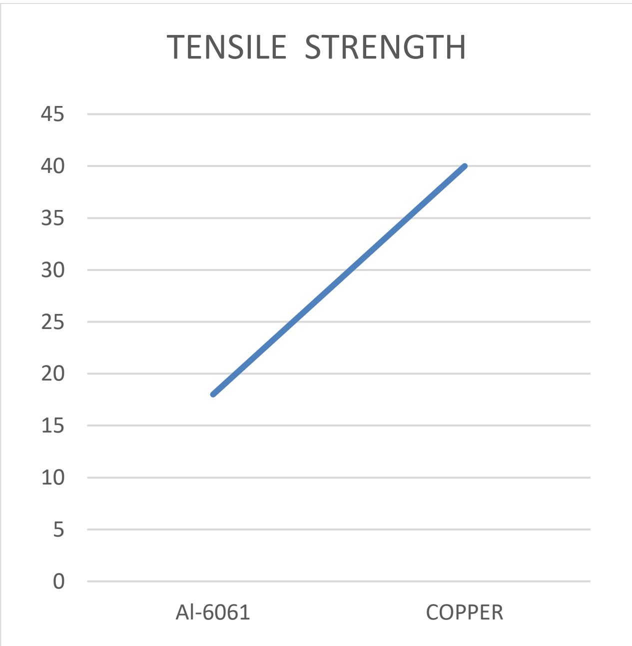


Fig 9 Al-6061&copper Before Testing

Fig 10 Al-6061&copper after Testing

Fig 11. Al-6061 & Copper placed on UTM

3.2 CALCULATIONS- COPPER :

Ultimate Compreesive Strength Test:

Dimensions Of A Specimen:

Length= 55mm

breadth=18mm

Thickness=23mm

For Copper (sample-1):

From UTM machine:

Breaking load=82.4KN = 82400N

Cross sectional area = 18*23 = 414mm^2

Compressive strength of copper = Breaking load / cross sectional area

$= 82.4 * 10^3 / 18*23(mm^2)$

$= 199.03 N/mm^2$

For copper (sample-2):

From UTM machine:

Breaking load=83.2KN = 83200N

Cross sectional area = 18*23= 252mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area

$= 83.2 * 10^3 / 18*23(mm^2)$

$= 200.96 N/mm^2$

Ultimate Compressive Strength Test:

Dimensions Of A Specimen:

Length= 55mm

breadth=18mm

Thickness=25mm

For Al-6061(sample-1):

From UTM machine:

Breaking load= 46.1KN = 46100N

Cross sectional area = 18*25 = 450mm^2

Compressive strength of Al-6061 = Breaking load / cross sectional area

$= 46.1 * 10^3 / (450mm^2)$

$= 102.44 N/mm^2$

For Al-6061(sample-2):

From UTM machine:

Breaking load=45.7KN = 45700N

Cross sectional area = 18*25 = 450mm^2

Tensile strength of Al-6061 = Breaking load / cross sectional area

$= 45.7 * 10^3 / (450mm^2)$

$= 101.55 N/mm^2$

Average value of Al-6061:

102.44 + 101.55 / 2 = 101.995N/mm^2

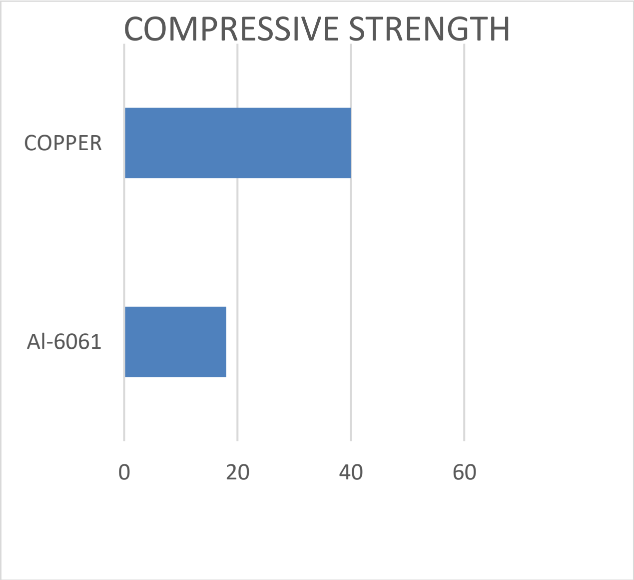
Average value of copper:

199.03 + 200.96 / 2 = 199.99N/mm^2

Table 4.compressive strength of samples

Samples	Compressive Strength N/mm^2
Al-6061	101.99
copper	199.99

3.4 Compressive Strength V/S Specimen



GGraph 2 : Chart representing variation in compressive strength with type of specimen:

In the above graph Al-6061 have low compressive strength compareto the copper. Copper havehigh compressive strength compare to Al-6061. The above graph shows compressive strength increase gradually.

Impact Test:

The Impact strength of the samples are assessed and demonstrated.

Figures 4.7, 4.8, 4.9 and 4.10 demonstrate the photographic view of the samples of Al-6061 and copper before and after test respectively.

Fig 12. Al-6061 Before Testing

Fig 13 copper Before Testing

Fig 14 Al-6061&copper After Testing

Fig 15. Al-6061 & copper placed on testing machine

4.1 CALCULATIONS-part-1

Dimensions of a Specimen :(Ioz Test)

Length= 100mm

Breadth=50mm

Thickness=50mm

Area = 50 * 50 = 2500mm^2

E1 = Energy absorbed without specimen

E2 = Energy absorbed for breaking the specimen

For copper (sample-1):

E1 = 170J

E2 = 130J

Impact strength = (E2-E1)/Area of cross section

= (170-130)/50*50

= 0.016J/mm^2

For copper (sample-2):

E1 = 170J

E2 = 120J

Impact strength = (E2-E1)/Area of cross section

= (170-120)/50*50

= 0.02J/mm^2

Average value of copper:

0.016 + 0.02 / 2 = 0.018J/mm^2

Dimensions of a Specimen :(Ioz Test)

Length= 100mm

Breadth=50mm

Thickness=50mm

Area = 50 * 50 = 2500mm^2

E1 = Energy absorbed without specimen

E2 = Energy absorbed for breaking the specimen

For Al-6061(sample-1):

E1 = 170J

E2 = 18J

Impact strength = (E2-E1)/Area of cross section

= (170-18)/50*50

= 0.0608J/mm^2

For Al-6061(sample-2):

E1 = 170J

E2 = 15J

Impact strength = (E2-E1)/Area of cross section

= (170-15)/50*50

= 0.062J/mm^2

Average value of Al-6061:

0.0608 + 0.062 / 2 = 0.0614J/mm^2

4.2 CALCULATIONS-part-2

Dimensions of a Specimen: (Charphy Test)

Length= 100mm

Breadth=50mm

Thickness=50mm

Area = 50 * 50 = 2500mm^2

E1 = Energy absorbed without specimen

E2 = Energy absorbed for breaking the specimen

For Al-6061(sample-1):

E1 = 300J

E2 = 10J

Charphy strength = (E2-E1)/Area of cross section

= (300-10)/50*50

= 0.116J/mm^2

For Al-6061(sample-2):

E1 = 300J

E2 = 8J

Charphy strength = (E2-E1)/Area of cross section

= (300-8)/50*50

= 0.1168J/mm^2

Average value of Al-6061:

0.116 + 0.1168/ 2 = 0.1164J/mm^2

Dimensions of a Specimen :(Charphy Test)

Length= 100mm

Breadth=50mm

Thickness=50mm

Area = 50 * 50 = 2500mm^2

E1 = Energy absorbed without specimen

E2 = Energy absorbed for breaking the specimen

For copper (sample-1):

E1 = 300J

E2 = 150J

Charphy strength = (E2-E1)/Area of cross section

= (300-150)/50*50

= 0.06J/mm^2

For copper (sample-2):

E1 = 300J

E2 = 140J

Charphy strength = (E2-E1)/Area of cross section

= (300-140)/50*50

= 0.064J/mm^2

Average value of copper:

0.06 + 0.064 / 2 = 0.062J/mm^2

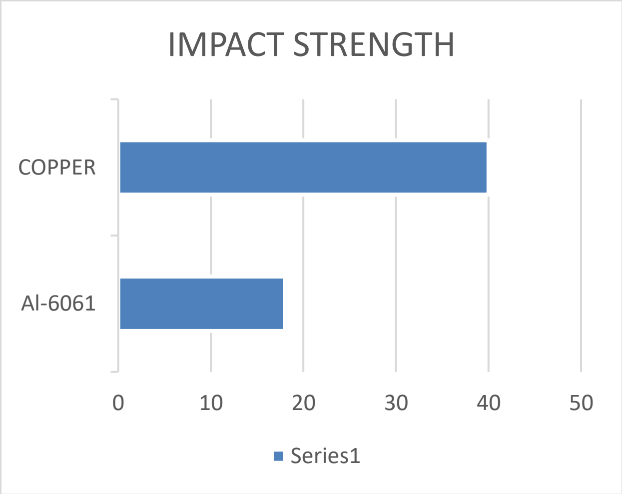
Table 5 Impact strength of samples

SAMPLES	IOZ TEST J/mm^2	CHARPHY TEST J/mm^2
Al-6061	0.061	0.011
COPPER	0.018	0.062

GRAPH 3: Chart representing variation in Impact strength with type of specimen:

In the below graph Al-6061 have low impact strength compareto the copper. Copper havehigh impact strength compare to Al-6061.The below graph shows impact strength increase gradually.

Impact Strength V/S Type of Specimen



4.4 HARDNESS TEST:

The Hardness test of the samples are assessed and demonstrated.

Figures 4.11 and 4.12 demonstrate the photographic view of the samples of Al-6061 and copper before and after test respectively.

Fig 16 Al-6061&copper Before Testing

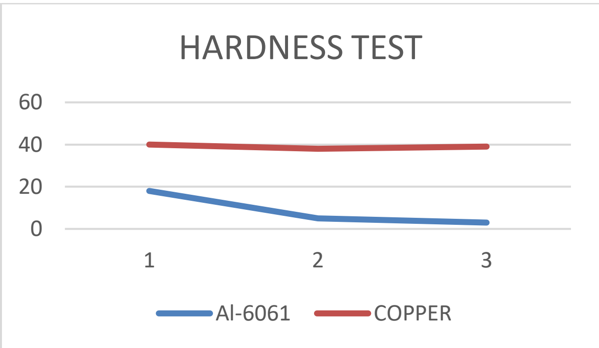
Fig 17. Al-6061&copper after Testing

Table 6 Hardness of samples

SAMPLES	TRAIL-1	TRAIL-2	TRAIL-3	MEAN
Al-6061	18	5	3	8.66
COPPER	40	38	39	39

GGRAPH 4: Chart representing variation in Hardness test with type of specimen:

Hardness Test V/S Type Of Specimen



In the above graph Al-6061 have low hardness compare to the copper. Copper have high hardness strength compare to Al-6061.Theabove graph shows hardness strength increase gradually.

Table 7. Final Results of the Tests

SAMPLE	ULTIMATE TENSILE STRENGTH N/mm2	COMPRESSIVE STRENGTH N/mm2	IOZ TEST J/mm2	CHARPHY TEST J/mm2	HARDNESS TEST (HRB)
Al-6061	71.891	101.99	0.061	0.116	8.66
COPPER	128.565	199.99	0.018	0.062	39

5 CONCLUSIONS AND FUTURE SCOPE

In this paper we are getting better ultimate strength on 128.565(N/mm^2) in copper and poor ultimate tensile strength on 71.891(N/mm^2) in Al-6061.

we are getting better compressive strength on 199.99(N/mm^2) in copper and poor compressive strength on 101.99(N/mm^2) in Al-6061.

we are getting better impact strength on 0.061(J/mm^2) in Al-6061. and poor impact strength on 0.018(J/mm^2) in copper.

we are getting better hardness on 39(N/mm^2) in copper and poor hardness on 8.66(N/mm^2) in Al-6061.

We have concluded that Al-6061 is less than copper. Another one we have concluded that copper is getting ultimate tensile strength, compressive strength, is high compared to Al-6061. And impact strength is more for Al-6061 as compared to copper. And hardness is more for copper as compared to Al-6061.

Future Scope:

Development of improved recycling methods to maintain the integrity and properties of Copper and Aluminum 6061 alloys.

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