ADVANCED SEM METHODS IN FATIGUE AND FRACTURE RESEARCH

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A comparative analysis of advanced results in the quantitative micro-fractography is performed. Fatigue crack propagation micro-mechanisms are discussed with respect to the fatigue striation spacing and features as well as to the retrospective of the FCP process. The correlation between statistics of local cleavage crack growth directions and main crack propagation direction provides an evidence of both the "coalescence" fracture mechanism and local approach to fracture acceptance. Stretched zone formation at crack initiation and its relation to fracture toughness of material is described. Intercrystalline rupture fractography is characterized with respect to the fatigue and stress corrosion cracking. Applications of fractography are given.

1. Introduction

Micro-fractography is a powerful instrument for the materials failure micro-mechanisms investigation. Such kind of investigations is important not only for science but also for practice. Very often fractography appears to be the only method able to establish the reason for failure of structural parts. This is why a great attention is paid to the fractography application, and the number of publications in this field is definitely growing. The available advanced instruments for fracture surface observation as light, transmission, scanning, and some other microscopies provide a possibility to get high quality pictures of surface micro-morphology. A more difficult task is to obtain quantitative information related to the crack propagation micro-mechanisms from fracture surface. Some important results of quantitative fractography are analyzed here: the fatigue striation mechanism and its relation to the actual fatigue crack growth rate, a cleavage river patterns statistics as a basis for a local approach to fracture, stretched zone appearance and its relation to the crack initiation and to the fatigue striation formation, ductile failure mechanism, intergranular stress corrosion cracking fractography.

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2. Quantitative fractography of the fatigue crack propagation

Fatigue striations are the most distinctive micro-feature of fatigue failure. Their detection on the fracture surface is a documentary evidence of cyclic loading as a main cause of failure. However, the mechanism of the fatigue crack growth by the formation of fatigue striations is not the only one. As indicated by numerous fractographic investigations depending on the material type and loading regime, the fatigue crack propagation (FCP) rate can also be influenced by "non fatigue" mechanisms such as cleavage, intergranular cleavage, dimple, etc., which usually accelerate the fatigue crack. The crack propagation by the fatigue striation mechanism is usually observed in the middle part of the FCP diagram. The lower is strength of steel or alloy, the higher is tendency to failure by the striation mechanism. The tendency toward departure from failure by the striation mechanism is usually observed for steels of low fracture toughness [1]. A common rule for most of materials is that in the presence of corrosive environment, especially in the range of low loading levels, they show a tendency to intergranular fracture.

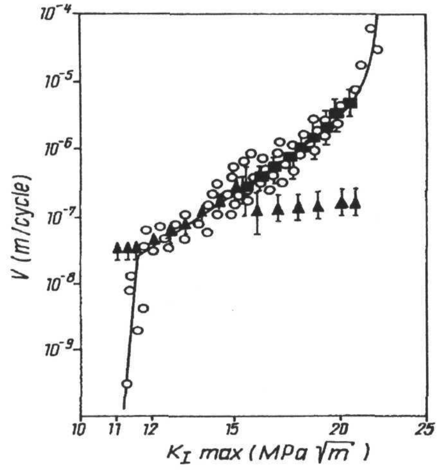

Fig. 1. The intergranular FCP diagram for coarse-grained pure nickel. Legend: ○ – average macroscopic FCP rate; ▲ – spacing of single striations; ■ – spacing of striation blocks.

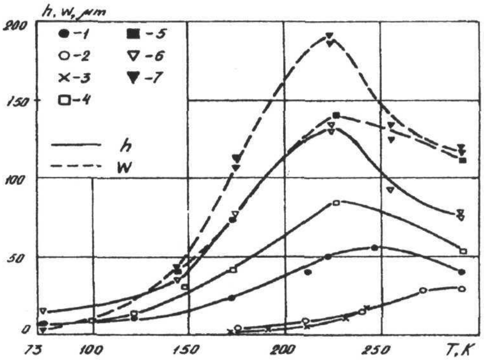

Fig. 2. Stretched zone height (h) and width (w) dependence on temperature at static (1, 4–7) and dynamic (2, 3) loading. Steels: 15Kh2NMFA (shell); 3 – CSN15313; 4, 5 – low-carbon; 6, 7 – 15Kh2NMFA (plate).

The comprehensive results on FCP micro-mechanisms in low carbon steel at low temperatures have been published elsewhere [1]. According to this work on the second and partially on the third part of the FCP diagram a correlation is observed between the average striation spacing and the macroscopic crack growth rate. One of important observations from these results is the conclusion that depending on temperature, loading level, material structure, corrosive environment, etc. several failure micro-mechanisms can contribute simultaneously to the FCP rate. The fatigue striation mechanism gives the minimum FCP rate, whereas other mechanisms, being superimposed on the fatigue striation mechanism, accelerate the crack.

A good illustration to the above statements are the results of the fractographic investigation of nodular cast irons of different microstructure and manganese content [2] as well as of ferritic ductile iron [3]. The SEM fractographic studies revealed an important role of graphite nodules in the process of failure. The latter part of the linear (Paris law) and the initial portion of the final (3rd) part of the FCP diagram are characterized by the formation of regular blocks of fatigue striations [2]. A good correlation was found between the macroscopic FCP rate and the individual striation spacing within the linear part of the $\log \mathrm{d}l/\mathrm{d}N$ vs. $\log \Delta K$ curve, as well as between the FCP rate and the striation blocks spacing at the end of linear part and at the initial portion of the last (3rd) part of the FCP diagram. The fracture morphology of ferritic matrix [3, 4] was a first international report on finding of mixed inter-transgranular character of FCP and the striations were observed on both trans- and intergranular facets. The intergranular crack growth rate measured by means of striation spacing did not exceed the transgranular crack growth rate. Both the explicitly intergranular FCP and the striations blocks formations were observed when studying the FCP in coarse-grained nickel [5] of high purity. The FCP diagram is presented on Fig. 1. As it can be seen from this diagram, the good correlation is observed between the single striation spacing and the macroscopic FCP rate for the first half of the middle part of the diagram and between the striations blocks spacing and the macroscopic FCP rate for the second half. The observed stabilization of single striation spacing at $K_{I\max} > 15$ MPa $\sqrt{\mathrm{m}}$ and good correlation of blocks spacing with the macroscopic FCP rate allow to qualify the individual striations within the block as a specific slip lines arrangements developed under the specific stress-strain field within the cyclic plastic zone ahead crack tip. A method enabling the reconstruction of fatigue process from the surface morphology has been developed in the work [6]. This method was successfully applied in many cases of service failures.

The process of fatigue striation formation is rather complicated due to the complex cyclic stress-strain fields at the fatigue crack tip. In order to explain this process a number of different models have been proposed [7]. The most important and often single feature of these models is the reversible plastic blunting process at the crack tip. The majority of models take into account only this process in order to explain the observed relationships between FCP rate and the crack tip loading range. Nevertheless, some doubt exists if it is possible to consider only one crack-tip plastic blunting process for the fatigue striation formation explanation. At least for the low cycle fatigue regime it has been shown by precision stereofractometry [8] that the FCP event during each loading cycle consists of two stages. As the subsequent tension half cycle begins, advance of the transverse shear (mode II) crack occurs. After the crack extends beyond the region of the cyclic-plastic-zone intense damage, it propagates by the mechanism of plastic blunting. This model seems to have a number of advantages over other models [8].

3. Brittle fracture

3.1 Crack propagation

One of the first quantitative fractographic investigations of the brittle fracture propagation was done by the authors of [9] on the low carbon steel and on low alloy steel. The data of these comprehensive statistic investigations provide the experimental evidence of the existence for engineering materials of the "coalescence" brittle fracture mechanism. With low carbon steels, for instance, fracture initiates, generally, at the grain boundary. As it follows from the cleavage pattern orientation, the direction of its local extension is independent of the direction of the main-crack propagation direction, i.e. within each grain there is almost equal probability for fracture to develop both in the direction of the main crack propagation or opposite to it. That means that brittle fracture propagation process is controlled by the nucleation of microcrack at some characteristic distance ahead the main crack tip and then by their coalescence. The corresponding K_μ-model [10] describes the temperature-loading rate dependence of fracture toughness as well as predicts the minimal fracture toughness of engineering materials.

3.2 Crack initiation

The process of crack initiation is directly related to the evaluation of fracture toughness of materials. The quantitative stereoscopic fractography provides an independent possibility to evaluate this process by the measurement of the stretched zone (SZ) geometrical parameters [11]. These parameters are expected to correlate with the CTOD and hence with material fracture toughness. Additionally to other methods of the materials fracture toughness measurement, the SZ has a number of unique properties, some of them are: i) a possibility of the material fracture toughness evaluation at any time after the fracture process has been completed; ii) a possibility of the direct and independent measurement of the offset critical CTOD related to the actual moment of the crack initiation; iii) accessibility of any SZ profile (and hence the CTOD) for measurement whatever its location along the crack front is, etc.

Our investigations involve two methods of stereoscopic measurement of the stretched zone geometrical parameters: measuring the profile of the SZ on a single fracture surface and superimposing the mating profiles of the two opposite fracture surfaces. Last method was originally developed and published together with Czech colleagues from Brno [12]. First of the aforementioned methods revealed essential scatter of results associated primarily with the irregular height and width of the SZ along the crack front. The scatter of the SZ measurement results obtained by the second method (Fig. 2) is much smaller and is comparable or even less than the scatter of the conventional fracture toughness measurement result. The main results provided by above mentioned methods are as follows:

i) A correlation was found between the SZ height and the fracture toughness characteristics of steels under static and dynamic loading in the temperature range where no sub-critical crack growth occurs prior to the specimen fracture;

ii) In the temperature range where a sub-critical crack growth is observed all the SZ measurements reveal that actual crack initiation occurs much earlier than it is predicted by the conventional techniques involving J_{Ic} and R-curve measurements;

iii) The SZ width and height were found invariant to the specimen thickness in the thickness range from 10 to 300 mm;

iv) A linear correlation was found between the SZ height and width.

The efficiency of the SZ measurement method is confirmed in different branches of fracture mechanics: crack blunting and crack initiation at J_{Ic} evaluation, failure analysis, dynamic fracture toughness at high loading rates, etc. Due to the identical geometric features of SZ and fatigue striation as well as to the same character of SZ width and striation spacing dependence on effective stress intensity factor some authors believe that fatigue striation spacing should be equivalent to SZ width.

4. Applications of quantitative fractography

A number of new advanced methods for the quantitative fractography have been developed recently. From all of them two should be mentioned here. The electro-optic holographic interferometry system has been used [13] to measure the three-dimensional displacement field around a fatigue pre-crack in 7075-T6 aluminum subsequently loaded in mode II shear. A new tool was presented in the work [14] to investigate cleavage fracture surface, based on the information fusion of crystal orientation measurements using the electron back-scattering diffraction technique and 3-dimensional surfaces reconstruction by an automatic surface reconstruction system. The both systems are the powerful instruments for quantitative fractography enabling to improve the accuracy of quantitative measurements as well as to avoid the very time consuming methods.

The field of quantitative methods of fractography applications is very wide and impressive. Aircraft, nuclear and fossill power plants, transport, chemical industry, pipe-lines, storage tanks, and pressure vessels, etc. gave many evidences for such useful applications. Some of these methods were even standardized in former USSR [15, 16, 17].

5. Conclusion

The qualitative and quantitative fractography becomes to be a powerful tool for establishing the features and micro-mechanisms of the engineering materials failure. The main qualitative features were microscopically identified as well as the main quantitative parameters were established for the fundamental failure micromechanisms such as trans- and intergranular cleavage, ductile failure, fatigue failure, crack initiation, etc. This provides in many cases a unique possibility to reconstruct the failure process and to make a retrospective failure analysis using the fracture surfaces. In some cases (e.g. fatigue striations spacing, stretched zone height) the quantitative fractography provides the results which accuracy and scatter is comparable or even better than the fracture toughness parameters from the conventional mechanical experiment. The new advanced automatized quantitative fractography methods promise together with the modern numerical methods including FEM, fractal analysis, etc. the entire description of failure processes of different engineering materials.

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