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STUDYING THE EFFECT OF RESIDUAL STRESSES ON FATIGUE CRACKS THROUGH FULL-FIELD METHODS (PREPRINT)

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14. ABSTRACT
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Studying the Effect of Residual Stresses on Fatigue Cracks through Full-field Methods

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ABSTRACT

In this effort, a corner crack was grown from a notch in a nickel-based superalloy specimen with a shot-peened surface treatment to induce residual stresses. The crack length was less than 200 microns, and the full displacement field near the crack was determined using advanced digital image correlation. The specimen was then annealed at elevated temperatures to reduce or eliminate the residual stresses, and the full displacement field near the crack was again determined. The displacements after annealing were indeed significantly larger than those previous to annealing, demonstrating the reduction in residual stresses. Modeling has been done to determine the approximate level of residual stresses induced and then reduced through annealing. Through this method, the effect of residual stresses on short fatigue cracks can be directly studied.

Further work will be discussed on the effect of temperature on residual stresses, an area of great concern in predicting fatigue lives of components. The degree to which these residual stresses are reduced under service conditions is not well understood, and the approach described here is expected to be extremely useful in determining and predicting this residual-stress reduction, leading to greatly enhanced life prediction where residual stresses are involved.

Introduction

Shot peening is extensively used to impart compressive surface residual stresses in metallic components [1]. The benefits of these residual stresses in increasing fatigue lives are well-documented [2,3]. However, there is some question as to the intensity of these beneficial residuals after extensive time under service conditions. This question is particularly important when considering the beneficial effect of shot peening on nickel-base superalloys, which are typically used where the absolute temperature may be at or near 70% of the melting temperature of the alloy and stresses may approach the yield strength of the material. In addition, the accuracy of predictions of remaining residual stresses also depends on the accuracy of the knowledge of the initial residual-stress conditions. The shot-peening process itself has many parameters, which contribute to the variability of imparted residual stresses, *e.g.*, shot size, hardness, coverage, and angle.

In order to predict fatigue lives with a reasonable degree of fidelity for shot-peened parts, it is vital that the effect of service conditions on residual stresses be better understood. In this effort, a method for studying the effect of shot-peening and the effect of service conditions on shot-peening-induced residual stresses is demonstrated through the determination of their effect on a particular mechanism of importance to fatigue-life prediction, the mechanical behavior of the material near a small fatigue crack. This study is accomplished through the use of full-field deformation mapping of this area.

Systems used for the determination of full-field displacements and strains have matured over the past few decades [4-9]. The most common experimental method used for determining displacement fields, and the one that is used in the present work, is known as digital image correlation, or DIC. DIC is accomplished by acquiring a series of images of the same area of a solid's surface while the solid is undergoing deformation. In the present study, the deformation near a small-fatigue crack is studied. Since DIC does not determine the displacement of specific material points, but instead determines the displacement of subsets of pixels in the acquired images, using DIC in situations with displacement discontinuities, especially cracked bodies, is particularly difficult. Therefore, most DIC software requires the user to "mask out" the area near a crack, but this is in many cases the very area of most interest. In the present study, special techniques were used to determine the displacement very near the crack [10, 11]. In addition, most DIC systems are not capable of working at the size scales of interest in this study.

A specialized system was used in the present study, which was developed at the Materials and Manufacturing Directorate, Air Force Research Laboratory. This system is capable of high magnifications, by light optics standards, and it is also capable of a wide variety of magnifications through combinations of various objective and photo-eyepiece lenses. Figure 1 shows the test set-up, which consists of a servo-hydraulic load frame and its controls (outside of area shown), with the specimen mounted in the usual position and a microscope system with a digital camera, which is capable of three-axes movement. Through combinations of various objective and photo-eyepiece lenses, a variety of magnifications are possible.

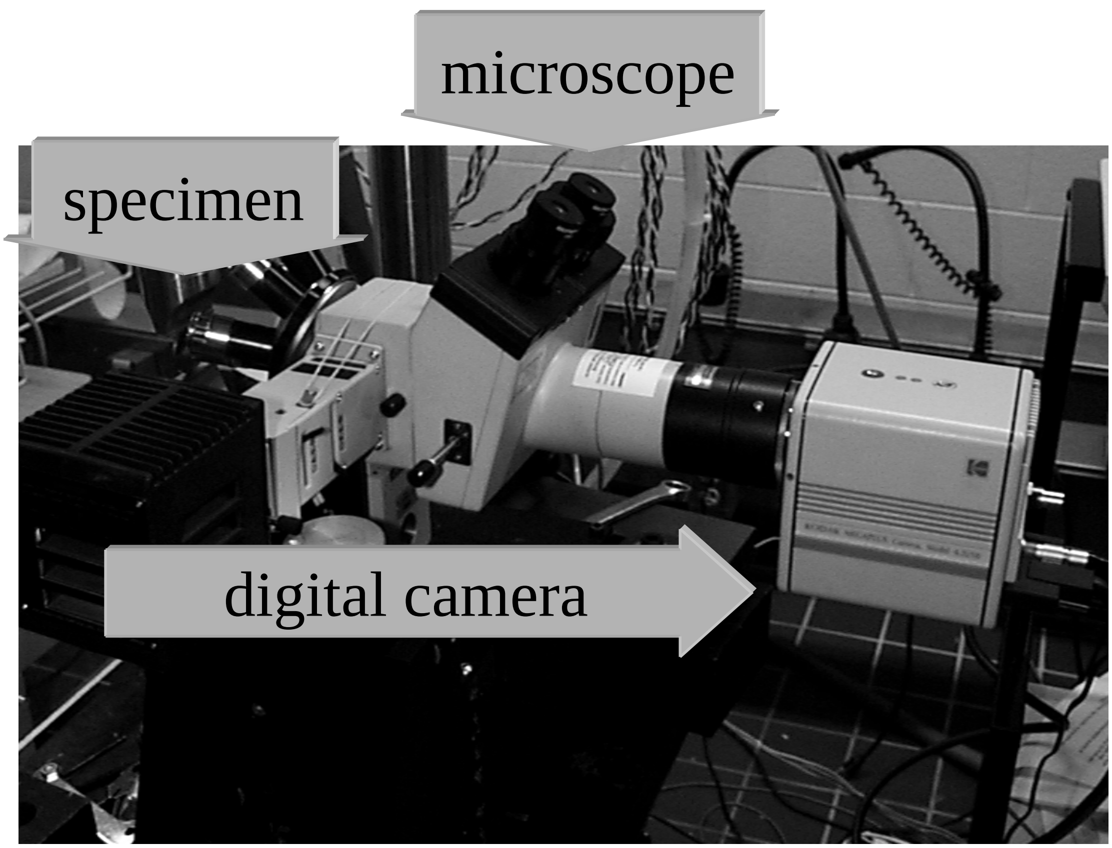

Figure 1: Test equipment.

Approach and Results

Figure 2 shows the specimen used in the study, which has a corner fatigue crack growing from one of the round notches. There is a starter notch on the corner, which was created through electrical-discharge machining (EDM).

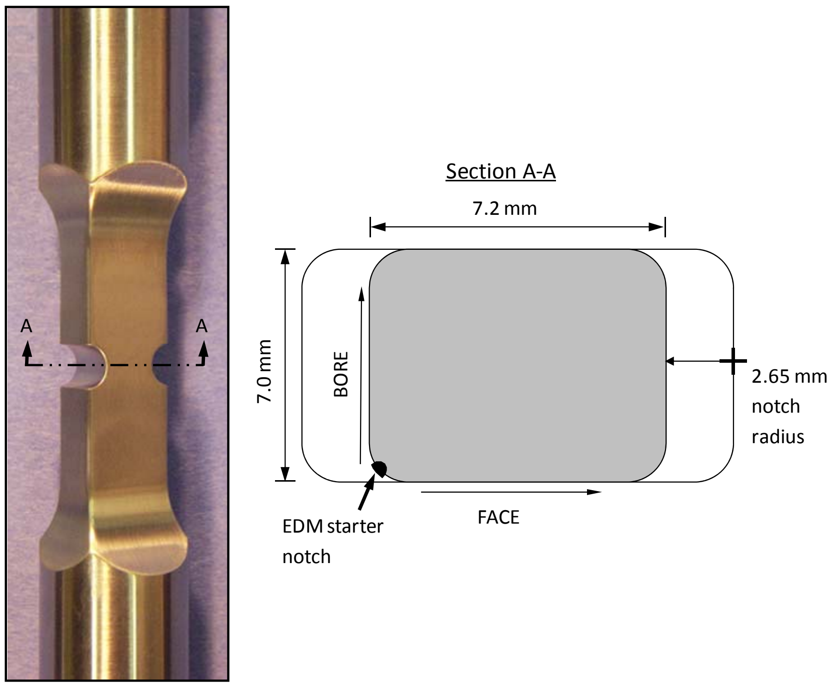

Figure 2 – Image of specimen and machine drawing of specimen geometry in region-of-interest.

The approach taken for this test is as follows. The specimen was shot peened, then a small quarter-circular starter notch was machined into the corner of one of the two larger notches through electrical-discharge machining (EDM), followed by growing a fatigue crack to the length shown. The goal was to minimize the redistribution of residual stresses associated with potential notch yielding and to advance the crack front away from the EDM notch. Figure 3 shows the surface of the specimen near the fatigue crack. At the top of the image, the end of the notch, from which the crack has been grown, can be seen. The test procedure is to acquire a first, reference image, and then acquire images while the specimen is under a series of different load conditions. Care needs to be taken to ensure that each image is spatially matched as closely as possible to the reference image. Because of stretching of the load-train, including the specimen, under load, the microscope is translated to keep the region-of-interest in view and match the reference image spatially. In addition to the motion in the loading direction, there is a limited amount of motion in the transverse in-plane direction. Images are acquired at various load levels in order to study nonlinear behavior.

Figure 4 shows a series of deformation maps, acquired at various load levels, after processing with the specialized DIC algorithms which enable calculations of displacements very near cracks. In each case, the displacement in the loading direction, *v*, and the displacement in the normal to the loading direction, *u*, are shown as surface plots. It should be noted that since the crack is not parallel to either the *x*-axis or *y*-axis (where the *y*-axis is in the loading direction and the *x*-axis is its in-plane normal), the difference in displacement across the displacement discontinuity, or crack, which appears to be a “cliff,” is neither crack-open displacement (COD) nor crack-sliding displacement (CSD), which would need to be measured perpendicular to or parallel, respectively, to the direction of cracking at each point along the crack. With this caveat, it is still useful to observe this behavior, because it does give a general idea of the level of displacement discontinuity across the crack. It is possible to calculate a "full-field" crack-closure level, by comparing this level to the level which would be predicted by a linear interpolation of the displacements at maximum loading. For example, if the displacement difference across the displacement discontinuity at 50% of maximum load is only 40% of the corresponding difference at maximum load, it indicates that there is crack closure. It is also possible to measure closure across any two points lying on either side of the crack.

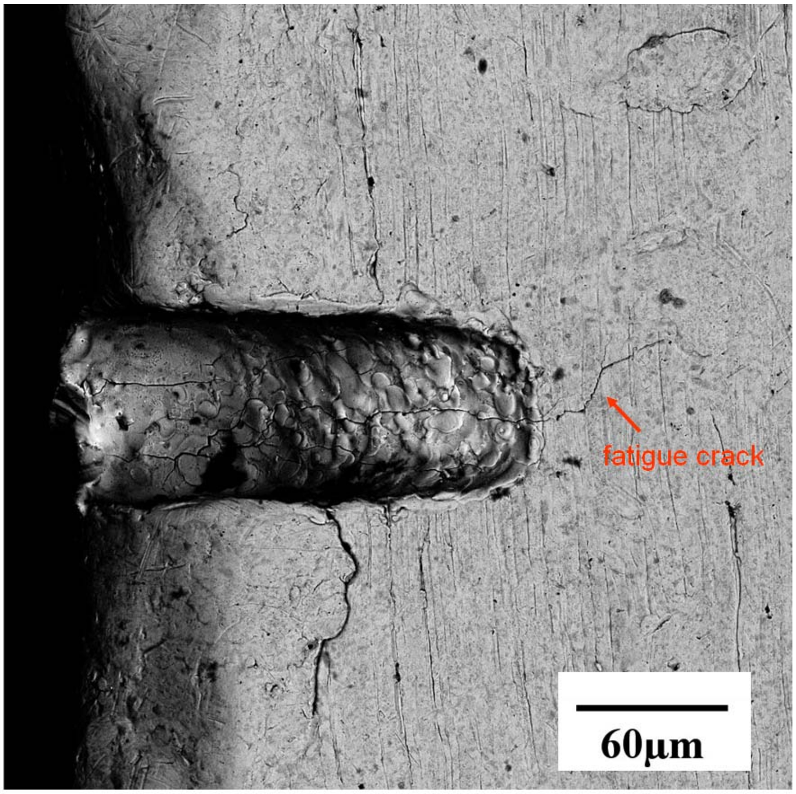

Figure 3 - Small starter notch and fatigue crack

The purpose of the present study is to compare the deformations determined before a thermal exposure of the specimen to those determined afterwards. It is expected that the residual stresses caused by the shot peening will be reduced through annealing by this thermal exposure, which should result in larger displacements at maximum load. Figure 5 shows that this is indeed the case. For this figure, all displacements are determined at the same maximum load. The top two surface plots show the displacement, *v*, in the loading direction and the displacement, *u*, in the normal to the loading direction before thermal exposure and therefore with the original residual stresses induced by the shot peening. The bottom two surface plots show the corresponding displacements after thermal exposure and therefore with reduced residual stresses. The overall average displacement magnitude of the after-thermal-exposure case is 194% of the average displacement magnitude of the before-thermal-exposure. This is obviously a significant increase, representing a significant reduction of residual stresses caused by the thermal exposure. Through comparison of this information with modeling results, it is possible to estimate the initial surface residual stress and the decrease in residual stress after simulated service conditions.

The great advantage of the method is that it can estimate residual-stress levels and changes by studying one of the most important mechanisms from an engineering perspective affected by residual stresses, which is crack behavior. By exposing the specimen to various levels of shot peening, thermal exposure, and mechanical loading, it should be possible to study a variety of important issues in the area of residual stress. In addition, it is possible to study the important effect of thermal exposure and mechanical loading on crack-closure levels.

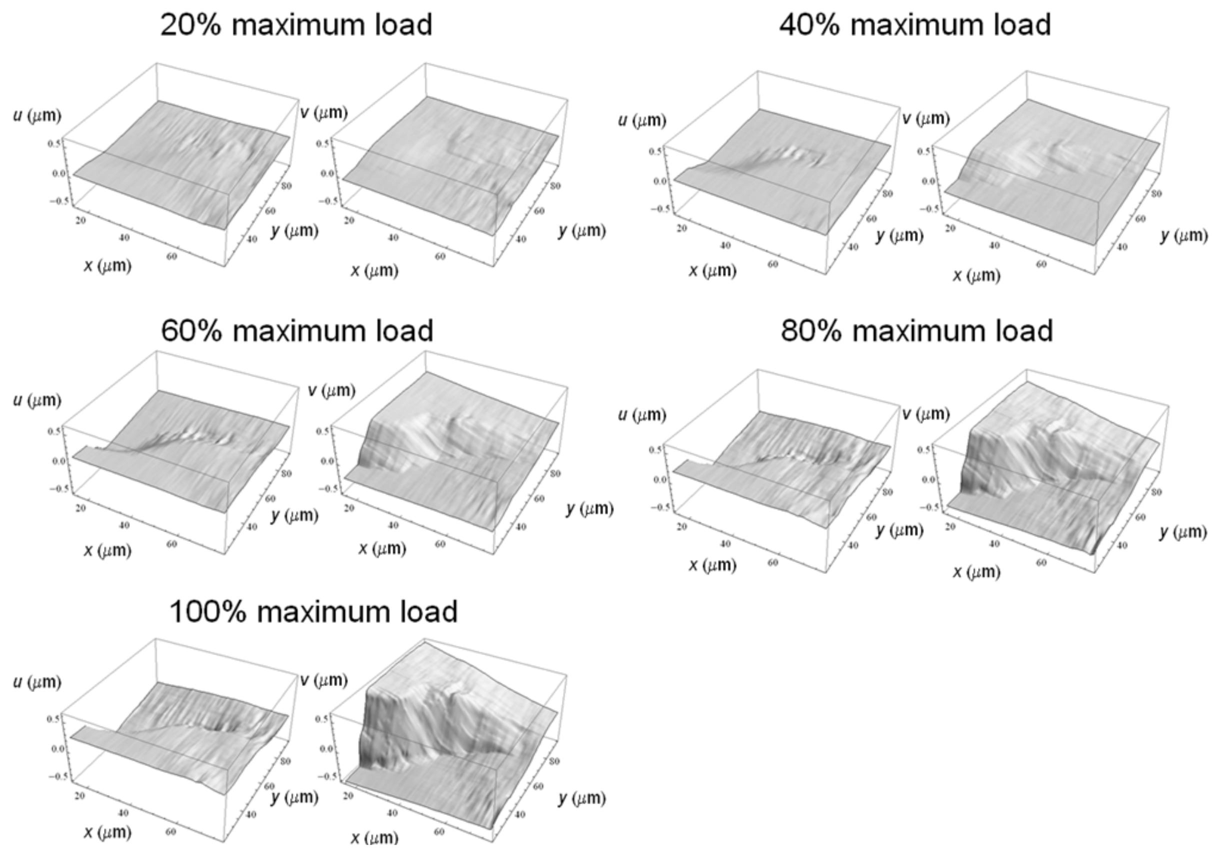

Figure 4 - Deformation maps at various load levels.

Conclusions

The effect of service environment on beneficial induced compressive residual stresses is not well understood. The present study demonstrates a very promising method for quantitatively determining this effect. The great advantage of the method is that it can estimate residual-stress levels and changes by studying one of the most important mechanisms affected by residual stresses, *viz.,* crack behavior. By exposing the specimen to various levels of shot peening or other surface treatments, thermal exposure, and mechanical loading, it should be possible to study a variety of important issues in the areas of residual stress and crack closure. Further work is on-going to correlate these important experimental results with numerical modeling of the specimen and the residual stress state.

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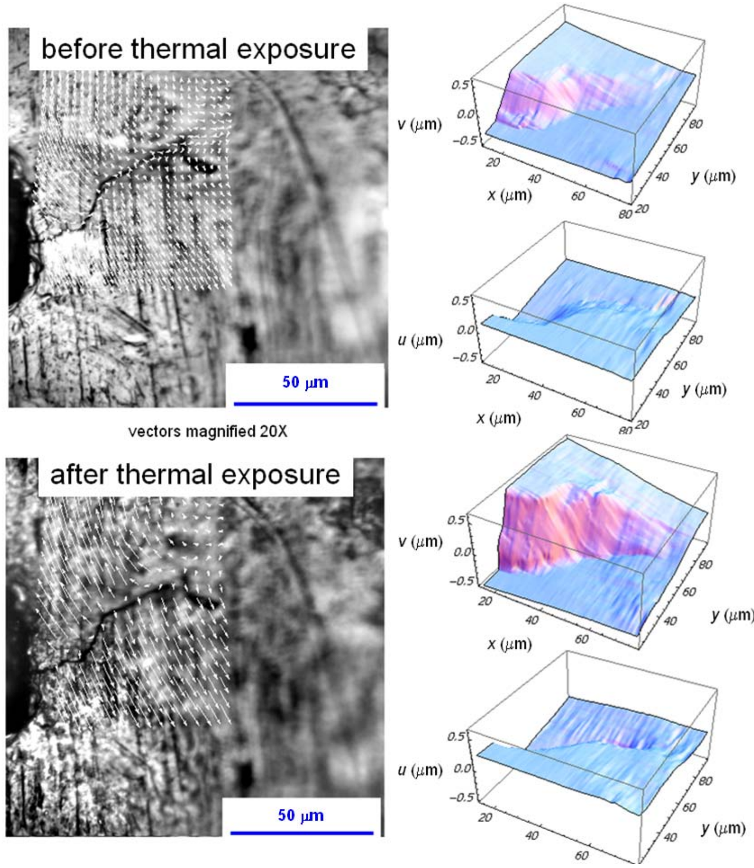

Figure 5 - Comparison of deformation maps before thermal exposure (top) and after thermal exposure (top).

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