RESEARCH REVISTA MEXICANA DE FÍSICA **60** (2014) 8–13 JANUARY-FEBRUARY 2014

Experimental accelerated method for determining fatigue in aluminum 2024 alloy

V. A. Yermishkin[a], P. A. Tamayo Meza[b], I. N. Ovchinnikov[c], J. M. Sandoval Pineda[b],
L. A. Flores Herrera[b] and G. J. Gutiérrez Paredes[b]
[a]*Russian Academy of Sciences, A.A.Baikov, Institute of Metallurgy and Materials Science,*
Lenninsky Prospekt 49, Moscow, Russian Federation
[b]*Instituto Politécnico Nacional, Escuela Superior de Ingeniería Mecánica y Eléctrica,*
U. Azcapotzalco, SEPI; Avenida de las Granjas 682, Col. Santa Catarina, Del. Azcapotzalco, México, D.F.
[c]*Bauman Moscow State Technical University,*
2-nd Baumankaya Street, 5-1 Moscow, Russian Federation
e-mail: ptamayom@ipn.mx; patamayo@prodigy.net.mx

Received 22 July 2013; accepted 9 September 2013

The time of developing a main fatigue crack resulting in a fracture represents only 10 to 30% of the life of a specimen. The method proposed by Paris and Erdorgan analyzes the kinetics of developing a main fatigue crack based on the theoretical framework of fracture mechanics. However, this method cannot be applied to fully analyze the crack incubation process stage, which is a fundamental part of the specimen life time according to this theory. Therefore we propose to solve this problem of fracture mechanics approach by means of a high resolution photometric and phase analysis for structure images (PHASI), evaluating the life of the material by analyzing structural damage of the specimen surface fragments by PHASI, experimentally constructing fatigue curves using 2–4 specimens and photometrically analyzing the specimen surfaces before and after the tests.

Keywords: Fatigue; fracture; resolution photometric; phase analysis.

Al momento de desarrollarse una grieta magistral como resultado de un proceso de fatiga, se representa solo un 10 al 30 % de la vida del espécimen. El método propuesto por Paris y Erdogan analiza la cinética de desarrollo de una grieta causante de la fractura por fatiga, dentro del marco teórico de la mecánica de la fractura. Sin embargo, de acuerdo a esta teoría, este método no es aplicable para analizar completamente la etapa del proceso de incubación de la grieta, que es una parte fundamental del tiempo de vida del espécimen. Por lo tanto, se propone para resolver esta inconsistencia de la mecánica de la fractura, un método fundamentado en el análisis fotométrico de imágenes estructurales (PHASI), evaluando la vida del material por análisis del daño estructural de los fragmentos superficiales del espécimen, y construyendo experimentalmente las curvas de fatiga usando 2 – 4 especímenes, y analizando fotométricamente las superficies del material antes y después de los ensayos de fatiga.

Descriptores: Fatiga; fractura; resolución fotométrica; análisis de fase.

PACS: 62.20.mm; 61.50.Ks; 32.30.Jc; 81.40.Tv

1. Introduction

It is difficult to study fatigue phenomena because they develop within a long time period. Besides, to construct their curves requires a large quantity of specimens. Results of fatigue tests can be analyzed by absolutely opposite principles. The most common method was proposed by Paris and Erdogan [1], in which the kinetics of fatigue – crack development is described in terms of fracture mechanics. Crack growth resulting in a fracture takes only from 10 to 30% of the specimen life. Crack incubation occupies a fundamental part of the specimen life but it is very difficult to analyze on the basis of fracture mechanics. We propose to solve this problem of fracture mechanics approach by means of high resolution photometry and phase analysis of image structures, estimating the life of the material by structural damage to specimen surface fragments, experimentally constructing fatigue curves using 2-4 specimens and photometrically analyzing the specimen surfaces before and after the tests.

2. Problem formulation

Fatigue causes 80-90% of machine component failures and produces fracture in structures. It is extremely complicated to analyze the factors operating in fatigue, and it has been impossible to develop a single method capable of accounting for various aspects of this phenomenon and of dealing with it. Besides, fatigue tests require a lot of time, and a large quantity of specimens is necessary to construct fatigue curves. Fatigue test results have been analyzed using completely opposite concepts and the most common approach is the Paris–Erdogan method. Fracture process due to fatigue finishes with the causing crack fracture development stage which takes from 10 to 30% of the specimen life. However, the Paris–Erdogan method cannot be applied to the initial stage of crack growth, which is a fundamental part of the specimen lifetime.

Palmgren and Miner [2-4] described fatigue damage accumulation in tests. Their analysis permits to account the accumulate damage experienced by the material by gradually varying the load applied during the test. The so-called linear hypothesis of cumulative fatigue damage put forward in the work of Palmgren and Miner can be expressed as:

$$\sum_{i=1}^{n}\left(\frac{n_i}{N_r(\sigma_i)}\right) \geq 1 \qquad (1)$$

Where n_i is the number of cycles applied in the tests to a specimen with an stress of amplitude σ_i; $N_r(\sigma_i)$ is the specimen life for the stress amplitude σ_i. The problem of this approach is related to the fact that the left-hand part of Eq. (1) depends on the load commutation sequence. When the commutation sequence of load σ_i is decreasing, the cumulative damage previous to the specimen fracture is less than one. When the load $\sigma_i$increases and varies between 0.25 and 4, the left-hand part of Eq. (1) is significantly more than one, meaning that the fracture is instant. Both methods estimate material fatigue damage only by test parameters, namely, crack length, number of test cycles for a particular load, and the specimen life for a similar amplitude. Nonstructural parameters are used to study sample surfaces for evaluating the deterioration degree experienced by samples during tests. For this reason, in this work we propose to improve these methods by the following: 1) to quantitatively evaluate fatigue damage using photometric analysis of structure specimen images PHASI; 2) to estimate the time life of the material by analyzing the structure of specimen surface fragments fractured during PHASI, 3) to construct fatigue curves using test specimen data (2–4 specimens) and carrying out photometric analysis of surfaces before and after fatigue tests.

3. Research methodology and the analyzed material

As a result of plastic deformation, surface roughness of tested specimens is sufficiently modified, because when the dislocations scape to the surface they form stair shape geometry. One individual dislocation generates one monoatomic stair step; however, the repetitive action of the dislocation sources, in the crystals volume, conducts to a notable change of surface roughness and this effect is the leading one. The reflected visible light, from the metal surface, can be analyzed as an indicator of the energetic states of the free electrons, because they act directly in the formation of their physical and chemical properties. In this case the estimation of the reflected spectra under the effect of the external energetic influence allows the determination of the changes related to the energetic states of the free electrons [5].

Their reflectivity also changes; the more is the stress amplitude applied cyclically in tests, the more is the reflectivity change. If we calculate the magnitude of the energy captured by the surface of a specimen exposed to fatigue while the specimen reflects an incident light beam, this can provide us with information which may serve as a measure of the damage experience by the material surface. For such purposes, it is possible to use the brightness spectrum of the visible light reflections from the specimen surface before and after its exposure to fatigue by scanning such surface. By means of a computerized processing of spectra and surface images taken in a numeric code using a particular algorithm, it is possible to obtain values of luminous energy absorbed by specimen surface fragments and the distribution of such fragments for a known level of energy absorbed by a surface. To achieve this and in order to obtain stable results in measuring the brightness parameters of the reflected spectra, it is necessary to strictly establish the conditions of taking images, as well as the conditions of photometric measuring of specimens accomplished not during load application but statically after the specimens were fractured during tests or after a particular number of cycles. During measuring procedures, it is important to keep surface illumination conditions constant as well as the temperature and humidity of the environment where brightness spectra of reflection are captured. It is necessary to remark here that the reliable photometric results were obtained by illuminating the surfaces with visible light and also with monochrome light beams of different color. Besides, big surfaces of flat specimens provide more stable reflection conditions compared to curved surfaces. For this reason, the use of big flat specimens guarantees significant advantages in photometric measuring.

Fatigue tests of cantilever specimens allow us to apply a wide range of load with respect to the specimen length which in its turn allows us to establish a tight relation between the stress amplitude and its correspondent characteristic of material fatigue damage. To study the influence of cyclic loads applied to fatigue cantilever specimen structure, both working surfaces are useful, namely, the superior surface and the inferior one, and both surfaces were employed in measurements. We used a structural damage quantitative metric D_s[6-9] defined on the basis of photometric measurement parameters according to the following equation:

$$D_s = \frac{p_i(N) - p_i(0)}{p_i(0)} \qquad (2)$$

where $p_i(N)$ and $p_i(0)$ are average brightness spectra densities of light reflections in a spectrum interval i after N load cycles and at the beginning of a test, respectively.

In many cases, it is possible to take $p_i(0)$ = $p_i(0)$, where p_o is the average spectrum density of the whole initial specimen surface in a spectrum interval i. When damage is caused by dynamic loads, optimal results are obtained using the extreme left-hand spectrum interval, where light absorption is dominant over the processes of light dispersion and reflection, see Fig. 1.

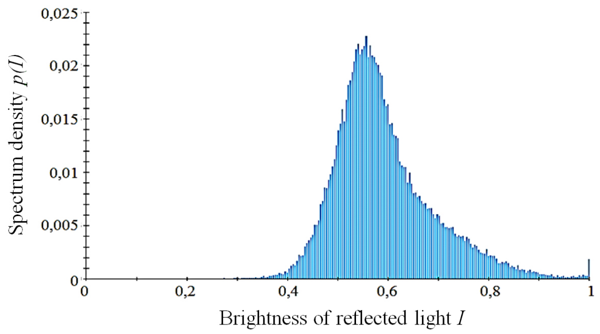

FIGURE 1. Brightness spectrum of the visible light reflections from the surface of one specimen fragment before fatigue testing.

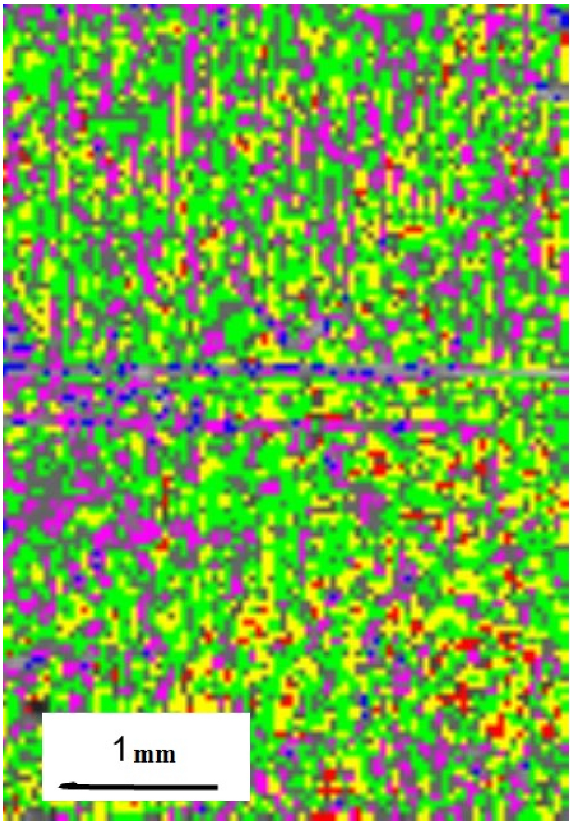

FIGURE 2. Fragments of the specimen surface before fatigue testing.

In Figure 2, surface fragments are observed in the same area shown in Figure 1, from the 2024 aluminum specimen before fatigue testing.

Figure 3 shows the brightness spectrum of light reflections from the same fragment of Figure 1 after it experienced fatigue crack in a test.

Spectral density of intensity of visible light reflected by the fragmented surface (in other words, brightness of light reflected by the specimen fragmented surface) is projected on the axis of ordinates for the graphs of specimen fragment images and is symbolized as $p(I)$, where I is the reflected light intensity, therefore

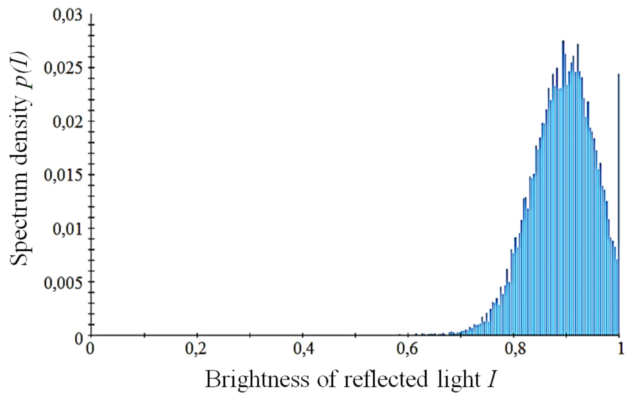

FIGURE 3. Range of reflected light brightness of the fragment of Fig. 1 after the specimen experienced fatigue crack in a test.

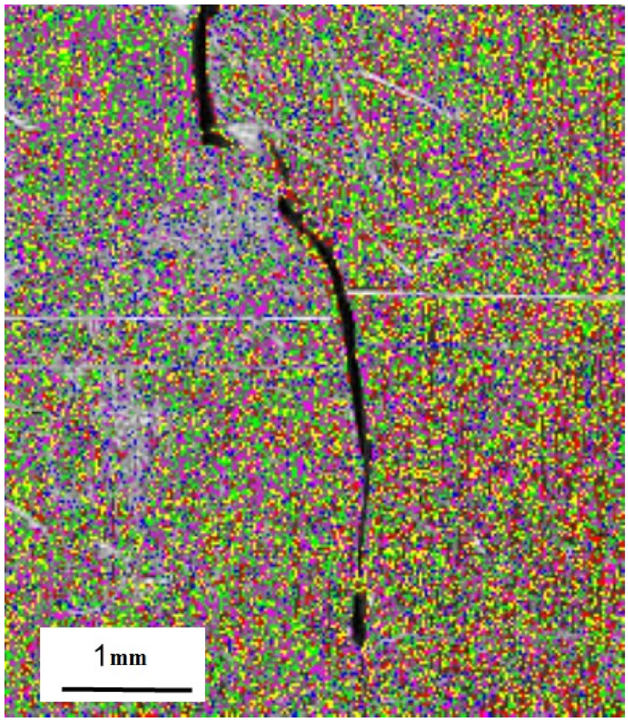

FIGURE 4. Fragments in the specimen surface after fatigue.

$$p(I) = \frac{N(I)}{N(\Sigma)},$$

where $N(I)$ is the number of pixels of reflection brightness I, $N(\Sigma)$ is the total number of pixels of the analyzed fragment; $p(I)$ is dimensionless and oscillates between 0 and 1.

The brightness of visible light reflected by the specimen surface fragments (in other words, the intensity I of visible light reflected by the surface fragments) is projected on the axis of abscissas. Physically, it is the energy of light reflected by a unit of fragment surfaces in a unit of time and is expressed in conventional dimensionless units. Therefore, it is considered that the black completely absorbs the incident light on the surface due to which $I = 0$, and the white light totally reflects the incident light, and its intensity (brightness)

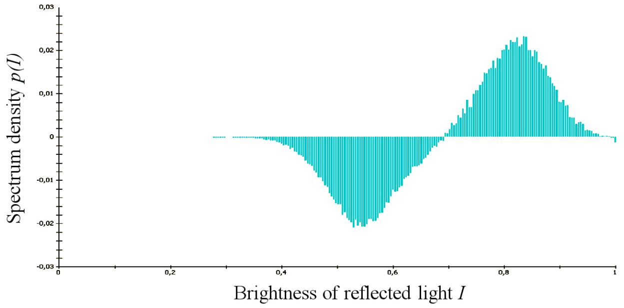

FIGURE 5. Difference in the brightness spectra of the visible light reflections from a fragment's surface (Specimen No. 1).

is $I = 1$. The intensity values corresponding to different shades of gray vary within the interval from 0 to 1.

It can be observed that after fatigue tests, the reflected light spectrum density decreases significantly in the whole spectral interval. The spectral line is noticeably deformed, and the spectrum moves into the direction of less intensity. This occurs because of an increase of the specimen reflective surface, in its turn caused by a rugosity increase due to cyclic load.

Figure 5, shows the difference between the spectra reflected by the same fragment of the specimen's surface before and after fatigue tests.

4. Results and discussion

In this work, to evaluate the structural damage rate, we used a parameter defined by the following equation:

$$D_s = \frac{S_i(0) - S_i(N)}{S_i(0) - S_{\max}(N)} \tag{3}$$

where $S_i(0)$ and $S_i(N)$ are integrals equal to the area below the curve of visible reflected light spectrum of the ith fragment of specimens at the beginning of experiments and after N load cycles, respectively.

As it can be seen, the concept of material structural damage has been modified. It was done with the purpose of taking the full advantage of the information obtained by photometric analysis.

On the other hand, since the integral equal to the area below the light spectrum curve is proportional to the energy reflected by the specimen's surface, this integral serves as the best definition of fatigue damage energy.

All calculations related to the definition of fatigue structural damage rate of the studied specimen's fragments are fulfilled according to the program designed especially for this case.

Estimating structural damage of fragments of both types, namely, the ones with fatigue fracture crack and the ones whose integrity is preserved during tests, we calculated the number of cycles taken place before the undamaged fragments of specimens (N_{ir}) was fractured using the following equation:

$$N_{ir} = \frac{D_{sr}}{D_{ir}} \times N_r \tag{4}$$

where D_{sr} is the fragment's structural damage through fatigue crack which fractured the specimen, D_{ir} is the structural damage of the ith fragment which preserved its integrity, N_r is the number of cycles before the specimen was fractured [10].

Equation 4 is obtained on the basis of a hypothesis that the number of cycles before specimen destruction is directly proportional to the structural damage at the moment of fracture. Photometric information obtained by scanning the surface fragments of specimens destroyed due to fatigue and processed by a computer program forms the operating system PHASI. This photometric information is represented as a matrix of specimens. If such matrix includes more than 20 elements, it is representative enough to characterize the fatigue resistance of the material and these results are not less to those obtained in a standard fatigue test.

This processing was accomplished for the results obtained from fatigue tests on wrought iron 08KP carried out by both methods [3,4]. To construct a fatigue curve, the data matrix $\{N_{ir}\}$ had to be complemented with a matrix of correspondent stress amplitudes $\{\sigma_i\}$ which affected the metal life value and generated the matrix $\{N_{ir}\}$.

Based on a previously developed method to evaluate material's structural damage PHASI [11,12], we developed an accelerated method to construct fatigue curves according to photometric analysis of surface structure of a limited number (2-4) of specimens exposed to cyclic load. A fatigue curve can be considered as the locus of limit states reached by the material during cyclic tests. The material surface reflects in consequence the evolution of patterns of the internal structure which is continuously affected by cyclic tensions.

If a specimen is loaded according to the cantilever bending scheme, then the stress amplitude over the specimen varies continuously, and by structural studies it is possible to detect the part which maintains a stable damage level under low determined test conditions. This corresponds to the fatigue limit of the material under study.

We evaluated a static approximation of load for a cantilever beam. The elastic line equation for a beam of a constant section exposed to a uniformly distributed load q according to [8] can be represented as follows:

$$EJy'' = qlx - \frac{ql^2}{2} - \frac{qx^2}{2} \tag{5}$$

where $ql^2/2$ is the bending moment at the fixed end, ql is the support reaction at the fixed end, E is the elastic modulus, x is the coordinate of the cross section measured from the fixed end, and J is the moment of inertia of the beam cross section. The right-hand side of Eq. 5 describes the distribution of bending moments along the beam. After the first integration, Eq. 5 is converted into the following expression:

$$EJy' = \frac{qlx^2}{2} - \frac{ql^2}{2} \cdot x - \frac{qx^3}{6} + C \tag{6}$$

where C is the first integration constant. Having been integrated again, Eq. (6) takes the following form:

$$EJy = \frac{qlx^3}{6} - \frac{ql^2x^2}{4} - \frac{qx^4}{24} + Cx + D \qquad (7)$$

where D is the second integration constant. The integration constants are determined by the initial conditions which in our case can be expressed as $y'(0) = 0$, y(0) = 0. Substituting the initial conditions in Eqs. (6) and (7), we find out that the constants are equal: C = 0 and D = 0. Therefore, Eq. (7) can be re-formulated as follows:

$$EJy = \frac{qlx^3}{6} - \frac{ql^2x^2}{4} - \frac{qx^4}{24} \qquad (8)$$

The maximum bending moment operating at the fixed end is equal to

$$M_{\max} = \frac{ql^2}{2} \qquad (9)$$

According to Eq. 8, the maximum stresses operating at the beam's fixed end are expressed by the following equation:

$$\sigma_o = \frac{ql^2}{2W} \qquad (10)$$

where W is the section modulus which for a rectangular beam is $W = 2J/h = bh^2$, here h is the height of the beam's cross section and b is its width. Having this expression for the section modulus, Eq. 9 can be re-written as:

$$W = \frac{2J}{h} = \frac{bh^2}{6} \qquad (11)$$

Substituting Eq. 9 in Eq. 7, we obtain:

$$y = \frac{2\sigma_o}{Eh} \cdot \left[\frac{x^3}{3l} - \frac{x^2}{2} - \frac{x^4}{12l^2}\right] \qquad (12)$$

Substituting the boundary condition $y(1) = A$ in Eq. 10, we get the equation to determine the stress σ_0:

$$\sigma_o = \frac{2EhA}{l^2} \qquad (13)$$

For the estimated values of the stress σ_0 and using Eq. 9, we estimate the uniformly distributed load intensity q. This allows us to express the stress distribution along the specimen with the equation:

$$\sigma(x) = \frac{\left[6qlx - 3ql^2 - 3qx^2\right]}{bh^2} \qquad (14)$$

Equation 12 permits to determine the localized stress corresponding to the limit fatigue values estimated according to photometric measurements as previously explained. Applying Eq. 12, we generate a matrix whose components are stress amplitudes which in combination with the data of corresponding durability allow us to construct a fatigue curve for the material under study.

For tests, we used specimens in the form of a blade with dimensions $\sim 1{\times}10{\times}145$ mm^3. Table II presents the parameters and conditions of the tests. The 2024 Aluminum blades were treated to the T8 type temper.

Using Eqs. (5-12) and the data in Table II, we calculated the maximum amplitudes at the fixed ends of the specimens and determined their distribution along each specimen. Some results of these calculations are presented in Table III.

According to photometric measurements of the working surfaces of the analyzed specimens and the data in Table III, we constructed the fatigue curves, see Fig. 6.

It can be observed in Fig. 6 that the constructed curves coincide almost completely. However, the curves obtained by photometric analysis PHASI were constructed using the data of four points, and the standard curve was constructed with the data of 12 points.

TABLE I. Chemical composition of aluminum alloy 2024 (D16 Russian standard).

Cu	Mg	Mn	Al	Fe	Si	Zn	Ti	Ni	Cr	Σ(Fe+Ni)	*Other impurities*	
											Each	Σ
				No more than								
3.8-4.0	1.2-1.8	0.3-0.9	Base	0.5	0.5	0.3	0.1	0.1	0.15	0.5	0.5	0.1

TABLE II. Dimensions and conditions for fatigue tests on aluminum alloy 2024 specimens. L is length , b is width, H stands for height, A is amplitude, *f* is frequency, *t* is time.

No. of specimen	*Dimensions of the specimens*, mm			*Test conditions*		
	L	*B*	*H*	*A*, mm	*f*, Hz	*t*, min
A-1	1.13	9.98	143	8.5	39.6	8742
A-2	1.11	10	143	6	40.8	901
				11	41.1	96
A-3	1.12	10	143	13.5	37.5	20
A-4	1.12	9.95	145	10	37.5	396
A-5	1.13	9.95	145	12	37.5	324

TABLE III. Parameters of fatigue tests on aluminum alloy 2024 (D16) specimens; σ is stress, q is normally distributed load, N is number

No. of specimen	σ in the fixed end, MPa	q,kg/mm	N of cycles
A-1	64.81931	0.013465	2.077×107
A-2	44.94499	0.009027	2.206×106
	82.39914	0.016549	2.367×105
$A-3$	102.0373	0.020864	4.50×104
$A-4$	73.51249	0.014547	8.91×105
$A-5$	89.00262	0.017928	7.29×105

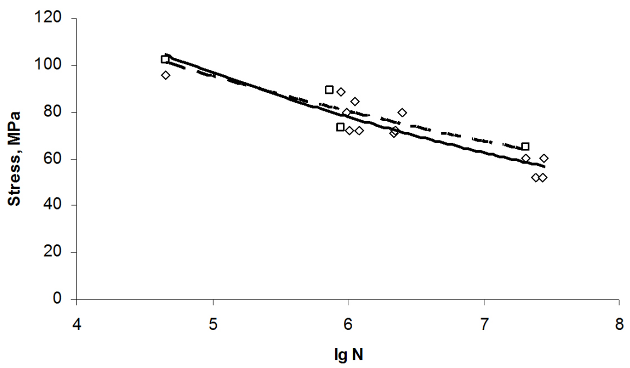

FIGURE 6. Fatigue curves for aluminum alloy 2024 (Obtained from the D16 Russian standard), constructed according to the data of standard tests (□) and by photometric analysis of the specimens' surfaces (◇).

5. Conclusions

In this work, it has been demonstrated that the accumulated damage during fatigue tests affects in a direct manner the surfaces of specimens in terms of their roughness. When stress applied during a long time period increases, the roughness also increases which is revealed in a major or minor capacity of reflecting an incident light beam directed to the specimen's surface. This effect can be directly observed in a displacement of brightness spectra of visible light, providing us important information concerning the processes of damage incubation in the initial stage of tests which is the most time consuming part of fatigue experiments. This permits to sufficiently reduce the fatigue test time and the number of specimens involved. With this in mind, we developed an accelerated testing method based on data obtained from photometric analysis of plane specimen's surfaces in the form of beams exposed to fatigue. The method is also based on the data we obtained by evaluating structural damage of surface fragments. Finally, the whole theoretic and experimental analysis procedure can be applied to any type of materials independently of severity and conditions of tests.

Acknowledgments

El presente trabajo fue posible dentro del marco del proyecto SIP N°20121012, Instituto Politécnico Nacional, Secretaría de Investigación y Posgrado; y proyecto CONACyT, N° 84309. Al personal del Laboratorio 20, Instituto de Metalurgia BAIKOV, Academia de Ciencias de Rusia; a los alumnos del Programa de posgrado del IPN, M.C. Ignacio Bautista Adame, por la realización de los ensayos de simulación y procesamiento de los datos.

1. P.C. Paris, and F. Erdogan, *Journal of Basic Engineering* **85** (1963) 528.
2. M.A. Miner, *J. Appl. Mech.*, **12** (1945) A159.
3. A.Z. Palmgren, *Z. Ver. Deutsch. Ing.* **68** (1924) 339
4. Z. Hashin, A. Roten, *A Cumulative Damage Theory of Fatigue Failure*. Scientific Report N°. 3, TAU-SOE/395-77, Grant AFOSR 76-3014. Dept. of Solid Mechanics, Materials and Structures, School of Engineering, Tel Aviv University, Israel, (1977).
5. Ch. Kittel, *Introduction Physics to Solid State*, 8_{th} Ed. (Wiley, 2005).
6. V.A. Yermishkin, D.P. Murat, V.V. Podbel'skiy, *Informatsionnye Tekhnologii* **11** (2007) 65.
7. V.A Yermishkin, D.P. Murat, V.V. Podbel'skiy, *Avtomatizatsiya i Sovremennye Tekhnologii*, **2** (2008) 11.
8. V.I. Fedosyev, *Resistance of Materials*. In Russian. Moscow: (Bauman Moscow State Technical University, 1999), pp 589.
9. V.A. Yermishkin, Yu. D. Lepeshkin, D.P. Murat, I.N. Ovchinnikov, Method of *Photometric Diagnostics of Materials Structural State according to the Data of the Analysis of the Digital Coded Image of their Surface*. Pat. No. 2387974. Byull Izobr 13, (2010) 14.
10. V.A. Yermishkin, Yu. D. Lepeshkin, D.P. Murat, I.N. Ovchinnikov, *Determinación de la capacidad de trabajo del material a la fatiga mediante el uso del programa PHASI. Conferencia Internacional* " New Horizont en la aviación" M.:ASTEC'07. pp.58-59.
11. I.I. Novikov, V.A. Yermishkin, *Physical Mechanics of Real Materials*. (Ìoscow: Nauka, 2004) pp. 321.
12. V.A. Yermishkin, Yu. D. Lepeshkin, D.P. Murat, and I.N. Ovchinnikov, *Method of Photometric Diagnostics of Materials Structural State according to the Data of the Analysis of the Digital Coded Image of their Surface*. Pat. No. 2387974. Byull Izobr 13 (2010).