or from more complex chemical reactions. In the simple form, it may appear as rust formation in a moist atmosphere at ambient temperature; various coatings are effective preventives. At high temperatures in either air or steam environments, steel materials are also subject to formation of a surface oxide scale causing a gradual loss of effective load-carrying wall thickness. If the corrosion rate is not too high, an adequate design precaution may be merely to provide some extra wall thickness or corrosion allowance in the original construction. Vessels intended for long-time service may not find this an economical solution, and it may be necessary to use a more resistant alloy. This can often be done by selecting an alloy the initial corrosion of which forms a more stable oxide layer on the surface. Chromium is recognized as one of the most useful alloying elements for improving resistance of steels to high-temperature oxidation. This type of corrosion is apparent from surface inspection of the affected material, and if noted in time, may permit some corrective action to extend the service life to the desired value.

Another form of corrosion which may reduce service life shows itself in embrittlement, or a drastic reduction of strength and ductility in the affected areas. Hydrogen embrittlement of carbon steel may occur under local areas in which a dense scale has been formed by improper water treatment; the steel under this layer is penetrated and decarburized by hydrogen evolved by the corrosion. In boiler service the remedy is improved water treatment to prevent the initial corrosion. In some petroleum or chemical processing where a substantial partial pressure of hydrogen is inherent, selection of a more resistant material (e.g., a steel alloyed with a certain percent of chromium) may be required. Caustic embrittlement may be encountered in crevices or local areas in which the concentration of caustic can occur. Embrittlement effects are not as readily detected by surface inspection of equipment, but can be demonstrated (when present) by metallurgical examination of suspected sections or by mechanical property tests on specimens taken from the material after service.

A third form of corrosion of vessel materials is stress-corrosion cracking. Regions of high tensile stress are susceptible to development of cracks which may propagate through the vessel wall, or reduce the effective thickness enough to cause failure. Useful steps to prevent this include stress relief to reduce residual stresses from forming or welding operations. Reduction of stress concentrations by care in design and fabrication is important, as is elimination of notches or crevices in which concentration of corroding agent can occur. Suitability of particular vessel material and fluid combinations can only be judged by experience. For example, the austenitic stainless steels, which have outstanding corrosion resistance to oxidation and embrittlement, are particularly susceptible to stress-corrosion cracking in the presence of chloride (or other halide) ions in water containing oxygen above a small amount. Visual inspection of a vessel surface, supplemented by magnetic powder or fluid penetrant examination, may be used if occurrence of this type of cracking is suspected but this cannot be considered complete assurance. In general, the preferable approach is to select a material which has been found by successful experience to be not susceptible to this type of attack in the fluid environment involved.

Power boilers are an example of a type of equipment in which long life is expected and usually achieved, in spite of numerous corrosion effects. The drums and large headers of modern water-tube units are kept outside of the gas stream to protect them from difficulties with coal-ash or oil-ash corrosion. Such corrosion may constitute a severe economic problem in some portions of the tubing comprising the heating surface, but does not cause a safety hazard. Internal or water-side corrosion in boilers is adequately prevented by deaeration and control of water chemistry. In these circumstances, ordinary carbon steel gives entirely adequate length of life at service temperatures up to about 800 F. At the higher temperatures encountered in superheater tubes and headers, a succession of higher-alloy steels is used for a combination of creep-rupture strength and resistance to oxidation. Approximate limits of these capabilities have been established by experience for several widely used alloys such as the chromium-molybdenum steels and the austenitic stainless steels, and similar information is being developed by trial service of sample tubes of newer materials.

There have been instances in which corrosion damage to materials has occurred during other than regular service. Inadequate control of acid-wash procedures can lead to localized corrosion never encountered in the same equipment in service. Storage of parts or long layup of equipment without precautions can cause a variety of troubles from condensation or atmospheric contamination.

One only partly recognized problem is the considerable influence which some environments, even those usually considered noncorrosive, have on such mechanical properties as fatigue strength. There are indications that fatigue behavior in water may differ significantly from results of laboratory tests in air. There are also indications that the extent of such discrepancies may be greater with high-strength materials (or with materials *used* at a higher stress level than past experience), but considerably more work is required before definite conclusions can be drawn.

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DISCUSSION

J. V. Mullin[3]

This paper presents a very broad discussion of failure modes encountered in pressure vessel design. One very significant fact concerning fatigue failure is worthy of note. Even in pressure vessels having long lives the cycles of loading are numbered in the hundreds or thousands. Clearly, this falls into the range of low-cycle fatigue and substantial saving in material can be obtained when the strains are allowed to exceed the yield point. Of course this requires detailed knowledge of the material behavior under low-cycle fatigue loading.

The pressure vessel represents a biaxial state of stress in fatigue, yet the design formulas such as equation (3) are concerned with only one of the principal stresses. Certainly, the fatigue behavior of a material under a biaxial stress state can be expected

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to differ in some respects from the uniaxial behavior. It would seem advisable then, to initiate test programs to obtain information on fatigue under these conditions.

It must be noted also that equation (3) is described as a development arising from equation (2). However, equation (2) is based on *completely* reversed axial strain-cycling data. This condition can never be approximated in a pressure vessel, since it is always subjected to *mean* strain by the very nature of the load mechanism. Thus, unless a satisfactory relation can be developed between mean strain and strain range under biaxial loading, the extension of Coffin's theory to pressure vessel fatigue is at best a rough approximation.

A recent study by A. J. Kennedy[4] has shown that creep strains are considerably increased when accompanied by cyclic loading. This is especially true in the presence of high temperature. It would seem then, that rather than static creep tests, dynamic creep tests should be conducted to examine the most critical creep condition.

Another point worth discussion is the rate of cycling in fatigue. The data collected in most fatigue studies are for cyclic rates much higher than those occurring in pressure vessel use. At high temperatures, the cyclic rate has been shown to exert considerable influence on fatigue life. Thus, the extension of fatigue concepts developed by Coffin, for example, have questionable value when applied to the very low rates of loading encountered in pressure vessel fatigue.

R. E. Peterson[5]

The authors show in Fig. 10 some estimates of the K_f factor for disk shaped cracks as given in one of my papers.[6] These factors seem reasonable for alternating (completely reversed) stressing as might be attained for severe thermal cycling. A word of caution, however, may be in order for other conditions. For a zero-to-maximum (pulsating) situation, as might be due to pressure cycles, a large factor would seem to be appropriate. In the latter case, the crack is open during the entire cycle, while in the completely reversed case, the crack is closed on the compression side. Tests by Frost [11][7] show that for a member with a crack the limiting fatigue range in the completely reversed case is about twice that of the pulsating case (i.e., practically no stress concentration effect of the compression side of the alternating test). The word of caution is that, unlike the case of an open notch, one must consider that for a member with a crack, K_f can vary significantly as a function of mean nominal stress.

The K_f values estimated in Fig. 10 are based on the assumption of failure when the elastic curve reaches the fatigue limit at a depth δ beneath the surface. The fatigue limit is usually somewhat lower than the yield strength or yield point, but since the elastic curve is used, it would be expected that, if the above method is applicable, it would be limited to the high cycle region. In the inelastic region, the stress concentration factor decreases and the strain concentration factor increases. For low cycle fatigue it would seem that the strain concentration factor would govern; this means that an estimate made using the lower elastic factor would be on the unsafe side. Examination of an example[12] worked out using strain concentration factors instead of the elastic stress concentration factor indicates that the life in the low-cycle region would be lowered by a factor of about 3 for geometries having $K_t = 1.8$ and $K_t = 3$. Since a factor of safety on life of 20 is used in pressure vessels, the effect of the above would be to reduce this to about 7 in this instance.

The two effects discussed in the foregoing are not firmly established experimentally for various kinds of steel. Some scattered data seem to be in reasonable agreement. More extensive tests especially planned to concentrate on these effects are needed.

Additional References

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Authors' Closure

The authors are appreciative of the highly pertinent comments which Messrs. Mullin and Peterson have made regarding the design methods for low-cycle fatigue.

Mr. Mullin suggests test programs to evaluate the effects of biaxiality, mean strain, dynamic creep, and cyclic rate. He will be glad to know that these phenomena have not been neglected in the formulation of the rules for fatigue design in Section III of the ASME Code. The effects of biaxiality have been introduced by means of the maximum shear stress theory of failure and recent tests by the Pressure Vessel Research Committee (not yet published) have confirmed the validity of this approach. The PVRC is also conducting tests on the effect of mean stress and mean strain, and preliminary results also confirm the validity of the corrections made in the Section III fatigue curves to account for these effects. Section III, in its presently published form, does not cover temperatures at which creep or cyclic rate are important factors, but Code Case 1331 does give some tentative rules and fatigue curves for these higher temperatures. The fatigue curves of this Case contain allowances for cyclic rate based on presently available data and the PVRC has a program scheduled to start in 1964 which will provide more data.

Mr. Peterson's points regarding the choice of fatigue strength reduction factors are well taken. His first point, regarding the opening and closing of cracks in complete reversal of stress, is applicable only during the crack propagation, not the crack initiation, phase of the phenomenon. Even though the allowable stresses are based on failure data, it is to be expected that the safety factors used will actually prevent initiation. Similarly, the safety factors used for primary and secondary stresses should preclude any gross yielding and thus prevent the appearance of a fatigue strength reduction factor significantly higher than the theoretical stress concentration factor. Mr. Peterson's warnings illustrate how important it is in the detailed analysis of a low-cycle fatigue failure to (*a*) consider the strain range at the point of failure; and (*b*) separate the failure process into the two phases of initiation and propagation. The design methods now used are only conservative approximations and will hopefully be refined when more data become available.

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[6] See authors' reference [10].

[7] Numbers in brackets designate Additional References at end of paper.