# CHARACTERIZATION OF FRACTURE PATH AND ITS RELATIONSHIP TO MICROSTRUCTURE IN A WROUGHT ALUMINUM ALLOY

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## Abstract

This contribution reports location specific quantitative fractographic evaluation of the fracture initiation path in a set of plane strain fracture toughness specimens of hot rolled 7050 aluminum alloy having different degrees of recrystallization. Fraction of fracture surface area due to different fracture micro-mechanisms was estimated in the fracture initiation portion of the path due to plane strain and plane stress states. The resulting information is utilized to correlate fracture path to the extent of recrystallization and state of stress.

## Introduction

The global crack front motion and consequent fracture surface generation is a summation of a series of local events that are governed by the local microstructure, local state of stress, and interactions between the microstructure and the stress. Thus, the geometry and topography of fracture surface are expected to contain the information concerning the processes that lead to fracture, and the role of microstructural features in such processes. The materials science literature contains a large number of contributions that relate qualitative SEM fracture surface observations to the failure processes and microstructure, in a variety of different materials. However, detailed quantitative studies on characterization of fracture path and its relationship to microstructure are scanty. The geometry of fracture surface is often location dependent ( i.e., heterogenous ), due to variations in the state of stress and local microstructure from one region to another. It follows that the " global " average values of the microstructural attributes of the features on fracture surface may not yield the information concerning the relative contributions of different micromechanisms of fracture to the fracture path, and the role of microstructural features in the fracture processes. Thus, location specific quantitative fractography is necessary to analyze heterogenous fracture surfaces such as those of plane strain fracture toughness test specimens. It is the purpose of this paper to present the methodology for location specific quantitative fractography of plane strain fracture toughness test specimens, and to apply it to the fracture surfaces of hot rolled aluminum alloy 7050 specimens having different extents of recrystallization. The objective of the investigation is to quantitatively correlate the extent of recrystallization to the initiation fracture path and the prominent micromechanisms of fracture initiation. In the wrought aluminum alloys such as 7050, the qualitative correlations between the extent of recrystallization and global fracture path have been reported by a number of researchers (1-5); qualitative correlations between fracture toughness and extent of recrystallization are reported as well (1). However, there have been no detailed studies concerning quantitative characterization of local fracture path, variations in the fracture path with the local state of stress responsible for fracture, and changes in the microstructure - fracture path correlation with the state of stress that generates fracture. These issues are addressed in the present contribution.

## Material and Quantitative Microscopy

The experiments were performed on wrought aluminum alloy 7050-T651 (Al-Zn-Mg-Cu with trace impurities of Fe and Si) supplied by ALCOA. The alloy plate was hot rolled to a thickness of 1.5 inch at different temperatures ranging from 550 to 825 °F, with an objective of changing the degree of recrystallization. This was followed by giving T651 temper to the plates, leading to peak aged condition of the alloy. For plane strain fracture toughness testing, one inch thick compact tension specimens of L-T orientation were machined from the rolled plate by removing 0.25" from each side in order to achieve homogeneous microsturcture throughout the thickness of the sample (see Figure 1). These specimens were precracked, and plane strain fracture toughness was measured as per ASTM E399-83 and ASTM B645. Figure 2 shows a typical microstructure on the LT plane of the plate. The microstructure consists of bright large pancake shaped recrystallized grains, very fine unrecrystallized grains, and Fe-Si based coarse constituent particles. The hot rolling process introduces microstructural anisotropy and a bimodal grain structure: grain size of recrystallized regions is about two orders of magnitude larger than that for unrecrystallized regions. The different types of internal surfaces observed in Figure 2 are: 1) between recrystallized grains; 2) between recrystallized and unrecrystallized grain, and 3) between unrecrystallized grains.

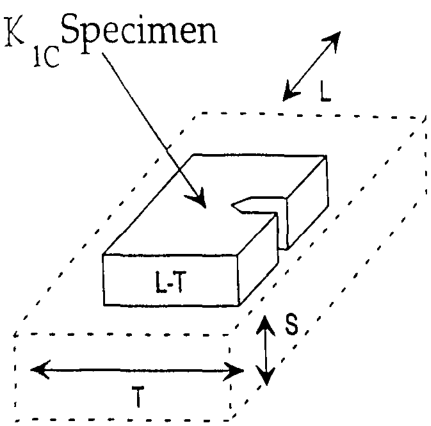
The volume fraction of recrystallized grains ($V_V^R$ ) represents the degree of recrystallization. The global value of the volume fraction of the bright recrystallized grains in the microstructure, and the global values for total surface area per unit volume ($S_V$) of different interfaces ( between unrecrystallized $S_V^{SS}$, recrystallized grains $S_V^{BB}$ ) were estimated by using the stereological technique described in (6,7). All these microstructural properties are likely to vary with location, and such local microstructural variations need to be taken in to account to correlate the local initiation fracture path to local microstructure. Considering this effect, the local values of the volume fraction recrystallized ( designated as $V_V^{LR}$ ) were also determined in the plane stress and plane strain region of all the samples of the fracture toughness specimens. Table 1 reports the global values of the stereological parameters of the bulk microstructures; while Table 2 and Table 3 report the values of local volume fractions. Note from Table 1 that the volume fraction of recrystallized grains in the microstructure increases as the rolling temperature is decreased. Further note that as stated earlier, grain size of bright regions is hundred times higher than that for small grain regions, and hence distinction between recrystallized and unrecrystallized grains can be done on the basis of their size.

## Fractographic Analysis

In this material three important micromechanisms of fracture are operative : intergranular fracture, micro-void induced dimple fracture, and coarse particle induced fracture. The present fractographic work involves quantitative assessment of area fractions of the fracture regions

Table 1. Global Stereological Parameters of the Microstructures

| Rolling Temp. °F | $V_V^R$ | $S_V^{SS}$ $mm^{-1}$ | $S_V^{BB}$ $mm^{-1}$ | Small Grain Size µm | Small Grain Size µm |
|---|---|---|---|---|---|
| 825 | 0.08 | 709.32 | 0.56 | 2.58 | 305.73 |
| 700 | 0.31 | 960.00 | 1.50 | 1.44 | 413.33 |
| 600 | 0.49 | 1250.67 | 9.26 | 0.80 | 106.26 |
| 550 | 0.63 | 1238.39 | 14.77 | 0.62 | 83.36 |




L : Longitudinal Direction

T : Long Transverse Direction

S : Short Transverse Direction

Figure 1. L-T orientation of Fracture Toughness Specimen

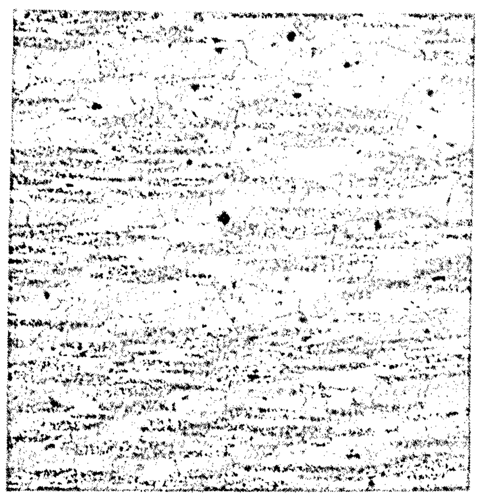


Figure 2. Microstructure on L-T plane at 200X

generated by these three micro-mechanisms, and changes in the fracture path due to variation in the extent of recrystallization, and stress state. The area fractions of different fracture regions were observed to vary with their location on the fracture surface. This is demonstrated in Figure 3 which shows fractographs of the mid-thickness ( plane strain region ) and the near surface ( plane stress ) regions ( Figure 3-a and 3-b respectively ) for the sample with global $V_V^R = 0.1$. Note that fractograph in the plane stress region of the fracture surface exhibits more intergranular nature compared to the one in the plane strain region; the area fractions of microvoid fracture regions also vary with the state of stress.

The area fractions of different fracture regions were also observed to vary with the degree of recrystallization. Figure 3-a and 3-c are the fractographs of the mid-thickness ( plane strain ) region of the sample with global value of $V_V^R = 0.1$, and with global value of $V_V^R = 0.63$, respectively : note that microvoid area fraction decreases with an increase in the recrystallized volume fraction in the microstructure. The same effect of degree of recrystallization is also observable in plane stress regions of the samples ( see Figure 3-b and 3-d ). Thus, the area fractions of the fracture surface generated due to different micromechanisms vary with the distance from the center of the specimen ( state of stress ) as well as with the degree of recrystallization. Since there is a variation in the area fractions generated by different micromechanisms as one goes from center to surface, the average values of area fractions estimated from random field placements are not physically meaningful, and they do not contain information concerning effect of microstructure on fracture path. The state of stress responsible for fracture varies significantly as one goes from the center to the surface of the specimen. The center of the specimen has a state of stress close to plane strain, whereas at the specimen surface it is close to plane stress condition. The area fractions due to different micromechanisms appear to depend on the local stress state for the fracture of that region. To quantify this correlation and its variation with the amount of recrystallized regions the area fraction measurements were carried out separately in the central zone of the crack ( ten consecutive fields of views of 100 μm each ), and in the plane stress region near surface ( ten consecutive fields of views of 100 μm each ) of the specimen. The appearance of the fracture surface also varies with the distance along the crack growth direction i.e. the fracture path in the crack initiation region may not be the same as in the fast fracture region.

Our main interest is in the initiation region as it contains information concerning effect of microstructure on fracture initiation. Due to this reason, ALL the area fraction measurements were restricted to a distance of less than 170 μm ( less than plastic zone size which is approximately 250 μm ) from fatigue pre-crack : area fraction measurements were carried out only in initiation fracture paths of plane strain and plane stress regions. The schematics of location of the fields of view in the region on the fracture surface where the measurements were performed, is given in Figure 4. Note that in each specimen, the locations of fractographs were precisely the same and hence the state of stress is quantitatively the same for plane strain and plane strain regions of all the specimens. Using this sampling scheme, a series of SEM fractographs were taken at 600X. The values of the area fractions of the microvoid induced fracture ( $A_A^{MVC}$ ), particle induced fracture ( $A_A^P$ ) and intergranular fracture ( $A_A^I$ ) regions in each SEM fractographs were determined using ZIDAS$^{T.M.}$ Image Analysis System of Carl Zeiss Inc. The individual areas occupied by microvoid and coarse particles on the fractographs were traced using cursor and the data was tabulated for each fractograph. The average of the values for the various area fractions occupied in the plane strain and plane stress regions were estimated from these data. Table 2 and Table 3 give the average area fraction data for plane strain and plane stress regions respectively along with the values of plane strain fracture toughness ( $K_{IC}$ ) and local values of recrystallization $V_V^{LR}$.

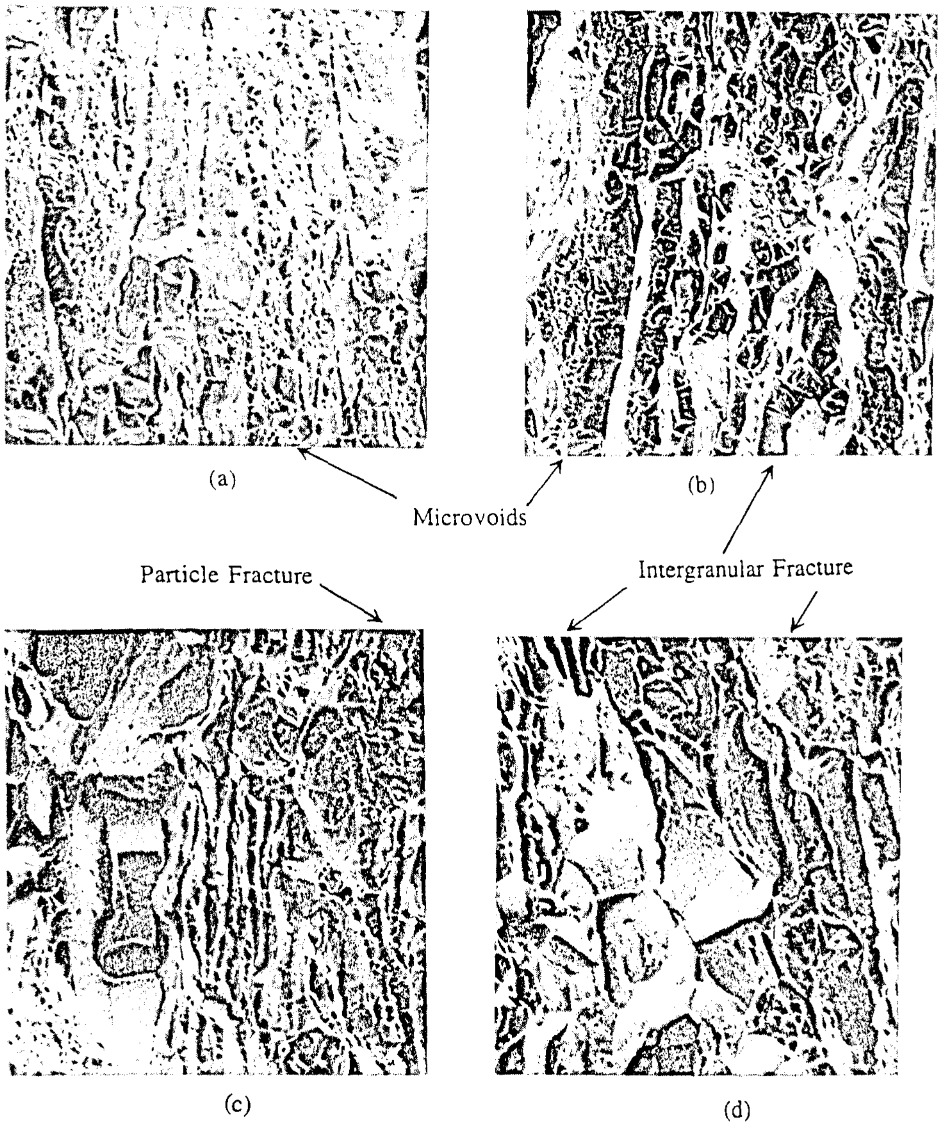



Figure 3. SEM Fractographs of the Alloy at 600X Showing Different Fracture Mechanisms; (a) Plane Strain Region of $V_V^R = 0.1$, (b) Plane Stress Region of $V_V^R = 0.1$, (c) Plane Strain Region of $V_V^R = 0.63$, (d) Plane Stress Region of $V_V^R = 0.63$

Table 2. Area Fraction Data for Plane Strain Stress State

| $V_V^{LR}$ | TYS KSI | $K_{IC}$ KSI$\sqrt{IN}$ | $A_A^{MVC}$ | $A_A^P$ |
|---|---|---|---|---|
| 0.11 | 78.3 | 32 | 0.18 | 0.20 |
| 0.25 | 76.2 | 35 | 0.10 | 0.12 |
| 0.42 | 75.7 | 30 | 0.10 | 0.18 |
| 0.66 | 76.6 | 29.5 | 0.08 | 0.16 |

Table 3. Area Fraction Data for Plane Stress Condition

| $V_V^{LR}$ | TYS KSI | $K_{IC}$ KSI$\sqrt{IN}$ | $A_A^{MVC}$ | $A_A^P$ |
|---|---|---|---|---|
| 0.06 | 78.3 | 32 | 0.10 | 0.10 |
| 0.22 | 76.2 | 35 | 0.05 | 0.16 |
| 0.49 | 75.7 | 30 | 0.02 | 0.12 |
| 0.73 | 76.6 | 29.5 | 0.00 | 0.09 |

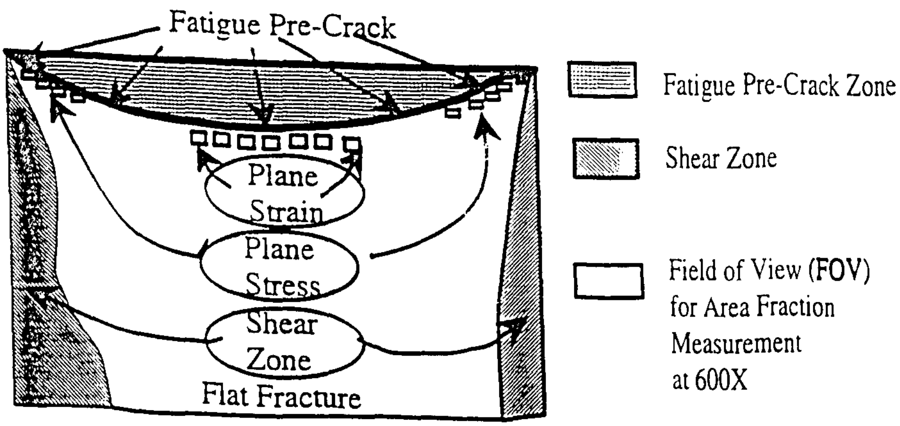



Figure 4. Schematic showing placement of FOV under study

## Results and Discussion

In all the specimens the area fractions of microvoid induced fracture $A_A^{MVC}$ were observed to be higher in the plane strain fracture regions as compared to the corresponding plane stress fracture regions. This trend has been observed in ALL the specimens on which the measurements were performed. Similarly, the area fractions of coarse particle induced fracture regions is generally observed to be higher in plane strain regions as compared to the plane stress regions ( see Table 2 and 3 ). These observations clearly demonstrate that the relative contributions of different micromechanisms to the fracture path depend on the local state of stress and local microstructure. It may be said that correlation of the local microstructure to the local fracture behavior may depend on the state of stress responsible for fracture. Figure 5 shows plot of variation of area fraction of microvoid induced fracture with the values of the local volume fraction of recrystallized regions $V_V^{LR}$ in the plane strain and plane stress regions respectively. In the plane stress region, area fraction decreases sharply with the increase in the local volume fraction of the recrystallized regions; it approaches zero for volume fraction of about 0.73. The area fraction of microvoid regions in the plane strain locations of the specimen does decrease with the volume fraction, however, the decrease, is not as sharp as in the plane stress regions. Since the area fractions of the microvoid regions on the fracture surfaces decreases with $V_V^{LR}$ for both plane strain and plane stress regions, it is expected that decrease in the degree of recrystallization should lead to increase in material toughness under both plane strain and plane stress conditions. However, the increase in the extent of toughness may be higher for plane stress fracture.

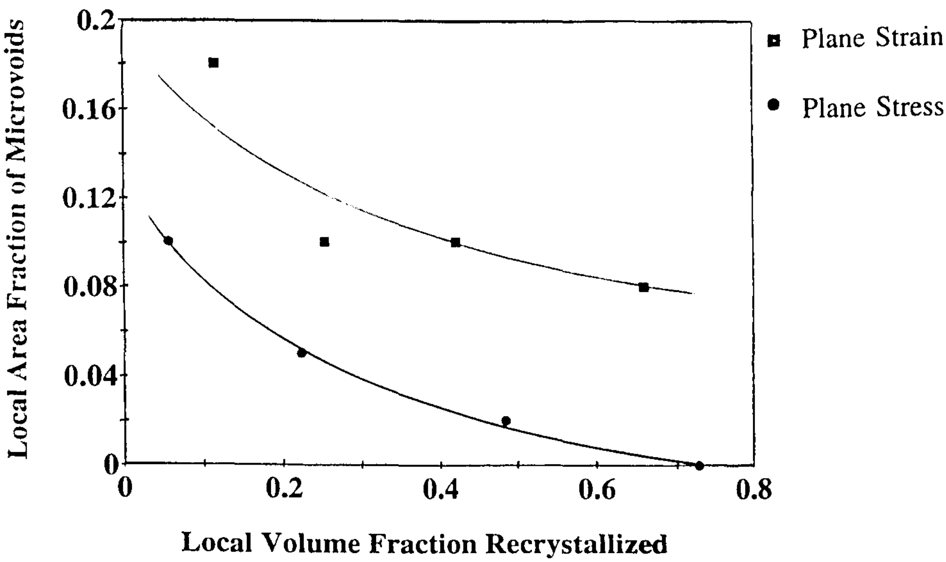



Figure 5. Plot of variation of the true area fractions of microvoids with the local values of volume fraction recrystallized for plane strain and plane stress regions

This demonstrates the effect of state of stress on microstructure-fracture path correlation. It is necessary to point out that these observations are based on limited amount of data and more experimental work is necessary to confirm these findings. In thin plates or sheets, one expects plane stress fracture, where as in thick plates the fracture initiation is expected to be caused by plane strain state of stress. It may be said that a significant gain in the fracture toughness of thin sheets or plates can be obtained by minimizing the extent of recrystallization.

## Conclusions

1) The fracture surface of fracture toughness test specimens is highly non-uniform; the area fractions of regions generated by different micromechanisms vary significantly with the location on the fracture surface and hence the average values obtained by random placements are not physically meaningful.
2) The operative micromechanisms and fracture paths are highly sensitive to the local state of stress responsible for fracture.
3) Although the recrystallized volume fraction varies with the location along the thickness of the plate, this variation is not sufficient to account for the differences in the fracture paths in the plane strain and the plane stress regions.
4) The increase in the recrystallized volume fraction decreases the value of the local area fraction of microvoids both in plane stress and plane strain stress states, indicating that control of recrystallization ( minimizing the $V_V^R$ ) should lead to an increase in material toughness under both plane stress and plane strain conditions, however the gain in toughness may be higher for plane stress state fracture.

## Acknowledgements

This research work was supported by research grants from Aluminum Company of America (ALCOA) and National Science Foundation ( DMR 90301986 ); this financial support is gratefully acknowledged. The authors thank Dr. J. T. Staley and Dr. John Liu of ALCOA for interesting discussions during the course of this work.

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