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Stardom Scientific Journal of Natural and Engineering Sciences

STARDOM SCIENTIFIC JOURNAL OF NATURAL AND ENGINEERING SCIENCES
PUBLISHED TWICE A YEAR BY STARDOM UNIVERSITY
Volume 2 - 2nd issue 2024
International deposit number : ISSN 2980-3756


بسم الله الرحمن الرحيم

Development and Optimization of a Low-Cost Tensile Testing Machine Based on ASTM D638 Standard

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Declaration

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ملخص البحث

يشرح هذا البحث بالتفصيل تطوير وتنفيذ نظام اختبار الشد الميكانيكي المصمم لتلبية معايير ASTM D638 ، والهدف الأساسي هو تحليل قوة شد المواد، وهو معيار حاسم لفهم السلوك الميكانيكي تحت الضغط. وقد خضع النظام لتعديلات كبيرة في كل من الأجهزة والبرمجيات لتعزيز الوظائف والتوافق مع معايير الصناعة. وتشمل تحديثات الأجهزة البارزة إعادة تصميم المقابض لتثبيت العينات بشكل آمن أثناء الاختبار. على جانب البرمجيات، تم إجراء تعديلات واسعة النطاق على رموز برمجة Arduino التي تحكم معلمات الاختبار وطرق استخراج البيانات. كانت هذه التعديلات ضرورية للامتثال لمعايير ASTM D638 وضمان توليد نتائج اختبار موثوقة. علاوة على ذلك، تم توجيه الجهود نحو تثبيت النظام وتحسين تنفيذ الاختبار. ركزت المرحلة الأخيرة على التعديلات المادية، وتحسين هيكل الآلة لتعزيز قدرات الاختبار، والالتزام المستمر بتقييم عينات الاختبار، ومقارنة النتائج بالتجارب السابقة، وتحسين الإجراءات لتحقيق الاتساق والدقة. يعد اختبار الشد أمراً بالغ الأهمية لتقييم ردود فعل المواد على حالات التحميل الواقعية، مما يجعل البيانات التي يتم الحصول عليها لا تقدر بثمن في مختلف التطبيقات الهندسية. يهدف هذا المشروع إلى توفير نظام اختبار شد ميكانيكي قوي ومتعدد الاستخدامات من خلال معالجة جوانب الأجهزة والبرمجيات.

Abstract

This research details the development and implementation of a mechanical tensile test system designed to meet ASTM D638 standards. the primary aim is to analyse material tensile strength, a crucial parameter for understanding mechanical behaviour under stress. The system underwent significant modifications in both hardware and software to enhance functionality and align with industry standards. Notable hardware updates include redesigned grips to securely fix samples during testing. On the software side, extensive modifications were made to Arduino programming codes governing testing parameters and data extraction methods. These adjustments were essential for compliance with ASTM D638 standards and ensured the generation of reliable test results. Furthermore, efforts were directed towards stabilizing the system and optimizing test execution. The latest phase focused on physical modifications, refining the machine's structure to enhance testing capabilities. the ongoing commitment lies in evaluating test samples, comparing results with previous experiments, and refining procedures for consistency and accuracy. Tensile testing is crucial for evaluating materials' reactions to realistic loading situations, making the data obtained invaluable for various engineering applications. By addressing both hardware and software aspects, this research aims to provide a robust and versatile mechanical tensile testing system.

Key words

Tensile test, ASTM D638, Stress, Strain, Arduino, Flexure tests

Introduction

Materials testing is essential to understanding material properties, and tensile testing is particularly important. It generates stress-strain curves and provides key insights into material strength, elasticity and overall performance. These tests are critical for quality control, safety and research to improve materials and reduce defects.
This research involved extensive research and standard comparisons prior to implementation. The ASTM D638 standard was selected because of its comprehensive guidelines, which required a thorough understanding and adaptation to the research requirements. This process included discussions with experts and thorough evaluations.
The work focused on hardware and software modifications:

- Hardware improvements included redesigning the testing machine, modifying the frame, and developing grips to allow both tensile and flexure testing with minimal adjustments.
- Software improvements included modifying codes to ensure accurate testing, optimising test speed and improving motor operation. A PID control system was implemented to provide real-time feedback to ensure accuracy and system stability.

These modifications increased the versatility and usability of the machine, overcoming technical challenges and improving functionality. The research successfully combined theoretical research with practical applications, laying a strong foundation for future advances in materials testing methods.

1.1. Aims & Objectives

The research focuses on conducting mechanical tensile tests to ASTM D638 standards to analyse material behavior under stress and assess tensile strength. Key objectives include significant hardware and software modifications to improve the testing equipment.
Steel is widely used in automotive components such as bodies, engines, chassis and wheels, helping to reduce weight and improve structural performance. Steel accounts for up to 55% of a vehicle's body weight, highlighting its importance in efficient manufacturing.[29]

2. Historical Perspective

Tensile testing has a long history dating back to the 18th and 19th centuries, with early contributions by Thomas Young and Thomas Hooke to the understanding of material behaviour under stress. Standardised testing methods emerged in the late 19th century because of industrial requirements, leading to the development of standards such as ASTM D638 for plastics by ASTM International. Advances in precision instrumentation have greatly improved accuracy, making tensile testing essential in industries such as aerospace and manufacturing.[1]

2.1. Instron 5960 Series Universal Testing Systems

The Instron 5960 Series is a powerful and versatile global testing system that operates on the principle of electromechanical control, as it uses precision motors to apply force to the specimens being tested, as this machine measures the force and displacement on the specimen to determine the mechanical properties in accordance with international standards such as ASTM D638 for Tensile Testing of Plastics. This machine is used in a wide range of industrial and research applications, such as aerospace testing, automotive industry, materials research, and others, where the tests that can be performed with this machine include Tensile, compression, flexure, bending, and repetitive stress tests, making it an essential tool for evaluating the performance of materials under various conditions. It should be noted that the specifications of this machine are shown in (Table-1) and (Figure-1), which illustrates the technical characteristics and detailed parameters related to its performance.

Feature	Specification
Type	Electromechanical Universal Testing System
Load Capacity	Typically ranges from a few N to 100 kN or more, depending on configuration
Displacement Resolution	Highly precise, often in micrometers (µm)
Speed	Variable, ranging from very slow to high-speed testing (mm/min to m/s)
Motor	Servo motors for precise force and displacement control
Maximum Sample Size	Accommodates various specimen sizes and geometries
Dimensions	Varies based on system configuration and setup
Power	Requires standard power supply based on system specifications
Weight	Depends on the configuration, often several hundred kilograms to tons

Table 1- Features and Specifications for 5960 Series [2].

(Figure-1) Instron tensile test machine 5960 Series [2].

2.2. Instron ElectroPuls E1000 and E3000 Series

Instron's ElectroPuls E1000 and E3000 series is an advanced electrodynamic testing system designed to perform dynamic and static tests such as tensile, stress, and Young's modulus tests. The ElectroPuls series is designed to comply with international material testing standards such as ASTM and ISO to ensure accurate and reliable results.

3. Mechanical Tensile Test

Tensile testing to ASTM D638 provides critical mechanical properties such as Ultimate Tensile Strength (UTS), Yield Strength and Elongation. This test assists in material selection and design by providing standardised insight into a material's behaviour under tension. Factors such as specimen size and geometry have a significant impact on test results, making real-world component testing essential for accuracy.

Mechanical testing serves several purposes, including

- Generating design data to ensure structural integrity and safety.
- Assessing material properties for joining procedures and operator acceptance.
- Verification of compliance with material specifications.

Tensile testing involves gripping a standardised specimen as shown in (Figure 2) and applying a gradually increasing uniaxial load to failure. Standardisation ensures reproducible and comparable results, making tensile testing a key tool for assessing material strength across all industries.

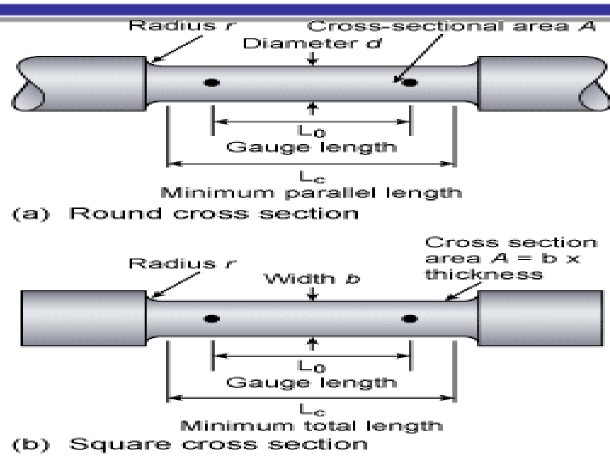

Figure 2- Standard shape tensile specimens [6].

3.1. Stress

Tensile strength is calculated by dividing the cross-sectional area of the specimen by the maximum achieved tensile force. Tensile strength (σ) = maximum tensile force (F) / specimen cross-sectional area (A), as shown in **(Eq 1)**:

$$\boldsymbol{\sigma = \frac{F}{A}} \quad \textbf{(Eq 1)}$$

Tensile strength is measured by performing a tensile test on a universal testing machine, and care must be taken to ensure that the results are accurate and repeatable. Evaluating a material by its tensile strength/yield strength in units of stress (Pa or psi) instead of force (N or lbf) helps with repeatability in results. This is because prepared materials/specimens have thickness and width tolerances that can vary, and stress accounts for thickness and width measurements of each specimen’s tensile strength calculation.

3.2. Strain

In a tensile test, strain refers to the deformation experienced by a material when it's subjected to tensile (pulling) forces. It specifically measures how much the material elongates or changes in length compared to its original dimension. This can be expressed as an absolute measurement in the change in length or as a relative measurement called "strain." Strain itself can be expressed in two different ways, as "engineering strain" and "true strain" [8].

Engineering strain is probably the easiest and the most common expression of strain used. It is the ratio of the change in length to the original length as shown in **(Eq 2)**:

$$\boldsymbol{\varepsilon e = \frac{L - L_o}{L_o} = \frac{\Delta L}{L_o}} \quad \textbf{(Eq 2)}$$

The true strain is similar, but based on the instantaneous length of the specimen as the test progresses, where L_i is the instantaneous length and L_0 the initial length as shown in **(Eq 3)**:

$$\varepsilon t = In\frac{L_o}{L_i} = In\frac{A_o}{A_i} \qquad \text{(Eq 3)}$$

3.3. Stress-Strain Curve

A stress-strain curve defines how a material behaves under load, which provides insights into the material's strength, stiffness, ductility, and failure limits. For example, a glass marble dropped to the ground would shatter immediately into pieces, while a rubber ball would return to its original shape after the impact. This difference in material behaviour between a glass marble and a rubber ball can be completely explained by stress-strain curves as shown in (Figure 3).[9]

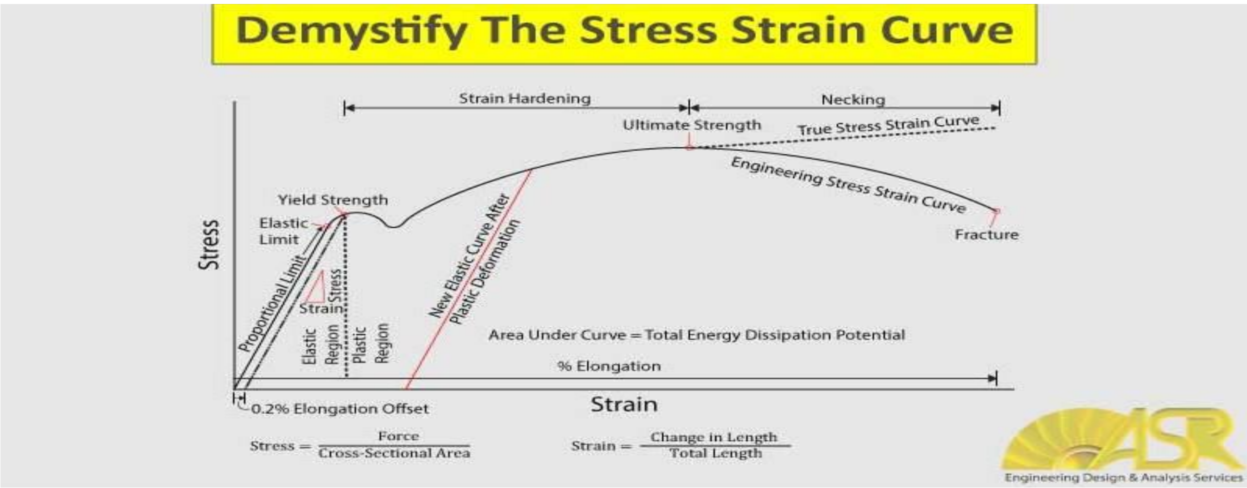

Figure 3- Stress-Strain curve [7].

4. ASTM D638 Standard

ASTM D 638 is a widely recognized and essential standard for evaluating the tensile properties of both unreinforced and reinforced plastics using standard dumbbell-shaped test specimens. This method provides a comprehensive framework for conducting tests under precisely defined conditions of pretreatment, temperature, humidity, and testing machine speed. It offers versatility by accommodating materials of varying thickness, up to 14 mm (0.55 in.), with thicker specimens requiring machining to meet the testing criteria. Additionally, ASTM D 638 includes the option to determine Poisson's ratio at room temperature, allowing for a more comprehensive characterization of material behaviour. It's worth noting that this standard is technically equivalent to ISO 527, which enhances its global applicability and acceptance in various industries as shown in Table 4. While ASTM D 638 acknowledges certain limitations associated with the constant rate of crosshead movement test method, it remains a practical and relevant tool for engineers and researchers. Despite theoretical considerations and variations in strain rates across the specimen, data obtained through this method remain valuable for engineering design purposes. The standard's widespread use underscores its effectiveness in providing critical insights into the mechanical properties of plastics, facilitating informed material selection and product design decisions [14].

5. Key improvements:

- Hardware modifications: Adapting the machine to accommodate different material shapes and sizes by integrating specialized grips. This ensures secure sample fixation, minimizes slippage and improves the accuracy of results.
- Software improvements: Align test parameters with ASTM D638 by fine-tuning speed, optimizing data extraction and formatting results accordingly. Arduino programming is implemented for precise control of test variables.
- Test integration: Combine tensile and flexure tests within the same fixture to improve efficiency and eliminate the need for frequent reconfigurations.

These enhancements aim to improve the accuracy, efficiency and reliability of materials testing while streamlining the overall testing process.

6. Results and discussion

- The results showed high accuracy in recording the stress-strain curve, as the material initially exhibited elastic behaviour with a Young's modulus of about 50 MPa, followed by a peak strain of over 100,000 kPa, and then entered the plastic deformation phase with relative stability, as shown in Figure 4. The results indicate that the machine can measure mechanical properties with high accuracy, reflecting its efficiency in the required tests.

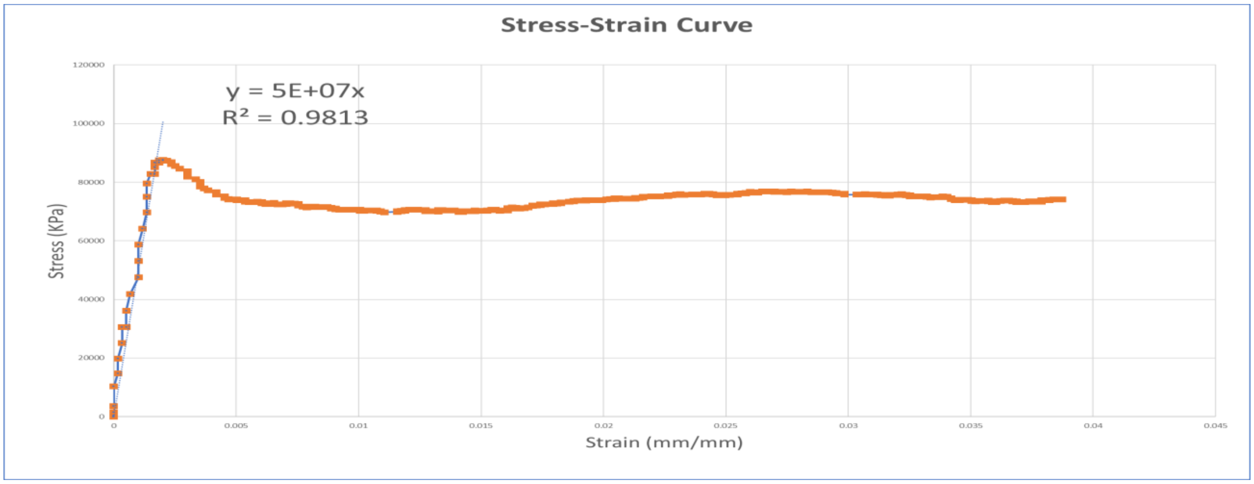

Figure 4- Stress-strain curve for the type V specimen.

- A low-cost tensile tester capable of analysing the mechanical properties of plastic materials according to ASTM D638 has been designed and developed.
- The instrument has demonstrated the ability to measure tensile strength, Young's modulus, and elongation with acceptable accuracy.
- The instrument was improved by redesigning the handle to ensure specimen stability during testing and to minimize slippage.
- The adhesive grip was chosen for its flexibility, reliability, ease of use, and manufacturability.
- The Arduino code was modified and a PID system was incorporated to accurately adjust the speed of movement to meet the requirements of the standard.
- The device was connected to Excel to generate live stress and strain curves during testing.
- An intuitive user interface was added with four well-organized buttons with clear labels for ease of use.
- The system had several technical limitations, including a linear actuator capacity of only 600 N, which limited the ability to test multiple types of materials.
- The current load cell can only support 490 newtons, reducing the accuracy of measurements at higher forces.
- The distance between the handles is insufficient to use a standard Type IV specimen, forcing the team to use thinner specimens that are difficult to obtain locally.

- Some of the mechanical challenges were overcome by using recycled components, such as the structural frame of the 3D printing machine and applying reverse engineering techniques.

7. Conclusion and Suggestion for Future Improvements.

This report outlines the mechanical tensile testing procedures, including modifications to the testing machine and operational protocols. It establishes research standards and provides comparative tables to aid in selecting adaptable testing devices. Arduino programming was utilized to determine testing speeds, extract and format data, visualize stress-strain curves, and document observations.

7.1. Identified Problems:

- Insufficient grip distance, preventing the use of Type IV specimens suitable for various rigidities.
- Grip design relies on human accuracy, leading to increased fixing errors.
- Incorrect actuator positioning, increasing measurement errors.
- Inability to test specimens with 4mm thickness, as only 2mm or thinner specimens are available in the region.

7.2. Dissection and Suggested Improvements:

- Replace the actuator with a 15,000 Newtons model for testing a wider range of plastic materials.
- Install a high-accuracy distance sensor to minimize errors.
- Upgrade the load cell to a higher-capacity sensor.
- Redesign the handle to reduce human dependency and minimize errors.
- Increase grip distance to accommodate Type IV specimens.
- We found that the current load cell, with a capacity of 50 kg (490 N), is less than the capacity of the linear actuator (600 N), which results in insufficient reading of maximum forces and limits the accuracy of the test.
- Type IV specimens cannot be used due to the limited distance between the grips, although this type is the most used to evaluate different levels of material hardness.
- The grip system should be redesigned to be more accurate with self-stabilization rather than manual stabilization.
- There is a clear effect of human error in fixing the specimen inside the grip, which affects the results, and this calls for the need to develop a safer fixing system to minimize human error.
- The need to use a displacement sensor with fast response time and high accuracy to ensure accurate tracking of specimen movement during the test.
- It is suggested to extend the capabilities of the tool to include additional tests such as flexure, creep, etc.

These modifications aim to enhance accuracy, reliability, and versatility in tensile testing.

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تصدر بشكل نصف سنوي عن جامعة ستاردوم
المجلد الثاني | العدد الثاني- لعام 2024م
رقم الإيداع الدولي : ISSN 2980-3756