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A Method for quantitative fatigue fracture surface analysis

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***ABSTRACT :** When fatigue failure occurs, it is important to identify the cause of failure. In terms of fracture mechanics, the ideal method is the one that permits the determination of maximum stress intensity factor, K_{max} and the load ratio R from a fracture analysis. Different techniques have been developed and have met with limited success. Such techniques include evaluation of roughness, fractal analysis or measurement of hardness. The authors have developed a method based on the determination of the areal coverage of significant fractographic features on the fracture surface. In this paper, after a brief presentation of the method, results obtained on a structural steel are highlighted and discussed.*

INTRODUCTION

In the case of fatigue crack propagation in polycrystalline metallic materials, the evolution of fractographic features from near threshold to high growth rates near failure have been qualitatively identified ever since the advent of scanning electron microscopy. Such quantitative analysis permit the identification of crack growth mechanisms. In the case of service failures, it is important to identify causes of failure in terms of fracture mechanics parameters, such as the maximum stress intensity factor, K_{max} and the load ratio R . Different methods have been developed to this end which have met with limited success :

- a) Striation topography [1],
- b) Texture analysis [2] or
- c) Fractal analysis [3]

The above references are given as examples and the list is not complete. One of the reasons for the lack of success for such techniques is that fatigue fracture surfaces reflect the local fracture mechanisms and sometimes it is difficult to identify the mechanisms involved by automated techniques.

The authors have developed a quantitative fractographic analysis technique which permits the estimation of the maximum stress intensity factor, K_{max} , and an "equivalent load ratio" that lead to the fatigue failure [4]. This method is based on the hypothesis that all the grains across the crack front do not undergo the same mechanical loading as that determined by the remote loading. This phenomenon is related to differences in grain orientation across the crack front. This aspect is schematically illustrated in figure 1.

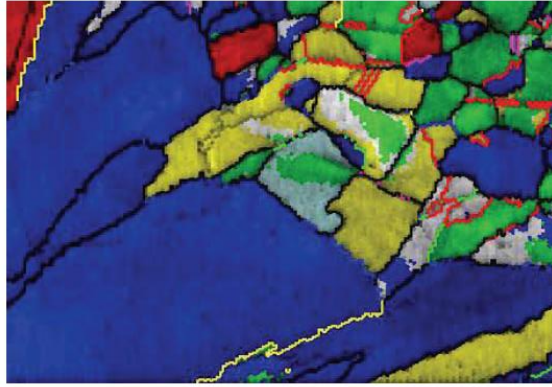


Figure 1 – Grain orientation changes across a surface – grains with same color have similar orientations.

The method was first developed in the case of an aluminum alloy[4]. The salient features of the method are now presented. In aluminum alloys, the fractographic features observed are :

- Crystallographic facets – figure 2a. These facets have been identified to occur on (111) planes, by etch-pitting techniques [5]. When such crack propagation occurs, the crack path can be quite tortuous – figure 2b.
- Pseudo-cleavage facets – Figure2c. Such features have been identified by Lynch [6] as crack propagation occurring simultaneously along two [110] directions and lying on a (100) plane. In this case, the crack profile, can follow slip lines – figure 2d.

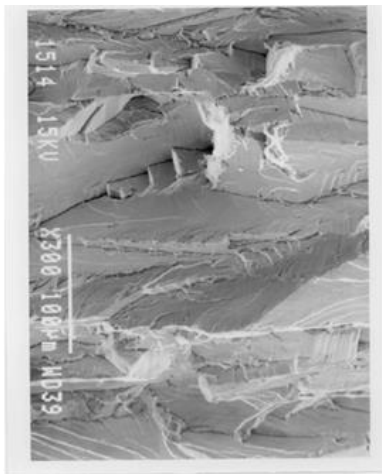


Figure 2a Crystallographic facets

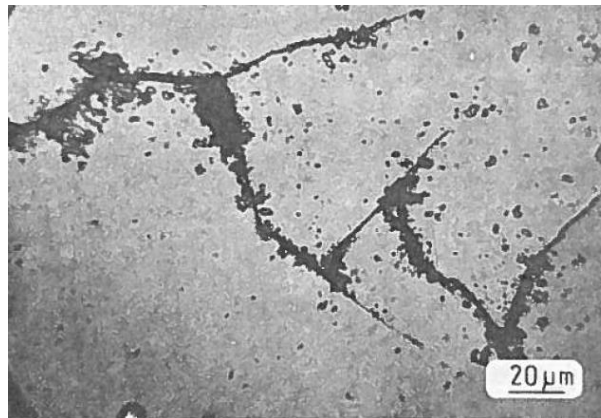


Fig.2b crack profile

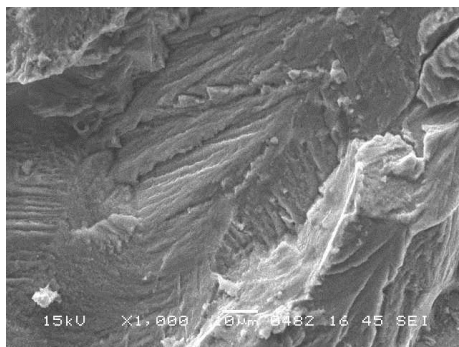


Fig.2c “Fishbone” fracture

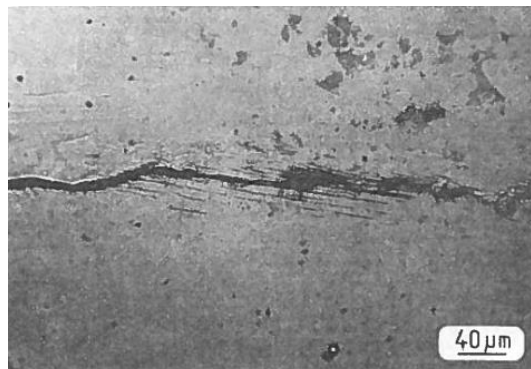


Fig.2d Crack following slip lines

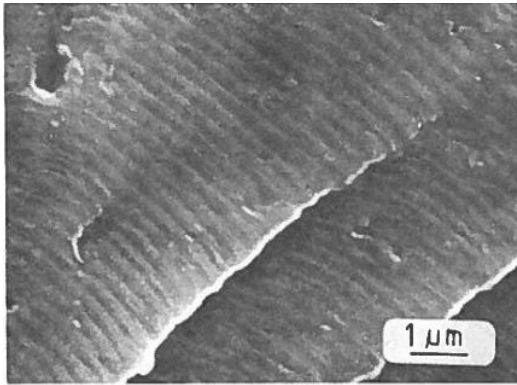


Fig.2e Striations

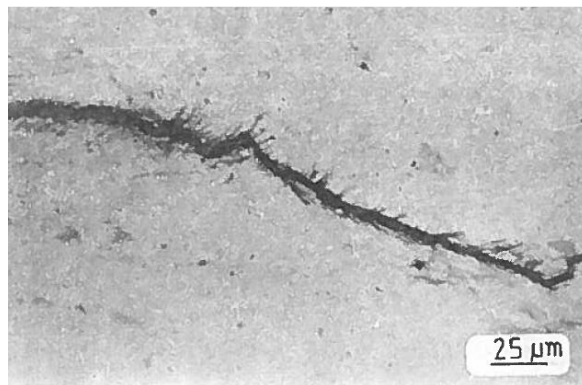


Fig.2f Straight crack profile

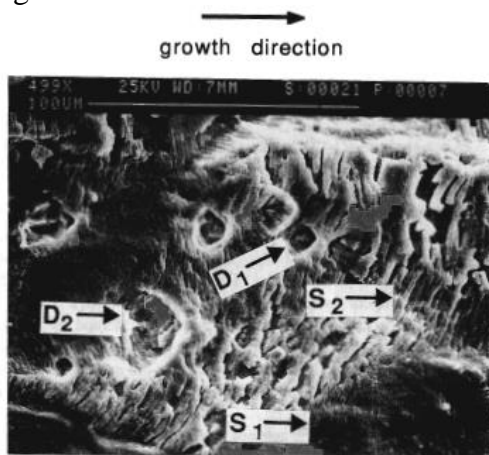


Fig.3a Mixed fractographic features



Fig.3b Inter-granular secondary cracks

- Striations. Two kinds have been identified : classical ductile striations, according to the mechanism identified by Laird [7], as shown in figure 2e and fragile striations .In such cases the crack path is quite straight- figure 2f.
- Dimples: Two kinds can be identified – small circular dimples and elongated ones The crack path can be slightly tortuous as the crack may follow local inclusions. Examples of the two kinds of striations and dimples are given in figure 3a
- Secondary cracks. In this case, the crack might follow the grain boundaries, if there is an environmental effect associated – figure 3b.

As was schematized in figure 1, the grain orientations can change along the crack front and one can expect a mixed distribution of the different fractographic features described above. In the original study [4], it was shown that the spatial distribution of significant fractographic features such as striations, pseudo cleavage facets, secondary crack length and dimples can lead to the determination of K_{max} , and R value under constant amplitude loading conditions. The method is succinctly described below.

Presentation of the method

Calibration tests are carried out covering constant amplitude tests at different load ratios. The fracture surface is cleaned in an ultrasonic bath. The specimen is then placed in a scanning electron microscope. The observations are made in the central plane strain region. The features can be different near the edges in plane stress and this aspect is not treated here. At different crack lengths (different ΔK levels), photographs are taken at low magnitudes (typically 500x) and for each crack length at least three photographs are used. A grill is then

placed on the photograph and the areal coverage of each fractographic feature is counted, according to the method proposed in [8].

Examples of results obtained in the 2024 T351 alloy are shown on figures 4a and 4b.

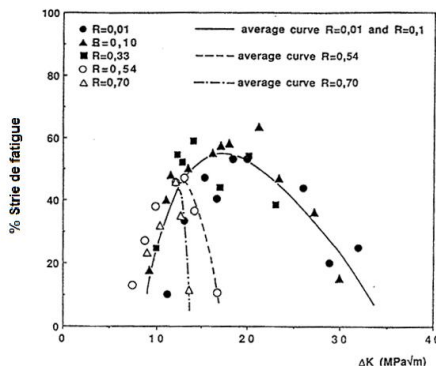


Fig.4a spatial coverage –striations

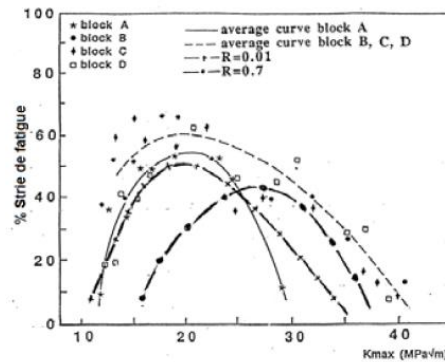


Fig.4b Spatial coverage striations VA tests

It can be seen here clearly, that the spatial distribution of striations reflect the ΔK level and the load ratio R. For example, ΔK de $12\text{MPa}\sqrt{\text{m}}$, one finds the presence of 50% striated areas at $R=0.1$, while this features occupys only 30% at $R=0.7$. It was also found that the striated areas can be added with pseudo-cleavage facets as these features are observed side by side. Dimpled areas can be analyzed in terms of K_{max} : for a K_{max} of $30\text{MPa}\sqrt{\text{m}}$, we find 60 % of dimpled areas for $R=0,1$ while this number falls to 15% at $R=0,7$ [9].

The results for a variable amplitude test can be found in figure 4b. This test is a block load test with five different load amplitudes [9]. The analysis based on quantitative fracture analysis permit the determination of an equivalent K_{max} and R ratio. It can be seen here that for Block A tests – the equivalent K values and R ratios follow the ones determined from constant amplitude tests at $R=0.01$. For the other block tests the equivalent R ratio is 0.01 at low K_{max} values, while it becomes equal to $R=0.5$ at high K_{max} values. Details are given in [10].

The current study is on the use of this technique on a structural steel

EXPERIMENTAL DETAILS

Tables 1a and 1b show the composition and nominal properties of the studied material

Table1a – Chemical composition of the steel EA4T

Nuance	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
EA4T	0,22	0,15	0,50			0,90		0,15		
	0,29	0,40	0,80	0,020	0,015	1,20	0,30	0,30	0,30	0,06

Table 1b – Nominal properties

Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)
➤ 420	650-800	➤ 18

Constant amplitude tests, using M(t) specimens were carried out at three load ratios of -1, 0 and 0.4, to determine calibration curves for the fracture analysis.

A variable amplitude spectrum, from the SNCF database was also carried out to determine the validity of the technique.

Figure 5 shows a sample of the spectrum load.

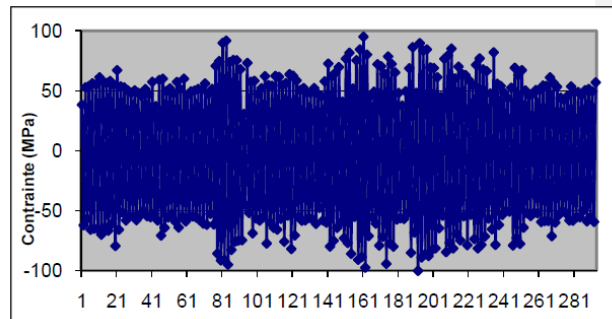


Figure 5 Railroad spectrum

After the tests the broken surfaces were examined under a Leitz SEM at convenient magnifications to examine the fracture surfaces. In the current study, the spatial coverage of different features were determined by numerical grill.

RESULTS AND ANALYSIS

In the case of the steel studied here, other fractographic features can be identified. Apart from striations and dimples, one can find classical cleavage facets, matted surfaces (under compressive loading) – examples are given in figures 6a and 6b. The crack profiles were not studied.

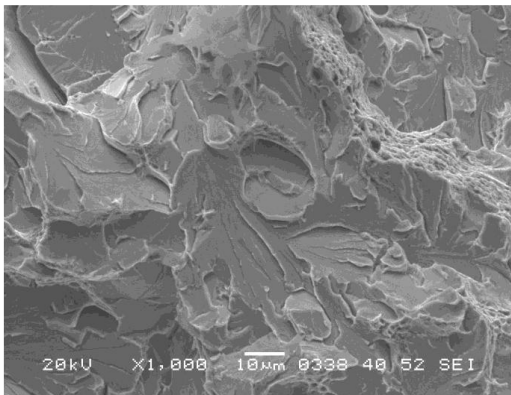
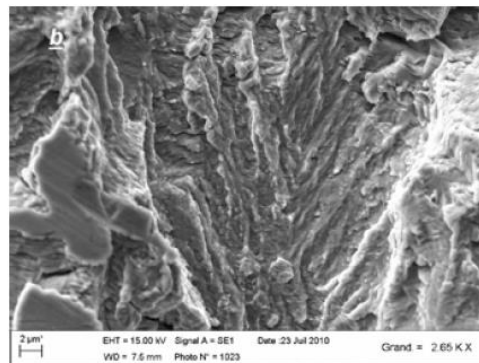


Fig.6a Cleavage factes



Fig;6b Matted facets and striated areas

Figure 7 shows the constant amplitude crack growth curve for this material. In the studied ΔK range, a Paris law slope of about 3 is observed. Figures 8a, 8b, and 8c, show respectively the evolution striated, the mean length of secondary cracks and area occupied by dimples for constant amplitude tests.

- It can be seen here that the evolution of striated areas show a similar evolution as for the aluminum alloy (figure4a)
- The behavior of $R=0$ and $R=-1$ are very similar in terms of areal coverage by striations
- The behavior at $R=0.4$ is very different as compared to the other load ratios.
- Matted areas are seen only at $R=-1$ (not shown in this paper).
- The mean length of secondary cracks permits a good differentiation between the three test conditions.

- The dimpled areas diminish with K_{max} in contrast to what was observed in the aluminum alloy. It should be noted here that dimples covered in this study concern low ΔK circular

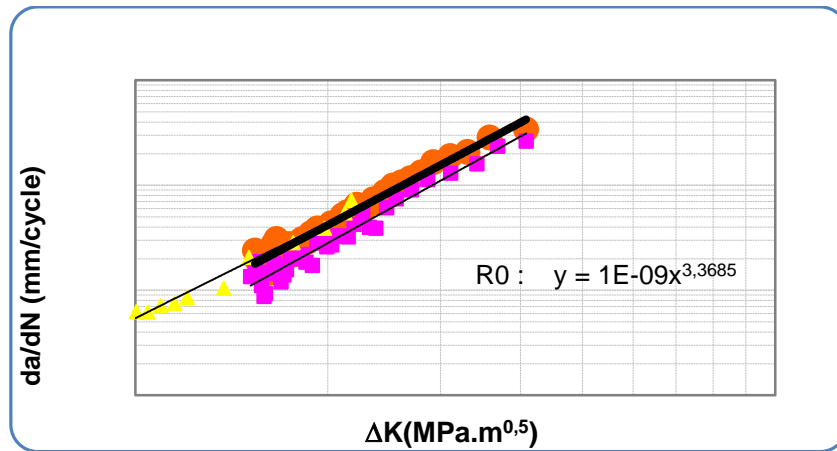


Figure 7 Constant amplitude crack growth curve

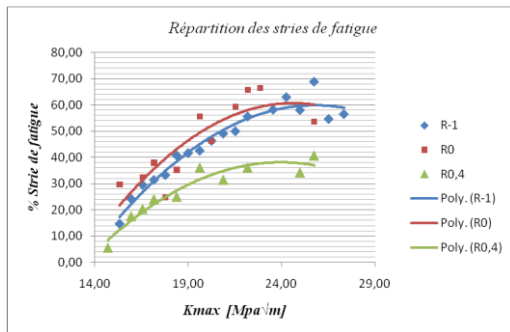


Figure 8a – Striated areas

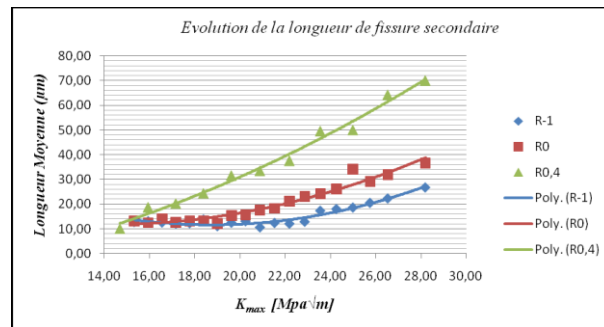


Fig.8b– Secondary crack length (average)

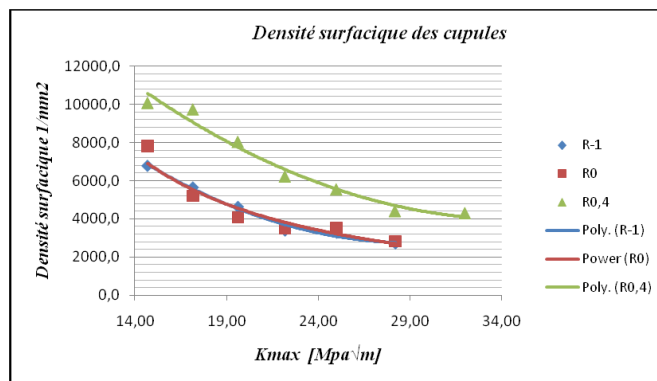


Figure8c – Dimpled areas

dimples, associated with an environmental effect [4].

The following table gives the spatial distribution of significant features in terms of R ratio for a K_{max} of $22 \text{ MPa}\sqrt{\text{m}}$.

Load ratio	Striated areas (%)	dimpled areas (1/mm ²)	Matted surface(%)	Mean length of secondary cracks (μm)
-1	56	4000	18	12
0	60	4000		20
0.4	38	7000		40

Table 2 – Spatial distribution of significant features

It can be seen from the above table that the study of the spatial coverage of significant fractographic features is an efficient way of analyzing quantitatively, the effect of mechanical loading parameters.

The variable amplitude test is now analyzed in terms of striated areas – figure 9. For the variable amplitude loading, a mean K_{max} value was determined from the analysis of the spectrum. The striated areas are compared with the evolution observed under constant amplitude loading conditions and it appears that an equivalent load ratio of -1 is a good approximation.

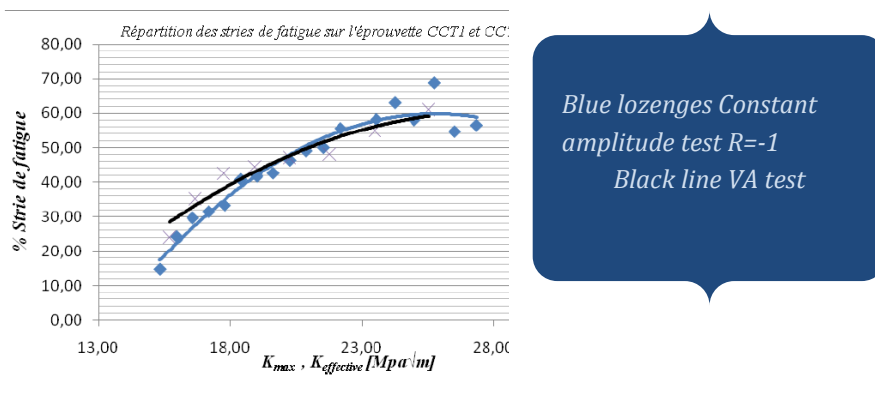


Figure 9 – Analysis of VA test in terms of striated areas

DISCUSSION

The method developed here is quite efficient to determine the fracture mechanics parameters on the basis of quantitative fracture surface analysis. At the present stage, it is a manual/ semi-automatic technique and depends upon the operator.

One can use image analysis – but it seems to be a difficult task to identify all the fractographic features by an automated method. Features like secondary crack lengths or dimples can be identified by automated techniques, but the authors feel (based on their experience) that the identification of fragile and ductile striations and pseudo-cleavage facets could be quite difficult.

Quite a few mechanical aspects are yet to be studied :

- The effect of specimen geometry
- Application to service failure analysis
- Study of material related variability (from one lot to another)

With respect to the first two points, the idea of determining a master curve is being explored,

The proposed method is not the only one that can be used. One can think of a comparison between the current method and the ones based on striation profile measurements, texture analysis or fractal analysis [1-3].

One of the drawbacks of the current method is that it is quite time consuming and that the user has to be trained on fractographic observations in identifying the mechanisms. This aspect can be improved by image analysis – but the authors are not convinced that such methods can replace the trained eye !

A good compromise could be to use image analysis techniques to detect evident features like Striations and dimples – complemented with observations by an operator. An aspect not treated in the current method is the aspect ratio of dimples that change with the presence of shear stresses [4]. One should also distinguish between dimples with broken inclusions inside and unbroken inclusions – an aspect that depends upon the local stresses.

CONCLUSION

The method for quantitative analysis of fatigue fracture surfaces gives encouraging results in a structural steel.

The method has to be developed in detail based on further experimental investigations.

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