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Andriy Slabkyi*

PhD in Technical Sciences, Associate Professor
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose Str., Vinnytsia, Ukraine
https://orcid.org/0000-0001-9284-2296

Serhii Kotyk

Postgraduate Student
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose Str., Vinnytsia, Ukraine
https://orcid.org/0009-0000-9396-7189

Innovative technologies in the study of mechanical properties of materials

Abstract. The article provides an overview of modern innovative technologies used to study the mechanical properties of materials using universal breaking machines. The focus is on the integration of machine vision technologies, machine learning algorithms and high-speed stereoscopy, which provide new capabilities for analysing the behaviour of materials during static and dynamic loads. An important aspect of the research is the improvement of traditional test methods through the introduction of innovative components: high-speed cameras that allow recording material deformations with microsecond precision; stereoscopic systems that create three-dimensional models of material behaviour under load; as well as lighting devices that provide uniform illumination of the test object. These technologies are synchronized with powerful computing modules capable of analysing large amounts of data in real time. The authors emphasise that the integration of computer vision and machine learning algorithms can significantly reduce the impact of the human factor on research results. Automated analysis systems are able to accurately detect and classify defects, simulate types of failures and predict the behaviour of materials under various loading conditions. Examples of the use of such systems in the study of complex composites, metal alloys and the latest polymers are also given. Additionally, innovative approaches to the creation of dynamic loads that allow testing for impact strength and endurance are considered. The article shows how automated test process management systems increase research efficiency by providing greater accuracy, repeatability of results, and faster data processing. The practical significance of the described developments lies in their wide application in industries where the study of the mechanical properties of materials is critical, such as aircraft construction, mechanical engineering, energy and construction. A high level of automation and accuracy of tests, provided by the introduction of modern technologies, allows setting new standards for the quality of research and creates prospects for the further development of materials science. Thus, the presented approach to improving universal breaking machines contributes to increasing the accuracy of measurements, expanding the functionality of traditional test systems and creating more efficient methods for studying materials

Keywords: universal breaking machines, machine vision, pulse loading, prediction of the behaviour of materials, optical measurement systems, machine learning algorithms, visualisation of deformations

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*Corresponding author

Introduction

Modern trends in the field of materials science demonstrate the rapid development of technologies aimed at improving the mechanical properties of materials, as well as improving the methods of their research. The relevance of this topic is determined by the increasing demands on the quality of materials in various industries, including mechanical engineering, construction, automotive, and aviation. Within the framework of this study, special attention is paid to innovative approaches presented in the works of leading scientists. In particular, the article [1] examines trends in improving the mechanical properties of materials created by the additive manufacturing method. The main emphasis is placed on the use of metal, ceramic and polymer materials, which, thanks to this technology, obtain much better characteristics. This study shows the prospects of additive manufacturing in the context of ensuring high mechanical parameters of products.

Another important study presented [2] focuses on the experimental study of the effect of vibration on the mechanical properties of parts made by extrusion of materials. The use of high-frequency vibrations made it possible to significantly increase strength and reduce stress in the material. This approach expands the possibilities of additive manufacturing by adding tools to improve the quality of the final product.

In addition, the article [3] discusses an innovative non-contact method for estimating the strain distribution using digital image correlation (DIC) and laser speckle pattern. This method provides high accuracy in determining local deformations and allows you to obtain data in real time without physical interference with the test process. The application of this approach significantly expands the possibilities of testing in materials science, making them more efficient and accurate.

In this way, these studies demonstrate how modern technologies can be integrated into the study of the mechanical properties of materials. This article will consider the further development of these ideas in the context of the introduction of innovative approaches to working with universal breaking machines and the use of machine vision for the analysis of deformation processes.

Results

Continuing the ideas presented in the studies reviewed, our work focuses on integrating machine vision and automated data acquisition systems to improve test accuracy. The use of high-speed cameras in combination with computer vision algorithms makes it possible to obtain three-dimensional models of deformations in real time and investigate the process of material shaping, deformation, crack formation, etc. [4, 5].

The integration of vibration technologies, as shown in the paper [6], can be applied to reduce residual stresses in the materials being tested. The addition of such modules to modern universal breaking machines will provide better quality results and allow for more repeatability of research. In addition, the introduction of digital image correlation [7] opens up new perspectives for non-contact deformation analysis. This method avoids the impact of contact devices on the sample, which is especially important when testing thin-walled or brittle materials.

Analysing traditional methods and means of studying the characteristics of materials of machine parts and structures, such as static tensile or compression load, it is advisable to single out the main components of such systems.

Load sensors – installed in the machine to accurately measure the applied load. The accuracy of the sensors is critical in determining the strength of the material [8]:

- Extensometers. Measure the deformation of the sample under load. Extensometers can be contact (mechanical or electronic) or non-contact (optical systems). Contact extensometers are attached to the specimen and record elongations, while non-contact extensometers use lasers or cameras to track deformations [9].
- Data collection and processing system. Includes software for real-time recording of load and strain readings. The data are analysed to plot stress-strain, determine the modulus of elasticity, yield strength and other parameters. This software also allows you to store, analyse, and visualize test results [10].

Measuring systems used in widely used test benches cannot be adapted to ensure the required test accuracy due to the high transience of processes during pulse and high-speed dynamic load studies.

Pulsed material testing equipment creates significant loads in a short period of time, requiring high-precision data collection and analysis. In such studies, the use of machine vision opens up new opportunities for observation and analysis of materials [11].

Modern machine vision systems significantly improve the quality of tests, as they allow you to analyse the behaviour of materials during fast-moving deformation processes that occur under the influence of impulse loads. Traditional measurement methods often have difficulty accurately capturing rapid changes in material, while machine vision provides high speed and accuracy in image acquisition [12].

The integration of machine vision into pulse equipment provides the possibility of detailed analysis of fast-moving processes, such as deformations and destruction of materials under the influence of impulse loads. This requires building a dedicated module that can efficiently capture images at high speeds and process them in real-time. A machine vision-based measurement system should consist of the following components.

1. Camera systems – high-speed cameras with a shooting frequency of 10,000-1,000,000 frames per second (FPS) to capture fleeting changes. Pulse tests, such as shocks or explosive loads, require the capture of events lasting only milliseconds. High-speed cameras (e.g., up to a million frames per second) can capture these short-lived processes, allowing researchers to see how material breaks down or changes under load. This technology is indispensable

for analysing the dynamics of crack propagation or instantaneous deformations [6]. For three-dimensional modelling of strain, it is advisable to use stereoscopic cameras, with the help of which you can create three-dimensional models of strains in real time. This allows you to investigate how a material responds to impulse loads in all three dimensions, which is important for materials with anisotropic properties. Three-dimensional visualization helps to better understand the behaviour of the material and allows for a deeper analysis of fracture processes [9]. The location of the chambers needs to provide coverage of the entire test area and the viewing angles required for analysis from different positions. Thanks to the use of high-resolution cameras, it is possible to detect microcracks or changes in surface texture that occur under the influence of pulse load. For example, when examining the impact strength of a material, it is important to identify the slightest initial defects that can lead to failure. Optical systems detect these changes even before they become noticeable in any other way [10].

2. Lighting system – pulsed LEDs or laser light sources that provide short-term and bright lighting for high-quality capture of frames without blurring. The lighting system must have a lighting synchronization system with the cameras to ensure the best image quality at high speeds [11].

3. Compute unit for image processing – processor or graphics processing unit (GPU) for fast processing of large numbers of frames in real time. Since pulse tests generate huge amounts of data in a very short time, it is important to use software that can process this data in real-time. Machine vision, combined with computer vision algorithms, allows for automatic analysis of the resulting images to identify key parameters such as deformation rate, crack propagation, and overall material behavior [12].

Computer vision algorithms including: detection of deformations and displacements: analysis of shifts and changes in material structure based on sequences of frames. Specialised machine learning algorithms can process and analyse the resulting images, providing accurate determination of deformation parameters and anomaly detection. This allows you to better predict the behavior of the material under load and makes the research process more efficient. Algorithms can also be used to classify types of fractures and analyse the nature of cracks [13]. Thanks to machine vision, it is possible to automate the process of detecting defects in samples after testing. This technology is able not only to record changes, but also to distinguish between types of deformations and damage, helping researchers make more informed decisions about further analysis or adjustment of materials.

Three-dimensional modeling of deformations using stereoscopic cameras allows for accurate analysis of changes in the structure of materials under load. The cameras capture synchronous images that are processed to create a 3D model of warps in all directions (X, Y, Z). It is a high-precision non-contact method that provides detailed analysis of complex deformations, particularly in composite materials. Such a system provides an in-depth understanding of the behaviour of materials, including in real time.

Interfaces with machine learning tools are integrated into data collection and analysis systems, which allows you to automate the processing of large amounts of information. They are able to classify types of fractures, such as ruptures, cracks or plastic deformations, based on pre-trained models. Also, these interfaces predict the behaviour of materials using algorithms that detect hidden patterns in the data. This improves the accuracy of estimates and allows you to predict material properties in difficult conditions.

4. Data collection and synchronisation system – this is a face for communication with pulse equipment: synchronization of the moment of shooting cameras with pulse load. A synchronisation controller to control the camera, lighting and computing unit system, ensuring the correct interaction of all components.

5. Data analysis and visualisation software is a user interface for adjusting test parameters such as frame rate and light intensity. Module for real-time visualisation of analysis results, including three-dimensional deformation models. An automatic reporting system that stores the collected data generates reports and visualisations for further analysis.

Figure 1 presents a schematic functional diagram of a measuring system based on machine vision for the study of impulse loads on testing machines.

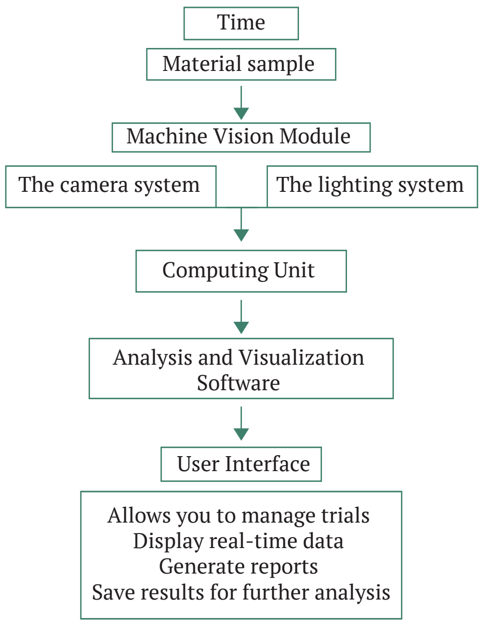

Figure 1. Schematic functional diagram of a measuring system based on machine vision for the study of impulse loads on testing machines

Source: developed by the authors

On the proposed functional diagram, the following structural elements can be distinguished:

1. Test stand. The module integrates with the test stand, where the sample is subjected to a pulse load.

2. Machine vision module:

◆ the camera system captures the deformations of the sample at high speed;

◆ the lighting system provides optimal lighting for high-quality image capture.

3. Computing unit: processes the obtained images, performs analysis and simulation in real time.

4. Analysis and visualization software: conducts automatic analysis and creates three-dimensional models of deformations.

5. User interface: allows you to manage trials, display real-time data, generate reports, and save results for further analysis.

Conclusions

The introduction of innovative technologies in the study of mechanical properties of materials opens up new opportunities for improving the accuracy and information content of tests. The use of machine vision, high-speed cameras and machine learning tools allows you to automate the processes of data collection and analysis, reducing the impact of human error and providing detailed control of deformations in real time. This greatly expands the possibilities of studying complex and composite materials.

The integration of such systems into test equipment contributes to a deeper understanding of the behaviour of materials under dynamic loads, allowing you to predict their strength and reliability in difficult conditions. The results obtained not only improve the quality of experimental research, but also provide practical solutions for industries where high accuracy and efficiency are required. Future research may focus on improving analysis algorithms and integrating even more sensitive data acquisition systems, allowing for an even better understanding of material properties and predicting their behaviour in challenging operational environments.

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Андрій Слабкий

Кандидат технічних наук, доцент
Вінницький національний технічний університет
21021, вул. Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0000-0001-9284-2296

Сергій Котик

Аспірант
Вінницький національний технічний університет
21021, вул. Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0009-0000-9396-7189

Інноваційні технології у дослідженні механічних властивостей матеріалів

Анотація. У статті представлено огляд сучасних інноваційних технологій, що використовуються для дослідження механічних властивостей матеріалів за допомогою універсальних розривних машин. Основну увагу приділено інтеграції технологій машинного зору, алгоритмів машинного навчання та високошвидкісної стереоскопії, які забезпечують нові можливості для аналізу поведінки матеріалів під час статичних і динамічних навантажень. Важливим аспектом дослідження було вдосконалення традиційних методів випробувань шляхом впровадження інноваційних компонентів: високошвидкісних камер, що дозволяють фіксувати деформації матеріалу з мікросекундною точністю; стереоскопічних систем, які створюють тривимірні моделі поведінки матеріалу під навантаженням; а також освітлювальних пристроїв, що забезпечують рівномірне освітлення об'єкта випробувань. Зазначені технології синхронізуються із потужними обчислювальними модулями, здатними проводити аналіз великих обсягів даних у реальному часі. Автори підкреслюють, що інтеграція алгоритмів комп'ютерного зору та машинного навчання дозволяє суттєво зменшити вплив людського фактора на результати досліджень. Автоматизовані системи аналізу здатні точно виявляти та класифікувати дефекти, моделювати типи руйнувань та прогнозувати поведінку матеріалів за різних умов навантаження. Також наведено приклади застосування таких систем у дослідженнях складних композитів, металевих сплавів і новітніх полімерів. Додатково розглянуто інноваційні підходи до створення динамічних навантажень, що дозволяють проводити випробування на ударну міцність та витривалість. У статті показано, як автоматизовані системи управління випробувальними процесами підвищують ефективність досліджень, забезпечуючи більшу точність, повторюваність результатів і пришвидшену обробку даних. Практичне значення описаних розробок полягає в їх широкому застосуванні в галузях, де вивчення механічних властивостей матеріалів є критично важливим, таких як авіабудування, машинобудування, енергетика та будівництво. Високий рівень автоматизації та точності випробувань, забезпечений впровадженням сучасних технологій, дозволяє задавати нові стандарти якості досліджень і створює перспективи для подальшого розвитку матеріалознавства. Таким чином, представлений підхід до вдосконалення універсальних розривних машин сприяє підвищенню точності вимірювань, розширенню функціональних можливостей традиційних випробувальних систем і створенню більш ефективних методів дослідження матеріалів

Ключові слова: універсальні розривні машини, машинний зір, імпульсне навантаження, прогнозування поведінки матеріалів, оптичні системи вимірювання, алгоритми машинного навчання, візуалізація деформацій