PREDICTING FATIGUE FAILURE USING A TWO – DIMENSIONAL X-RAY DETECTOR

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ABSTRACT

Fatigue damage results in the progressive localized permanent structural change and occurs in materials subjected to fluctuating stresses and strains and the fatigue life of any specimen or structure is the number of stress (strain) cycles required to cause failure.¹ The use of two-dimensional x-ray detectors allows for the observation of these changes through visual changes in the Debye ring. Decreases in the spottiness of the rings and peak broadening can be readily observed and measured. This paper examines changes of the Debye ring for FCC metal structures at various stages (cycles) of “cold working” and how these changes may be used to predict or evaluate fatigue failure.

INTRODUCTION

The earliest two-dimensional detector, film, was used to examine metallographic structures. Hearsh and Kellar in 1951 studied particle volume, particle shapes and misorientation of cold worked aluminum using x-ray microbeam techniques.² In 1936 Stephen et al. studied the use of x-ray methods for determining grain size and internal strains in metals.³ Current two dimensional detectors such as multiwire proportional counters, charged coupled devices, and image plates can examine these structural changes. Employing image technologies and computers both qualitative and quantitative assessments can be made on materials that exhibit structural changes due to fatigue. The work reported here is a preliminary examination of the changes observed during low cycle high stress conditions of FCC aluminum and copper metals. The interpretation of high cycle low stress fatigue using a two dimensional detector will be examined in future papers.

BACKGROUND

Hooke’s Law states that stress is proportional to strain unless you exceed the elastic limit or the material yields plastically. Schematically Figure 1 represents the stress - strain curve for a typical ductile metal. Region 2) shows that when a stress is applied the material strains elastically and macroscopically the material returns to its original shape. This is the high cycle low stress region, a region of high engineering importance because of the subtlety of crack (fatigue) initiation leading to failure. Examples include pressurizing and depressurizing airplane cabins or heating and cooling of pipe welds. Region 1) shows what happens when a stress is applied above a materials elastic limit (dotted line). The material behaves plastically and does not return to its original state and
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continued strain will cause rapid fatigue and subsequent failure. Examples of these include the bending back and forth (cycles) of a coat hanger or paper clip until it breaks or metal scaffolding collapses due to exceeding the recommended structural weight limits. This region of low cycle high stress was used in this preliminary investigation because the likelihood of observing changes of the Debye ring in the two-dimensional detector is greater. The more subtle high cycle low stress will be examined in future work.

As metals deform plastically, microscopic changes in the grain structure occur. Microstrain develops due to increases in dislocations and the formation of subgrains, both attributing to peak broadening. Also as these grains change the texture of the original surface decreases. Macrostrain or residual stress causes a shift in d-spacing depending on the type and amount of strain. I.C. Noyan and J.B. Cohen give an excellent detailed description of x-ray line broadening due to macro and micro strain for Bragg-Brentano geometry.

**INSTRUMENTATION**

A two-dimensional detector with appropriate x-ray optics can allow the visual assessment of peak broadening and textural changes of one or several hkls in real time that can not be done using conventional Bragg – Brentano geometry. Figure 2 shows the two-dimensional detector used here. It is a xenon - filled two-dimensional multiwire proportional counter manufactured by Bruker X-ray Analytical Systems. It has a large 11.5cm imaging area and high dynamic range, which allows for fast visual comparisons of the Debye ring even for low diffracted intensities from higher order hkls. The capillary optics scheme, shown in Figure 3, are for the pinhole and total reflection types. The total reflection optics has the advantage of increased spatial resolution (smaller spot sizes) and greater intensity over pinhole optics. The drawback is that these capillaries have a higher divergence angle of the emerging x-ray and consequently a closer distance between sample and capillary is needed to minimize this divergence. Typically a range of capillary sizes are needed to obtain an initial spotty pattern resulting from differences in grain size of the material being analyzed. Typically for metals analyzed here a 300µm pinhole capillary was used.
The two-dimensional detector (with a Ni filter for Kβ reduction) and the x-ray optic are coupled with a motorized xyz stage and a 12kW rotating Cu anode with a 0.3x3mm focal spot as the source to create the complete instrumental setup.

![Multiwire Proportional Counter](image1.png)

![Schematic of Pinhole and Total Reflection Capillary](image2.png)

RESULTS AND DISCUSSION

The frame or diffraction image generated by the two dimensional detector allows for rapid visualization of a portion of the Debye ring. The closer the detector is to the sample the larger the angular range seen but with lessened resolution. The further away the detector the better the resolution but with a smaller angular range. The detector-to-sample distance used here was 20cm, which allows for an angular range of approximately 30 degrees in both 2 theta and chi. The generated diffraction pattern can be integrated to obtain FWHM using a Pearson VII function and Kα2 elimination.

In order to see the effects of low cycle fatigue on the diffraction pattern, a piece of 1mm diameter copper wire was (cold worked) bent 90 degrees and returned to a straightened position (i.e.1 cycle). After each cycle a diffraction pattern of the Cu (220) was taken. This was repeated until the copper wire failed (14 cycles). The patterns in Figure 4 show the changes in the Debye ring at various cycles. Note that the pattern becomes less spotty and that the intensity along the ring (chi) becomes more uniform with increasing cold work.

![Diffraction frames](image3.png)

Figure 4: Diffraction frames showing the changes of Cu (220) line after low cycle fatigue of a 1mm diameter Cu wire.
Integration of these patterns show an increase in FWHM with increased cold work (Figure 5). This is expected since greater dislocations and subsequent microstrain increase with increasing cold work. If one knew a priori the % increase in FWHM for failure in Cu and the cyclical nature that the sample was subjected to, it would be a simple matter to predict failure from these patterns. However, even a qualitative visual comparison of the unstrained and strained Cu would be of great help in determining areas of suspected fatigue.

![Figure 5: FWHM of Cu (220) for cold worked Cu wire.](image)

Next, an Al bar (23mm wide and 2mm thick) was cold worked until failure much similar to the cold work of the Cu wire. This time diffraction patterns were taken for Al (400), (331) and (420) starting from a non-fatigued region and working toward the crack (failure). Again the visual comparisons of the diffraction patterns showed similar trends found for the Cu wire including merging of Kα1 and Kα2, which are resolved at the higher 2 theta angles. Since the two-dimensional detector captures such a large 2 theta angular range (30 degrees) all three Al lines could be viewed and integrated simultaneously. What is interesting is that the FWHM changes at different rates for different hkls as the crack is approached. Figure 6 shows the plot of these hkls from the non-fatigued region to the crack. Three separate regions of hkl spread were observed. Region 1 the non-fatigued region shows no difference in FWHM for the various hkls. Region 2 the mid-fatigued region begins to show a separation of FWHM. Finally in Region 3 or high-fatigue region the separations are striking and an almost exponential increase in the FWHM is observed approaching the crack. The differences observed in the FWHM for the various hkls is mostly due to the elastic anisotropy in various crystallographic directions that are exhibited in most materials. This subtle FWHM
separation at the mid-fatigue region may be exploited to examine high cycle low stress fatigue.

CONCLUSION AND FUTURE WORK

It has been shown that the two-dimensional detector can assess visual changes in the Debye ring for low cycle high stress fatigue of FCC metals. These visual changes include decreases in the spottiness of the pattern, increasing uniformity of intensity and the merging of Kα1/Kα2 peaks. Also, integration of these rings indicates an increase in FWHM as the fatigue failure is approached and the rate of change of FWHM for various hkls is also apparent. Examination of suspected fatigue regions and comparison to non-fatigued regions using the two-dimensional detector can indicate changes in the diffraction pattern and FWHM, thus predicting the likelihood of failure. Future work is planned for continued examination of the low cycle high stress fatigue and also the examination of the more important high cycle low stress fatigue. This will be done using a programmable cyclic tensile tester adapted for the XYZ stage in order to observe in situ changes of the Debye ring. A modeling effort is also planned in order to generate a two-dimensional x-ray diffraction pattern based on instrumental parameters and material crystallography. This will allow us to predetermine the material’s non-fatigued state and subsequently let us determine small changes from the differences in the observed spots on the Debye ring. Ultimately by making use of smaller, higher resolution detectors, small power higher intensity sources, and higher efficiency x-ray optics coupled with image analysis and pattern modeling a portable “fatigue sensor” is envisioned.

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