SUMMARY

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In summarizing the results of the Symposium on Effect of Cyclic Heating and Stressing on Metals it is convenient to classify the papers into two groups: cyclic effects on scaling resistance and cyclic effects on creep or rupture. This latter class can, in turn, be broken into three subgroups: effects with thermal stresses, thermal cycling effects without added thermal stresses, and finally, stress cycling effects.

In the class devoted to scaling resistance there was the one paper, by Messrs. Eiselstein and Skinner. The summarizing charts of weight change *versus* temperature with chromium and nickel contents as parameters are particularly worthy of note. It would appear that they are directly usable by the designer who is dealing with equipment subject to the rather common type of thermal cycle used.

Under the subgroup of thermal cycling effects with thermal stresses there was also a single paper—that by Coffin. He first considered rupture due entirely to repeated thermal stresses. Of particular interest was the comparison between the number of cycles to failure by straining alone and by thermal cycling to the same strain. Thermal cycling was found to be more detrimental.

Mr. Coffin also showed how to take uniform specimen data and apply it to at least two types of stress concentrations one might encounter, either from a particular design configuration or from material variations. He defined, in a general way, the series type and parallel type concentration. This classification could well be adopted generally throughout all work relating to stress concentration problems in engineering.

Of the remaining six papers, that by Miller discussed thermal cycling effects (without thermal stresses) on creep or rupture; the paper by Simmons and Cross discussed stress cycling effects; and the papers by Dorn and Shepard, Smith and Houston, Caughey and Hoyt, and Guarnieri discussed both. For the purpose of drawing some generalizations all six will be discussed as a group.

On the theoretical side Dorn and Shepard showed a quantitative method for calculating rupture time or creep under cyclic conditions. They based it on a physical theory of creep, also outlined in the paper, and applied it to one case, that of nickel tested over a moderate temperature range. Agreement with experiment was good.

A great deal of controversy is currently raging over various theories of creep and rupture including that outlined by Dorn and Shepard. However, several starts in the direction of explaining the creep or ruptures processes is much better than none at all; satisfactory answers will quite likely come from a synthesis of a number of such theories.

There is another theory for calculating

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rupture life or creep under cyclic temperature or stress conditions which, indirectly or directly, appeared throughout the group of six papers referred to above. It assumes first that stress or temperature cycles may be broken up into constant stress or temperature increments. Next the creep or fraction of rupture life for each increment, obtained from constant stress, constant temperature, creep and rupture data, may be summed up to give either the total creep after a given number of cycles or the rupture life when the individual fractional rupture lives add up to one. Robinson[2] was one of the first to propose at least the calculation of rupture life under cyclic temperature conditions by this method. It is obvious that, if correct, the above method of calculating high-temperature performance from constant stress-constant temperature data is an excellent way of handling the principal problem considered by this Symposium. It seems worth while, therefore, to examine the rather large volume of experimental data contained in the six papers from the point of view of the generalized Robinson method.

In the paper by Miller it was found that for the "super-alloys" S-816, M-252, 16-25-6, and A-286 thermal cycling to temperatures of 1800 F for M-252 and S-816 and lower for the balance gave rupture times reasonably well predicted by the Robinson method.

Smith and Houston found that thermal cycling up to temperatures of 1500 F with 18-8 and 1300 F with 18-8 Ti and 12 Cr, $\frac{1}{2}$ Mo gave creep rates greatly accelerated over those predicted by the generalized Robinson method, while lower temperatures resulted in rates predicted by the Robinson method.

[2] E. L. Robinson, "Effect of Temperature Variation on Long Time Rupture Strength of Steels," *Transactions*, Am. Soc. Mechanical Engrs., Vol. 74, p. 777 (1952).

Either repeated or single over-temperaturing of Inconel at 1700 to 1800 F was noted by Caughey and Hoyt to be detrimental to rupture life when compared to the Robinson prediction.

Guarnieri found that cycling between room temperature and some elevated temperature type 321 failed prematurely when the top temperature was 1350 F but showed no weakening when the top temperature was 1200 F. For N-155 the temperatures for weakening and no weakening were 1500 and 1350 F, respectively. Inconel "X" showed no weakening up to 1500 F. Titanium 130A at 800 F and 24ST3 at 600 F showed no weakening. FS1H (magnesium alloy) showed some weakening at 450 F.

On the stress cycling side, Smith and Houston found that for operating temperatures up to 1500 F alternate loading and unloading of 18-8 (low carbon) did not result in excessive creep rates by the generalized Robinson criteria.

Simmons and Cross found the same thing for type 310 sheet at 1500 F. 24S-T1 and 24S-T3 sheet stress cycled at 300 F also showed no excessive creep rates.

Guarnieri found, however, that stress cycling of 24S-T1 sheet at various temperatures between 300 and 600 F showed increasingly poorer creep resistance by the Robinson criteria as the temperature of test rose.

Guarnieri also found that with 24S-O no weakening for both creep and rupture occurred in the 300 to 600 F temperature range. Finally, he found that no excessive creep rates were observed with stress cycling between zero and full load of type 321 up to temperatures of 1350 F, N-155 to 1500 F, Inconel to 1500 F, and FS1H (magnesium alloy) to 450 F.

From the above summarization, it appears that there is a critical average temperature characteristic for each alloy where either stress or thermal cycling results in creep rates larger or rupture times shorter than that predicted by the generalized Robinson method of calculation using constant stress and temperature data. Further, the critical temperature appears to be different for thermal cycling than for stress cycling. The data for 24S-T aluminum are particularly illuminating in this respect. Stress cycling to 300 F gave creep rates or rupture adequately predicted by the Robinson method, while above 300 F weakening sets in. Temperature cycling on a cycle between room temperature and up to 600 F apparently gave no weakening.

A possible clue for cyclic weakening above the "critical" temperature was found by Guarnieri when he compared data taken on 24S-T3 with 24S-O. With the latter he found that the critical weakening temperature under stress cycling was about 600 F, while with the former the critical temperature was approximately 300 F. Guarnieri pointed out that possibly precipitation reactions are accelerated under cyclic conditions, such acceleration giving mechanical weakness.

The lack of dependability of the Robinson design method certainly leaves the results of the symposium in an unsatisfactory state as far as a general method of predicting high-temperature cyclic behavior is concerned. What is needed is a design method of proven reliability for cyclic stress and temperature applications, preferably working from constant stress and temperature data. The only solution for this is further work on the problem. Some rather fundamental work on this, not covered in this Symposium, is under way,[3] and it is hoped this will be continued and expanded.

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[3] A. J. Kennedy, "The Creep Deformation of Metals Under Discontinuous Stress and Temperature Conditions," *Mechanical World*, Feb., 1954.