A NOVEL FABRICATION TECHNIQUE FOR PRESCRIBED INTERIOR CRACKS IN A METAL

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INTRODUCTION

One of the major concerns in nondestructive evaluation (NDE) is the detection and characterization of cracks in structural materials. In the development of NDE methodologies, laboratory samples containing known flaws are very useful for the experimental verification of models and algorithms. Simulated flaws made to specific design serve to check the correctness of various aspects of an NDE technique under development. In addition, model flaws are also used in the calibration of nondestructive testing equipments. A familiar example is the ubiquitous flat bottom hole test blocks.

Surface-breaking cracks may be simulated by electrodischarge machine (EDM) notches produced in a metal or by fatigue cracks grown from a starter notch. Interior cracks in metals are much more difficult to produce. A diffusion bonding technique\(^1\) has been used in the past for fabricating interior cracks in titanium alloy and in IN100. Either a simulated crack (often in the shape of a pillbox) is machined in one of the surfaces before bonding or an unbonded area is created using yttria powder. The diffusion bonding procedure is very time consuming and expensive. Moreover, the machined "cracks" are often too thick to be realistic and the yttria crack may resemble a powder inclusion. Nonetheless, such simulated interior cracks have served useful purposes in the development of ultrasonic NDE techniques in the recent past\(^2-3\).

In a research project conducted at Ames Laboratory on flaw reconstruction using a multiviewing ultrasonic technique\(^4\), laboratory samples containing different types of flaws (voids, inclusions and cracks) of various size and shape are needed. An effort to produce interior flaws in metals has led to a novel method for fabricating interior cracks of prescribed shape, size and orientation in iron. The cracks produced are only a few micrometers thick and the procedure is quite simple and inexpensive. A variety of crack geometries may be produced, including nonplanar, bifurcated cracks, or cracks with simulated partial contacts.
The fabrication method for interior cracks is based on a powder metal­lurgy (P/M) technique. Iron powders of nominal -100 mesh (with 34% of the particles less than 44 micrometers) are first placed in the die of a press. The powder is packed down by applying a light load. A copper foil, about 0.005" thick and cut to the size and shape of the desired crack, is placed flat on the packed powder. The foil is then covered by more iron powder and a load of 40 Tsi (tons per square inch) is applied at ambient temperature to produce an iron slug. The slug is removed from the press and sintered at a temperature of 2050°F (above the melting point of copper) for 30 minutes in a furnace. After removal from the sintering furnace, the slug is cold-pressed again to a load of 50 Tsi. This procedure was found to produce a crack a few micrometers in thickness and of identical lateral size and shape as the original copper foil.

TESTING OF INTERIOR CRACKS

The existence of the cracks and their size and shape are confirmed in the following manner. First, a 0.5"x0.5" square crack was produced at the center of a 1" thick and 2" diameter P/M iron disk. The crack surface was parallel to the flat faces of the sample. A 1"x0.25"x0.25" square post was then cut with a low speed diamond saw from the center of the iron disk. The square post fell apart into two pieces upon completion of the cutting. No copper was observed on the exposed surfaces by the naked eye. Next, a 1/8" diameter circular crack was produced at the center of a sample of similar size and a square post containing the crack was cut from the sample. This post was loaded into a tensile test machine and pulled apart. The fracture occurred at the crack and the fractured surfaces indeed showed a 1/8" diameter circle, as shown in Fig. 1.

Prior to destroying the samples, ultrasonic tests were made to examine the interior cracks. Figure 2 shows two frequency spectra of broadband ultrasonic pulses produced by a 10MHz, 1/4" diameter transducer. Spectrum A is for a pulse reflected at normal incidence from the 0.5"x0.5" interior crack located 1/2" below the surface. Spectrum B is for a pulse reflected at normal incidence from the back surface of a 1/2" thick slab of the same P/M iron material. The fact that the two spectra are nearly identical again confirms the existence of a flat crack with no surface contacts. The interior cracks showed no observable transmission of sound energy.

Fig. 1. Photograph of an interior crack 1/8" in diameter in P/M iron, taken after the specimen was pulled apart to reveal the crack.
Fig. 2. A comparison of the spectra of two ultrasonic pulses: (a) a reflection from an interior crack 1/2" below the front surface of a P/M iron sample, and (b) a reflection from the backwall of a 1/2" thick blank P/M iron sample.

The 1/8" circular crack was examined ultrasonically at an oblique incidence of 16° in the solid. The transducer (again 1/4" diameter) was scanned across the crack as shown in Fig. 3. The crack signals show the expected phase reversal associated with the two tip diffractions. In the middle position shown in Fig. 3, two pulses of opposite polarity are seen because the sound beam is broader than the crack.

Fig. 3. Ultrasonic pulse echo signals from a 1/8" diameter crack in P/M iron as the transducer (1/4" diameter) was moved laterally from position A to position C. The incident angle was 16° in the solid when measured from the vertical.
The acoustic impedances of copper and the P/M iron were found to be quite close. The P/M iron has a longitudinal sound velocity of 0.557 cm/µs (as compared to 0.596 cm/µs for Armco iron\(^7\)) and a mass density of 7.48 g/cm\(^3\) (as compared to 7.85 g/cm\(^3\) for Armco iron\(^7\)). The acoustic impedance of P/M iron is therefore 4.32 g/cm\(^2\) µs. For rolled copper\(^7\), the acoustic impedance is about 4.47 g/cm\(^2\) µs.

To demonstrate the ability for producing cracks of arbitrary shape, a copper foil was cut into the shape of a head and a 1/8" diameter hole was punched as an eye, as shown in Fig. 4. Using the new technique, this foil was turned into an interior crack of the same size and shape in an iron slug. An ultrasonic C-scan image of this crack, also shown in Fig. 4, shows that the size and shape were indeed maintained.

PHYSICAL PROPERTIES OF CRACKS IN P/M IRON

The mechanism for crack formation in the P/M procedure described above is believed to be as follows. After the copper foil is melted during sintering, the liquid copper is drawn away from its original location and into the adjacent voids of the porous powder metal matrix by capillary action. Some of the liquid copper then diffuses into the iron particles. The reasons that the thickness of the crack is much less than the original thickness of the copper foil are not totally understood. It is probably a combination of the flowing of solid copper during the first cold pressing and the reduction of the crack cavity thickness caused by the final pressing.
Metallographic examinations were made on sectioned and polished samples containing interior cracks. Figure 5 shows photomicrographs of portions of the crack at two different magnifications. The P/M iron matrix is about 95-96% dense and therefore contains 4-5% voids. Etching of the surface, at a location away from the crack, revealed that the grain size was of the order of 40 μm. The crack surfaces created by flat copper foils were found to be quite smooth. Figure 6 shows a surface profilometer trace of an exposed crack surface.

Fig. 5. Left--Photomicrograph of an interior crack in P/M iron at 80x magnification. (The total length of the crack was 1/2\".)
Right--The same crack at 1000x magnification.

Fig. 6. Profilometer trace of the crack surface roughness Y in μm. The lateral distance X is expressed in mm.
Neither the surface sectioned perpendicular to the crack nor the exposed crack surfaces showed the color of metallic copper. At high magnification (1000x), small droplets of copper metal approximately 5 \( \mu \text{m} \) in size sparsely dispersed in the matrix were observed. Etching the surface cut perpendicular to the crack in Nital revealed a band of "copper affected zone" approximately 4-5 millimeters wide and centered on the crack as a different shade of grey. An order of magnitude estimate of the copper diffusion distance \((Dt)^{1/2}\) using \(D = 10^{-4} \text{ cm}^2/\text{sec} \) and \(t = 1800 \text{ sec}\) gave 4 mm as the length of diffusion. This is of the same order of as the observed size of the copper affected zone. The distribution of copper was also examined with a scanning electron microscope. The SEM photomicrograph (Fig. 7) shows that copper had diffused partly into some of the iron grains near the crack and caused such grains to be surrounded by a copper affected layer. Energy dispersion spectrum taken at the center of an iron grain (Fig. 8a) showed no traces of copper, while the spectrum taken in the copper diffused layer revealed copper peaks (Fig. 8b).

DISCUSSION

The powder metallurgy technique for producing interior cracks in iron can be used in the fabrication of any desired crack shape and, to a reasonable lower limit, size. The cracks produced are very tight, about 50 times thinner than EDM notches, and apparently have no surface contacts or asperities. Nonplanar cracks such as a bifurcated (Y-shaped) crack have been produced with this technique to simulate intergranular stress corrosion cracking (IGSCC). With this capability, surface breaking cracks of different configurations can be easily achieved by first making an interior crack and then machining the sample to expose the crack. Crack geometries not possible with EDM notches, such as a crack smaller at the opening and larger under the surface, can be produced. Cracks with simulated partial contacts and with bridging of the surfaces have also been made using this method for ultrasonic and eddy current investigations.

Fig. 7. Scanning electron micrograph showing copper partially diffused into iron grains near the crack (indicated by arrows). Light grey regions are iron, and black regions are voids.
Fig. 8 (a) Elemental analysis using the SEM revealed no copper in the interior of an iron grain (dark grey region in Fig. 7).

(b) Copper peaks were observed in the copper diffused outer layer of iron grain (light grey region in Fig. 7).

Interior cracks produced in this manner have obvious advantages over flat bottom holes commonly used as simulated cracks for ultrasonic NDE. The flat bottom holes can simulate cracks only for normal incidence, while the tight interior cracks in P/M iron may be tested at any incidence angle. The porosity in the matrix does increase the ultrasonic attenuation, but not to a prohibitive level. The presence of copper near the cracks did not seem to pose any problem in ultrasonic applications. The precipitated copper droplets are very small in size and their acoustic impedance is closely matched to that of the host.

Preliminary results have been obtained in controlling the crack thickness by varying the press and sinter sequence and the sinter temperatures. Applications of this technique in other metals and ceramics are being explored. The same technique can of course be used in producing inclusion flaws and, with appropriate fabrication parameters yet to be optimized, also volumetric voids. This technique is expected to have wide applications in a number of NDE methods including ultrasonics, eddy current, magnetics and radiography.
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