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2D AND 3D SELF-AFFINE CRACK PROPAGATION ON ALUMINUM ALLOYS

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ABSTRACT

The self-affine exponents associated with the crack propagation phenomenon are evaluated on samples of aluminum alloys both on 2D and 3D experimental conditions. Fracture surfaces were generated by Charpy impact tests on samples of A319-type aluminum cast alloy. Roughness exponents and correlation length on the perpendicular and parallel directions with respect to the crack propagation direction were determined, this analysis was also performed for the arrested crack propagation front. In the two-dimensional case, cracks were propagated on notched tension specimens of aluminum foil and the resulting self-affine crack paths were recorded and analyzed, the self-affine parameters were determined for both longitudinal and perpendicular direction in order to investigate the effect of the microstructural anisotropy.

Self-affine analysis was carried out using the Zmax variable bandwidth method. The combined use of different techniques (SEM, AFM, Optical microscopy and stylus profilometry) enabled the analysis over up to seven decades of length scales. The results are analyzed in terms of recent crack propagation models and the self-affine parameters are found to be correlated with microstructural characteristic lengths.

KEYWORDS

Roughness exponents, self-affine crack paths, fracture surfaces, aluminum alloys, crack propagation.

INTRODUCTION

Crack propagation and the fracture of materials are catastrophic phenomena of considerable scientific, technological an economical importance [1-4]. Despite the scale of the problem and the considerable effort that has been undertaken by engineers and scientists of different disciplines, there is at present no clear understanding of the fracture process. In recent years much interest has been devoted to the self-affine character of fracture surfaces and crack propagation [5-7]. The fractal nature of fracture surfaces was first quantitatively studied in the mid-eighties [8]. At about the same time it was suggested that the fracture of heterogeneous media has some universal properties similar to critical phase transitions [9]. Later, experimental evidence led to the conjecture of the existence of a universal roughness exponent [10] for the fracture surfaces of many different materials [11], though this is still a controversial topic [7,12]. Anyway, it is now clearly established that fracture surfaces are self-affine objects that can be quantitatively described by self-affine parameters like one or more roughness exponents and one or more characteristic lengths such as cut-off lengths separating different scaling regimes, and the correlation length.

One of the main goals of materials scientists is to find clear and useful relationships between the microstructure of materials and their macroscopic properties. In our particular field of interest this traduces to finding quantitative relationships between the microstructural features and the relevant self-affine parameters associated with the fracture surface and the crack propagation process that led to its creation. From the statistical physics point of view the question is related to how disorder affects crack propagation considering that rupture is the culmination of a self-organization of cumulative damage and cracking characterized by power-law regimes which result from the fact that disorder is present at different length scales in the form of impurities, vacancies, grain boundaries, porosity, phase boundaries and so forth.

The first attempts to relate fractal parameters of the fracture surfaces [8] of maraging steels with mechanical properties were very promising and inspirational though unsuccessful, it is clear that the fractal dimension of a fracture surface is not clearly correlated with the toughness of the material. Moreover, fractal dimension is not an appropriate parameter to describe self-affine surfaces [13], the roughness or Hurst exponent should be used instead. At present [6, 7], results from experiments in a wide variety of materials tested in different kinetic conditions and analyzed with different topometric techniques over up to seven length scales [14] suggest the coexistence of two self-affine regimes, at high enough propagation speeds and/or large enough length scales the so-called *universal* exponent $\zeta \approx 0.78$ is detected, whereas at slow propagation conditions and/or small enough length scales the detected exponent has a value close to 0.5. The cut-off length separating these two regimes is apparently dependent on the propagation speed [15], it also appears to be affected by local plastic deformation at the crack tip in ductile materials. Neither of the two above mentioned exponents seems to be associated in any manner whatsoever with the microstructural features of the materials. Experiments in Al-Ti alloys suggested that the cut-off length might be linked to the size of intermetallic compounds embedded in the metallic matrix [16]. Recent results [17-19] have shown that the correlation length, *i.e.* the upper limit of the self-affine regime(s) is directly related with the largest heterogeneities in materials such as metals [14, 17, 18], polymers [19, 20] and certain glasses [19].

With the hope to provide more experimental evidence that can help to improve our knowledge and refine the existing theoretical models of crack propagation, in this work we report the experimental analysis of the self-affine parameters of fracture surfaces and crack paths in aluminum alloys. A cast aluminum alloy is broken in mode I and the three associated roughness exponents are recovered along with the respective correlation length is some cases. We have also tested an aluminum foil in 2D mode I condition and have analyzed the self-affine nature of the crack paths. In both cases special attention is paid to the possible relationships between the microstructural features and the self-affine parameters.

EXPERIMENTAL PROCEDURE

We have performed the self-affine analysis of the fracture surfaces of aluminum samples, the same analysis was done for the crack paths generated in mode I in 2D conditions using samples of aluminum foil. The quantitative analysis was carried out using height profiles which were recorded by different techniques. The resulting topometric data sets are processed using the variable bandwith method [21] in which the following quantity was calculated:

$$Z_{max}(r) = \langle \max\{z(r')\}_{x<r'<x+r} - \min\{z(r')\}_{x<r'<x+r} \rangle_x \propto r^{\zeta}$$

Where r is the width of the window and $Zmax(r)$ is the difference between the maximum and the minimum height z within this window, averaged over all possible origins x of the window. A log-log plot of $Zmax(r)$ *vs.* r gives a straight line for a self-affine profile.

The experimental details and results for the two cases considered in our work are presented below.

3D case, A319-type Aluminum alloy

The cast aluminum alloy employed for this part of our work is an A319-type alloy, which is commonly used in the automotive industry. The typical chemical compositon is as follows (wt %): Si:7.147, Cu:3.261, Fe:0.612, Zn:0.664, Mn:0.0374, Ni:0.041, Ti:0.154, Mg:0.313, Sr:0.014, Al: balance. Fig.1 shows the microstructure of this alloy as observed by optical microscopy, the dendrites of alpha aluminum-rich phase is observed along with a numbre of different phases in the interdendritic regions. There is also a grain structure which was revealed using a special preparation. Image analysis measurements showed that the largest heterogeneities were the dendrites and the grains, with characteristic lengths identified as the primary dendrite arm length (800 μm) and the grain size (950 μm).

Samples of this material were broken in Charpy impact tests according to ASTM standard E-23-93. The resulting fracture surfaces were examined by Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and an stylus profilometer. These three techniques were used to obtain topometric profiles both in the perpendicular and parallel direction with respect to the crack propagation direction, see Fig. 2. Profiles of the arrested crack front were also recorded using a different procedure which is described later in this section. Using these profiles we were able to determine the perpendicular out-of-plane roughness exponent $\zeta_{\perp}$, the parallel out-of-plane roughness exponent $\zeta_{//}$, and the roughness exponent of the crack front ζ_f, Fig. 2.

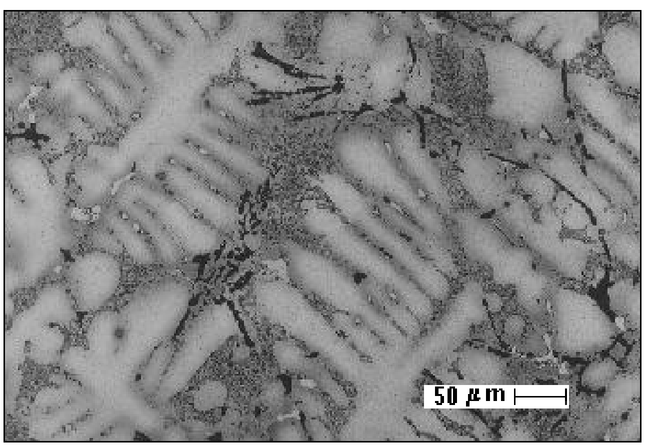

Fig.1 Optical micrography showing the microstructure of the A319-type alloy.

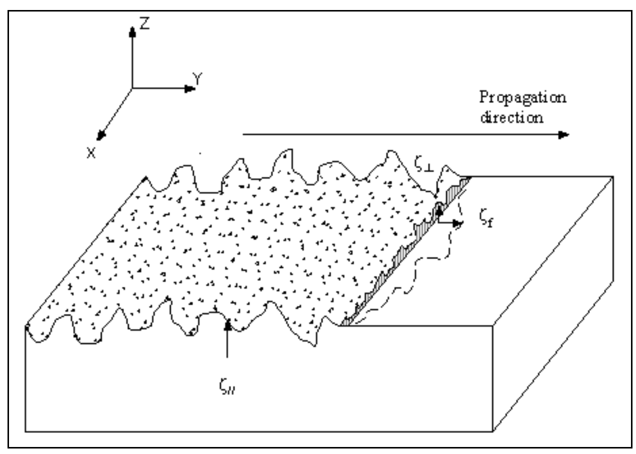

Fig. 2 Scheme illustrating the height profiles in the parallel and perpendicular directions with respect to the propagation direction, the crack front and the three roughness exponents are also included.

The SEM topometric profiles in the parallel and perpendicular directions were obtained by sectioning the surfaces previously plated with nickel, then SEM images are recorded using backscattered electrons and the profile is extracted by image analysis procedures. More details of these technique can be found in references [6, 15-17]. SEM profiles of 1024 points were obtained at magnifications ranging from 100X to 4000X. The AFM profiles are directly recorded by scanning the uncoated surfaces, we have used the contact mode in air. Profiles of 512 points with scan sizes ranging from 0.5 to a maximum of 6 μm were obtained. The stylus profilometer provided us with profiles of a maximum length of around one centimeter, a typical profile consisted of around 10,000 points with resolution of 0.25 μm.

Figures 3 and 4 show the self-affine curves obtained for the perpendicular and parallel directions, respectively. The exponents $\zeta_\perp$, $\zeta_{//}$ have very similar values: 0.81, 0.78, repectively.

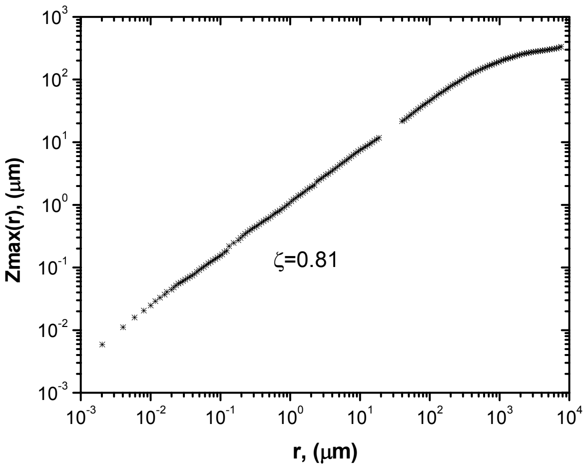

Fig. 3 Self-affine curve for the profiles in the perpendicular direction, the roughness exponent $\zeta_\perp$ has a value of 0.81.

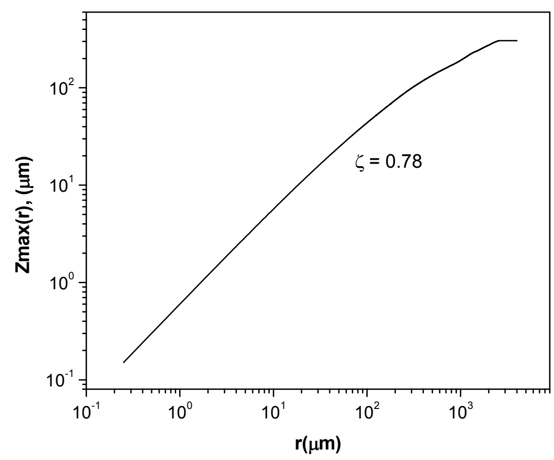

Fig. 4 Self-affine curve for the profiles in the parallel direction, the roughness exponent $\zeta_{//}$ has a value of 0.78.

Profiles of arrested crack fronts were obtained by a very different method, we have run interrupted torsion tests over hollow cilindrical specimens then marked the crack front using a commercial penetrating die commonly used in crack inspection and failure analysis. The specimens were then broken in the torsion machine and the arrested crack front was registered by SEM using secondary electrons, profiles were extracted by image analysis. Figure 5 shows the self-affine plot for the crack front which has a roughness exponent $\zeta_f = 0.79$.

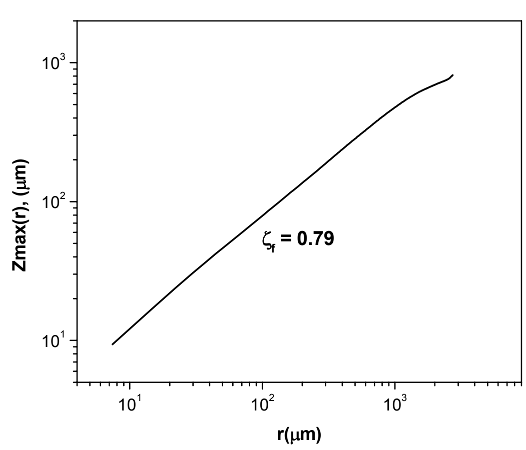

Fig. 5 Self-affine curve for the arrested crack front, the roughness exponent ζ_f has a value of 0.79

These self-affine curves permit only an estimation of the correlation length. However, as it can be observed, in all cases it has a value of the order of 1 millimeter, which is very close to the size of the largest dendrites and grains.

2D case: Self-affine crack propagation in aluminum foil

Tension specimens of aluminum foil (alloy 1145-O) were prepared as shown in Fig. 6, then fractured in 2D mode I condition. We have then performed the self-affinity analysis of the resulting crack paths. The purpose of these experiments was to evaluate the self-affine parameters paying special attention to the possible effect that the anisotropic grain structure might have on the self-affine character of the crack paths. As it is shown in Fig. 7, the grains are elongated in the rolling direction, it is known that this causes anisotropic behavior of mechanical properties so one can expect an analogous effect on the self-affine parameters.

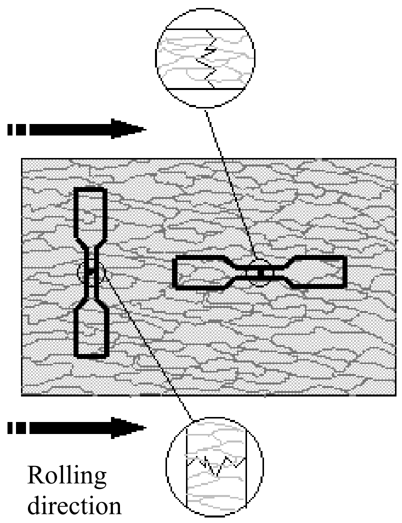

Fig. 6 Scheme showing the orientation of the tension specimen with respect to the rolling direction.

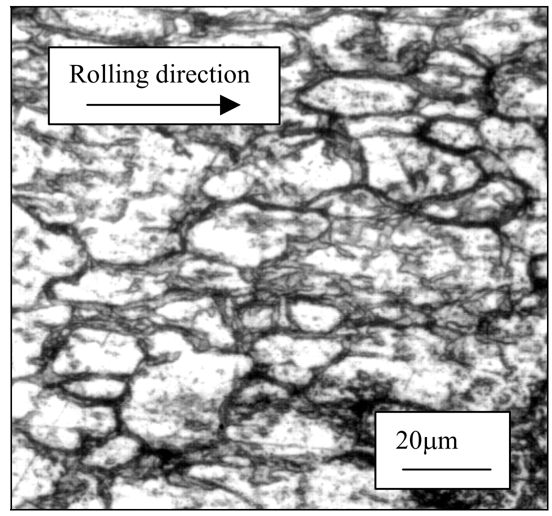

Fig. 7 Microstructure of the aluminum foil showing grains elongated in the rolling direction.

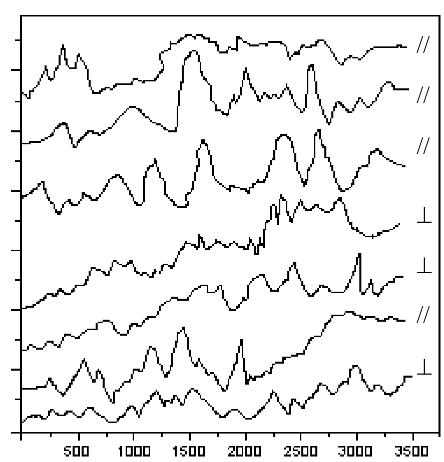

Fig. 8 Samples of the recorded crack paths in the rolling direction (//) and the perpendicular direction (⊥).

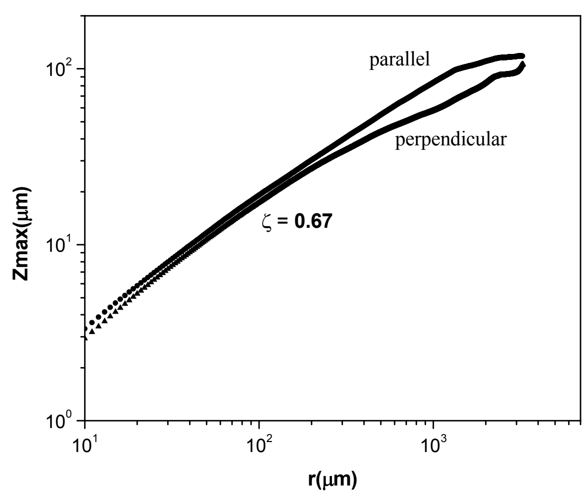

Fig. 9 Self-affines curves for the profiles in the parallel and perpendicular direction respectively, both curves reveal that the roughness exponent ζ has a value of 0.67

The crack paths obtained as a results of the tension test were recorded at various magnifications using SEM, optical microscopy and a conventional document scanner. Samples of the recorded self-affine paths are shown in Fig. 8 where paths belonging to cracks propagating in the rolling direction are "wider" and clearly distinguishable from those propagating in the perpendicular direction. The self-affine plot shown in Fig. 9 reveals that the roughness exponent has about the same value for both directions, ζ = 0.67, this value is in good agreement with the results predicted by the random fuse model and a 2D simulation of crack propagation reported in reference [16]. It is not possible to estimate with good precision the correlation lengths but Fig. 9 suggest that this parameter is larger for the parallel direction compared to that of the perpendicular direction, one can speculate that this can be interpreted as an effect of the elongation of the grains caused by the rolling process.

CONCLUSIONS

We have determined the self-affine parameters of the fracture surface of a cast aluminum alloy. The parallel and perpendicular out-of-plane roughness exponents were determined with values of 0.78 and 0.79, respectively. The roughness exponent of the arrested crack front was also determined, with a value of 0.79. It was corroborated that the correlation length is in all the cases related to the size of the largest heterogeneities present in the complex microstructure. The analysis of the crack paths in aluminum foil as developed in 2D mode I loading allowed the determination of the respective self-affine parameters. It was found that the roughness exponent has a value of 0.67 for both the parallel and transverse direction of propagation with respect to the rolling direction. The anisotropy of the microstructure has an observable effect in the correlation length whereas the roughness exponent is apparently unaffected by this condition.

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