A novel method of tracing the inception and progress of fatigue crack-growth in steel

Una metodología novedosa para identificar el origen y evolución del crecimiento de grietas de fatiga en acero

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Abstract

A series of SEM micro-graphs were obtained from the cracked surfaces of samples from two types of AISI-1018 steel after applying fatigue tests at a stress ratio of $R=-1$. Various strain-control levels were used in the range $\pm 0.0008 \leq \epsilon \leq \pm 0.0014$ following a sinusoidal load pattern. From the many micro-graphs obtained, eight types of cracks were determined to be the most typical ones which are found to also be a function of the localization within the cross section of the sample. For each type of micro-crack, a color was assigned depending on geometrical parameters that were approximately measured (diameter for dimples and striation spacing for fatigue striations); this defines the "Color Code" - CC crack equivalent. Using the CC was useful in determining the variation of the fatigue crack front, which was also dependent on the magnitude of the applied strain level. Finally it was discussed how the use of the CC crack equivalent with elements of fracture mechanics are powerful tools to give insights regarding the distribution of the number of applied cycles as damage took place (micro-cracks) during crack front advance.

Keywords: Fractography, steel fatigue, fatigue striations, color code, fatigue initiation, crack advance, dimples

Resumen

Con ayuda de un SEM, se obtuvo una serie de microgramas de las superficies fracturadas de muestras de dos tipos de acero AISI-1018, después de haber aplicado una serie de ensayos de fatiga con relación de esfuerzo $R=-1$. Se usaron varios niveles de carga controlada por deformación unitaria en el rango $\pm 0.0008 \leq \epsilon \leq \pm 0.0014$ siguiendo una carga de tipo sinusoidal. De los muchos microgramas obtenidos, se determinaron ocho tipos de grietas como los más típicos, que estaban en función de la localización dentro de la sección transversal de la muestra. Se asignó un color a cada tipo de microfisura, dependiendo de los parámetros geométricos que se midieron de manera aproximada (diámetro para los hoyitos y espaciado de las estrías de fatiga); lo anterior define la fractura equivalente en el Código de Colores - CC. El uso del CC fue útil en la determinación de la variación del frente de grieta por fatiga, que también depende de la magnitud de la carga aplicada. Finalmente, se discute cómo el uso de la fractura equivalente en el CC, junto con algunos elementos de mecánica de la fractura, pueden ser herramientas útiles para explicar la distribución del número de ciclos aplicados a medida que se produce el daño (microfisuras) durante el avance del frente de grieta por fatiga.

Palabras Clave: Fractografía, fatiga de acero, estrías de fatiga, código de colores, inicio de fatiga, avance de grieta, hoyitos

1. Introduction

According to the ASM (American Society for Metals) Handbook on fractography, the most common fracture modes in which a structural member made of metal can fail are dimple rupture, cleavage, fatigue striations, intergranular decohesion and creep (ASM, 1992). However, structures such as buildings, bridges, pipe lines and vessels don't usually fail due to intergranular decohesion (by chemical agents in the atmosphere) nor creep due to high temperature effects, because service conditions don't reach the minimum temperature of 400 °C required for creep crack growth in low carbon steels (S. Taira, R. Ohtani and T. Kitamura 1979; as cited in ASM, 1992). Dimple rupture is associated to high energy cracking (HEC) mechanisms, and is mainly caused by concentrations of stress, which leads to plastic behavior. Depending on the microstructure, plasticity of the material and high loads, dimples can exhibit a deep conical shape.

In this investigation, a series of fatigue tests on samples of two types of AISI-1018 steel (steel type A and steel type B), were performed using a hydraulic actuator that applied strain controlled loads following a sinusoidal shape in time, with a stress ratio of $R=-1$, at a frequency of 5Hz.

Once the samples reached failure, the fracture surfaces were analyzed using a scanning electron microscope (SEM) device to characterize the various types of cracks at the micro-level, and their position with respect to a specific axis of reference. Also, a statistical analysis of the micro-geometry of the diameter of dimples and the spacing of fatigue striations was carried for both types of steels. The size of the dimples was found to be a function of the applied external stress (strain), and only found at the shear lip area where ductile failure is associated with high-energy cracking. Thus, for the present investigation large diameter dimples, open dimples and small diameter dimples are all assumed to be of the high-energy cracking (HEC) type.

Cleavage fracture is a low-energy cracking fracture (LEC) that moves in low-index crystallographic planes or cleavage planes (Frediel, 1995; as cited in ASM, 1992). In theory, such planes move along grain boundaries; however, in the case of AISI-1018 steel (polycrystalline structure), it forces jumps from one plane of failure to other lower-index planes of failure, forming a series of planes of cracking.

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Fatigue striations are also associated with LEC that moves along crystallographic planes, but these change direction at imperfections, inclusions and at grain boundaries. This type of crack, as it advances, is periodically arrested creating marks that are a visual record of the advance of the crack as the material undergoes continued cycles of load applications. The occurrence of striations has been previously been remarked as a record of the material that slips, and occurs at the crack tip (Hertzberg, 1995), (Pippian et al, 2010). Furthermore, crack striation distances are a function of such variables as magnitude of loading, strength of the material, environmental effects and temperature.

However these categories are a simplistic way of classifying cracks between those that arise from HEC causes and those that are due to lower load demands - LEC. Recently in a study made by Zheng et al., a wheel of a car was tested following a typical cornering fatigue test according to GB/T 5334-2005 standard. The steel used was a commercial-grade hot-rolled steel, and when the cracks were visible, samples were cut and then a SEM was used to identify the geometries of the leading cracks. The crack types were divided into fatigue striations, beach marks, river marks, voids and ratchet marks (Zheng et al., 2014). Said cracks were identified in isolated regions but no throughout analysis was performed on the surface. Crack direction was presented by arrows but due to the magnification factor used (30x), it is hard to quantitatively prove the direction of the crack.

Similarly, as discussed by Tchoufang-Tchuindjang et al., recent data suggest that for high cycle fatigue tests, the failure crack may have inception in the specimen's subsurface. In this same reference, there were identified four cracking categories that were described mainly by their appearance and not by any approximated measurable quantity (Tchoufang-Tchuindjang et al., 2006).

However as presented in the present research, even for samples that failed at higher number of applied cycles of load ($>1,000,000$ cycles), failure finds inception near the surface. Also the cracking types described are based on geometrical parameters that were approximately measured.

2. Experimental methods

Two types of AISI-1018 steel were used to investigate the cracked surfaces that result when samples were subjected to alternating loads using an MTS machine. Samples with a circular cross section of 0.25in (6.35mm) were systematically tested under strain control, with strain ranges varying from $\pm 0.0008 \leq \varepsilon \leq \pm 0.0014$, and a stress ratio $R=-1$ following a sinusoidal strain pattern in time applied at a frequency of 5 Hz.

Steel type A was annealed in an uncontrolled atmosphere where oxygen led to decarburization when it was being cooled down. Steel type B, on the other hand, was normalized using a controlled temperature rate and it was cooled down in an argon (Ar) atmosphere minimizing oxidation. Later, pieces of steel type B were slightly polished to remove any oxidation by-products and to improve the surface finish of the samples.

The test was stopped, and the sample was considered to possess an "infinite fatigue life" whenever the trials reached 10,000,000 cycles. Also, for strain levels

below the endurance limit, no separation was encountered. Hence, for these samples, no fractography was undertaken.

2.1 Cracked surface preparation

Samples after separation were kept in a closed environment away from any humidity or moisture sources; the cracked surface was carefully removed from the specimen, performing a cut 1.25cm away from the zone of fracture. These pieces were labeled as "scope samples". Immediately after this, the scope samples were sonidized for a total time of 280 seconds in a solution of methanol to remove any organic particles or impurities. After this, the samples were dried and carefully placed inside the examination chamber of the microscope.

2.2 Sem pictures and exploration pattern

Once the sample was inside the examination chamber, the SEM recorded low-magnification pictures of the cracked surface; the SEM then was made to follow an exploration pattern, to identify as much information as possible from each cracked surface. For this purpose, the four quadrant coordinates of the sample with respect to the SEM laser beam were determined by manual exploration, and then were used in a computer program to determine the other coordinates needed to define the "exploration pattern", which was the guide for the SEM to obtain the high-magnification pictures. (See Figure 1).

Every time two reference lines intersected one another on top of the cracked area of the section of the sample and at the various quadrants, the SEM took a high-magnification picture which was correlated with the coordinates of reference. The SEM changed magnification scales until a clear micro-cracked characterization was determined. The exploration pattern moved from left to right and from top to bottom starting at location A-45 and finishing in H-56 (Refer to Figure 2), always starting at the shear lip zone, and finishing in the brittle-cracked flat surface.

Figure 1. Grid plan from which micro-photography was obtained. Each line was assigned a coordinate in X and Y direction after obtaining the quadrant's coordinates

Figure 2. General scheme for the color code (CC) by crack type and position within a cracked surface. Crack energy diminishes clockwise

2.3 The color code as a fractography equivalent

From the more than 1,000 micro photographic records obtained in this investigation, it was found that there are mainly eight different types of micro-cracks. The coordinates of the SEM pictures were used to construct a color code (CC) equivalent of the low-magnification representation of the cracked surface. This color code provided a useful tool to understand crack evolution from inception until reaching instability near the shear lip.

The CC corresponded to the eight types of micro-cracks observed, using eight different colors in the RGB (red, green, blue) scale (www.mathworks.com/help/matlab/ref/colormap.html). The Mathworks), varying from red to purple. Each color represents an associated geometric parameter of interest expressed in terms of either diameter for dimples (HEC) or striation spacing for fatigue striations (LEC). Because of the inherent complexity of the phenomena neither cleavage nor transition cracks were geometrically characterized;

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however, they were localized within the cracked surface as complementary information. This CC is a simple and powerful tool to transform the cracking evolution observed in low-magnification pictures of the surface into an easy-to-read diagram that describes the changing nature and geometry of the micro-crack structures occurring during separation and also to show the probable path from inception of the crack until culminating in high-energy cracking at the shear lip. This brings a better approximated representation of the crack evolution, rather than following arrows drawn on top of SEM low-magnification pictures.

In Figure 2, the color correlation is explained showing, clockwise, an ever-decreasing crack energy

formation. That is, dimple fracture which is a high-energy cracking fracture is assigned a red color, the transition from low-energy cracking to high-energy cracking is labeled by a yellow color, and fatigue striations are denoted by "cold" colors (blue, cyan, magenta, purple), depending on the magnitude of the striation spacing.

Although each of the micro-photographs from the various samples do not match exactly the geometry of the type of crack assumed to define the CC, every time a particular micro-crack formation is found, the overall appearance can be discerned in one of the categories described in Figure 3, 4 and 5.

Category	CC	Microstructure example
<p>Big and Open Dimples (Type 1): These are dimples of large size, occur near the edges and are opened by shear tearing. These types of cracks present a deep cone depth of several microns. (Mag: <1000X)</p>	RED R=255 G=0 B=0	20kV X1,500 10mm 12 30 SE1
<p>Small Dimples (Type 2): These are dimples of smaller size, compared to the previous ones. Small dimples do not contain deep cones, and tend to be abundant in number. (Mag: 1000X – 1500X)</p>	ORANGE R=255 G=128 B=0	20kV X1,000 10mm 15 32 SE1
<p>Transition LEC->HEC (Type 3): It is a mix of dimples, very large striations and irregular high energy cracking such as residual open dimples. Due to its complexity, these micro cracks are located in the general cracked surface but were not measured. (Mag: 1000X)</p>	YELLOW R=255 G=255 B=0	20kV X1,000 10mm 14 32 SE1

Figure 3. The Color Code (CC) used herein to describe the cracked surface in terms of the nature of the micro-cracking structures observed with the scanning electron microscope (Type 1, Type 2 and Type 3)

<p>Cleavage (Type 4): This type of crack is unusual but is found in some cases, and shows planes in which the low-energy micro crack moved along the crystallographic planes at the same time as the general crack. (Mag: 1000X)</p>	<p>GREEN R=0 G=255 B=0</p>
<p>Wide-Fatigue Striations (Type 5): These cracks are fatigue cracks due to their geometry, but they have large spacing among the striations when compared to the scale bar of the microscope. These cracks were found close to the areas where there were transition cracks. (Mag: 1000X – 1500X)</p>	<p>CYAN R=0 G=255 B=255</p>
<p>Small-Fatigue Striations (Type 6): Similar to the previous type, but the distance measured between striations requires a higher magnification to be observable. (Mag: 2000X – 2500X)</p>	<p>BLUE R=0 G=0 B=153</p>

Figure 4. The Color Code (CC) used herein to describe the cracked surface in terms of the nature of the micro-cracking structures observed with the scanning electron microscope (Type 4, Type 5 and Type 6)

<p>Micro-Fatigue Striations (Type 7): Similar to the previous ones, but the distance measured between striations requires a higher magnification to be observable. (Mag: 2500X – 5000X)</p>	<p>PINK R=255 G=0 B=255</p>
<p>Nano-Fatigue Striations (Type 8): Smallest visible cracks describing fatigue striations. They sometimes occur in conjunction with nano-oxide particles visible as spheres. These cracks are typically found near the inception of the major crack, and are mainly located close to the surface (Mag: >5000X)</p>	<p>PURPLE R=127 G=0 B=255</p>

Figure 5. The Color Code (CC) used herein to describe the cracked surface in terms of the nature of the micro-cracking structures observed with the scanning electron microscope (Type 7 and Type 8)

3. Results

In Table 1 and Table 2 results of the fatigue tests are presented (Nunez, 2014). For those samples that failed, CC cracked equivalent surfaces were determined. The results show a typical fatigue fracture where an initiation zone can be identified followed by the flat fatigue cracked surface and, near the end of the fatigue life, the appearance of the shear lip. Typically for those samples that failed, low-magnification pictures are useful in the general determination of the fracture type, but they lack more refined information, and what is more important, they don't shown the particular changes that took place during crack advance.

In Figure 6, a sample of AISI-1018 steel type A is represented in two ways, the typical low-magnification representation built from superimposed pictures of various low-magnification records, and a CC equivalent representation of the same surface. When the low-magnification diagram is presented alone, the cracked

surface shows shapes and patterns that are clear differentiators between brittle failure and ductile failure, but it doesn't give any other information regarding the way the general crack changed from initiation until it reached ductile failure. However, if these two diagrams are presented together, it can be inferred that there was an evolution in the flat fatigue area, in which striations of small distances (Purple) evolved into larger striations (Blue), which then turned into very large striation distances (Cyan), followed by a transition between high-energy cracking and low-energy cracking (Yellow), which led to the instability zone of HEC, mainly composed of big dimples (Red), and some small dimples (Orange) towards the edge of the sample.

Figure 7 and 8 present a summary of the results for both types of steel showing the differences in the crack growth as strain was increased, and the micro-geometric data distribution of both dimples (diameter) and striations (spacing) as a function of applied strain. Also, the arrows indicate the general trend of the mean values of the diameter of dimples and of the spacing of striations.

Table 1. Basic results of fatigue tests for AISI-1018 Steel Type A

Test number	CODE	Strain of Test (in/in)- (mm/mm)	No Cycles (N_f)	Hours
1	T-017-12	0.0014	117,471	6.53
2	T-018-12	0.0014	130,710	7.26
3	T-019-12	0.0013	169,888	9.44
4	T-020-12	0.0013	178,088	9.89
5	T-021-12	0.0012	170,173	9.45
6	T-022-12	0.0012	190,541	10.59
7	T-001-13	0.0011	235,122	13.06
8	T-002-13	0.0011	366,756	20.38
9	T-003-13	0.0010	752,245	41.79
10	T-004-13	0.0010	1,884,587	104.7
11	T-005-13	0.0009	>10,000,000	555.0
12	T-006-13	0.0009	3,660,412	203.4
13	T-008-13	0.0008	>10,000,000	556.9

Table 2. Results of fatigue tests for AISI-1018 Steel Type B. (*) This test was done only for confirmation purposes. It was stopped after reaching 1,000,000 cycles

Test number	CODE	Strain of Test (in/in) (mm/mm)	No Cycles	Hours
1	T-010-13	0.0014	136,628	7.58
2	T-011-13	0.0014	150,991	8.38
3	T-012-13	0.0014	185,946	10.30
4	T-013-13	0.0013	131,040	7.28
5	T-014-13	0.0013	210,060	11.67
6	T-015-13	0.0013	158,940	8.83
7	T-016-13	0.0012	310,969	17.27
8	T-017-13	0.0012	329,470	18.30
9	T-018-13	0.0012	575,748	31.98
10	T-019-13	0.0011	485,041	26.93
11	T-020-13	0.0011	897,271	49.83
12	T-021-13	0.0011	605,531	33.63
13	T-022-13	0.0010	>10,000,000	>555
14	T-026-13	0.0010	2,040,167	113.3
15	T-027-13	0.0010	>10,000,000	>555
16	T-028-13	0.0009	>10,000,000	>555
17	T-029-13	0.0020	58,399	3.23
18	T-030-13	0.0020	47,327	2.62
19	T-031-13	0.0020	36,961	2.03
20*	T-032-13	0.0008	>1,000,000	>55

Figure 6. Cracked surface in low-magnification and with the color code (CC) representation for test T-020-12, AISI-1018 steel type A

Crack evolution as a function of strain. Steel Type "A" (AISI-1018 Annealed+Decarbed)

Figure 7. Summary of cracked surfaces in color code (CC) as a function of applied strain, for Steel Type A

Crack evolution as a function of strain. Steel Type "B" (AISI-1018 Annealed+Polished)

Figure 8. Summary of cracked surfaces in color code (CC) as a function of applied strain, for Steel Type B

4. Discussion

Monochromatic low-magnification representations of fatigue cracks can give relative information about the crack, and show the general differences between brittle failure and ductile failure. They can also help to identify macro-changes in the crack depending on such factors as geometrical changes, load distribution, etc.; but again, in these representations mainly two types of cracking nature are discussed (Barsom J., and Rolfe S., 1987). These preliminary investigations can also indicate the initiation zone of the crack, and sometimes depending on the magnification scale that is used by the SEM, information about the general change of the crack tip as the test continues. Detailed information about the evolution of the crack is important, because gives new information about damage that can be later correlated to some other measurable quantities such as magnetic fields (Nunez, 2014), (Erber et al., 2012), temperature (Kucharczyk P., et al., 2012) or visible signals of damage (Muller et al., 2011). One of the findings obtained when using the CC is the changing nature of the micro-crack ahead of the crack tip as a function of applied strain. The higher the applied strain, the larger the fatigue striation spacing near crack initiation, and the smaller the band width in which transition cracking is present. This behavior differentiates between those samples possessing longer fatigue lives with respect to those samples with short fatigue lives (less than 150,000 cycles of load). This can be understood from the

point of view of fracture mechanics. The basic empirical equation that relates the crack growth rate and the mechanical characteristics of the material used, is the Paris law, given by:

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

where C and m are material constants, ΔK is the stress intensity factor defined as a function of the crack length (a) and the alternating applied stress (ΔS): $\Delta K = F(a)\sqrt{\pi a}\Delta S$, and da/dN is the crack growth rate. If, in the case of material instability, the stress intensity factor is made equal to the fracture toughness K_{IC} of the steel used to find the maximum theoretical crack length, then Equation 1 may be expressed in terms of the number of cycles to failure, up to a given crack length, then the expression becomes:

$$N = \int_{a_0}^{a_f} \frac{da}{C[F(a)\sqrt{\pi a}\Delta S]^m} \quad (2)$$

where a_0 is the assumed initial fatigue cracking or original flaw, a_f is the final crack growth of interest, and $F(a)$ is a geometrical function of the crack length that depends on the cross section of the sample (in this case, the diameter). For the present investigation, the circular cross section diameter (D), and the crack length (a), specifying the ratio (a/D) affects the outcome of $F(a)$, in the same way as the ASTM standard compact specimen (Dowling, 2012). A schematic diagram of this behavior is shown in Figure 9.

Figure 9. Schematic of the behavior of $F(a)$ as a function of the ratio a/D

The larger the current crack length, the larger the value of $F(a)$, and thus, the smaller the number of cycles that Equation 2 suggests to reach a particular a_f . This clearly indicates that the largest portion of the specimen's fatigue life is spent in creating the early advance of the crack. For smaller strains, a large fatigue life occurs and is characterized by smaller fatigue striations near the crack initiation zone. In the case of large applied strains, the energy input creates a large micro-plastic demand that is mostly constant along the cross section of the specimen and represented by the large flat areas mainly composed of wide fatigue striations (CC: Cyan). However, as a larger number of cycles are applied to the steel, the a/D factor grows faster and the energy input at a micro-structural level grows larger and is traced as ever-increasing fatigue striation spacing. This is particularly clear for steel type B, which is slightly opposite to that for steel type A; showing a difference of the material behavior possibly due to the different annealing processes used, (Figure 7 and 8).

When examining the diameter of the dimples, a similar behavior is apparent: The larger the applied strain, the larger the mean value of dimple's diameter. This is a consistent observation for both types of steel employed herein regardless of the annealing process.

Although the geometric parameters measured (diameter of dimples and striation spacing) have a small inter-quartile distance with respect to the median (meaning a clustered distribution of magnitudes), the difference between the third quartile (<75% of all data points) and the maximum value is many times larger than the same difference between the first quartile (<25% of all data

points) and the minimum. This suggests a log-normal distribution of data, and that the largest magnitudes of diameter or striation spacing have a very low probability of occurrence, and can be treated as outliers. Such scatter might occur because of the complexity of the cracking itself, and the many sources of variability that at the micro-level can affect the resulting cracked surface.

An application of the CC diagram of the cracked surface used together with the theoretical approach of fracture mechanics expressed as the number of cycles to reach certain crack length, can lead to an understanding of the most probable micro-cracking pattern associated with the number of cycles of load applied.

Fracture mechanics estimates service life, based on statistical results of fracture toughness of materials and the maximum theoretical expected crack length applied at a constant alternating stress. However this doesn't explain the ever changing nature of the crack observed herein. As an example of how the color code can complement the results of fracture mechanics, the color code diagram of T-020-12 for steel type A, (See Figure 6) is displayed along with the cumulative curve of number of cycles needed to reach a certain crack length (c.f. Figure 10).

It may be observed that the least number of cycles of load applied to sample T-020-12 for steel type A, creates the largest high-energy damage in terms of transition cracks (yellow), small dimples (orange) and big/open dimples (red); whereas most of the fatigue life was spent only in creating the initiation (purple) and the first main advance shown by micro-fatigue striations.

Figure 10. Color Code cracked surface for T-020-12, for steel type A and the fracture mechanics curve for the number of cycles to reach a certain crack length

5. Conclusions

The present work presents a novel way of expressing and identifying the various characteristic micro-structural components of a fatigue crack as it moves from the point of origin until it reaches plastic damage at the dimples areas. In spite of great variability at the micro-level, the fatigue crack may be expressed in terms of eight principal types of cracks that were further divided into four main types: high-energy cracking (dimples), transition cracks, cleavage and low-energy cracking (striations). When a color is assigned to each of these types of cracks, a cracking map may be constructed with several micrograms taken at high-magnification scales, thus configuring the surface into a CC cracked equivalent.

For the two types of steels used herein, micro-geometrical characterization in terms of diameter of dimples and fatigue striations distance was determined.

Although the samples of steel were subjected to an alternating stress (strain) regime with constant maximum magnitude, the micro-geometry of the crack changed

greatly from the origin until it reached a band of transition between brittle and ductile failures. This is clear for smaller applied strains, whereas for larger applied strains the striation spacing tends to be more homogeneous in the brittle area of the crack.

The CC diagram of the crack, when compared with the low-magnification micrographs, gives a valuable means to identify the crack origin, and most importantly, the nature of the crack front as it moves from its origin to the shear lip.

Also, joint work between the resultant CC equivalent cracked surface and the theory of fracture mechanics (crack length in terms of number of cycles of load applied), improves the information about crack advance useful to predict the probable types of micro-cracking expected at a certain number of applied cycles.

Finally, a larger number of high-magnification pictures used in the discretization introduced in Figure 6, can improve greatly the results and make a better approach to an understanding of the nature of brittle crack changes during fatigue failure of steel.

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