Design, Development and Performance Evaluation of A 5-Ton Capacity Brinell Hardness Testing Machine

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Abstract-
Material testing machines are necessities in structural metal industries and engineering training institutions. Cost of importations had however made acquisition of the equipment difficult in most developing countries. This research aims at developing a hardness testing machine with 100% locally sourced components with a level of accuracy comparable with globally recognized manufacturers of similar equipment. A 5-Ton capacity Brinell-type hardness machine was designed, developed and tested. The machine has dimension specification: Base (602mm × 602mm); Height (1219.2mm). Total weight is 135 kg. The cubical frame is made of two structural I-channel of depth (600mm) × width (65mm) × web (5mm). The horizontal I-channel that absorbs the bending load is of specification 600mm Depth ×65mm width×5mmWeb. Design indentation load of 50000N transmitted at the centre of I-channel was used resulting in maximum stress of 48.5N/mm². A 5-Ton hydraulic jack, with attachments for workpiece support is placed rigidly on the lower I-channel. Sperical steel ball from ball bearings was used as indenter ball, positioned in a casing and rigidly fixed to the upper channel of machine in inverted position. Hydraulic jack pressure was monitored through an oil pressure meter connected through an orifice at the base. An upward movement of the ram lifts workpiece against stationary indenter. Indentation diameter on workpiece is measured with a micrometer travelling microscope. Repeated tests carried out on Aluminium, Copper and plastic gave diameters 2.9, 3.2, 7.5mm coressponding to 74.098, 60.56, 9.5BHN. Similar tests carried out on Brinell Hardness Tester Model (EEDB) and serial number (EEDB/13) give 79.6, 69.1, 9.5BHN percentage variation of locally developed machine from the standard machine used were 6.91, 12.36 and 0%. The effect of applied indenter force on hardness value was examined and results showed a maximum range of 1.428 BHN standard deviation. Test results indicated good reliability for use in basic material testing.

Keywords: Material Testing, Brinell, Hardness Tester, Bending Stress, Indentation, Hydraulic Jack, Pressure meter.

1. Introduction
Hardness is one of the most important properties of engineering materials [1]. It forms the bases for material selection, success or failure of a particular heat treatment operation on a material and quality assurance by meeting the required specifications. Hardness tests involve forcing of indenter to hit a material under test so as to determine its resistance to indentation, plastic deformation, abrasion, matching and scratching. Hardness test is principally used to express fundamental mechanical properties of a material under applied load. Consequently, this will aid design analysis and proper material selection [2]. Hardness of materials has long been assessed by its resistance to scratching or cutting. Early methods generally consisted of scratching [3, 4]. It is scale of testing consisted of a scratching bar, which increased in hardness from one end to the other. However, these methods do not give accurate numerical data and hence, are limited in practical use [5].
In the late 19th century, more investigations were carried out on hardness and its measurement. Johann A. Brinell, a Swedish engineer, presented a paper to the Swedish Society of Technologists describing his “ball” test. This suddenly became known as the Brinell test and became generally acceptable in the metalworking industry [5]. At present, many machines have been developed for making these tests more rapidly and accurately, but the principle has remained essentially unchanged. The fundamental principle adopted generally in hardness tests is to characterize the hardness based on the shape of the impression created by an applied indentation load. It measures the depth or area of indentation, which in turn is related to a hardness number, the smaller the indentation the higher is the hardness. The main difference between the tests is the use of different indenter shapes, and indentation loads [1].

However, in a world where material fabrication and metal heat treatment are outsourced, engineers needs to be sure that the proper procedures have been performed on the material and check material composition before it is put to use. The answer is hardness testing, a quick, minimally destructive testing that can provide peace of mind and eliminate costly rework and warranty issues [6]. More so, there are several constraints related to the hardness testing machine available in the Nigerian market. Firstly, they are expensive. The cost of purchasing a hardness testing device forms a major part of the initial cost of setting up small laboratories/workshops or small industries or upgrading existing ones [5]. Secondly, they are not readily available in Nigeria. Most manufacturers of hardness testing devices are based in developed countries such as USA, UK and other parts of Europe. Hence, to get a testing device from the manufacturer may take time and there may be ordering problems related to the device (such as delay in shipping and custom clearance).

Hence, there is a need for a hardness testing machine which does not depend on electricity, easy to operate and made from materials that are cheap and readily available. Therefore, this research aims at designing and developing a hardness testing machine for effective and efficient measurement of the resistance of a material to indentation taking cognizance of quality, precision and accuracy of the machine.

2. Methodology

In this work, the idea is to develop a hardness testing machine that can measure the resistance to hardness of any material when certain amount of load is applied on it. In order to ensure that this machine can be a good substitute for industrially manufactured hardness testing machine, the design calculation was computed to ensure that the support frames can withstand the maximum load of 5 Ton that the tester will be subjected to, calibration was made on the machine to make sure that the direct reading of the force applied by the indenter on the material can be measured and finally performance of the hardness tester was evaluated to ensure that it is a precise substitute for Imported hardness testing machine.
2.1 Components Description and Specifications

Measuring hardness of materials require equipment with high rigidity and stability for good repeatability of results. In this work, the hardness testing machine has the following components:

- Mainframe
- Indenter
- Hydraulic System

2.1.1 Mainframe

The mainframe is made of mild steel angle bars, square bars and 3mm thick steel plate, because it is designed to be rigid. It is reinforced at the sides to provide stability and prevent tilting when the load is applied. The structural frame is fully welded at different positions based on the design shown in Figure 1.
2.1.2 The Indenter
The indenter is the part attached to the upper part of the hardness tester. It is inserted in the indenter holder and locked with a key. The indenter makes an indentation on the material to be tested and the diameter of indentation is measured using a travelling micrometer microscope.

The indenter used was constructed using two nuts of 45mm diameter and an externally threaded shaft of 25 mm diameter both components are made of steel. Both ends of the shaft were drilled, one for easy placement of the ball and the other end to enable easy removal of indenter from the indenter holder.

The indenter ball of 10mm diameter was inserted in the lower nut with half of the surface protruding for indentation. The sectional view is shown in Fig 2 below:

![Sectional view of the indenter assembly](image)

2.1.3 The Hydraulic System
The hydraulic system consisting of a hydraulic jack is an integral part of this hardness testing machine. It is used to apply the force needed for the indentation of the test material. Depending on the amount of force needed and the capacity of the hydraulic jack, it ranges from 2 Tons to 32 Tons which is equivalent to 20KN to 320KN. But for the purpose of this research, a 5 Tons hydraulic Jack was used

Since,

\[ F = \text{applied force} = \text{area of the piston} \times \text{maximum pressure} \]  \hspace{1cm} (1)
\[ \text{Area} = \frac{\pi d^2}{4} \quad (2) \]

Where \( d \) is the diameter of the inner piston of the hydraulic jack = 40mm

This was obtained by measuring the inner piston of the hydraulic jack

Therefore,

\[ \text{Area of the piston} = 1256.6 \text{mm}^2 \quad (3) \]

And based on pressure meter rating,

The maximum pressure of the hydraulic gauge meter is 6000KPa = 6N/mm² \( (4) \)

The maximum force based on pressure meter rating from Eq. 1

\[ F = \text{Area} \times \text{Pressure} \]

\[ F = 7540 \text{N} \]

Maximum force = 7540N

2.2 Application of the Pressure Gauge as Force Indicator

For direct reading of the amount of force being applied at any time during the test, the hydraulic pressure gauge was recalibrated to indicate measurements in force and not pressure.

At 1000KPa = 1 N/mm²

From Eq. 1

\[ F = 1256.64 \times 1 \text{ N} \]

\[ F = 1256.6 \text{ N} \quad (6) \]

Then at 2000KPa = 2 N/mm²

\[ F = 1256.64 \times 2 \text{ N} \]

\[ F = 2513.28 \text{ N} \quad (7) \]

2.3 Work piece support and spring application

Work piece support and spring systems were incorporated into the hydraulic system. The work piece to be tested is placed on this support which serves as a stable and rigid table. On the other hand, the spring is attached to the work piece support for rigidity and also to enable the jack to return to its initial rest position when the key is unlocked see Fig 1 and 3 for details.
2.4 Design Consideration and Specifications

2.4.1 Stress Analysis and Deflection of the Maximum Load on the Support Beam

For the construction of the model hardness tester, four main beams were used to support weight of the maximum force that can be exerted by the hydraulic jack used. The beams were designed to resist bending moments and shear stresses due to the effects of the loads imposed on them by the bottle jack. Therefore, stress analysis was carried out on the beams to ensure they have sufficient strength to resist bending and shear.

Also the deflection of the support beam was also considered, it is equally important that the beam should be adequately stiff to resist deflection. The beam was therefore designed in such a way that it is stiff enough not to deflect more than the permissible limit.

Below are the analysis of each part of the machine, the final dimension and model of the hardness testing machine was as a result of each beam meeting each failure criteria.

Figure 4: Free body diagram of load beam showing the forces acting on it
Considering the figure 4 above

Using the equilibrium equation to determine shear force

Maximum shear force \( V_{\text{max}} = 25 \text{KN} \) \((8)\)

Similarly using the equilibrium equation to determine the bending moment

\[ M_{\text{max}} = 7525 \text{KNm} \]

Moment of inertia

By reasons of symmetry, with centroid \( C \) and thus the neutral axis

\[ I = \sum (I + AC) \]

\((9)\)

Using bending moment equation

\[ \sigma = \frac{M}{y} \]

\((10)\)

Sectional modulus of the wide flange beam

\[ Z = 45.083 \times 10^3 \text{mm} \]

\((11)\)

2.4.2 Shear Stress

(Rajput, 1939) \((12)\)

\[ \tau_{\text{max}} = 48.5 \text{N/mm}^2 \]

3 Testing the Hardness Testing Machine

3.1 Test Procedure for the Hardness Testing Machine

To measure the hardness of a material using this device, the following procedure should be followed:

1. Fix the indenter with the aid of a key to the indenter holder and ensure the indenter is locked using a key.
2. The material to be tested must be placed on the hydraulic system sit.
3. The release valve at the bottom of the hydraulic jack is locked using the handle and turning it in the clockwise direction
4. Insert the operating handle into the socket and the indenter is then lowered by up and down movement of the handle the indenter, stop when the indenter tip just touches the surface of the material
5. Force is applied on the material by applying more pressure on the hydraulic pump plunger by up and down movement of the handle within a specified period of time. This presses the material against the indenter.
6. Once the desired time for load application is reached, the pressure applied by the indenter on the material is read from the pressure gauge.
7. The release valve is then turned anticlockwise to lower the indenter
8. The material (specimen) is removed and the diameter of the indentation made is measured using a travelling micrometer microscope.
9. The hardness of the material is calculated using the formula below.
Where \( BHN = \) Brinell hardness number
\( d = \) diameter of indentation made

4. Test Results

This Better By Far (BBF) hardness testing machine was used for various tests in order to
determine whether it is suitable to be used as replacement for imported hardness testing
machine.

Brinell Hardness Tester Model (EEDB) and serial number (EEDB/13) was used to compare the
results gotten from the BBF hardness testing machine. The various standardization test carried
out include:

1. Comparison of BBF hardness machine versus Imported hardness testing machine test
   values

2. Effect of applied force on hardness value

4.1 Comparison of BBF Hardness Machine with Imported Hardness Testing Machine

Test Values

Having completed the construction and various components appropriately assembled, a 500kg
load was applied on different materials.

The samples tested with both hardness testing machine include:

1. Aluminum
2. Copper
3. Plastic
4. Teflon

These samples were placed under the indenter. The load was applied to the samples for 10
seconds each. Visible indentations were observed on the samples as shown below:

![ALUMINUM](image1)

![COPPER](image2)
Fig 5: materials tested with the BBF hardness machine.

The indentation made on Aluminum plate was wider and deeper than that one made on mild steel. From standard tables, mild steel hardness value is higher than the hardness value of Aluminum.

The hardness values of the indentations made on the material samples were measured from repeated tests and their average results are as shown in the Table 2 below:

| S/N | Material | Load Applied (Kg) | Average Indenter Dia(mm) | Constructed Indenter Dia(mm) | Constructed Hardness value (HBN) | Imported Indenter Dia(mm) | Imported Hardness value (HBN) | Percentage difference (%) |
|-----|----------|-------------------|--------------------------|-----------------------------|---------------------------------|--------------------------|-----------------------------|---------------------------|
| 1   | Aluminum | 500               | 2.9                      | 74.098                      | 2.8                             | 79.6                     | 6.91                        |
| 2   | Copper   | 500               | 3.2                      | 60.56                       | 3                               | 69.1                     | 12.36                       |
| 3   | Plastic  | 500               | 7.5                      | 9.5                         | 7.5                             | 9.5                      | 0                           |

4.2 Effect of Varying Force on Hardness value

The effect of varying force on hardness value was also investigated to determine whether hardness is an intrinsic property by varying the load and applying a constant ball diameter and the result is presented in the Table 3.

| S/N | Material | Load Applied (Kg) | Indenter Dia(mm) | Constructed Indenter Dia(mm) | Constructed Hardness value (HBN) |
|-----|----------|-------------------|------------------|-----------------------------|---------------------------------|
| 1   | Aluminum | 500               | 10               | 2.9                         | 74.098                          |
| 2   | Aluminum | 550               | 10               | 2.9                         | 76.06                           |
| 3   | Aluminum | 600               | 10               | 3.2                         | 72.64                           |
| 4   | Aluminum | 700               | 10               | 3.4                         | 74.82                           |
| 5   | Aluminum | 800               | 10               | 3.5                         | 76.0                            |
Table 4 Standard deviation of varying force on hardness value

| Constructed Hardness value (BHN) | RESULTS                      |
|----------------------------------|------------------------------|
| 74.098                           | Mean                         | 74.7236 |
| 76.06                            | Sample standard deviation    | 1.428042 |
| 72.64                            |                              |         |
| 74.82                            |                              |         |
| 76                                |                              |         |

**Fig 6: Effect of force on hardness value**

5. **Results and discussions**

From Table 2 It was observed that the calculated percentage difference of Aluminum is low 6.9%, in other word, the hardness number of the local machine is very close to the hardness number of the imported hardness number. This is same for copper, it has a percentage difference of 12.36% which is also very low and this indicates that the hardness value measured by the BBF hardness machine is close to the imported hardness machine.

Also, the percentage difference of the plastic measure is 0%; this indicates that the hardness value of the BBF machine is equal to the hardness value of the imported machine.

From the above comparison, it can be deduced that the machine is a good replacement for imported ones. The minute difference in the hardness value from the imported one can be attributed to error during the reading of the diameter of indentation on the micrometer microscope.

Furthermore, it was observed that the indentation made on copper plate was wider and deeper than that made on Aluminum. From standard tables, Aluminum hardness value is higher than the hardness value of copper.

It was also observed that the hardness is an intrinsic property of material and so it is independent of how much force is applied by the indenter ball see Figure 6.
6. Conclusion
A new and effective method for testing hardness of material has been successfully developed. A test procedure was outlined on how to use the BBF hardness tester. Quantification of the force applied using the pressure meter was stated and the hardness number generated for tests of certain materials were compared with the imported hardness machine and from the readings obtained, it can be concluded that the machine is accurate and precise and can be used has replacement for imported machine and possesses other unique features like

1. It requires no electrical power supply to operate.
2. It is very cheap to procure and produce.
3. It has an accessories cabinet.
4. A detachable indenter for different indenter ball.
5. All material used were locally sourced.

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