Strength and Ductility of Metals at Elevated Temperatures, by W. F. Brown, Jr., M. H. Jones, and D. P. Newman, Proceedings of the ASTM, vol. 53, 1953, pp. 661–676.

9 "An Experimental Study of the Strength and Ductility of Steels at Elevated Temperatures," by J. Glen, Symposium on Strength and Ductility of Metals at Elevated Temperatures, ASTM, STP No. 128, 1952, pp. 184–222.

10 "Some Additional Creep and Rupture Data on Mo, Cr-Mo, and Mo-V Steels," by J. Glen, *Journal of Iron and Steel Institute*, vol. 179, 1955, pp. 320–336.

11 "The Damage Line in Creep," by A. Thum and K. Richard, *Archiv. für das Eisenhuttenwesen*, vol. 20, 1949, pp. 229–242.

12 "Effect of Variation in Normalizing and Tempering Procedure on Stress Rupture Strength, Creep Embrittlement and Notch Sensitivity for a Cr-Mo-V and 17 Cr-4 Ni-4 Cu Steel," by M. H. Jones, D. P. Newman, G. Sachs, and W. F. Brown, Jr., Trans. ASM, vol. 47, 1955, pp. 926–954.

Discussion

M. J. Manjoine.[8] The data presented by the authors is of prime importance to the machine designer. It appears that "damage" to a material under stress at elevated temperature may result from two nearly independent mechanisms. The first mechanism is related to the structural changes and microfissuring which occur in the strained lattice at points of high internal stress such as at the junctions of grain boundaries. The second is related to the strain, strain hardening, and structural changes which occur in the matrix. Damage caused by the latter is not permanent and can be almost completely removed by reheat-treatment. The former mechanism results in permanent damage which affects only a small volume of the material. A change in test condition which alters the flow pattern may not reveal the presence of this damage. The authors show that notch sensitivity is closely associated with creep damage. It may be possible to study the two mechanisms of damage by comparing low-stress creep tests of notched and smooth bars and by an examination of the microstructures.

K. Richard.[9] It is surprising that the authors' Cr-Mo-V steel becomes brittle and notch-sensitive in a relatively short time in a creep test. This steel with its relatively high carbon content is similar to one which the writer tested at 500 C (932 F).[10] This latter material maintained its ductility up to 100,000 hr.[11] The authors' steel was tempered at a higher temperature and might be expected also to maintain its ductility in the stress-rupture test. The fact that the authors' testing temperature (1000 F) was about 40 C (70 F) higher would not appear to explain this difference in embrittlement.

Fig. 2 of the paper appears particularly instructive. Notch weakening begins after 100 hr at 1000 F and after 20 hr at 1100 F. It appears that after 2000 hr the strengths of the notch and smooth specimens would be equal. This would indicate that the steel softens rather rapidly under these testing conditions and thereby does not exhibit notch weakening or brittleness at sufficiently long times to rupture. It should be possible to verify this by measuring the changes in hardness. The steel tested by the writer[10] had an initial hardness of 380 Vickers (about 39 Rockwell C), corresponding to a room-temperature tensile strength of 124 Kg/mm^2 (176,000 psi). After 5000 hr of creep at 500 C (932 F), the hardness had dropped to 250 Vickers (about 22 Rockwell C) and to 215 Vickers (about 17 Rockwell C) after 30,000 hr. The authors' steel cannot soften to the same degree because of its lower initial hardness.

If the authors' steel softens rapidly, then it might be expected that no permanent damage was found. The time interval at 1000 and 1100 F in which notch sensitivity and brittleness appear is too short for development of thorough damage.

The writer also has tested a Cr-Ni-Mo steel which exhibits very low ductility in stress rupture tests at 500 C (932 F).[11,12,13] This steel which was tested over much longer times should exhibit a behavior similar to the authors' Cr-Mo-V steel after times above 100,000 hr because after this time the notch sensitivity at 500 C (932 F) gradually vanishes, the rupture elongations are again equal to the very short time value of 10 per cent, and the steel has thoroughly softened. The authors' steel should behave in a similar manner to the Cr-Ni-Mo steel if it were tested at 500 C (932 F).

All in all the writer does not feel that his somewhat different results are contradictory if the phenomena of softening are taken into account in the manner indicated. However, before the processes affecting notch sensitivity and damage in heat-resisting steels are understood completely, a considerable amount of additional experimental work will be required.

Authors' Closure

The authors wish to thank both Mr. Manjoine and Dr. Richard for their remarks. We feel that creep damage due to certain structural changes can be healed by reheat-treatment. This has been demonstrated in the present paper for only one alloy and over a very limited range of creep conditions. On first thought it would seem that those materials undergoing a complete phase transformation on reheat-treatment would exhibit the strongest healing tendencies. We are extending the phase of this work relating to reheat-treatment to include a variety of creep conditions for the Cr-Mo-V steel and will also study these phenomena in a precipitation-hardening austenitic heat-resisting alloy.

Mr. Manjoine has suggested that an examination of the microstructures may be instructive. We do not doubt that such procedures would be desirable. Unfortunately, we have been unsuccessful in detecting damage other than actual cracks by conventional metallographic procedures. However, we are not experts in steel metallography and hope that other investigators will pursue the question of the exact nature of the structural changes responsible for creep damage in this steel.

The authors have noted that the 2.58 Cr steel tested by Dr. Richard at 500 C (932 F) exhibits much less embrittlement than the presently reported Cr-Mo-V steel tested at 1000 F. However, this is not unexpected when the differences in steel composition, heat-treatment, testing temperature, and specimen geometry are considered. Of these differences, the testing temperature and notch geometry are probably in large part responsible for the observed dissimilarities in notch embrittlement and creep damage. Dr. Richard employs a notch sharpness (ratio of one-half notch diameter to notch radius) of 118 as compared with the authors' 150 and a notch depth of 20 per cent compared with the authors' 50 per cent. As pointed out previously[14, 15]

[8] Research Engineer, Westinghouse Research Laboratories, Pittsburgh, Pa. Mem. ASME.

[9] Doctor of Engineering, Farbwerke Hoechst, Frankfurt (M), Hoechst, Germany.

[10] Composition: 0.31 C, 2.58 Cr, 0.26 Mo, 0.58 V. Heat-treatment: 850 C (1562 F) water; 600 C (1112 F) air.

[11] "Results of 500° C Rupture Tests Up to 100,000-Hour Duration With Low Alloy Steels," by A. Thum and K. Richard, *Schweizer Arch.*, vol. 19, August, 1953, p. 235.

[12] Composition: 0.11 C, 0.72 Cr, 1.53 Ni, 0.88 Mo. Heat-treatment: 870 C (1598 F) oil; 590 C (1094 F) air.

[13] "The Damage Line in Creep Testing," by A. Thum and K. Richard, *Arch. fur das Eisenhutten*, vol. 20, 1949, p. 229.

[14] "A Critical Review of Notch Sensitivity in Stress Rupture Tests," by W. F. Brown, Jr., and G. Sachs, NACA TN 2433, August, 1951.

[15] "Time Temperature Dependence of the Notch Effect and the Influence of Notch Depth in Stress Rupture Tests on a Cr-Mo-V Steel," by D. P. Newman, M. H. Jones, and W. F. Brown, Jr., Proceedings of the ASTM, vol. 53, 1953, pp. 677–692.

an increase in sharpness and depth would result in larger notch weakening. Superimposed on this effect is the 90 F higher test temperature employed by the authors which would increase the rate of embrittlement.

We are not certain that we completely understand Dr. Richard's argument regarding the role of softening as it may influence notch behavior and damage. We feel that at least two processes are occurring in this steel during creep: (1) The softening; and (2) a time-temperature-dependent structural change responsible for notch weakening. Softening in the Cr-Mo-V steel is indicated by progressive loss in room-temperature yield strength with increasing 1000 F prestrain time as shown in Fig. 12 of the present paper. Notch sensitivity develops in spite of this softening. However, we feel that the softening contributes to the eventual recovery of the notch properties. We note from Dr. Richard's previous work[13] (fig. 18) that a very brittle Cr-Ni-Mo steel exhibits a similar loss in yield strength with progressive creep at 932 F (500 C). The development of creep damage in this steel and in the authors' Cr-Mo-V steel is similar in that large damages occur for those creep stress levels yielding high notch sensitivity. The major difference is that we show no permanent damage, while Dr. Richard is able to develop damages that cannot be completely recovered by reheat-treatment. In this connection it should be noted that the Cr-Ni-Mo steel is extremely brittle, possessing a minimum rupture ductility of less than one per cent at 932 F (500 C). On the other hand, the authors' steel shows 5 per cent ductility under the most brittle condition investigated. Therefore, it may be that the Cr-Ni-Mo steel develops cracks (permanent damage) much earlier in the creep test than does the Cr-Mo-V steel. We would suspect that permanent damage would be observed for the Cr-Mo-V steel if the creep times were extended to around 10,000 hours. At these long test times considerable intercrystalline cracking occurs throughout the test section in spite of recovery in ductility.