DISCUSSION

L. F. Coffin, Jr.[2]

Low cycle fatigue design for pressure vessels is gradually being recognized as a necessary step to assure their safe performance during service life. For nuclear applications and other situations where cyclic operation is frequent, this consideration is essential. Accompanying design is the equally important need for information regarding the response of the material to cyclic plastic strain. The present paper serves a useful purpose in this connection.

The authors have considered the effects of cyclic plastic strain on the subsequent ductility and crack formation for two pressure vessel steels. The writer would like to make several comments regarding this investigation.

First, use of equation (2) should be restricted to cases where plastic strain and total strain are equivalent, i.e., for strain ranges greater than 3 percent and for cyclic lives less than 500. For many practical design situations, the plastic and elastic strains may be of the same order of magnitude. As the plastic strain range becomes small relative to the elastic strain range, the error in equation (2) becomes large. To avoid confusion and error on the part of the designer, the limitations of equation (2) should be more strongly emphasized. Second, in equation (2) the ductility term ϵ_f' is reduced by the amount of prestrain ϵ_0. A similar point of view was taken by the author some time ago, reference [20],[3] but attempts to support this behavior generally have not been successful. While prior cold work (a fixed prestrain) has been shown qualitatively to have the effect indicated in equation (2) for AISI type 347 stainless steel [21], it has also been shown that, in the case of OFHC copper and 1100 Al, prior cold work was completely washed out by cyclic plastic strain and there was no effect of prestrain on fatigue life [22]. In the tests reported in the present paper, and in particular, in Fig. 6, the prestrain is not a fixed value, but a variable quantity bearing a fixed ratio to the total strain range chosen for a particular test. This means that the prestrain decreases to insignificantly low values as the total strain range decreases (as is reflected in the high cycle end of Fig. 6). Consequently it is difficult to draw any real conclusions regarding the role of prestrain until tests employing fixed prestrain are made. From the tests performed to date, then, the equation given in Fig. 7 properly reflects the experimental evidence presented regarding prestrain, but equation (2) does not.

The results indicating the remaining fracture ductility as a measure of fatigue damage from prior cyclic plastic strain bear a close similarity to tests conducted by the writer [23] on AISI type 347 stainless steel. It is interesting to note that in both sets of experiments, some small increase in ductility can be detected if a relatively few cycles of strain are imposed prior to tension testing. The reason for this effect remains obscure. In the writer's tests thin walled tubes were used and these showed a much greater sensitivity to the presence of small cracks than solid specimens in subsequent tension tests. However, the technique of subtransition temperature tensile tests would appear to be an equally sensitive technique for determining the degree to which cracking has occurred.

The fact that fatigue cracks can be produced early in the life in low cycle fatigue tests, raises the question as to the role played by cyclic plastic strain on the transition temperature of pressure vessel steels. This is a question of real concern in pressure vessel application, and particularly where radiation induced elevation of the transition temperature enters into the picture. The authors have clearly demonstrated the presence of cracks after one third of the cyclic life. The influence of these cracks on the transition temperature is also of interest.

Additional References

20 L. F. Coffin, Jr., "Design Aspects of High-Temperature Fatigue With Particular Reference to Thermal Stresses," TRANS. ASME, vol. 78, 1956, p. 527.

21 L. F. Coffin, Jr., and J. H. Read, "A Study of the Strain Cycling and Fatigue Behavior of a Cold Worked Metal," International Conference on Fatigue of Metals, Inst. Mech. Eng., London, 1956.

22 L. F. Coffin, Jr., and J. F. Tavernelli, "The Cyclic Straining and Fatigue of Metals," *Trans. Metallurgical Society*, AIME, vol. 215, 1959, p. 794.

23 Reference [5], pp. 931–950.

H. Majors, Jr.[4]

The authors have reported the results of their many studies on low cycle fatigue in a concise form which represents a large cooperative effort at Syracuse University.

Is any significance attached to the subsequent strain direction after the tensile mean strain (prestrain) was obtained? Have prestrains been applied under biaxial stress conditions? Were any tests performed under a negative prestrain?

Figs. 6 and 7 show two methods of plotting strain-controlled low cycle fatigue data. Is there a preference in the method of plotting?

The technique of the authors for following the progress of damage during strain cycling by observing the static tensile properties at −320 F and room temperature is a good one. A similar procedure was employed by Grossman and MacGregor[5] but the authors centered their interest on the influence of prior fatigue cycling on the shift of the brittle transition temperature as detected by the slow notch bend test. This shift is reported for a range of strain rates. Did the authors conduct the tension tests as initial elastic strain rates of the same magnitude as those rates for the strain controlled tension-compression tests?

All fatigue curves in Figs. 6 and 7 are in the region 0 to 400 cycles of strain reversal. Is it implied that the influence of the mean strain or prestrain is small beyond 1000 cycles of strain reversal in a plot of total strain range versus cycles to failure?

Authors' Closure

The authors are grateful for Dr. Coffin's pertinent comments. His long-standing efforts in this area and his close association with practical problems in pressure vessel design lends weight to the need for consideration of low cycle fatigue phenomena in the design of pressure vessels.

It was assumed throughout the paper that the error in using total strain instead of the plastic component is negligible for the strain ranges considered. With respect to the effects of prestrain and the equations reported in Figs. 6 and 7, it should be pointed out that these equations are mathematically identical to equation (2). Accordingly, parallel lines with a slope of $-1/2$ would be expected from fixed prestrain experiments, as is shown by Coffin and Tavernelli [22]. A representation such as the one chosen for the present paper, where the ratio $\epsilon_{\min}/\epsilon_{\max}$ is held constant, leads of necessity to curves rather than straight lines for any strain ratio different than −1 in both a log ϵ_{TR} versus log N as well as a log $\epsilon_{\max}$ versus log N representation. The general mechanisms of prestrain and their subsequent effects on life under strain cycling remain obscure and may be washed out rather rapidly in certain materials, as shown by the discusser.

The thesis that the presence of cracks may in turn affect the measured fracture ductility after partial cycling has also occurred to the authors and is expressed in terms of the reference to the

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[3] Numbers in brackets designate Additional References at end of this discussion.

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[5] Grossman and MacGregor, "Significance of Transition Temperature in Fatigue," W. M. Murray, editor, Fatigue and Fracture of Metals, M.I.T. Technology Press and John Wiley & Sons, Inc., New York, N. Y., pp. 229–251.

interdependence of both the strain exhaustion and the crack growth process. The metallurgical effects caused by strain cycling and radiation damage may well raise the transition temperature, especially since with the advent of cracks the material is now subjected to a plane strain state at the tips of these cracks. This has been shown by the authors in another paper [24]. The authors agree with the discusser, that this is an area of serious concern which warrants further studies.

A number of pertinent points have been raised by Professor Majors some of which point toward urgently needed studies. In this category are studies on the effects of prestraining direction relative to fatigue straining direction, the effects of biaxial prestrain, and the effects of negative prestrain. The prestraining of wide specimens in bending with subsequent bend cycling, reported elsewhere [6, 25], can be regarded as a study of prestraining and testing under plane strain conditions. There are also test results available on the effects of prestraining in tension on subsequent cycling in bending. Of the materials studied, the effects of increasing biaxiality to a plane strain condition are to reduce the life for a given strain amplitude. However, the effects of biaxiality fade out rapidly (similar to those of prestrain) and become insignificant at approximately 1000 cycles.

The authors have no preference as to a presentation of low cycle fatigue data according to Fig. 6 or Fig. 7. The tensile tests at −320 F were conducted at the same strain rate as the fatigue cycling.

The authors are grateful for Professor Majors' discussion. His remarks concerning the effects on the transition temperature are taken up in the authors' reply to Dr. Coffin's discussion.

Additional References

24 V. Weiss and J. G. Sessler, "Analysis of Effects of Test Temperature on the Notch Strength of High Strength Sheet Alloys," ASTM STP No. 302, 1961.

25 V. Weiss, J. Sessler, and P. Packman, "Low Cycle Fatigue of Pressure Vessel Materials," Final Report to the Atomic Energy Commission, Contract AF(30-1)-2141, June, 1962.