GAS ADSORPTION INDICATOR METHOD: AN INNOVATIVE EXPERIMENTAL APPROACH FOR NDT LABORATORY INSTRUCTION OF ENGINEERING STUDENTS.

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ABSTRACT

Non Destructive Testing (NDT) is a technology of significant importance for determining the integrity of engineering materials in a myriad of applications. NDT has become inherent to virtually every process in industry where the condition of parts and assemblies need to be evaluated in order to determine their usefulness and serviceability. The testing of materials plays a significant role in design and manufacture of engineering equipment and, therefore, it is an essential ingredient of engineering education and training. This paper presents a simple, inexpensive and effective method to convey the underlying science of penetrant techniques (PT) for nondestructive testing (NDT) of metals, ceramics, and composites, and the details of an experimental approach that can be easily adopted in educational laboratories to enhance engineering curricula. The proposed procedure is referred to as Gas Adsorption Indicator Method (GAIM). This is a relatively unknown NDT technique in the United States, but it has been used for several years in the former Soviet Union, and more recently in the Russian Federation, in the Aerospace, and Power Generation industries. The educational benefits derived from the inclusion of GAIM approaches in NDT Laboratory instruction are discussed. The underlying phenomena of the GAIM technique are explained, and graphical documentation, procedures and experimental results are presented in order to substantiate the suitability of GAIM as an educational tool in laboratory instruction of engineering students in disciplines such as, Mechanical, Chemical, Aerospace, and Nuclear.

INTRODUCTION

Non Destructive Testing (NDT) is defined as the examination of objects using techniques that do not affect their future usefulness [7,8]. There are several techniques that fit this definition. The following are some examples of these techniques: ultrasound, eddy current, thermography, magnetic particle, and liquid penetrant.

Non Destructive Testing (NDT) is of significant importance for determining the integrity of engineering materials in a myriad of applications. As such, the use of Non Destructive Testing can be traced to ancient times. Early blacksmiths and bell-makers, for instance, are reported using "sonic" or "visual" techniques to determine the quality of their products. Later in history, other NDT techniques were developed to respond to the needs of industrial advances. For example, the first "thermographic" observations can be traced to the beginning of the 19th Century. During and after the years of the Second World War, NDT experienced unprecedented development. Today, NDT has become inherent to virtually every process in industry where the condition of parts and assemblies need to be evaluated in order to determine their usefulness and serviceability [3].

In effect, the testing of materials plays a significant role in design and manufacture of engineering equipment and, therefore, it is an essential ingredient of engineering education and training.

Frequently, however, the education and training of engineering students in this area is restricted to "destructive" testing, that includes tensile, torsion, fatigue, and impact tests[4]. Substantial educational benefits, however, can be derived from the inclusion of Non Destructive Testing theory and laboratory, in order to provide a broader spectrum in the study of strength and failure of materials, and its implications in design, manufacturing and engineering product development.

Unlike some categories of Destructive and Non Destructive Testing that may require substantial investment of equipment and instrumentation, Penetrant Testing (PT) is a Non Destructive technique that offers ample opportunity to convey the principles of the subject matter with a modest monetary investment[7]. Given the common budgetary constraints of educational institutions, the incorporation of PT for NDT training of engineering students offers a unique opportunity to implement new and/or enhance existing experimental studies and laboratory-oriented curriculum in the field of materials testing.

PENETRANT TESTING (PT)

PT is a nondestructive technique frequently and specifically used to detect *surface discontinuities* of components and parts. This technique has been used for more than one hundred years in the United States. In effect, records of its use can be traced to inspections of locomotive parts and components in the late 19th century. When using this technique, surface defects are revealed by a material (the penetrant) that seeps into and out of the surface discontinuity much like coffee is able to reveal cracks in a ceramic coffee cup (see figure 1).

In its early stages of development, PT was performed using oil diluted with kerosene as the penetrant material. The oil trapped in the discontinuities allowed railroad inspectors to visually test and evaluate the integrity of parts and components with relative ease.

Figure 1. Crack revealed by coffee on the ceramic wall of a coffee cup

PT made significant progress during World War II, particularly, in applications for the aircraft industry. The use of *dye penetrants* was introduced. As a result, the sensitivity of the PT method was improved considerably. At present, specialized penetrants have been developed for specific situations. Attention to safety and the effect on the environment have determined the need to use special chemical formulations that facilitate pre-cleaning, post-testing penetrant removal and proper cleaning of the component parts being tested[6,9,11].

THE GAS ADSORPTION INDICATOR METHOD (GAIM)

Gas Adsorption Indicator Method (GAIM) is a PT technique researched and developed in the former Soviet Union and relatively unknown in the United States [1]. This technique is a rapid, simple and inexpensive category of nondestructive testing that allows the inspection of discontinuities for a large variety of systems, components parts, and materials that are open to the surface, such as, surface cracks, through-cracks, micro porosity, corrosion and other surface anomalies.

GAIM can be considered an innovative refinement of the nondestructive PT technique. In effect, GAIM utilizes a special concentration of a gaseous formulation as the penetrant, and it is highly portable as other standard PT techniques of common use in the United States. However, there are two clear advantages of this method over conventional PT methods, as follows:

a) GAIM requires minimum or no pre-test cleaning, does not contaminate the component parts under testing, and does not require post-testing cleaning, and

b) Permanent records of cracks and other surface discontinuities can be obtained considerably faster (in the order of seconds) than conventional PT methods.

In addition, GAIM is capable of detecting and revealing surface discontinuities in a wide variety of engineering materials including metals, ceramics, and composites, without additional requirements. GAIM is indeed extremely versatile and inexpensive PT technique, and can be used in engineering laboratory education, and several areas of industrial inspection and testing including aerospace, nuclear and conventional power generation, petrochemical plants, automotive and marine manufacture and maintenance.

UNDERLYING PHENOMENA OF *GAIM* PENETRANT TESTING.

GAIM has its roots in the phenomena of *adsorption* and *desorption*. When using this NDT technique, the solid object under test (the adsorbant) is exposed to a gaseous formulation (the adsorbate) for a period of time. This time may vary between 5-15 minutes depending on the surface characteristics of the object, and the composition of the adsorbate. Within this period, molecules of gas are *adsorbed* by the solid and adhere to surface discontinuities, such as, cracks and pores. This phenomenon is also referred to as *physisorption*, and it is attributed to *van der Waals* attraction forces between the gas and the solid molecules at the surface of contact [10]. There is no chemical bonding between molecules. Therefore, the molecules of gas remain intact and can be freed with relative ease (See figure 2).

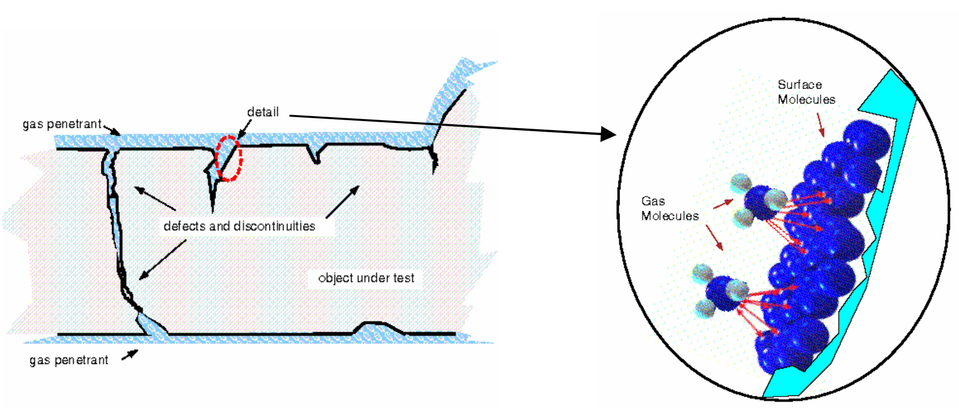


Figure 2. Gas adsorption on surface discontinuities

The *desorption* of gas molecules (gas molecules are freed from the surface) will occur as soon as the exposure of the object to the gas penetrant is interrupted. The rate of change of the coverage due to the adsorbate leaving the surface is proportional to the number of adsorbed species and inversely proportional to the time of evaporation, which is referred to as the *stand time*. This time is an important parameter of the theoretical model that relates the diffussion flux of penetrant and the depth of surface defects.

Molecules leaving the surface discontinuities can be captured by an *indicator* attached to the surface of the object. In the GAIM technique, this indicator consists of special paper material chemically treated to *absorb* the gas molecules, and provide a colored imprint of surface defects [2]. Figure 3 depicts schematically the *desorption* of gas molecules from a crack, and the *absorption* of molecules by the indicator.

The time required by the indicator sheet to reveal imprints of discontinuities is referred to as the *exposure time*. This time may vary between 2 seconds and two or three minutes depending on the depth and opening size of surface discontinuities, the rate of diffusion of gas molecules from the defect, and the sensitivity of the indicator. The indicator paper utilized in the GAIM technique is inexpensive, safe, and readily available in the United States [5].

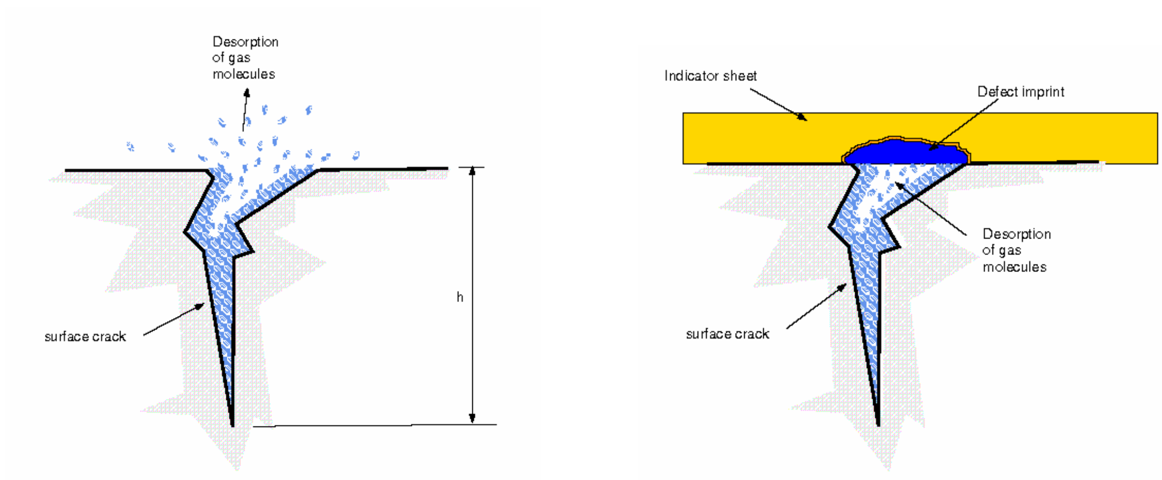
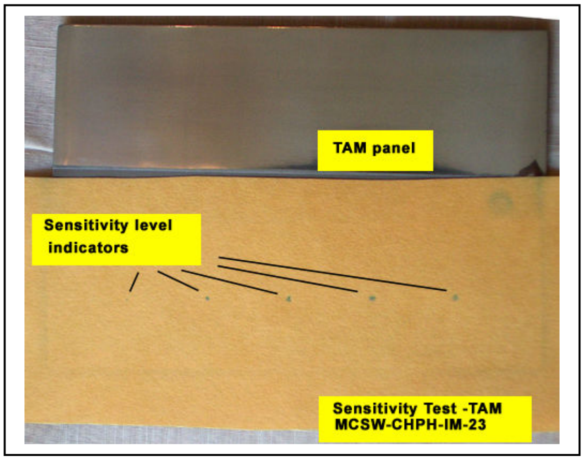


Figure 3. Desorption from surface discontinuity and absorption of gas molecules by GAIM indicator

An example of actual experimental results obtained with this technique is shown in Figure 4. This figure presents results obtained when GAIM is utilized to conduct the system performance check on the standard penetrant system monitor, PSM-5, an American industrial standard also known as "star burst" penetrant testing and monitoring (TAM) panel. Tests like these are a requirement in industrial and military applications in the U.S. in order to satisfy standards established by interested parties. Examples of these standards are: the military standard MIL-STD-6866 and the industrial standard ASTME E 1417. Figure 4 also shows the imprint of crack defect detected on the surface of a turbine blade. A simple visual inspection would be unable to detect this type of defects. Conventional processes available in the USA for this purpose would represent a considerable monetary investment. In contrast, the GAIM technique provides fast and reliable results for a small fraction of conventional costs.



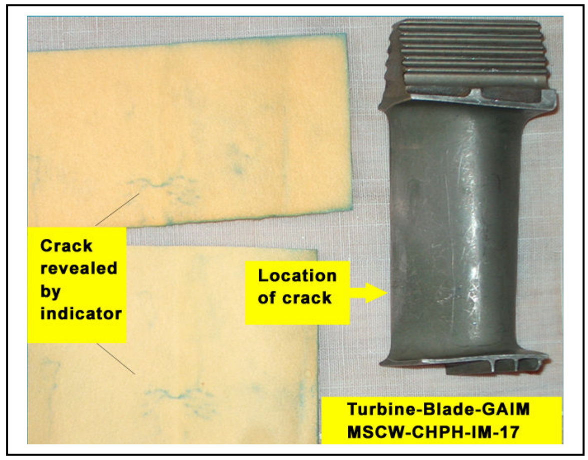


Figure 4. Experimental imprints of known defect standards, and unknown surface cracks.

UNDERLYING THEORY OF *GAIM* DETECTION OF SURFACE DEFECTS.

The *desorption* process of gas penetrant from cracks or micro cracks at the surface of the tested specimens is the key indicator of the presence and characteristics of discontinuities when using the GAIM technique. In fact, the diffusion flux density (number of molecules per unit area per unit time (I)) of gas penetrant flowing out of defects during the *desorption* process can be shown to be dependent on the depth (h) of the defects, and the stand time (t) of the desorbed gas penetrant.

Theoretical studies of desorption kinetics reveal three clearly identifiable stages of gas penetrant desorption. Each desorption stage is characterized by its own trend form as explained below.

The first desorption stage is found to be a rapid decrease in concentration of gas penetrant inside the defect until the condition referred to as the *"mono layer concentration equilibrium"* is reached. The duration of this stage is very short, and can be modeled by the following simple mathematical relationship:

$$t_1 = \frac{h^2}{D}$$

Where:

t_1 = Duration of the first stage of desorption (s)
h = Depth of defect (m)
D = Diffusion coefficient of gas penetrant in air (m^2/s).

The mathematical model of the *diffusion flux density (I)* during this stage is complex and of little practical use.

During the second stage of desorption, on the other hand, the *diffussion flux density (I)* can be described more explicitly in terms of parameters that are known to be inherent to the phenomena of absorption and desorption. These parameters are as follows:

Lifetime (τ) of adsorbed molecule of gas penetrant. The magnitude of this term is evaluated from:

$$\tau = \tau_0 \exp(Q_a / RT)$$

Where:

τ_0 =Atomic oscillation period of adsorbed molecule (~10^{-13} s)
R = Absolute gas constant (R = 8.314 $J.mol^{-1}.K^{-1}$)
T = Temperature (K)
Q_a = Heat of adsorption of penetrant molecules (42-84 $KJ.mol^{-1}$ for the majority of polar gases).

Effective diffusion coefficient (D_{eff}) of the gas penetrant (m^2/s). The magnitude of this coefficient is much smaller than the diffusion coefficient of gas penetrant in air ($D_{eff} << D$). This is because of processes of readsorption of penetrant molecules. Values of D_{eff} can be estimated from:

$$D_{eff} \approx \frac{D}{1 + \sigma k_w \tau}$$

Where:

σ = specific surface factor (m^2/m^3),
k_w = Constant involving the probability of adsorption (f_a), and thermal velocity of the gas penetrant (U), such that: $k_w = f_a U/4$, (m/s).

These parameters are utilized in the evaluation of the *diffussion flux density (I)* occurring during the second stage of desorption as follows:

$$I(t) = \frac{n_{so} D_{eff}}{k_w \tau} \left(\frac{2D_{eff}}{\sigma k_w \tau} t \right)^{-\frac{1}{2}}$$

Where:

I(t) = Diffusion flux density from defect (number of gas penetrant molecules per unit area per unit time, $1/m^2.s$).
n_{so} = Number of molecules of gas adsorbed per unit area. ($1/m^2$)

Notice that the diffusion flux during this stage varies with time but its trend is independent of the depth (h) of the defect. The duration of this stage can be estimated from the equation:

$$t_2 = \frac{h^2 \sigma k_w \tau}{2D_{eff}}$$

It is during the third desorption stage that the *diffusion flux density (I)* provides an indication of the depth (h) of surface defects (cracks, fissures, porosity, etc.). During this stage, the flux density can be modeled by a decaying exponential function of time affected by its dependency on the depth (h) of the discontinuities. This model is as follows:

$$I(t) = \frac{\pi D_{eff} n_{so}}{2hk_w \tau} e^{-\frac{\pi^2 D_{eff}}{4h}(t-t_2)}$$

In order to illustrate the trend of the desorption stages a plot of the *linear* diffusion flux density I_ℓ (molecules per unit length of crack per unit time, 1/s.cm) is presented in figure 5 as a function of the stand time (t). The plot is developed for the second and third stages of desorption and for different crack depths (h). The *linear* diffusion flux density (I_ℓ) is obtained simply by multiplying the diffusion flux density (I) by the crack opening (b). In the case shown below, a crack opening (b) of 1 μ and crack length (ℓ) of 0.01 m were selected for the plot.

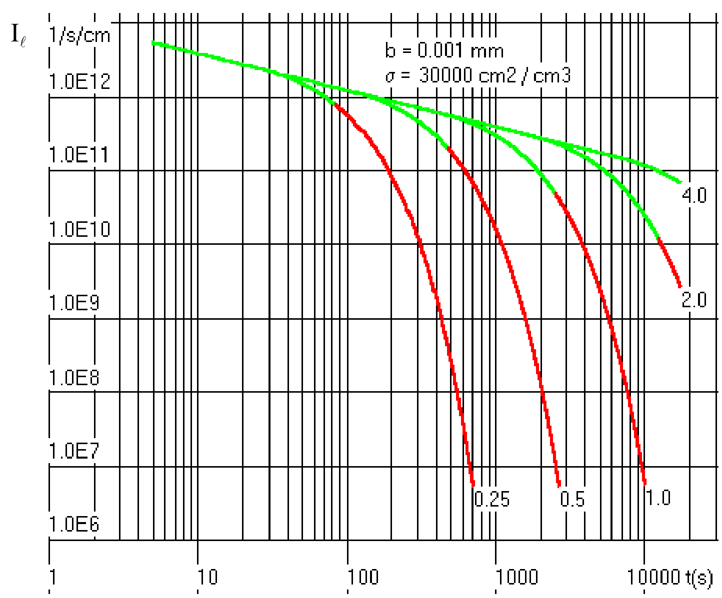


Figure 5. Linear diffusion flux density of gas penetrant as a function of stand time for surface defect depths ranging from 0.25 mm to 4.0 mm.

It is clear from this plot that the deeper the defect, the longer the diffusion flux. In principle, GAIM is able to detect surface defects and provide an indication of the depth of these defects by comparing indicator imprints obtained at different desorption stand times as suggested by the mathematical model. Therefore, once a suitable *exposure time*, is selected, the imprints obtained from the indicator *at* short *stand times* will reveal shallow and deep defects indistinctly. As the stand time elapses, the imprints obtained *at* longer stand times will reveal deeper defects correspondingly. At longer stand times, imprints of shallow defects will vanish since the diffusion flux of gas molecules decreases rapidly as observed in the plot. Consequently, by comparing imprints from successive tests run at different stand times on the specimen, one is able to discern the shallow defects from the deep defects, as well as, provide an indication of the depth of defects as predicted by the theoretical plot. In practice, however, adjustments to the theoretical model are necessary because the flux of gas molecules into the indicator is also a function of its affinity for the gas penetrant. Calibration of the process using known defect standards is required in order to obtain the proper correction constants that can be used in actual applications.

GAIM: AN EDUCATIONAL TOOL TO CONVEY ENGINEERING PRINCIPLES OF SAFETY AND RELIABILITY

Virtually all undergraduate engineering programs aim to enrich and culminate their curricula with capstone projects where students are encouraged to apply their knowledge and skills in one of the most fundamental activities of their future profession, i.e.: The design of artifacts, systems and procedures that aim at satisfying human needs. There are innumerable aspects involved in engineering design. Among them, **safety** and **reliability** are of primordial importance. Because the testing of materials is intimately related to these two factors of the engineering profession, the inclusion of laboratory to impart the principles and the practice of Non Destructive Testing of materials can decisively and substantially enhance engineering curricula and the educational experience of students. The testing of materials plays a significant role in design and manufacture of engineering equipment for safety and reliability and, therefore, they need to be considered as essential ingredients of engineering education and training.

In this educational context, the Russian-developed GAIM technique for non destructive testing of materials proves to be a simple, inexpensive and readily accessible technique to expose and teach engineering students the underlying principles behind safety and reliability of parts and systems. GAIM can be used in virtually any specimen that one may suspect to have surface defects ready to be detected, studied and analyzed not only from the theoretical perspective but, most importantly, from the practical one. Although GAIM is not well known in the U.S., materials and equipment needed for teaching purposes are inexpensive and readily available. Educational tests can be easily performed either in the classroom or in the laboratory as a demonstration, or for in-depth training of engineering students in this important aspect of their education.

CONCLUSION.

Non Destructive Testing of materials has become inherent to virtually every process in industry where the condition of parts and assemblies need to be evaluated in order to determine their usefulness and serviceability. There exists a myriad of applications in engineering where NDT is of significant importance to determine the integrity, safety and reliability of systems of common use in human activity.

Nowhere, for example, have these aspects been considered in more detail and depth than in the design of manned spacecraft, where the testing and re-testing of systems and equipment is a engineering practice of primordial importance to validate cutting-edge technology. Technical experiences (successes and failures) such as those of the aerospace industry and other industries show the importance of materials testing in engineering. Therefore, the exposure of engineering students to the principles and practice of NDT of materials, early in their curricula, can substantially benefit their technical training and educational experience.

The Gas Adsorption Indicator Method (GAIM) is a versatile technique developed in the former Soviet Union and relatively unknown in the United States that offers an innovative, simple and inexpensive educational alternative to convey the underlying science and the practice of Non Destructive Testing (NDT) of materials. NDT of materials using GAIM is accomplished through the use of a penetrant-indicator combination capable of detecting and characterizing surface defects based on the phenomena of adsorption and desorption of a gaseous composition. Understanding these principles, as well as, examining experimental results from the GAIM technique teaches students fundamental bases to determine safety and reliability of engineering parts and systems based on NDT.

GAIM is not only experimentally versatile but also offers opportunity for rigorous study of the underlying phenomena from a theoretical perspective. A simplified discussion of these phenomena and a mathematical model has been presented in this paper in order to provide theoretical context to the technique. Representative observations from theoretical analyses and experimental work are also displayed as a graphical documentation of the technique. GAIM is indeed a mature technique that has been used and proven in the Russian Aerospace and Power industry, and can be easily adapted in theoretical and practical curricula of engineering programs.

Materials and equipment to perform tests and studies of the GAIM technique are readily available at a substantially lower cost than those normally utilized in other penetrant techniques for NDT of materials. The low cost of the GAIM technique added to its excellent safety characteristics and portability make this penetrant technique a very attractive educational tool to impart instruction to engineering students in the area of Non Destructive Testing.

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