Tomasz GIESKO
Institute for Sustainable Technologies – National Research Institute, Radom
Dariusz BOROŃSKI
University of Technology and Life Sciences, Bydgoszcz
Andrzej ZBROWSKI, Piotr CZAJKA
Institute for Sustainable Technologies – National Research Institute, Radom

DETECTION AND MEASUREMENT OF FATIGUE CRACKS IN SOLID ROCKET PROPELLANTS

Key-words

Solid propellants, fatigue crack, crack measurement, machine vision.

Summary

A method and machine vision system capable of automated crack detection and measurement have been developed for fatigue tests on solid rocket propellants under mechanical and thermal stresses. In image analysis and crack detection, the digital image correlation method (DIC) was used. Examples of crack images acquired using the developed system are presented.

Introduction

Solid rocket propellants are the oldest and simplest of all forms of rocket propulsion, dating back to antiquity. The solid-propellant engine is formed as a tube filled with a solid-form mixture of chemicals, which burn at a rapid rate and produce gases, that are ejected from a rocket nozzle. Solid propellants have a high density and can burn very fast. Because of the relative chemical stability and resistance to shock and vibration, they can be manufactured and stored for future use. The main disadvantage of solid propellant engines is that, when ignited, they burn uninterrupted and cannot be turned off until all the propellant is used.

A solid propellant burns along all exposed surfaces. The active surface area of the burning propellant determines the generated thrust. Cracks generated in the structure increase the exposed burning surface area and may lead to an unstable combustion. As a result the propellant burns faster than planned. In situation when there are too many cracks inside, the pressure inside the engine rises dramatically and the rocket propulsion may explode. Very large forces and thermal shock during a rocket launch can generate cracks in solid propellant, that was inspected before and qualified as defect-free.

The resistance of solid rocket propellants to mechanical and thermal stress is the subject of numerous studies and experiments [3, 5]. The mechanical properties including fatigue susceptibility are determined during tensile and compressive tests. In available published literature, only limited information concerning the mechanical properties of solid rocket propellants are presented. Usually, only basic ballistic factors in accordance with the mechanical properties of solid rocket propellants are disclosed. In published papers machine vision methods for on-line monitoring of cracks during fatigue tests of solid propellants are not presented. The video extensometer was employed in fracture toughness testing in [10]. So far, the direct method based on a visual observation with the use of a microscope is very popular [4]. Indirect methods (e.g. ultrasonic, acoustic imaging and radiography) are used to monitor damage initiation and crack evolution [6, 7, 9].

1. Concept of method and measurement system

The presented method of detection and crack monitoring on a surface of solid rocket propellants incorporates a machine vision technique. The system consists of a vision module, a specimen positioning module, loading machine and computer (Fig. 1). Communication between the measurement system and loading machine is ensured by GPIB interface. During loading tests, images of the observed surface are captured by CCD camera and transferred to the computer. Next, the computer performs image processing and analysis. The general concept is very similar to the SMP system developed for automated on-line crack measurement in metallic materials [1].

Basic defined requirements and parameters for the measurement system include the following:

- The detection of cracks in the surface of size from 5x5 mm to 50x50 mm;
- The measurement of crack length with resolution not worse than 50 µm;
- An-line measurement mode;
- Automated tracking of crack propagation;
- The determination of the total length or surface of cracks; and,

– the possibility to perform tests on a loading machine including tests in a thermal chamber.

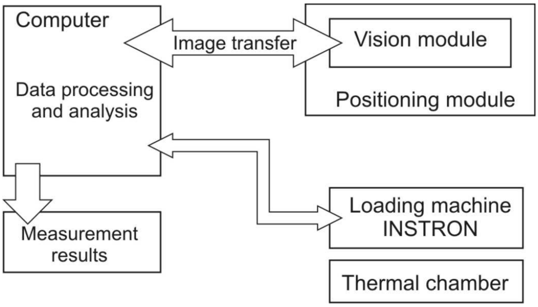


Fig. 1. Structure of the measurement system

The developed method includes the requirements included in standards concerning mechanical properties of explosive materials and discussed in [2]:

– Polish standards: NO-91-A523-3 (Solid rocket propellants – Determination of the resistance in static tensile test) and NO-91-A523-4 (Solid rocket propellants – Determination of the resistance in static compressive test);
– NATO standards: STANAG 4506 (Explosive materials, Physical/mechanical uniaxial tensile test and STANAG 4443 (Explosives, Uniaxial compressive test).

2. Vision module and measurement parameters

Basic parameters of optics: the working distance and angles of view were adjusted to the requirements and limitations concerned with test conditions, the loading machine and thermal chamber. The vision module consists of the CCD monochromatic camera, zoom lens and lighting module. Due to the required measurement resolution, the camera has a sensor of 1388x1024 pixels. High acquisition rate is ensured by IEEE 1394 interface (FireWire). Because the observed area should be changed according to a specimen size, a manually operated zoom lens was applied. The measurement optical resolution depends on a zoom value and has a value of:

– approximately 5 μm for the surface size of 5 mm x5 mm; and,
– approximately 50 μm for the surface size of 50 mm x50 mm.

Illumination is one of the critical factors that affect the image quality and the possibility to find defects on the surface with the highest possible resolution. In optical inspection of non-transparent surfaces, the high contrast of micro-cracks and scratches is ensured by using a dark-field and low angle illumination. Despite that fact the front-light LED illuminator was applied, which offers an very good uniformity of light distribution on the observed surface, critical for digital image correlation method used in the system.

3. Crack detection and measurement method

The method of crack detection is based on the on-line analysis of images acquired one-by-one in the process. Using a searching algorithm, characteristic points recognized as cracks are indicated. On the basis of these points, the direction vector is determined and crack trajectory can be drawn. The procedure is shown in Fig. 2.

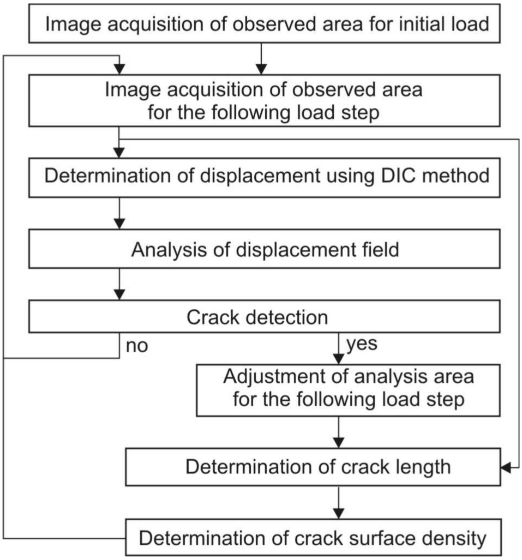


Fig. 2. Procedure of crack detection and measurement

For crack detection on a surface of solid propellant the digital image correlation method (DIC) was applied [6]. Digital image correlation is an optical fully non-contact method to study and measure the deformations on a surface. The correlation algorithm is based on the tracking of the grey value pattern in a small local surface area before and after deformation. In the initial phase, two procedures were worked out that are different in the correlation coefficient used to compare the intensity of images.

These procedures use *Least-square correlation coefficient* and *Cross-correlation coefficient*. In the first procedure the analysis is based on an iterative solution process for finding the minimum of the *Least-square correlation coefficient*. The displacement field in the neighbourhood of a reference point located within the subarea may be determined during the analysis of coefficient C_1 defined as

$$C_1 = \sum_{i=a}^{b} \sum_{j=c}^{d} \left[I_n(x_i, y_j) - I_m(x_i, y_j) \right]^2 \tag{1}$$

where:

$I_n(x_i,y_j)$ – greyscale level of the point in the reference (x_i, y_j), for the phase *n* during deformation process,
$I_m(x_i,y_j)$ – greyscale level of the point in the reference (x_i, y_j), for the phase *m* during deformation process,
(a, b), (c, d) – size of subset along x and y directions.

The second procedure uses the *Cross-correlation coefficient* defined as:

$$C_2 = \frac{\sum_{i=a}^{b}\sum_{j=c}^{d} I_n(x_i,y_j) I_m(x_i,y_j)}{\left[\sum_{i=a}^{b}\sum_{j=c}^{d}\left(I_n(x_i,y_j)\right)^2 \sum_{i=a}^{b}\sum_{j=c}^{d}\left(I_m(x_i,y_j)\right)^2\right]^{0.5}} \tag{2}$$

where used variables are analogous as for Equation (1).

The value of C_2 can vary between 0 and 1. When $C_2=1$, acquired images of neighbourhood of a reference point are identical. When $C_2=0$, these images are completely different.

The flow chart of the measurement procedure with the use of least-square correlation coefficient C_1 or cross-correlation coefficient C_2 is shown in Fig. 3.

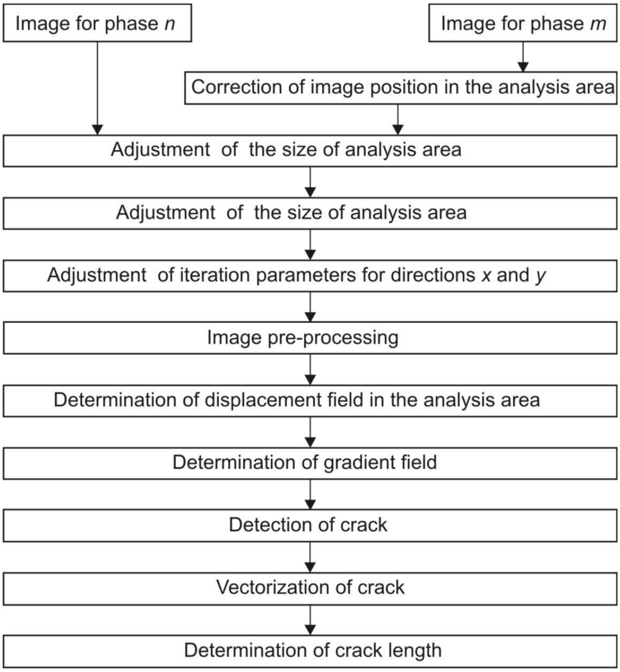


Fig. 3. Flow chart of crack measurement procedure

Both procedures were tested during experiments. Model displacement and gradient fields were determined in experiments with the use of applied procedures and are shown in Fig. 4 and Fig. 5. On the basis of the displacement field, the gradient field is determined and presents information about possible cracks or other local defects. Using inline expansion and vectorisation the crack vectors can be drawn. After comparative tests, the Cross-correlation coefficient was chosen to apply in the method for better accuracy and effectiveness of image analysis.

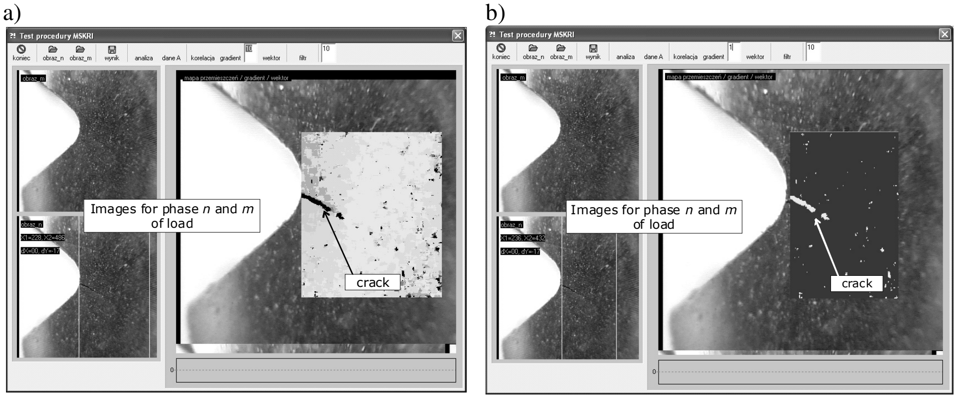


Fig. 4. Displacement field (a) and gradient field (b), determined with the use of *Least-square correlation coefficient*

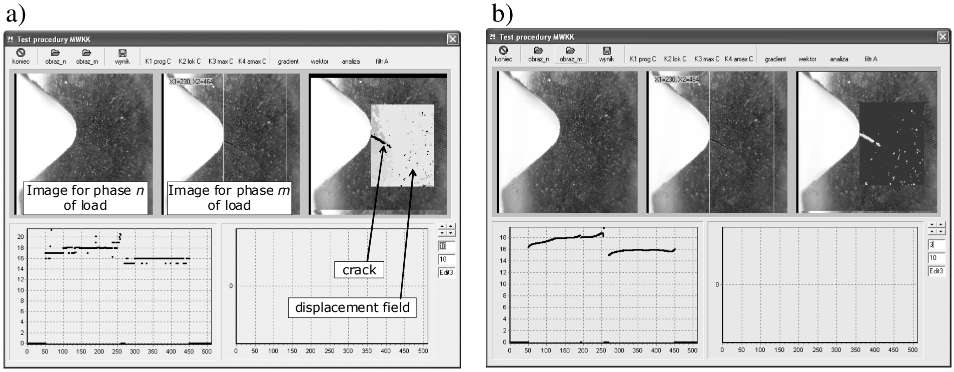


Fig. 5. Displacement field (a) and gradient field (b), determined with the use of Cross-*correlation coefficient*

Algorithms of image analysis, crack detection and measurement were applied in system software. To meet the requirements of the advanced measurement system the model data base was developed that can include measurement data, images and specimen identification parameters.

4. System application and experimental results

The developed measurement system was applied for laboratory tests with the use of a loading machine Instron (Fig. 6). The developed software contains procedures for performing following functions: calibration, diagnostics, loading test, analysis and crack measurement, and data management.

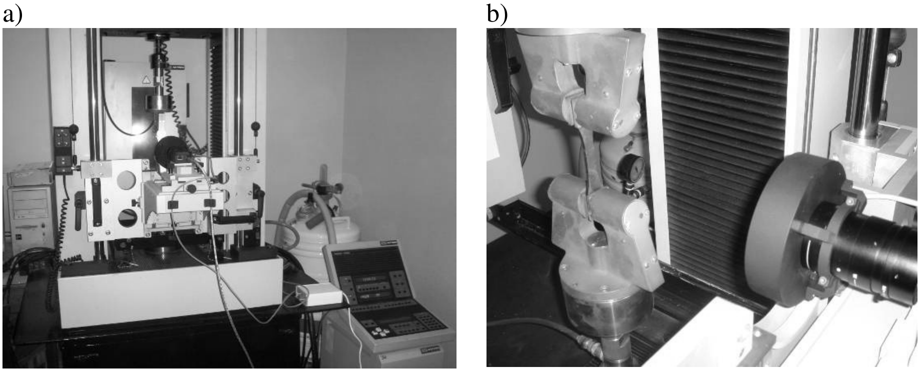
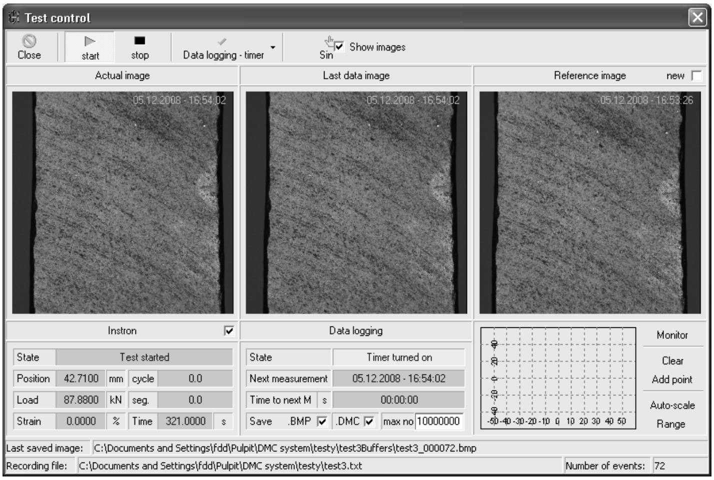


Fig. 6. Measurement system: a) general view, b) specimen of solid propellant in grips under test

Fatigue tests of specimens of solid rocket propellants were carried out under uniaxial monotonic tensile loads in a load-controlled mode. The measurement window (Fig. 7) presents images captured during tests, and also the reference image. To observe the process states the current test parameters are shown. On the basis of images analysis displacement fields (Fig. 8) and crack trajectory (Fig. 9) were determined. The experimental loading curve is shown in Fig. 10.



Instron ☑

State	Test started				
Position	42.7100	mm	cycle	0.0	
Load	87.8800	kN	seg.	0.0	
Strain	0.0000	%	Time	321.0000	s

Data logging

State		Timer turned on
Next measurement		05.12.2008 - 16:54:02
Time to next M	s	00:00:00
Save	.BMP ☑	.DMC ☑ max no 10000000

Last saved image: C:\Documents and Settings\fdd\Pulpit\DMC system\testy\test3Buffers\test3_000072.bmp

Recording file: C:\Documents and Settings\fdd\Pulpit\DMC system\testy\test3.txt

Number of events: 72

Fig. 7. Measurement window

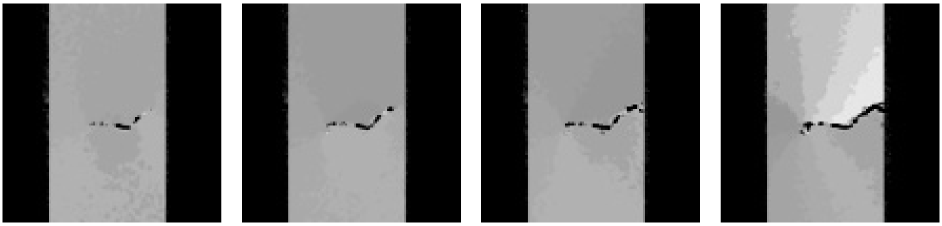


Fig. 8. Selected images of displacement field

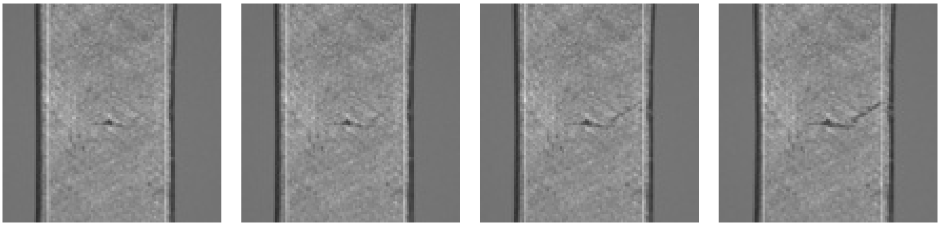
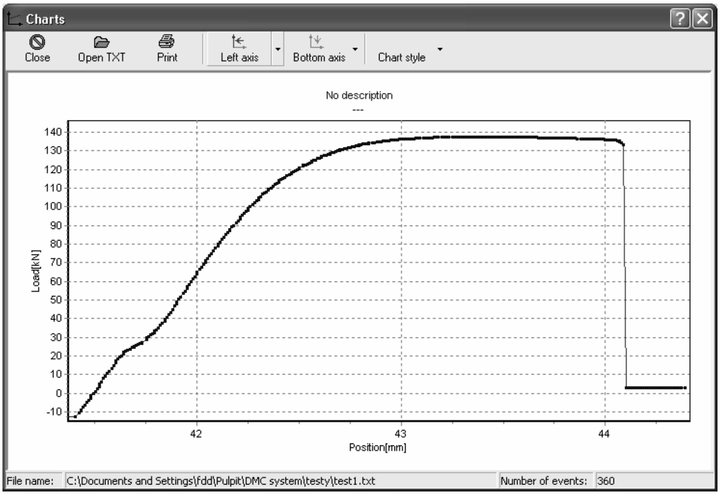


Fig. 9. Determined crack trajectory in the following images from Fig. 8



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Number of events: 360

Fig. 10. Experimental loading curve (load – vertical axis; displacement – horizontal axis)

As shown in Fig. 10, the drawn curve presents the loading process of a specimen from the elastic deformation phase to the crack.

5. Conclusions

A noncontact optical method was used to detect and measure cracks in solid rocket propellants during fatigue tests. The method incorporates a digital image correlation used for full field strain measurements and the detection of deformation fields.

Optical measurement resolution is limited by the camera resolution in correlation to the observed area size. Accuracy of the applied DIC method depends on the uniformity of light distribution, the quality of the speckle pattern and good image contrast. To avoid the decorrelation effect caused by the higher variability of surface images the analysis should be carried out with high-speed acquisition. The measurement systems based on DIC methods very often require non-standard computers capable of high-speed data processing and analysing.

Feasibility of using the developed measurement system was successfully verified during laboratory experiments. The system can be used for tests of solid rocket propellants that included the determination of static and cyclic mechanical (fatigue) properties under controlled mechanical and thermal stress. It is possible to use the developed system for tests of other materials similar to solid propellants.

The scientific work is financed by the Ministry of Science and Higher Education and carried out within The Multi-Year Programme "Development of innovativeness systems of manufacturing and maintenance 2004–2008".

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Reviewer:
Paweł PYRZANOWSKI

Wykrywanie i pomiary pęknięć zmęczeniowych w stałych paliwach rakietowych

Słowa kluczowe

Stałe paliwa rakietowe, pęknięcie zmęczeniowe, pomiar pęknięcia, maszynowe widzenie.

Streszczenie

W artykule zaprezentowano metodę i system maszynowego widzenia do automatycznej detekcji i pomiarów pęknięcia w stałych paliwach rakietowych poddawanych obciążeniom mechanicznym i termicznym w trakcie badań zmęczeniowych. W opracowanym systemie do analizy obrazów i wykrywania pęknięć zastosowano metodę cyfrowej korelacji obrazów (DIC). Przedstawiono przykładowe obrazy pęknięć zarejestrowane za pomocą opracowanego systemu.