STP462-EB/Jan. 1970

DISCUSSION

S. S. Manson[1] *and C. R. Ensign*[1] (*written discussion*)—The papers by Impellizzeri and by Morrow et al have emphasized the importance of residual stresses in their analyses of cumulative fatigue damage. Their comments concerning some recent tests of ours, in which residual stresses caused some extraordinary effects, would be welcome.

Figure 1 shows the technique that we are using to examine the effect of residual stresses in our two-stress-level rotating-bending fatigue tests. In the polished hour-glass-shaped specimens, we have ground a slotted notch with a stress-concentration factor of approximately 3. The sketch of Fig. 1 shows how residual stresses are introduced. A specimen is subjected to n_1 cycles at a high stress level and then the load is removed and the rotation stopped. The specimen is next positioned so that the slotted notch is perpendicular to the direction of the applied load and another half cycle of the same load is applied in plane bending. The specimen is then run to failure in rotating bending at a second and lower stress level, and we record n_2, the number of cycles to failure.

Figure 2 shows results of a series of two-stress-level tests using 7075-T6 aluminum. Each plot gives the fraction of life remaining at the second stress level, $n_2/N_{f,2}$, *versus* $n_1/N_{f,1}$, the number of cycles applied at the first stress level expressed as a fraction of the expected (median) life. The first plot (*a*) shows that, for widely spaced stress levels (65 to 20 ksi), compressive residual stresses introduced after a fatigue crack has been initiated at the root of the notch can lead to very long remaining lives at the low stress level. Note that this effect increases, as the damage at the first stress level increases, and can reach a life of over one hundred times longer than might be predicted by the Miner summation set equal to unity, which is indicated by the dashed line. The fracture surfaces of the particular specimens giving results of $n_2/N_{f,2} >$ 100 showed that the crack which initiated at the notch propagated through the compressive residual stress field to failure. For the two specimens with only 6 or 7 times the expected life, however, the crack growth was arrested by the residual stress and the failure resulted from cracks which eventually initiated on the polished surface of the specimen, opposite the notch. The

[1] Chief and Materials Research Engineer, respectively, Materials and Structures Division, NASA-Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

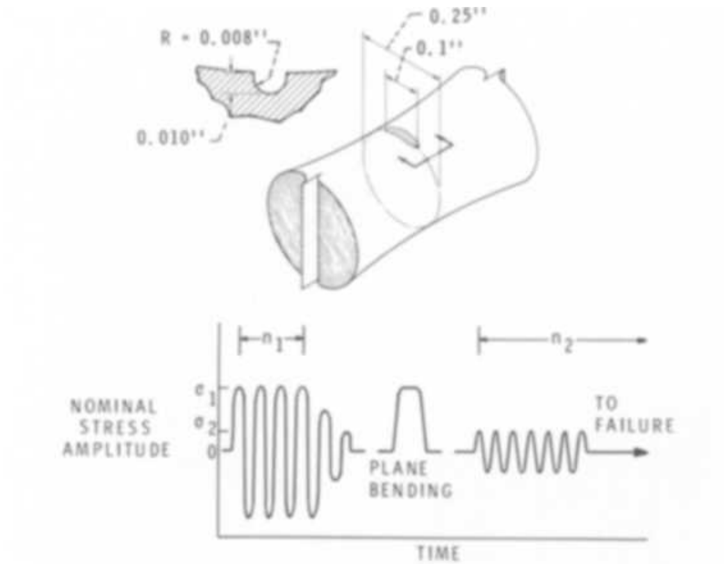

FIG. 1—*Test techniques for residual stress tests.*

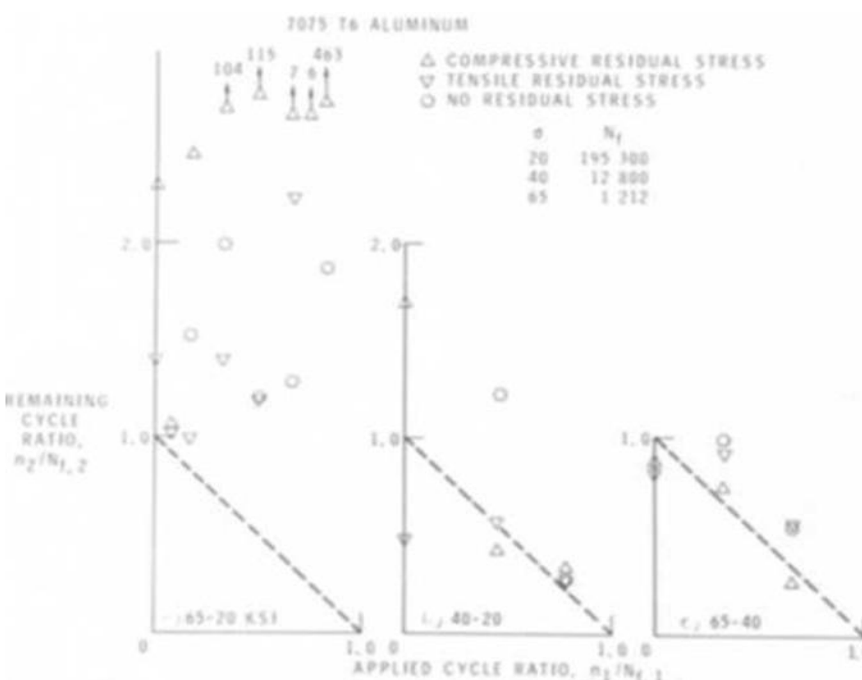

FIG. 2—*Residual stress effects with 7075-T6 aluminum.*

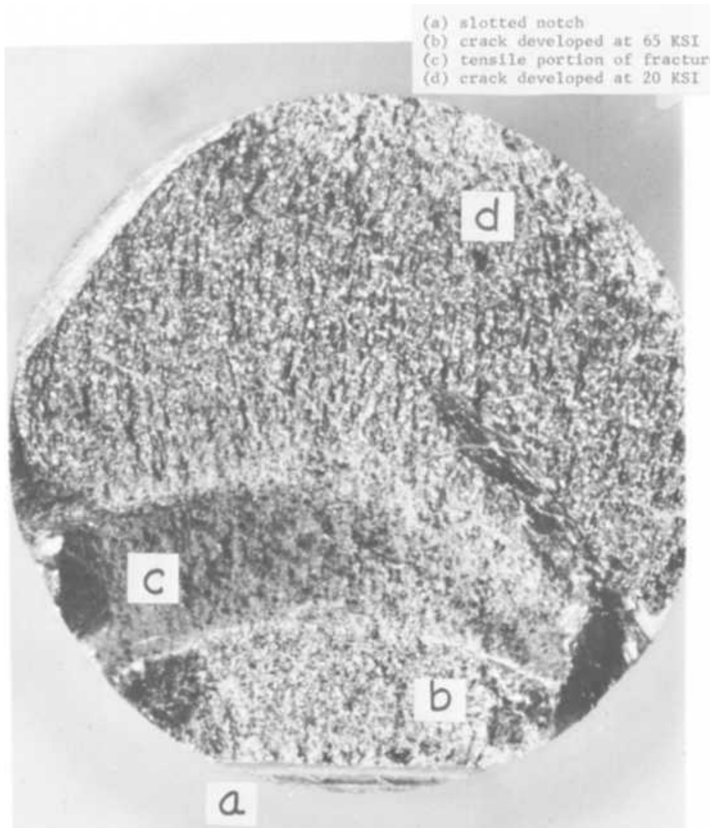

FIG. 3—*Crack growth from notch completely arrested by residual stress.*

fracture surface (Fig. 3) of one of these specimens shows the extent to which the crack emanating from the notch had progressed before it was arrested by the half cycle of bending stress.

Parts (*b*) and (*c*) of Fig. 2 show that the extreme beneficial effects of the compressive residual stress are not obtained if the stress levels are not widely spaced.

Another series of tests, using 4130 steel showed the same general effects of residual stresses, but the beneficial effect of compressive stresses was minor compared to the extreme results with the 7075-T6 aluminum. The compressive residual stresses with widely spaced test-stress levels (140 to 40 ksi), shown in Fig. 4, caused increases to only twice the expected life. For the 120 to 50 ksi stress levels the compressive residual stresses showed consistently little effect on the life. For both combinations of stress levels, the tensile residual stresses were detrimental.

In summary then, the main observations from these two-stress fatigue tests are:

1. With 7075-T6 aluminum, great increases in life at the second stress level can be achieved by the addition of compressive residual stresses after some damage at the first stress level. This occurs only when the first stress level is much higher than the second.

2. Increasing the damage done at the first stress level before the introduction of the residual stress, increases the beneficial effect of the compressive residual stress. That is, the larger the fatigue crack propagated at the first stress level, the larger will be the compressive residual stress field ahead of the crack caused by the addition of the half cycle of bending stress. Beyond a certain point, however, the crack becomes so large in relation to the cross section that the resulting residual stresses due to overload cannot stem further growth at subsequent cycling even at the relatively low stress level.

3. Materials behave differently in this respect, the 7075 aluminum alloy showing marked sensitivity to the residual stresses while 4130 steel shows much lower sensitivity.

L. F. Impellizzeri (author's closure)—The test results presented by Manson and Ensign are very interesting and emphasize the author's belief that the interaction effects of one stress level on another must be considered to provide any kind of reliable cumulative damage analysis. Their data further suggest

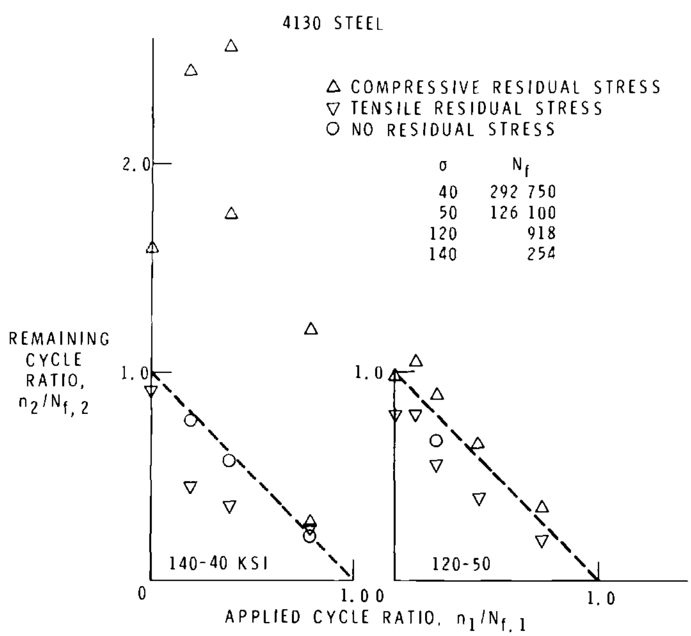

FIG. 4—*Residual stress effects with 4130 steel.*

that it might be advisable, at least in some instances, to account quantitatively for the effects of crack growth in computing residual stress levels.

The qualitative trends exhibited by the rotating-beam test results are generally as would be expected. For example, the data show that the beneficial effect of the first load level is less pronounced when the second load level is increased. This is simply a result of the residual stress magnitude produced by the first load level being reduced in relation to the second load level. In fact, it would be surprising if this trend were not evident since obviously the beneficial effect must disappear altogether when the second load level is increased to the point where it equals the first load level. The test results in the discussion also show that the beneficial effect of the first load level is greater after it has produced a small crack. This could be explained by a larger compressive residual stress being introduced because of the higher stress concentration of the crack as compared to the original notch. This trend is reversed when the crack introduced by the first load level becomes large.

Manson and Ensign note that two of the rotating beam specimens failed from a crack originating on the side opposite the notch. Examination of the fracture surface indicated that the crack on the notch side had not restarted after being arrested by the compressive residual stress field. Three other specimens tested in a similar manner failed as would be expected from the crack originating at the notch. These three specimens failed at about 20 times the life of the first two specimens mentioned. It is probable that the cracks away from the notch started at some small surface imperfection which would explain the lower life. Had they been given more time, the cracks at the notch would have surely restarted. It would have been interesting to determine when the cracks at the notch did restart on the three long-lived specimens. This could have been done with the electron microscope. Tests performed at MDC provided results similar to those of Manson and Ensign. A specimen with tapered interference fit fasteners installed failed at a particularly long life through a crack emanating from surface scratches caused by the fastener washer. Apparently, the beneficial residual stress due to the interference fit decreased the notch effect of the hole to such an extent that minor surface scratches became the most fatigue-critical item.