discussions and assistance with J. J. Murphy and H. M. Soldan are deeply appreciated. Finally, the author would like to acknowledge the technical ingenuity and able assistance of J. H. Read of the Knolls Atomic Power Laboratory, who contributed to the experimental phase of this investigation.

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Discussion

A. R. C. Markl.[7] While already inherent in the rules on "expansion and flexibility" of the 1942 Code for Pressure Piping,[8] the concept of the stress range as criterion of failure of piping under restrained cyclic thermal expansion was first openly recognized in the 1955 Code. By that time a considerable body of evidence had become available on the role of the stress range in fatigue caused by *mechanical* cycling, most of this being derived from room-temperature tests. In formulating the Code rules, it was realized that behavior under *thermal* cycling; i.e., the case where mechanical strains are induced by fully or partially restrained thermal expansion and contraction, would probably not be entirely the same; but in the absence of pertinent test data it was reasoned that the over-all effect would not be too dissimilar to permit applying the same laws. This point of view was supported, or at least not refuted, by favorable experience with design of high-temperature piping installations on this basis extending over a period of 25 years. The present investigation was instituted to provide a more scientific check of its validity.

The author is to be highly commended on the ingenuity of his test setup, the excellent results obtained therewith, and their clear presentation; this paper should prove of great interest to everyone concerned with fatigue of metals. In the writer's opinion, however, he has not carried the interpretation of his data far enough to establish proper correlation with the information on which the Code rules are based. In the following, the writer will attempt to supply the missing link.

From the standpoint of the piping-flexibility analyst, the gist of the paper is contained in Equations [8] and [9]. As the author has pointed out, these equations agree well with Equation [1] with respect to the exponent, but rather poorly with respect to the constant.

In order to enable a more searching comparison, the writer has taken the liberty of modifying the author's equations by pivoting his straight lines (on a log-log plot) about the point corresponding to $N = 7000$ in such a manner that the slope is now defined by an exponent of 0.2 in all three equations. The value $N = 7000$ has been selected because it describes the highest number of cycles for which no stress-range reduction factor is required by the Code, and the exponent has been taken as 0.2 because the stress-range reduction factor has been approximately based on this value.

The writer further has introduced a stress-intensification factor i' in Equations [8] and [9] to take account of the fact that these have been derived from tests on highly polished specimens, whereas Equation [1] relates to pipe as installed in an average piping system.

As modified, the three formulas read as follows for AISI Type 347 stainless steel at 1050 F

$$SN^{0.2} = 367{,}000 \qquad [1a]$$
$$SN^{0.2} = 1{,}110{,}000/i' \qquad [8a]$$
$$SN^{0.2} = 899{,}000/i' \qquad [9a]$$

The important difference between the author's formulation and this reformulation of Equations [8] and [9] resides in the introduction of the quantity i' which requires further discussion. While i' is of the nature of a stress-intensification factor, it is *not* the same as the value i used in the Code; there a stress-intensification factor $i = 1$ is assigned to plain straight pipe joined to other pipe or fittings by a circumferential butt weld, or, in other words, straight pipe is used as the reference point for other shapes.

However, it has been shown by tests (5) that the endurance strength of plain pipe is not the same as that of polished-bar specimens taken from the same material, and that butt-welded girth joints introduce a stress-intensification factor of the average order of 1.6 as compared with plain unwelded pipe. While the trend of the *S-N* curve for polished bars does not parallel that for pipe or fittings, an over-all stress-intensification factor within ±25 per cent of a value of 2 has been found appropriate for butt-welded pipe with reference to polished bars; that this is about right, also can be reasoned from the fact that the stress-intensification factor for curved pipe in relation to plain butt-welded pipe as determined from bending-fatigue tests closely approximates

[7] Tube Turns, Louisville, Ky.

[8] Using symbols defined in the 1955 Code, the allowable combined stress due to bending and pressure in the 1942 Code can be expressed as $S_A + S_{lp} = 0.75f\,(S_c + S_h)$, where f, however, is not a continuous variable as in the 1955 Code, but jumps from 1 for normal operation directly to 0.5 for definitely cyclic operation.

one half the theoretical stress-intensification factor deduced from mathematical analysis. In practice, even higher stress-intensification factors may be obtained in the presence of weld defects.[9] If we adhere to $i' = 2$ as a reasonable average evaluation, the author's constants in Equations [8] and [9] would reduce to 555,000 and 450,000, respectively, in terms of the Code reference basis, as compared with 367,000 in Equation [1].

Assuming that the difference between 555,000 and 450,000 comes about through differences in behavior under mechanical and thermal cycling, as the author's investigation would tend to show, there still remains an unexplained difference between the latter value and 367,000. Not being familiar with the intimate details of either the author's or Stewart and Schreitz's tests (the latter being particularly difficult to interpret because of the many changes made in test conditions), the writer is not in a position to account for this residual difference. However, too close a correlation can hardly be expected considering the many differences (other than surface condition) between the two test series and the uncertainties attendant upon difficult control problems encountered in both:

1 The author's tests were run in direct tension and compression, Stewart and Schreitz's in bending.

2 The assemblies used in the two investigations obviously differed vastly in over-all elasticity.

3 In the author's tests the temperature across the thin tube wall may be assumed to have been reasonably constant; by comparison, Stewart and Schreitz's tests probably involved sharp temperature gradients, since their primary purpose was to uncover the effects of thermal shock. Moreover, both investigators admitted to difficulty in maintaining close temperature control.

4 The speed of cycling was different in the two test series, and it is likely that creep may have significantly affected the results of one series and not the other.

5 Finally, while the materials used were of the same general type, they were not necessarily identical as to physical properties, chemistry, or metallurgical conditions.

Summing up this study, it has been demonstrated that the author's Equations [8] and [9] and the writer's Equation [1a] can be brought into fair accord, if the constants in the former are corrected to the basis used for the latter by application of stress-intensification factors reflecting differences in surface condition and contour between the test specimens used in the two investigations from which the equations were derived. What differences remain would tend to indicate that Equation [1] errs on the conservative side, which would mean that the safety factor available in the Code rules as predicted by the writer (4)[10] for Type 347 at 1050 F represents a low estimate; it possibly does, but the writer would prefer to hold to it pending further evidence.

D. B. Rossheim[11] and J. J. Murphy.[12] This paper is a fitting sequel to the author's initial paper, reference (13) of the Bibliography, and provides an answer to the two questions listed in the "objectives" of the experimental program undertaken which could not be answered with certainty from the initial work. An understanding of the basic principles underlying the fatigue performance of metals under imposed cyclic straining in combination with temperature change is essential for the establishment of a meaningful design basis for all pressure equipment. The problem has been most acute in connection with the design of piping for expansion flexibility and the attention which has been focused upon it led to the rules for expansion and flexibility now incorporated in the ASA B31 Code for Pressure Piping. These rules are in an advanced status compared to the code rules for pressure and applied external loadings inasmuch as they alone treat the problem from a fatigue approach with consideration of the influence of high local stresses. These rules were developed by reasoning from available fatigue-test data at constant temperature, largely room temperature, and under applied mechanical strain.

The author's initial tests provided much-needed supporting evidence that cyclic strain induced by restraining thermal expansion could be treated in a similar manner to imposed mechanical strains and would cause fatigue failure. During the formulation of code rules, there had been some opinion that for high-temperature piping the period at high temperature would have a beneficial effect and either prevent fatigue damage or restore the material characteristics. Since these initial thermal-cycling tests induced compression at the high-temperature end of the cycle and tension at the low-temperature end, it was believed essential in the ASA B31 Code for Pressure Piping to check whether reversal of these conditions would affect performance; also to investigate the effect of variable strain range for a given temperature change, and to authorize the experimental extension reported in this paper.

The writers were privileged to be associated with the formulation of the program and its details and wish to congratulate the author on the proficiency and efficiency with which he carried out the program and for his clear and thorough presentation.

As a result we now know that, for practical purposes, we do not need to distinguish between compressive and tensile strains or between mechanical and thermally induced strains, and that the present ASA Code design approach is basically sound. The aim of this program was essentially qualitative to establish basic principles. However, the author has contributed an interesting comparison of his results with those of Markl in his Equation [8] and shows good correlation, except for the equation constant, when using a fictitious calculated elastic-stress basis. Surface conditions can explain part of the difference in the constant as pointed out in Markl's discussion. However, both Markl and the author could express their equations in terms of permissible strain range per cycle and a different constant. This would be decidedly preferable since strain range rather than stress range has been shown in these and tests by many other investigators to be the significant parameter for assessing performance in the plastic or plastic-elastic range. In deference to customary design procedures which evaluate stresses to elastic theory, assessment of expected performance by comparison of the calculated stress range to an empirical formula such as Equations [1] or [8] can be made even for fictitious stresses above the yield strength provided it is appreciated that the calculated values are then being used merely as an index of strain range.

While this program has yielded valuable basic data, it does not provide all the information needed for the design basis for high-temperature piping inasmuch as plastic flow (creep) with time at temperature will influence fatigue performance. At the present time, in the absence of fundamental test data for this effect which cannot be obtained from any short-time tests, the ASA Code Committee has established rules based on reasoning and have made the permissible stress range a function of the allowable stress at room temperature and the long-time allowable creep or creep-rupture stress. More basic data in this range are greatly needed.

While comments in this discussion and in the paper have been directed toward the usefulness of the fatigue approach in piping-

[9] See, "The Influence of Weld Faults on Fatigue Strength With Reference to Butt Joints in Pipe Lines," by R. P. Newman, Transactions of the Institute of Marine Engineers, vol. 78, June, 1956, pp. 153–172.

[10] See Table 1.

[11] Assistant to Vice-President, Charge of Engineering, The M. W. Kellogg Company, New York, N. Y. Mem. ASME.

[12] The M. W. Kellogg Company, New York, N. Y.

flexibility design, the basic data developed are broadly applicable to all equipment and will permit extension of the approach for design assessment of the influence of all types of cyclic loadings on equipment performance, a step which is fast becoming an absolute necessity with the advent of nuclear applications. The writers shortly expect to present a paper illustrating how this can be integrated into a co-ordinated design approach.

Author's Closure

The author wishes to thank Messrs. Markl, Rossheim, and Murphy for their discussions to this paper. Since they have for many years been active in the continuing study and improvement of the design basis for piping structures, the comments they have made in relating this paper to their fields of interest and competence are particularly appreciated.

There appears to be one point, brought up in both discussions, which requires further comment. This pertains to the interpretation of the results for the laboratory conducted tests given here, to those obtained for engineering structures. In particular the designer is interested to know the factors contributing to the difference between the results of these tests and those found in service, such that he can utilize this information more effectively. Actually it was not the intent of the investigation to determine such information, but rather, to obtain under carefully controlled laboratory conditions the effect of cyclic stress (or mechanical strain) and temperature. This objective, it is the author's belief, has been adequately stated in the paper and is further emphasized in the discussion of Messrs. Rossheim and Murphy. The effect of material, heat-treatment, surface condition, shape and size, type of joint, etc., all influence the results quantitatively. The test results given here have not been obtained with such variables in mind; these should be found from a program carefully formulated for that purpose. One fault of many experimental investigations is to make the objectives of the program so broad that severe dilution results and very little gain in knowledge is realized. It is to the credit of the Task Force that the objectives were limited sufficiently so that the desired results could be achieved.

Nevertheless, it is tempting to interpret the results in terms of engineering materials and service environments. Unfortunately, when dealing with a phenomenon such as fatigue, at best this can be done qualitatively. It is well recognized that fatigue is a highly selective process. Imperfections which escape normal visual inspection play a major role in the results obtained. Shape, prior history of the material, and corrosive effects of the environment act to increase the selectivity of the phenomenon. This is admittedly of little help to the engineer in search of design information; however, it is perhaps wiser to admit ignorance rather than to make an evaluation that might, because of that ignorance, result in misinformation.

In the experiments reported here, great care was taken to eliminate as many variables as possible which contribute to the selectivity of the fatigue process. Surface conditions and material quality are two sources for the difference between the present tests and those of Stewart and Schreitz (represented by Equation [1*a*]). Other possible causes for the difference are the effect of size (the results of Stewart and Schreitz were obtained on full-size pipe), uncertainty in calculation of mechanical strains, and the various items listed by Mr. Markl. Most of these factors would tend to bring the two sets of experiments closer together; the effect of direct stress versus bending would tend to increase the gap.