STP128-EB/Apr. 1953

# SYMPOSIUM ON STRENGTH AND DUCTILITY OF METALS AT ELEVATED TEMPERATURES

## INTRODUCTORY SUMMARY

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In the past several years, considerable interest has developed regarding the effects of notches on metals at elevated temperatures under either static or dynamic loading. The papers and discussion comprising this Symposium bring together much of the information available on the subject.

Sachs and Brown have prepared a thorough survey of the prior literature on both notch effects and long-time embrittling effects at elevated temperature. The analysis indicates that the notch effects may be intimately related to long-time changes in the metal at elevated temperatures. The part of the survey on notches is devoted partly to a number of German investigations and partly to the work of Brown, Jones, and Newman, which comprises another paper in this symposium. The German investigations indicated that notch weakening (notch strength less than unnotched strength for a given time) occurs when the smooth-bar ductility is less than 5 or 6 per cent, but that notch strengthening (notch strength greater than unnotched strength) occurs for higher values of smooth-bar ductility. Also, the German investigations revealed the smooth-bar ductility exhibits a minimum when the notch weakening is at a maximum.

The latter correlation between minimum smooth-bar ductility and maximum notch weakening is also found by Messrs. Brown, Jones, and Newman; but contrary to the German results, notch weakening occurred with smooth-bar ductility values anywhere from 8 per cent to 20 per cent or more. The correlation of notch weakening with notched-bar ductility is more consistent than with smooth-bar ductility. Messrs. Brown, Jones, and Newman also find that notch weakening is more severe at lower temperatures than at high temperatures, but longer times to rupture are required before notch weakening set in if the temperature is comparatively low.

Messrs. Hull, Hann, and Scott find good correlation between the smooth-bar ductility and the notch-strength ratio (notch strength divided by unnotched strength at the same rupture time); but, just as found by Brown, Jones, and Newman, the boundary values of smooth-bar ductility between notch weakening (notch strength less than unity) and notch strengthening (notch strength greater than unity) is higher than that reported by Sachs and Brown for the earlier German investigations.

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Furman and Talbot find that there is no definite value of unnotched ductility marking the boundary between notch weakening and notch strengthening. They observed a notch strength ratio of unity for unnotched ductilities as low as 5 per cent and as high as 15 per cent.

Davis and Manjoine find that the notch-strength ratio is greater than unity for smooth-bar ductility values between 25 and 40 per cent and that the notch strength ratio is less than unity for all but the most mild of notches for smooth-bar ductility values between 2.5 and 4 per cent; but for smooth-bar ductility values between 7 and 12 per cent, the appearance of notch weakening or notch strengthening depends upon the grain size. The coarse-grained material shows notch weakening, while the fine-grained material of the same smooth-bar ductility shows notch strengthening.

Whereas the other investigators used a single arbitrary notch geometry, Davis and Manjoine investigated a variety of values of notch sharpness (notch root radius divided by specimen diameter at the notch). They find the behavior similar to that at room temperature as revealed by the investigations of Sachs and Lubahn; the notch-strength ratio tends to increase due to triaxiality as the notch becomes sharper, but the more brittle materials show an eventual decrease again in the notch-strength ratio when the notch becomes sufficiently sharp.

From the above four papers that contain smooth-bar and notched-bar information, it appears that one is not justified in making the generalization that notch weakening always occurs when the smooth-bar ductility is less than a certain value and that notch strengthening will occur when the smooth-bar ductility is greater than that value.

Siegfried's paper contains data that permit correlation between the notch-strength ratio and the nature of the propagation of the failure. For one of 15 stainless steels, the notch strength is considerably less than unity, and the crack is of the brittle, rapidly propagating variety. Of the other 14 steels, those with notch-strength ratios near unity show many intercrystalline cracks, filling a large volume before final failure, and those with notch strength ratios considerably in excess of unity show ductile type of cracks, where gradual tearing open is accompanied by considerable strain.

Frey attempts to explain the fact that aging improves the ductility at high stress but not at low stress and the fact that notch strengthening occurs at high stress while notch weakening occurs at lower stress. He uses a concept that envisions fracture at high stress being caused by the piling up of dislocations at a grain boundary or phase boundary, while fracture at low stress is caused by the growth of initial microcracks because of thermal fluctuations.

Toolin investigates the effect of notches on the elevated-temperature fatigue behavior. He finds that the notch fatigue strength is less than the unnotched fatigue strength for both coarse-grained and fine-grained material. The notch strengths of the two materials are about the same, but since the unnotched fatigue strength of the fine-grained material is higher than for the coarse-grained material, the notch has the greater weakening effect on the fine-grained material.

The second part of this two-part symposium is concerned with the effects of metallurgical changes on strength and ductility of metals at elevated temperatures. This is an aspect of elevated-temperature metallurgy with which we have been concerned under various guises for a number of years: metallurgical changes, microstructural stability, microstructural instability, or internal stability. The term elevated temperature should be taken in a relative sense, recognizing that in some metals changes may take place at room temperature, or even lower.

Many kinds of metallurgical changes take place in metals under the influence of time and temperature, whether or not the metal is subjected to stress, though stress and plastic deformation may alter the rate at which they occur; illustrative of the changes which may occur are carbide spheroidization or graphitization in low-alloy steels, sigma precipitation in the ferritic chromium or austenitic stainless steels, and precipitation phenomena of one kind or another in a wide variety of alloys.

These metallurgical changes and their effects are of interest in any investigation of metals at elevated temperatures. Thus, while the papers of the latter part of the symposium deal specifically with this subject, it is also true that the papers dealing primarily with notches, reviewed above, have in a number of cases considered metallurgical changes as being responsible for certain observed effects—for example, the change in effectiveness of notches with time to rupture.

Metallurgical changes take place even in pure metals if we use the term in its broad sense, as we should, and include the phenomena of recovery and recrystallization. The paper by Lequear and Lubahn is concerned with the particular type of change known as recovery, which occurs in strain-hardened metals and is characterized by a decrease in the amount of strain hardening in the absence of any observable change in the microstructure. (Strain hardening is also decreased by recrystallization, that is, the formation of new undistorted grains.)

Whereas the recovery of strain-hardened metal on heating is readily demonstrable, there has been heretofore little or no effort to investigate the rôle of recovery occurring at the same temperature as the strain hardening, as, for example, in a creep test. Thus, the popular characterization that the curve of creep against time represents a running balance between strain hardening and recovery has been lacking in experimental support.

Lequear and Lubahn investigate this question by interrupting creep tests of quenched-and-tempered chromium-molybdenum-vanadium steel with results which demonstrate the occurrence of recovery at 1000 F (but not at 800 F). This is shown by the fact that the creep rate after reapplying the load is greater by an amount which increased with the duration of the interruption.

The authors further demonstrate how to obtain the "plastic creep curve" by substracting the anelastic strain from the total creep strain. The plastic creep rate is observed to become constant if recovery occurred, but in the absence of recovery this rate decreases continuously.

The paper by Glen summarizes an investigation of the effects of manganese (up to 3.5 per cent) and of molybdenum (up to 1.5 per cent), as well as deoxidation with aluminum, on strength and ductility of steel at elevated temperatures. This leads to the conclusion that precipitation phenomena are capable of explaining many of the observed effects. The author was led to the investigation by the well-known fact that the elevated-temperature strength of steels may be altered by change of initial microstructure by heat treatment and that the optimum treatment for one test temperature and strain rate is not necessarily optimum for other conditions, which is presumably explainable in part on the basis of metallurgical changes occurring during test.

Glen's investigation consists in making true stress-strain tension tests of the steels over a range of temperature. In the tests of plain low-carbon steel, a maximum in the stress for a specific strain is observed at about 400 F. This may be recognized as what is commonly called strain aging. With the addition of manganese or molybdenum a second maximum appears, falling at about 575 F in the case of manganese and at about 930 F in the case of molybdenum. In alloys containing both manganese and molybdenum, peaks corresponding to both these elements are observed. Mr. Glen attributes these maxima in stress for a given strain to precipitation during straining; this is not to exclude precipitation during heating prior to test, which is, in fact observed, and explains some aspects of the observations. The maximum in the plain-carbon steel as well as the lower peak in the alloy steels is attributed to iron carbide (or nitride) precipitation, whereas the additional peaks in the alloy steels are attributed to precipitation of alloy carbides.

Deoxidation of several manganese steels with aluminum reduces the strain-aging corresponding to the first stress maximum and provides further confirmation of the idea that nitrogen is of greater importance in strain aging than carbon, but has little or no effect on the higher temperature maximum.

The results further show that, associated with each maximum in stress at a given strain, there is a minimum in strain at fracture. These minima are also attributed by Glen to carbide precipitation, in this case, at the grain boundaries, giving rise to intergranular weakness.

On the basis of these experimental results Mr. Glen is led to make a number of interesting suggestions which would appear to explain certain observations regarding the effects of heat treatment on creep strength and ductility of low-alloy steels. These suggestions furnish much food for thought and ideas for future research.

The paper by Smith and Dulis is concerned with evaluating the specific rôle of the sigma phase on strength and ductility of 25 Cr-20 Ni steel at elevated temperatures. Considerable interest has lately developed in this phase which forms in high chromium or chromium-nickel steels. By comparison of samples initially containing no sigma with other samples in which appreciable quantities of this phase are developed by 7500-hr exposure at 1300 F, it is found that sigma is slightly deleterious to creep or rupture strength at 1300 F. Since sigma phase is precipitated during the testing of metal not initially containing sigma, it seems not unlikely that at sufficiently long time, exposed and unexposed metal might exhibit the same strength; a trend in this direction is experimentally observed.

In contrast to its effect at elevated temperatures, sigma causes increased yield and tensile strengths and reduced ductility at room temperature, in confirmation of previous knowledge. The most pronounced effect of sigma is to reduce notch impact strength, even at the maximum temperature studied, namely 500 F.

The final paper, by Wilder and Ketterer, describes some of the results of a continuing investigation into the nature and effects of the metallurgical changes occurring in a wide variety of steels during long heating in the temperature range 900 to 1200 F. In this particular paper, microstructural observations made on various ferritic and austenitic stainless steels heated for up to 34,000 hr are described, along with the results of tension and creep-rupture tests.

In both the ferritic and the austenitic grades, the principal microstructural changes observed are carbide spheroidization and agglomeration and the precipitation of sigma phase. The most marked mechanical property change of the steels examined in this respect is observed in room temperature tension tests of the 17 per cent chromium steel exposed at 900 F, which increases 35 per cent in tensile strength with associated loss of ductility. This is a manifestation of familiar 885 F embrittlement. Changes in room temperature tensile properties of the remaining steels are not of great magnitude.

The 17 per cent chromium steel exposed at 900 F also shows a large change in creep-rupture strength. The stress for rupture in 1000 hr of this grade is one third greater after 10,000-hr exposure at 900 F than before exposure. The 18 Cr-8 Ni-Mo grade exposed at 1050 F also shows increased creep-rupture strength as the result of exposure. In contrast, the 18 Cr-8 Ni-Ti and 18 Cr-8 Ni-Cb grades show significant loss in creep-rupture strength in some instances. The remaining grades show comparatively minor changes. The ductility of the rupture tests either remains essentially unchanged or increases slightly, with the exception of the free-machining 18 Cr-8 Ni exposed at 900 F, which suffers a loss.

Wilder and Ketterer also made tests of a few materials exposed for 10,000 hr at 1050 F under stress (maximum working stress, ASME Boiler Code) with results showing little difference from material exposed without stress.

In summary, it seems unnecessary to state that much yet remains to be done in this matter of metallurgical changes. There can be little question that these changes are of great importance in the field of creep, particularly of metals of commercial purity, and in fact that they may be the greatest deterrent to the development of adequate theories of creep behavior.