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Measurement of Fatigue Cracks by Nondestructive Testing

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ABSTRACT. Detection of cracks in metallic specimens subjected to fatigue loading by nondestructive inspection techniques is demonstrated. In the experimental phase of this study, standard rod specimens were fatigue loaded. The tests were performed at different constant stress amplitudes at room temperature. To measure crack size, the specimens were removed from the testing machine after certain number of load cycles and were nondestructively inspected via ultrasonic, eddy current and X-ray techniques. In this way a measure of the crack width and depth as function of the applied load level and number of cycles was obtained. A brief review of the methods of nondestructive inspection of fatigue cracks is also given. Advantages and disadvantages of the different inspection techniques are discussed. It is concluded that the ultrasonic inspection is the most reliable method.

1. Introduction

Nondestructive testing (NDT) techniques are used in a variety of industries for evaluating the structural integrity of critical components in a noninvasive manner. NDT in various forms has been used for many years to detect defects which are detrimental to the in-service performance of components[1-5]. Considerable cost savings and improvements in reliability have been achieved by using NDT techniques to predict fatigue life of structural components[6-11].

In particular three NDT methods are most common in the assessment of geometry and the detection and location of flaws in structures. These are ultrasonic, X-ray and eddy current techniques. The major aspect in using these methods is related to defect characterization.

The ultrasonic technique has been used extensively in this field. It has been used to detect cracks[12], to measure crack depth[13,14], to investigate fatigue crack growth[15,16] and to characterize materials in general[17-20]. In addition, some theoretical studies regarding ultrasonic inspection technique have been carried out. Ogilvy[21], for instance, has put a model for ultrasonic inspection of defects, while Perdijon[22] has applied statistics to assist in acceptance decision making in ultrasonic testing.

X-ray inspection technique, being a more difficult procedure, has been used in much less studies. Hadden[23] has investigated the use of radionuclides for inspection, while Murphy *et al.*[24] and Daum *et al.*[25] have studied automated X-ray inspection procedures.

Eddy current technique has also received less attention as far as material inspection is concerned. Burke and Rose[26] have used the technique with thin plates, while Wittig[27] has studied crack detection on riveted joints. Junger and Brook[28] have offered some guidance about using eddy current technique.

The present research paper concentrates on the investigation of the three selected nondestructive inspection methods and their important role in detecting damage in mechanical and structural components. Through nondestructive testing techniques it is possible to detect damage and monitor it in order to take a decision as to when a certain component should be repaired or replaced. This report contains details on fatigued specimens tested nondestructively, using the three selected methods, to detect fatigue damage. Scanning electron microscopy is also used here as a verification tool of failure modes.

2. Experimental Procedure and Results

The material studied in this investigation was aluminum alloy of commercial quality, the chemical composition of which is given in Table 1. The material was supplied in the form of long bars of circular cross section. Since the properties of the material were not known, it was necessary to carry out characterization tests. The complete experimental program consisted, therefore, of the following consecutive steps :

TABLE 1. Chemical composition of the experimental aluminum alloy specimens.

Material	Percentage
Aluminum	98.41 %
Copper	0.04 %
Iron	0.42 %
Manganese	0.43 %
Magnesium	0.63 %
Zinc	0.03 %
Chromium	0.04 %

1) Nine standard tension test specimens were manufactured from the long bars and then tested under static tension conditions using an Instron 1197 universal testing machine. The average results for the mechanical properties obtained are as follows: modules of elasticity, E = 71.25 GPa, yield strength (0.2% proof), σ_y = 340 MPa, and ultimate strength, σ_u = 414 MPa.

2) Fatigue test program was then conducted to establish the *S-N* curve for the test material. The *S-N* curve represents the life of the material (counted in number of cycles

to failure, N) under certain applied stress amplitude. The fatigue tests were performed on a rotating beam fatigue testing machine (model Fatigue Dynamics RBF-1500) using a standard test specimen as shown in Fig. 1. Bending moment was applied to the test specimen while rotating, which resulted in completely reversed cyclic stress.

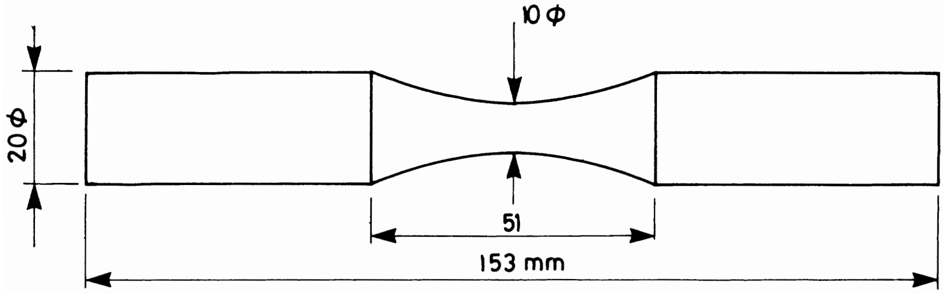

FIG. 1. Test specimen.

Each specimen was subjected to certain bending moment until it failed. The maximum stress, σ_m , was calculated from its relation with the bending moment, *i.e.*, $\sigma_m = Mr/I$, where M is the bending moment, r is the radius of the circular cross section, and I is the second moment of area of the cross section ($I = \pi r^4/4$). The number of cycles to failure was read on the machine. The resulting S-N curve is shown in Fig. 2.

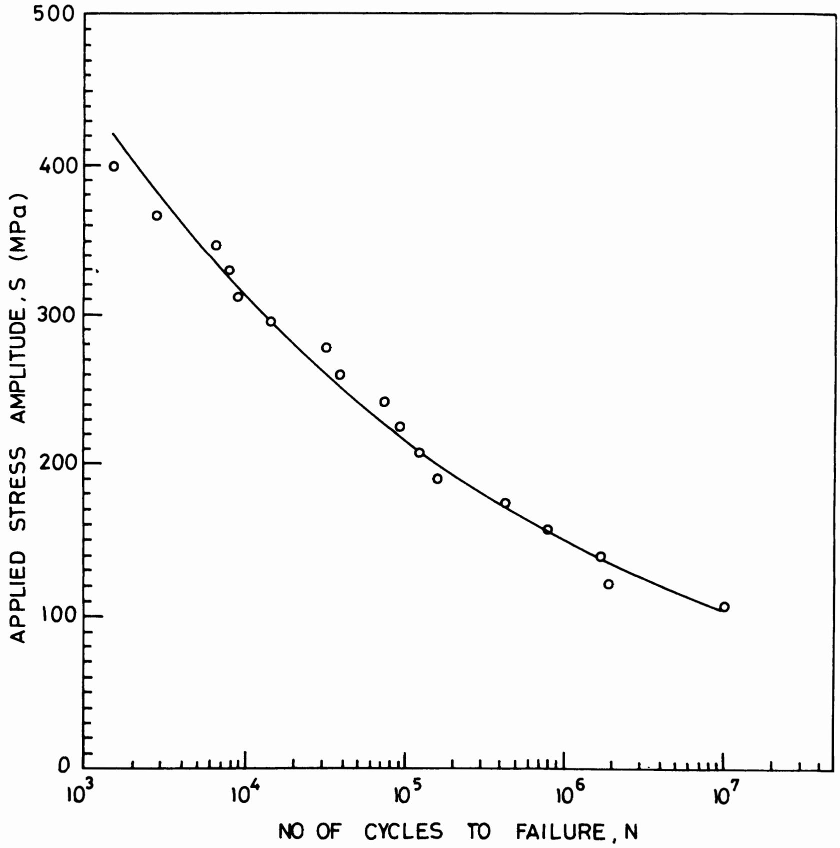

FIG. 2. S-N curve for the material tested..

3) Sixteen virgin specimens similar to the one shown in Fig. 1 were then manufactured for the main investigation in the present work. These specimens were first inspected using both X-ray and ultrasonic techniques to make sure that they were free from cracks or other defects prior to any testing. They were all found to be so. The specimens were then subjected to cyclic loading conditions on the rotating fatigue machine, but they were not taken to failure. Rather, each specimen was subjected to the fatigue loading to a number of cycles equals to more than 90% of its life (as taken from the *S-N* curve) to ensure that cracks had already initiated and started to propagate.

4) All the specimens were then inspected using radiography first. One of the specimens was X-rayed few times to determine the amount of radiation needed to show the crack[29]. The following values for the circuit parameters were found to give good result: voltage = 100 kV, current = 4 mA, and time = 120 s.

The films obtained from inspection showed presence of cracks in all the test specimens. Figure 3 shows a photograph of one of the X-ray films where the crack can be seen clearly. It was not possible to measure the crack size from the X-ray films.

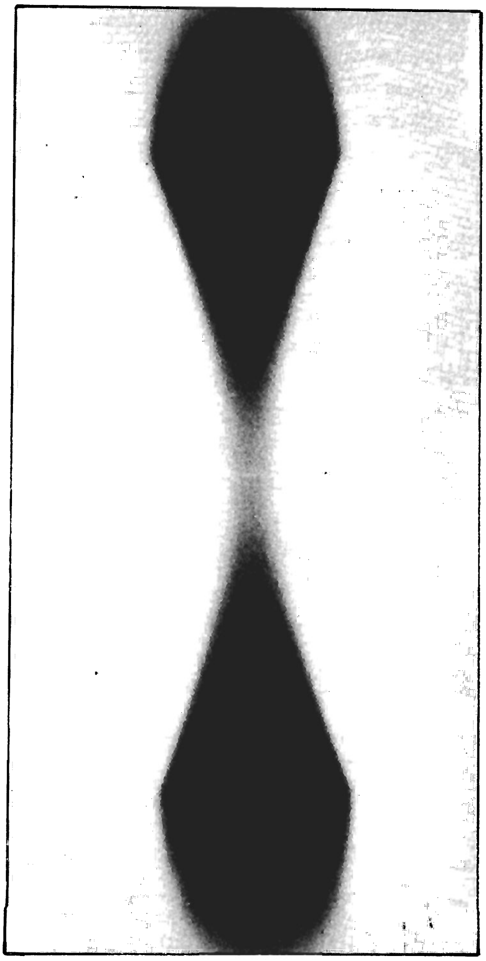

FIG. 3. Photograph of the X-ray film.

5) The width of the crack, Fig. 4, was measured by using TV camera and projector (type Talyvis) and the results obtained are given in Table 2.

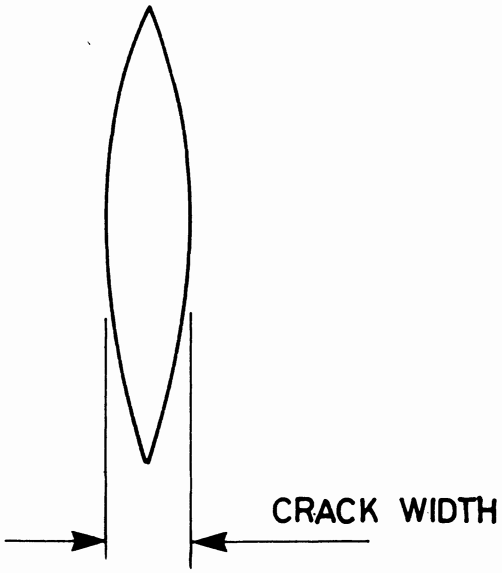

FIG. 4. Crack width.

TABLE 2. Results of measurement of crack size.

Specimen no.	Maximum stress (MPa)	No. of cycles of fatigue loading	Crack width (μm)	Crack depth by ultrasonic (μm)	Crack depth by eddy current (μm)
1	400	1,950	20	130	150
2	366	2,650	25	140	150
3	346	5,950	10	100	100
4	329	6,850	20	260	300
5	312	8,100	15	170	200
6	294	13,900	20	230	250
7	277	28,950	40	700	800
8	260	29,000	15	160	200
9	242	41,000	30	470	500
10	225	87,800	40	520	700
11	208	100,900	35	510	600
12	190	151,600	45	780	890
13	173	350,800	10	130	200
14	156	735,000	30	380	500
15	139	1,570,500	15	120	200
16	121	1,690,000	20	110	100

6) The second nondestructive inspection technique used was ultrasonic inspection. UJ Reflectoscope was used for this purpose with an edge probe. Discontinuity indications were compared to a standard reference with known crack size (measured by laser equipment). The results of crack depth measurements are given in Table 2.

7) The third nondestructive test used was eddy current technique. The instrument used was Forster-Deflectometer H. Here again a standard reference of known crack size was used. Any crack in test specimens caused a deflection in the pointer of the instrument proportional to the depth of the crack. The results obtained are given in Table 2.

8) Finally, scanning electron microscopy was used to inspect the fracture surface. Figures 5-7 are micrographs of the region of the immediate vicinity of the crack, starting from low magnification in Fig. 5 to high magnification in Fig. 7. These micrographs reveal that numerous secondary cracks exist and the fracture surface exhibits a quasi-brittle character in general. Also the small dimple size (about 10 micrometers) round the crack is indicative of brittleness.

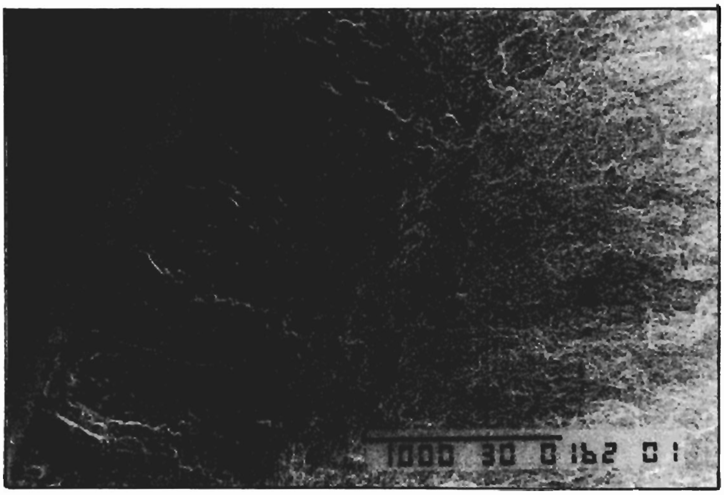

FIG. 5. Micrograph of a test specimen (low magnification).

3. Discussion

The evaluation of structural components durability and reliability is dependent upon having the capability to characterize defects and subsequent defect growth to fracture. The main objective of this investigation was the evaluation of methods of detecting damage in metallic structural components.

The three NDT methods of inspection which are studied in the present paper were all found effective to investigate cracks and crack propagation in structural components. However, the three methods differ from each other in many ways as far as crack detection is concerned, not to mention the principle of each of them.

Although radiography detection technique has some advantages such as providing permanent test record and its ability to detect cracks in areas not accessible for visual inspection, it was found to have the following limitations: 1) It is expensive (in equipment and supplies), 2) Too many precautions must be taken into account due to the fact that X-rays are very damaging to human body, 3) Repeated tests must be done in order to determine the amount of radiation needed to show the cracks (in general higher voltage is needed for material of higher density and for thicker specimens), 4) Results are dependent on the inspection direction (in general better results are obtained when examination is done in the direction of the shorter dimension), and 5) More than one shooting (with some overlap) may be needed to cover inspection of an area of certain dimensions.

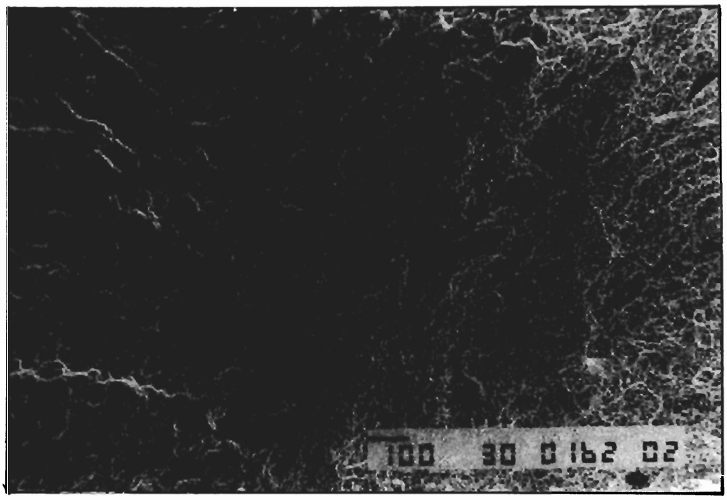

FIG. 6. Micrograph of a test specimen (medium magnification).

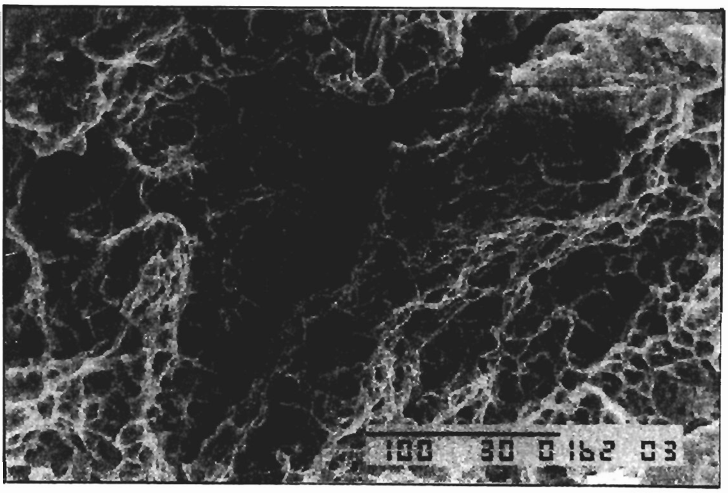

FIG. 7. Micrograph of a test specimen (high magnification).

Eddy current inspection technique was found simple, fast and efficient method, but required skill. It is also found to be sensitive to small cracks and provides immediate, but not reviewable, results. When there is a crack in the specimen there will be a change in the flow of eddy current due to variation in conductivity within the cracked region. This will cause deflection in the pointer of the instrument. This deflection is proportional to the crack depth. Eddy current technique for detecting and assessment of damage was found to provide useful information. However, this technique is suitable only for conductive materials, *i.e.*, metallic materials, and not applicable to thick-walled structures.

Ultrasonic inspection technique was found to possess the following advantages: 1) It provides immediate results, but, as in the case of eddy current technique, not reviewable, 2) It is also sensitive to small cracks, 3) It can be used to detect small defects in subsurface, and even behind large defects, 4) The material under inspection does not have to be conductive (in fact inspection can be carried out on almost all types of materials), and 5) There is almost no restriction on the thickness of the inspected piece (a thickness up to 9 meters is reported to have been inspected, whereas a thickness of 0.15 m can be regarded as upper limit for radiography). However, there are some limitations for ultrasonic inspection method such as the surface of the inspected part must be accessible to the test probe, and there is interference between the echo coming from the roughness of the surface of the inspected part and the echo of the crack.

The micrographs indicate that the fracture of the specimens is brittle in nature. This observation is supported by the fact that no crack was detected until the specimens reached approximately 90% of their number of cycles to failure.

It is believed that early fatigue damage is more widespread throughout the test section of the specimens with many small damage sites. Later fatigue damage is probably the result of agglomeration of many small origin sites to form a dominant defect which propagates very rapidly. This hypothesis is strengthened by the presence of numerous secondary cracks as shown in the micrographs.

In all the nondestructive testing methods used no damage other than the fatigue cracks were noted. It is also noted that the measurement results of the crack depth by both eddy current and ultrasonic techniques are comparable. However, ultrasonic seemed to show the most promising damage detection technique.

4. Conclusion

It appears that there are many indications of fatigue damage in mechanical and structural components, which can be explored to develop in-service detection scheme. X-rays, eddy current and ultrasonic inspection methods have proved to detect damage at early stages. Each one of these systems is technically feasible for the in-service damage detection. However, there are disadvantages associated with each procedure. Thus it is suggested that more than one method have to be used together to get the advantages of multiple methods at the same time. Some of the disadvantages may be overcome with sophisticated equipment, at additional expense. For inspection of damage after fatigue loading ultrasonic inspection technique is probably one of the most useful methods, at least as a research tool. There are other configuration-sensitive aspects, which should be investigated by additional research effort. These aspects include fatigue behavior of welded, bolted or riveted joints and the applicability of damage detection to such joints.

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مراقبـــة شـــروخ الكلال بوساطـة الاختبـــارات غـير المتلفـــة

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المستـخلص . تمت في هذا البحث عـمليـة الكشف عن الشـروخ الناتجـة في عينات معدنية خاضعة لأحمال كلال ، وذلك بطرق الكشف غير المتلفة . وقد تمت التجارب على عينات قياسية من الألومنيوم تم إخضاعها لأحمال كلال مختلفة القيمة تحت ظروف درجة حرارة الغرفة . ولمراقبة نمو الشروخ ، تمت إزالة العينات من آلة اختبار الكلال بعد عدد معين من دورات التحميل ، ثم تم الكشف عليها بثلاث طرق من طرق الكشف غير المتلف ، وهي : الكشف بالموجات فوق الصوتية ، والكشف بالتيارات الدوامية ، والكشف بالأشعة السينية . وتم بهذه الطرق قياس عرض وعمق الشروخ كدالة لمقدار الحمل وعدد دورات التحميل . كما تمت في هذا البحث أيضًا مراجعة طرق الاختبار غير المتلف في الكشف عن الشروخ الناتجة من الكلال ، وتمت مناقشة مزايا ومساوئ كل طريقة . ونتيجةً لذلك ، فقد تم التوصل إلى أن طريقة الكشف بالموجات فوق الصوتية هي الطريقة الأكثر اعتمادية من باقي طرق الكشف غير المتلف .