Multilayer Thin Film Sensors for Damage Diagnostics

(short summary on the results of the scientific research)

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EXECUTIVE SUMMARY

The new innovative approach to damage diagnostics within the production and maintenance/servicing procedures in industry is proposed. It is based on the real-time multiscale monitoring of the smart-designed multilayer thin film sensors (MTFS) of fatigue damage with the standard electrical input/output interfaces which can be connected to the embedded and on-board computers.

MTFS is a thick multilayer (~ 0.2-0.4 mm) structure which could be rigidly attached (glued, welded or sputtered) to the underlying aircraft component with complex geometry. The first lowest layer is a highly sensitive soft single crystalline film that undergoes the permanent evolution due to external deformation influence from the underlying aircraft component. The second layer is assumed to be made from different polymers with physical characteristics (electrical resistance, inductance, capacity, etc.) which are highly sensitive to form changes. The third layer is a multiscale grid of contacts for data acquisition that creates the standard interface for plugging to the embedded or onboard computer systems of aircraft.

MTFSs supply information about the actual unpredictable deformation damage, actual fatigue life, strain localization places, damage spreading, etc. MTFS is suitable for diagnostics of the constructive elements which failure could lead to catastrophe in the following engineering fields:
(i) in automotive industry with possibility to find optimal solution of 2 antagonistic problems: to provide the operation safety and high economic efficiency;
(ii) in high-pressure reservoir and reactor materials, joints, welds to extend the integrity and lifetime of installed pipelines and their various components;
(iii) in bridge building, civil engineering, etc., especially under the real random spectra of loading conditions (overloads, transverse locations of vehicles, etc).

The expected benefits of MTFS could be summarized as followed:
- to reduce frequency of inspection periods and engineering constructions and vehicles downtime,
- to provide real-time data on structural condition of critical engineering elements therefore giving greater safety assurance,
- to enable further reduction of conservatism in design because of ‘real-time’ safety net,
- to offer new design approaches for weight and maintenance optimization.

INTRODUCTION

To the moment the desire to decrease a weight of constructions without detriment to strength is a very hard challenge and interesting task for specialists in engineering. As a result, the problem of fatigue and other deformation damages became quite important and diagnostic methods were very intensively developed. We propose the innovative approach for online instant estimation of the resource exhaustion level for engineering elements that can lead to their unstable or uncontrollable behavior up to destruction.

METHODOLOGY

We propose to use the new online synergetic technique for estimation of fatigue damage and prediction of resource exhaustion level of the components made of aluminum alloys in engineering systems. For this purpose we analyzed the surface pattern of plastically deformed aluminum pure single crystal foil («smart» sensor, i.e. the first lowest layer of the MTFS) rigidly attached to aluminum alloy specimen under fatigue. It is assumed that this surface pattern is caused by plastic deformation of the foil under influence of strains in underlying aluminum alloy specimen.

Firstly, by this way one could construct the correspondence between the strain localization field in underlying specimen and surface relief of the foil attached.

Secondly, on this basis one can obtain the indirect gauge for calibration of fatigue history of underlying specimen and estimation of its fatigue damage and level of resource exhaustion level.

To monitor fatigue damage and resource exhaustion level in engineering constructions we analyzed «smart» sensor (i.e. the first lowest layer of the MTFS) by following stages:

- preparation of smart sensors and their binding to specimens (Fig. 1, 2);
- online sensor surface scanning,
- capturing information about surface evolution on many scales,
- processing this information by qualitative and quantitative techniques.

Fig. 1. The shape of sample and typical orientation of the «smart» sensor.

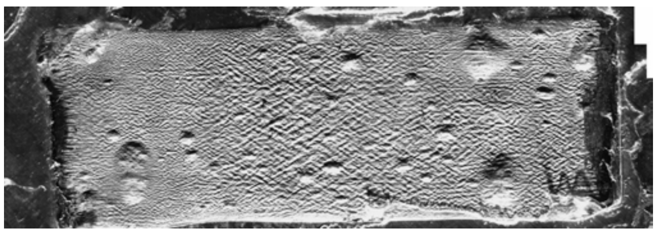


Fig. 2. The increased view on sensor.

EXPERIMENTAL TECHNIQUES AND SCIENTIFIC OUTPUTS

1. *<u>Qualitative</u> Technique* consists in elaborating the classification of structural primitives which appearance and evolution can be observed due to optical light microscopy:

a) preparation of sensors and their binding to specimens (see Fig. 1,2);
b) mechanical tests of specimens;
c) image acquisition, conversion and storing.
d) data mining in the expert system,
e) qualitative image analysis and classification.

<u>*Scientific Output:*</u>

FEATURE CLASSIFICATION — we propose the following classification scheme for the main ***stable*** qualitative signs of sensor surface evolution (Fig. 3).

- High-contrast horizontal flat band-like pattern (*'flat bands'*).
- Low-contrast shadow pattern created by small ellipsoidal horizontal extrusions (*'hills'*).
- Appearance and gradual growth of big solitary nearly equiaxial extrusions (*'blisters'*).
- Appearance of merging and coalescing 'hills' with creation of the larger hills (*'ridges'*) inclined to the tension axis (angles are nearly equal to ±34–38°).
- Creation of the whole net of 'ridges' — 'highlands'.

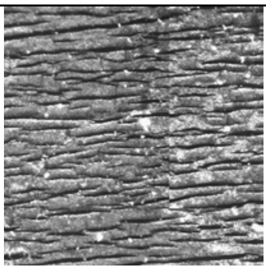
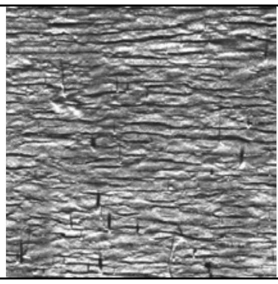
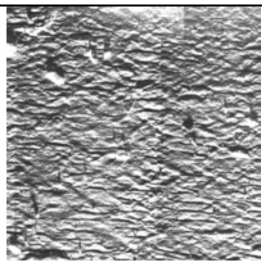
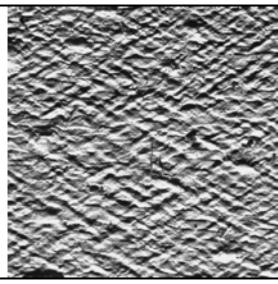
			
a) flat bands 56 000 cycles	b) hills 96 000 cycles	c) ridges 270 000 cycles	d) highlands 970 000 cycles

Fig. 3. Typical stable surface features observed for all stress amplitudes from 146 up to 250 MPa (these snapshots were obtained for 146 MPa).

IMAGE DATA BASE — On the basis of these elementary structural notions we created database of standard patterns, correspondent numbers of cycles and stresses, form-factors of specimens and sensors.

PRE-EMPTIVE TENDENCY OF SURFACE EVOLUTION — After careful image data processing we derived the persistent pre-emptive tendency (Fig. 4) for initiation ranges of surface features along with the increase of the number of cycles for different stress levels.

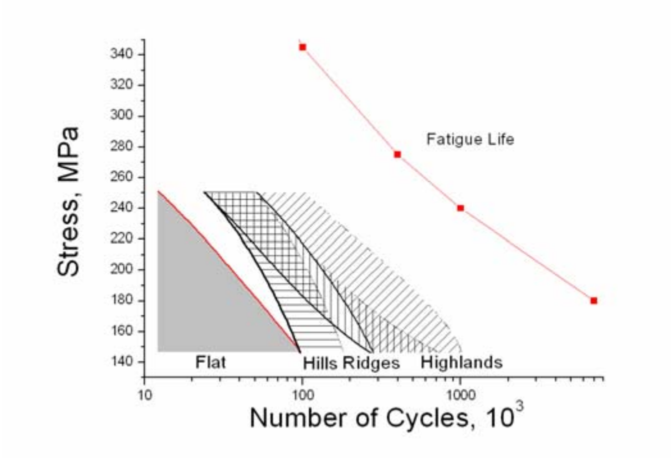
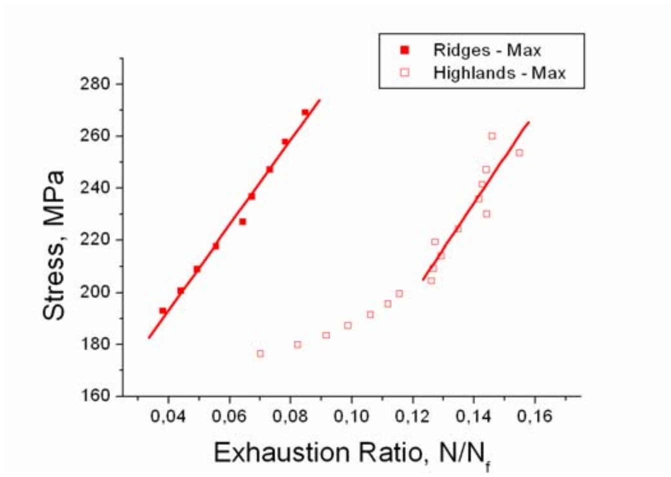


Fig. 4. The persistent consequence of initiation ranges of surface features (see Fig. 3).

STRICT PREDICTION OF THE FATIGUE RESOURCE EXHAUSTION LEVEL — We rescaled the curves that indicate the initiation ranges of some surface features (ridges and highlands) by fatigue life curve. As a result we obtained the exhaustion ratio N/N_f, where N is the number of cycles when the feature (ridges or highlands) appears and N_f is the fatigue life.

Two fitting lines in Fig. 5 show the correspondence between the resource exhaustion level for the certain stress.



c)

Fig. 5. Exhaustion ratio N/N_f , where N is the number of cycles when the feature (ridges or highlands) appears and N_f is the fatigue life.

2. *Quantitative Technique* consists in calculating the multiscaling characteristics and modified with time and change of loading conditions

f) preparation of sensors and their binding to specimens (see Fig. 1,2);
g) mechanical tests of specimens;
h) image acquisition, conversion and storing.
i) creation of panoramic view on sensor; .
j) quantitative image analysis.

We used several projections of the real 3D-surface created by directed and diffuse ring illumination. These projections are only manifested in different coloration (Z-axis). The main idea is supported by theoretical results that projections of self-similar objects inherit the self-similarity of original objects.

Finally, under these conditions we considered two types of the processed patterns:
— irregular coloration pattern in 3D-embedding space, i.e. the gray scale map with the spatial X-axis, the spatial Y-axis, and coloration Z-axis;
— irregular coloration pattern in 2D-embedding space, i.e. the gray scale map with the spatial X-axis and coloration Z-axis.

The core formula that was used for calculation of information fractal dimension (D) is as follows:

$$D = \lim_{e \to 0} \left(\log[I(e)] / \log[1/e] \right),$$

where $I(e)$ is the average surprise in learning learning which e-cell contain a component of the complex object.

We preferred to use information dimension because it gives the richest and most useful information. We carried out some tests on the objects with well-known fractal dimension and information dimension was the most precise method among other box-counting methods. The idea of calculation was proposed by B.B.Mandelbrot, D.E.Passoja, and Paullay, A. J. The core formula was invented by Francis C. Moon and the best optimization method was published in Internet by John Sarraille and Peter DiFalco (1997). On this basis we developed the code and used it for the further calculations.

Scientific Output:

EVOLUTION OF INFORMATION DIMENSION — We found that these multiscaling characteristics change with time and loading conditions (Fig. 6).

MAXIMUM OF INFORMATION DIMENSION — The shape of dependence of information dimension vs. the number of cycles has maximum, and ***shift of maximum*** can be caused by ***increase of stress*** amplitude (Fig. 6).

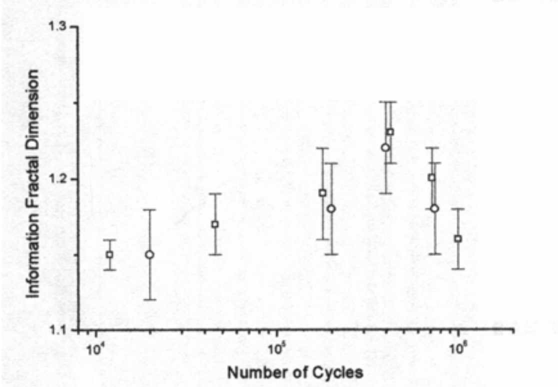
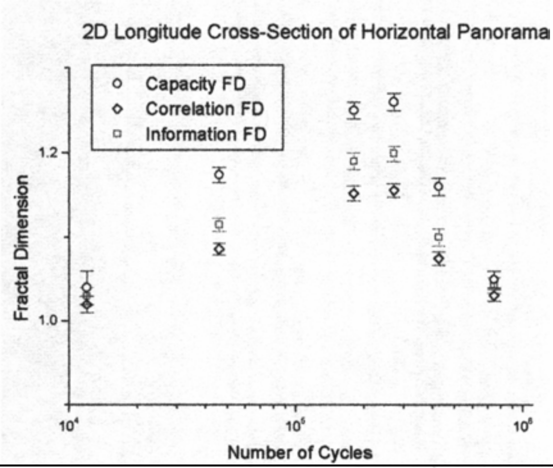
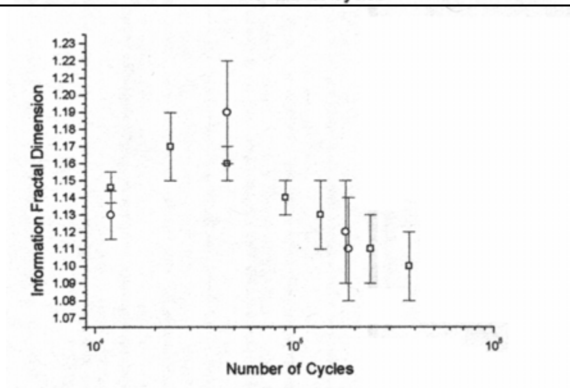
	146 MPa
	175 MPa
	193.2 MPa

Fig. 6. Shift of maximum of information dimension

ISOLINES OF SPATIAL DISTRIBUTION — We found that quantitative analysis based on the calculation of the information dimension averaged by sensor area does not have much sense for sensors near ***strain localization places***. In this case we propose improvement, which is based on calculation of *equidimensional maps* (Fig. 7). In this case we can not only find strain localization places, but also envisage its dynamics. It should be noted that large sensors, which can fully cover the possible place of stress localization, are necessary for this purpose.

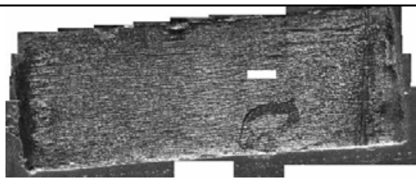
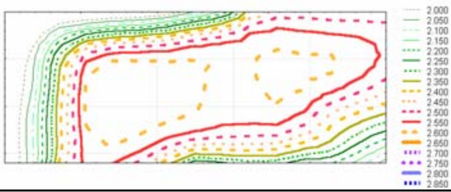
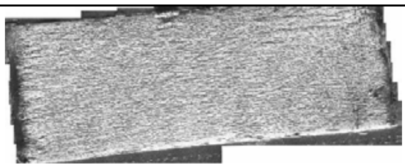
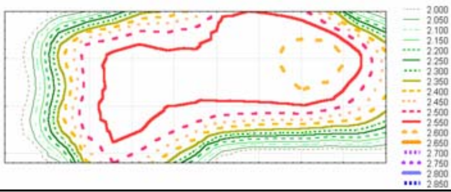
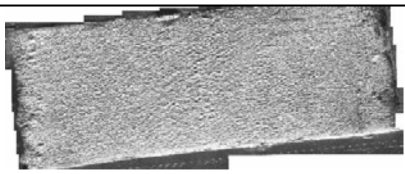
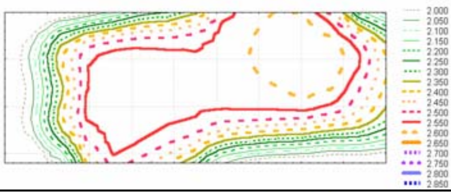
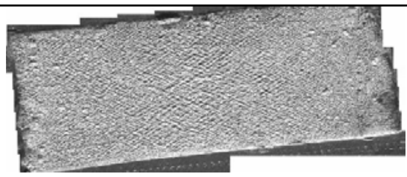
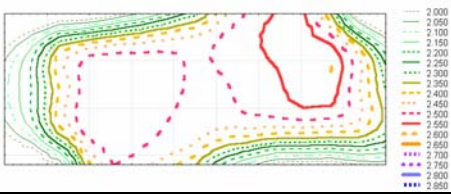
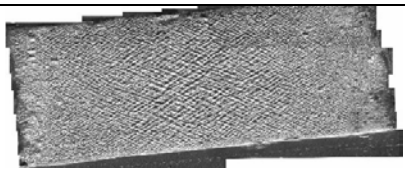
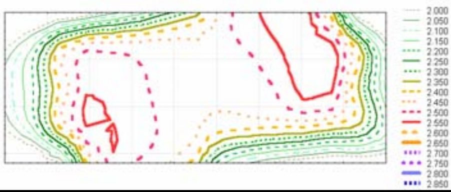
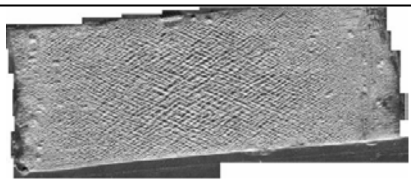
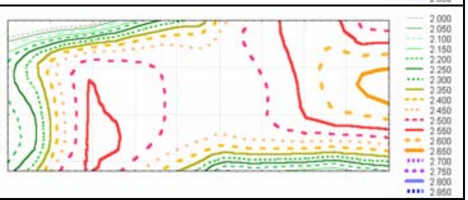
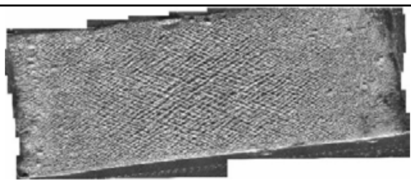
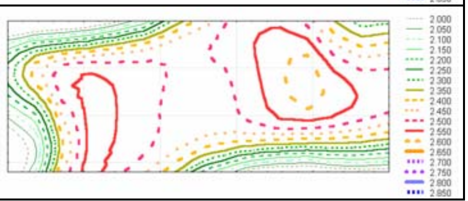
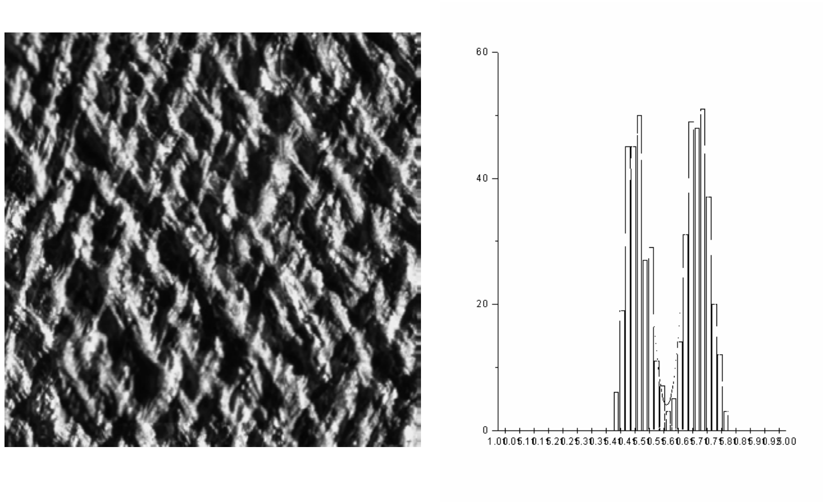
Number of cycles	Panorama	Contour Plot
6,000		
25,000		
50,000		
100,000		
200,000		
400,000		
664,000		

Fig. 7. Evolution of sensor surface visualized by solitary snapshots, panoramas, and contour plots of information dimension (stress amplitude 232 MPa)

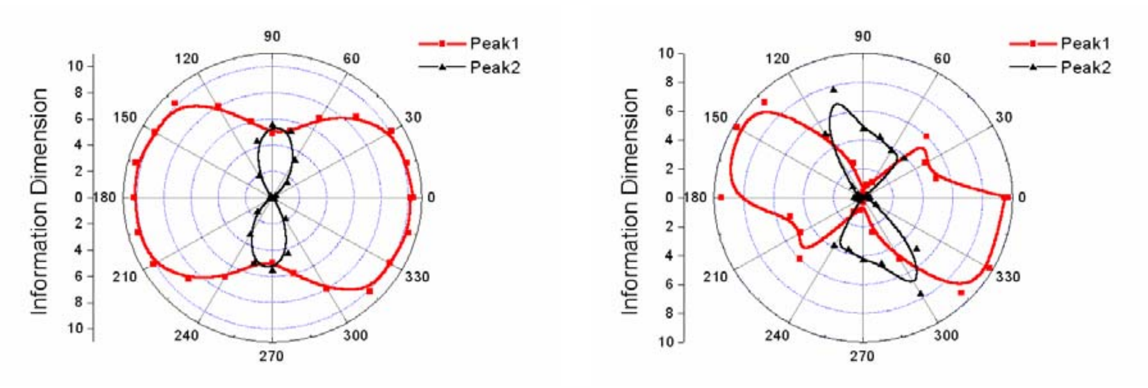
DEPLETION OF INFORMATION DIMENSION — We have found abrupt ***appearance of two*** values of information dimension (where the second value has much larger value than the initial one). Moreover, ***shift of depletion point*** can be caused by ***increase of stress*** amplitude.



a) b)

Fig. 8. Typical region of investigation (a) (512x512 pixels) and histogram of two peaks of information dimensions (b) measured in 2D embedding space (512 longitude cross-sections of central part of ROI).

ORIENTATIONAL DEPENDENCE OF MAXIMUMS — Analysis of polar plots (Fig. 9) for angular dependence of information dimension allows us to bring to light not only anisotropic features of sensor surface, but also catch increase of angular distortions and asymmetry of polar dimensional plots caused by persistent strain localisation.



a) low strain area

b) high strain area with a strain localization

Fig. 9. Polar representation of angular dependence of 2 peaks information dimension measured in 2D embedding space (512 longitude cross-sections of central part of ROI).

CURRENT WORK AND FUTURE PROSPECTS

Non-optical methods of information capture are developed and tested now on the basis of "Smart" Nanoscale Electro-Mechanical Actuator (SNEMA) with electrical and magnetic responses. It is based on the deposition of the several specially prepared sub-nanoscale layers of conductor and insulator, which in contrary to the standard resistive stress sensors are sensitive to accumulated (but not instant!) mechanical damage.

The approach is based on the real-time multiscale monitoring of the smart-designed multilayer thin film sensors (MTFSs) of fatigue damage with the standard electrical input/output interfaces which can be connected to the embedded and on-board computers. MTFS is a thick multilayer (~0.2-0.4 mm) structure which could be rigidly attached (glued, welded or sputtered) to the underlying component with complex geometry. The first lowest layer is a highly sensitive soft Al single-crystalline film (see above) that undergoes the permanent evolution due to external deformation influence from the underlying component. The second layer is made from different conducting and semiconducting polymer matrix composites (PMCs) with electrical characteristics (resistance, inductance, capacity, etc.) which are highly sensitive to shape changes. The third layer is a terminal, i.e. a multiscale grid of contacts for data acquisition that creates the standard interface for plugging to the embedded or onboard computer systems.

The Secure Technical Electronic Passport (STEP) is developing now on the basis of the standard cheap smart cards (Schlumberger e-gate USB smart cards are tested now) for secure saving the information about actual technical state and preventive routine maintenance of the engineering constructions and automotive vehicles.

The standard diagnostic link connector (DLC) in the modern OBDII compliant automotive vehicles is assumed to be used along with the "Smart" Nanoscale ElectroMechanical Actuator (SNEMA) and Secure Technical Electronic Passport (STEP) for (i) monitoring the current accumulated damage of the vehicle (in-card data database), (ii) unplugging the e-gate smart card and analyzing the ways for tuning the vehicle at home, maintenance site, research facilities (Fig. 10).

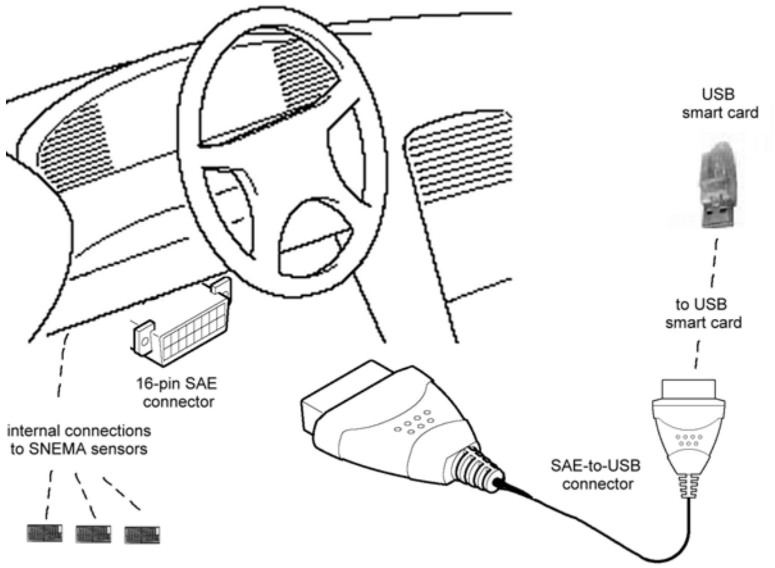


Fig. 10. Standard diagnostic link connector (DLC) in the modern OBDII compliant automotive vehicles is assumed to be used along with the "Smart" Nanoscale Electro-Mechanical Actuator.

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