SURVEY ON CREEP DAMAGE TO METALS

Creep can be considered as a deformation process which progressively damages a metallic material until, ultimately, fracture occurs. In an ideally "stable" microstructure the damage would only arise from the process of creep itself. In practice, thermally-induced time-dependent changes in the microstructure which in turn change the creep resistance and alter other mechanical and physical properties are an important part of "creep damage." The creep process may in itself influence the changes in microstructure and consequently affect the properties. In addition, surface alteration of the metal can damage the metal through corrosion, cracking, alloy depletion or the introduction of alloying elements from the environment.

There are a number of practical and theoretical considerations arising from the creep damage concept:

1. The engineer often needs to know how much useful life remains in materials which have accumulated creep damage during partial service under creep conditions with little indication of deformation.

2. The performance of materials as conditions of temperature and stress change involves consideration of the accumulation of creep damage.

3. The possibility of using heat treatments to restore properties after creep damage from partial service is often important.

4. Alteration of other mechanical and physical properties than merely the creep-rupture life by accumulation of creep damage often is more influential on service experience than creep strength itself.

5. Knowledge of the nature of creep damage could allow the metallurgist to combat deterioration by means of compositional, processing and heat treatment controls.

6. The correct understanding of creep damage might contribute to the understanding of the mechanisms of creep.

General Analysis

An analysis of the nature of creep damage requires knowledge of the commonly accepted mechanisms by which creep occurs. At the same time careful attention must be given to the influences of changes in the microstructure. Both of these phenomena can be extremely complex. As would be expected under these conditions, certain phenomenological concepts or "working rules" of creep damage have developed:

1. Creep damage arising from the creep process itself is permanent and cannot be restored by normal heat treatments.

2. While heat treatments after creep are presumed not to restore damage due to creep itself, they can have important effects on concurrent structural changes which have damaged the properties. For instance, restoration of precipitation hardening that had overaged while creep was occurring could restore creep resistance and prolong life. On the other hand, removal of strain hardening resulting from creep would accelerate subsequent creep.

3. Damage accumulates on a percentage basis in structurally stable materials (sometimes called the "life-fraction" rule. For instance, if a material is exposed for 25 percent of its life at one set of conditions, it will continue to creep under another set of conditions as if 25 percent of its life had been expended under the new conditions.

Consideration of metallurgical principles indicates that such generalities regarding creep damage contain certain limitations:

1. Creep which occurs by gross slip and the other modes of ordinary low-temperature plastic deformation ought to respond to heat treatment and such damage need not be permanent. Permanent damage, if it exists, presumably must arise from the creep which manifests itself in grain boundary deterioration,

Thus, if eventual fracture occurs by a process of necking followed by transgranular fracture, the creep damage should be removable by heat treatment. If fracture eventually occurs by intergranular cracking, the damage may be permanent. The important difference is the requirement of a change in the mode of deformation to something other than the plastic flow characteristic of hot and cold working which does not permanently damage the material.

2. Metals and alloys vary widely in the structural changes which occur during prolonged exposure to temperature. An almost infinite number of possibilities exist. Furthermore, several reactions can occur simultaneously. Some of these reactions may be beneficial to creep resistance or other properties while others are detrimental. The effects of heat treatments after exposure to creep will depend on the specific cases. For an increase in creep life by heat treatment, a correction of structural weakening must result. The destruction of a favorable precipitate dispersion, removal of strain hardening, or the development of substructures are examples of structural changes that reduce life. The very fact that creep can occur implies that conditions are favorable to structural changes and are almost certain to occur. The complexities of structural changes are a contributing factor to creep damage and the response to subsequent heat treatment.

3. The life-fraction rule would be expected to hold only if there is not a change in the mechanism of creep as a result of changing conditions. The structural instability effect would also have to be minor. The life-fraction rule would, therefore, be expected to hold best when the changing conditions do not involve too wide changes in temperature and creep rate.

Nature of Creep Damage

It can be presumed that damage mechanisms start as soon as creep starts. The modes of deformation may change during creep as well as being dependent on the temperature, stress level and time period, as is very evident from the voluminous literature on the subject. If so, the damage mechanisms also vary. Most theories indicate primary creep to be recoverable and the life expended in primary creep should be recoverable by heat treatment. On the other hand, it is well known that a large proportion of so-called primary creep in engineering materials is not recoverable by simply removing the stress. Some proportion of the primary creep may, therefore, occur by a mechanism which imparts permanent damage. The same statements probably apply to secondary creep with even less chance for the existence of recoverable types of creep.

Superficially at least, it appears that third-stage creep offers more information on the damage factors. Most theoretical treatments of the creep process attribute tertiary creep to the increase of stress in constant load tests as reduction of area progresses. Constant stress tests, however, usually also show tertiary creep. A number of explanations have been advanced to account for this behavior with one or more of the following being recognized for individual cases:

1. Voids and cracks that form in the metal as creep progresses. (These reduce the effective load carrying area and introduce stress concentrations from notch effects.)

2. Progressive weakening structural changes such as overaging of precipitates, spheroidization, etc.

3. Loss in section by general corrosion.

4. Intergranular corrosion reducing the load-carrying area and introducing stress concentrations.

5. Alloy depletion or contamination of the metal surface.

All of these sources of damage, with the possible exception of void formation, would progress from the start of creep. The concurrent presence of creep may, however, alter the rate and extent of their effects. The surface damages would all be permanent in that they could not be corrected by heat treatment. Furthermore, tests conducted after surface deterioration has been removed by machining have shown a strong probability of the existence of permanent damage. Current knowledge of creep damage suggests that void formation and growth of cracks is the most likely source of permanent damage.

There is a large literature on the subject of void formation. Voids have been reported to be present in samples before the end of first-stage creep. The formation of voids by creep have been observed more frequently while creep is in the second-stage. The Russian literature almost universally attributes second-stage creep to the formation and growth of voids to cracks. Voids and cracks seem to be a well accepted cause for third-stage creep. These generalities are not completely universal, however, and some writers attribute the deterioration largely to weakening by structural changes such as overaging of precipitates and spheroidization.

Several reasons probably exist to account for the various interpretations. The most important is probably the variation in the mechanisms of creep with alloy system, temperature, stress and time. At relatively low temperatures and/or high strain rates where creep may largely occur by movements within the grains, it would be reasonably expected that void formation would be delayed or even not occur. When creep becomes more a function of the grain boundaries as temperature is increased and/or the strain rate reduced, void formation leading to intercrystalline cracking should become more active and could occur during first-stage creep. There is also reason to believe that the sensitivity of methods of void detection have varied considerably leading to a divergence in the reported results of their occurrence.

Void formation would be expected to be highly structure-sensitive. Thus its occurrence would vary considerably from compositional and heat treatment variables. It seems likely that any mechanism which strengthens grains relative to grain boundaries promotes intercrystalline cracking. It has been proposed that this is due to the resistance to relaxation of stress concentrations accompanying the voids and cracks which must be accommodated by the grains.

Several investigators have shown that second phases, such as inclusions, carbides, grain boundary films, etc can initiate voids and cracks. Others have shown that trace amounts of elements such as boron and zirconium can act to retard crack formation and growth to a marked extent. It is presumed that there are other elements whose presence in trace amounts can act both to promote and retard the formation of voids and cracks.

If voids are the source of permanent creep damage, there is some question as to why they cannot be removed by heat treatment. One explanation might be that normal heat treatments are not conducted at sufficiently high temperatures to provide the necessary diffusion to heal the voids by the familiar sintering reaction. Perhaps certain reactive elements in solution in the metal may accumulate at the voids and form insoluble compounds that prevent healing.

It should also be recognized that creep manifests itself in the structure in other ways than by void formation. For instance, the often reported phenomena of substructures resulting from creep may be important to damage concepts.

A tendency in the literature seems to be to pay little attention to structural instability or surface deterioration in considerations of creep damage. This in part arises from these phenomena not being unique to creep. There is no question, however, that they are major factors in most cases and should receive equal attention. Creep is presumed only to modify the course of the structural changes. It should perhaps also be recognized that there is often more time for structural changes in creep tests than is usual in separate studies of structural changes.

The whole problem of understanding creep damage is, therefore, mainly related to the mechanisms by which creep occurs. In addition, structural instability usually contributes to the overall effects and environmental factors operating through the surface of the metal can also be important. All of these factors are sensitive to metal composition and structure. Clarification of the actual causes of creep damage requires careful attention to the details of each specific case. It does seem, however, that fruitful general information could be obtained by study of void formation in relation to permanent creep damage.

AVAILABLE INFORMATION

There is very little documental evidence to support the more popular ideas regarding the effect of partial service on subsequent life and the lack of rejuvenation by heat treatment. In recent years there have been studies of the response to varying conditions of service and there has, of course, been a great deal of attention given to structural changes and their influence on other physical properties--so-called stability effects. However, the major part of this information serves to demonstrate that materials which are used are free from this difficulty. Apparently cases of adverse effects on properties are not too often recorded.

Estimation of Remaining Creep-Rupture Life

It is commonly considered that if a material has been in service for part of its creep-rupture life, it will have only the remaining life left for continued service or at some other service condition.

For example, a very common question is the conditions under which equipment should be replaced. This requires means of estimating the percentage of the useful creep-rupture life remaining in equipment which has been in service under more or less unknown conditions. Presumably, tests on materials after service should be reliable.

The strongest support for the concept appears to arise from the common laboratory experience with interrupted creep-rupture tests. If a creep-rupture specimen is cooled and reheated under stress it will usually continue to creep and finally rupture just as if there had been no interruption. This observation is usually qualified by the statement that the interruption should not introduce or accelerate a structural change or distrub a protective scale.

Apparently a number of investigators have carried out limited studies of experiments designed to obtain more information on this point. Very little data have been published (as is the case for such work in the authors' laboratory.) A limited number of experiments have been conducted at the University of Michigan for the Timken Roller Bearing Company in which specimens were allowed to creep for part of their life, removed from creep units, remachined and then used to establish new stress-rupture time curves. The results have, in general, shown that the life in the subsequent tests was reduced by the percentage of life used in the original test.

Details in such experiments may become important. If new specimens are prepared after exposure to creep, the stress is usually reduced due to the removal of the reduction of area occurring during the prior creep. Such preparation also removes possible surface deterioration during prior creep. In addition, there is an opportunity for recovery if the specimen is heated and temperature adjusted before the load is applied.

The role of recovery does not seem to be well established. Some data indicates that any recovery during heating without stress is rapidly lost and creep continues very much as if there had been no recovery. Guarnieri (ref. 1) reported recovery reduced damage. On the other hand, considerable data indicates an acceleration of creep after recovery. Careful experiments would probably show that acceleration of creep is due to a structural change such as the removal of strain hardening in addition to the recovery factor.

The estimation of remaining creep life of equipment after partial service is subject to many of the same variables. Usually, original properties and prior service conditions are not known in sufficient detail to estimate the amount of life used up before testing. Anisotropic effects may influence test results, as for instance, longitudinal specimens from a tube subjected to circumferential creep. Perhaps the most difficult problem to cope with is the relatively small percentage of life represented by the prior service in most such cases. Design and service requirements usually limit creep to one percent or less. Larger amounts of creep render the part inoperative or introduce geometrical instabilities which accelerate failure. Thus, in most practical cases there is no interest in remaining life unless the total prior creep has been very small and consequently represents such a small part of the total life that the loss is well within the limit of accuracy of tests. For this reason such tests usually indicate no appreciable loss in life. (See ref. 2). Wilder and Ketterer (ref. 3) showed that exposure of 0.5 Mo, 1 Cr - 0.5 Mo and 18 Cr - 8 Ni steels produced little change in tensile and rupture properties even after prolonged exposure to ASME Boiler Code Stresses.

Examples of cases where there is true structural stability during partial service are extremely rare. Estimations of effects then become quite complicated. For instance, low-alloyed steels of the type which are commonly used for piping on steam plants undergo spheroidization. This usually lowers rupture strength at short-time periods, but also reduces the slope of the stress-rupture time curve to give extrapolated long-time rupture strengths no different than were indicated by the tests on the original material.

In such cases the interpretation of data becomes difficult. The short-time strengths have been reduced by a structural change. Apparently, however, the rupture curve for the original material correctly included prediction of the effects of the structural changes at long-time periods. Because there was little exhaustion of rupture life, the extrapolated rupture strengths were similar from the tests before and after service. This seemed to be the case for C-Mo pipe after prolonged service (ref. 2).

Creep data are more difficult to interpret. As previously mentioned, actual testing experience indicates that creep continues with no change after an interruption of temperature. Thus, if a specimen were taken from a part after partial service and started in a creep test at the same temperature and stress as existed in service, it ought to continue to creep the same as if it had been in service. If a part had not attained third-stage creep in service, the creep test should show no change in creep rate from the original material. However, it could be very close to the start of third-stage creep with no indication that it would start in the near future. The usual extrapolation of creep-rate data would thus be seriously in error if third-stage creep was about to start. This problem is discussed in reference 2 where creep tests on C-Mo pipe after 100,000 hours service checked measured creep by the pipe in service. There is a need for more information on the relationships between the start of third-stage creep and the usually measured creep properties.

Varying Stress and Temperature

The subject of the behavior of materials under varying stress and temperature is covered in another survey by Manson. For this reason, the discussion of this subject will be brief and confined to creep damage concepts. Furthermore, it will be limited to the problems associated with the evaulation of creep damage by tests after partial service.

Service conditions seldom involve steady temperature and load as do the usual creep-rupture tests. The actual stress and temperature are also frequently uncertain. Consequently, the usual tests at relatively high stresses and short-time periods to evaluate remaining creep-rupture life often involve different conditions than exist in service. It may also be desirable to evaluate future performance for different service conditions than existed during the prior service.

If the life-fraction rule holds, then the tests should show a reduction in strength equal to the fraction of life represented by the prior service. Presumably this would be the case for tests at any temperature and stress level for a structurally stable material, provided the mechanism of creep was not changed by the altered test conditions. Good proof of this would be desirable.

It is, however, very evident that if conditions are changed and structural changes occur the properties may be far different from those anticipated from the simple life-fraction rule. This apparently was a major factor in the experiments of Jones, Newman and Brown (ref. 4) on Cr - Mo - V steel. Guarnieri (ref. 1) found a number of instability effects to complicate the life-fraction rule, although it worked quite well for stable materials. Any application of the life-fraction rule to varying conditions of stress and temperature must take into account the effect of structural changes on properties at the new conditions as well as damage resulting from creep itself.

Original data for materials with no prior service include effects of structural changes to varying degrees. For instance, it has been found (ref. 5) that the stress-rupture time curve for 2024-T86 aluminum at 400°F fairly well includes overaging effects for cases where stress decreases with time as in a notched-specimen rupture test. In this instance, the stress-concentration of the notch decreases with time causing the effective stress for rupture to decrease with time. At the same time, overaging rapidly reduces strength of the material. The life-fraction rule did a fairly good job of predicting rupture time under the decreasing stress at the notch or in stepped-down rupture tests. If, however, the stress was increased with time, the results were very much in error due to the much lower strength which existed when the material was exposed to high stress.

If a change in the mode of deformation results from changing stress or temperature during service, it is doubtful that life-fraction rule will apply. For instance, it is known that many materials can be exposed to creep until nearly all the rupture life is expended. If the stress is then increased to the extent that deformation changes from largely a grain boundary phenomena to slip within the grains the material will show the original or improved strength rather than a prior exhaustion of most of the strength. On the other hand, when there is not a change in the mode of deformation (and structural changes are not influencing results appreciably) the strength should be reduced in accordance with the percentage of life previously expended.

Experiments in progress at the University of Michigan for the NACA suggest that if structural change effects are evaluated separately from damage due to creep itself it is possible to estimate quite closely the performance to be expected under varying stress and temperature conditions by adding the two effects. Strict attention must, however, be paid to detail to be sure that the data are applicable to the particular conditions.

Finally, it should be recognized that when it is possible to test materials after partial service, the test data should be just as reliable for predicting future service as they are for virgin materials. There seems to be no reason to expect that there are hidden damages not reflected in tests. This assumes that the usual care is exercised to be sure that the data is applicable to the future service conditions. The main source of possible error would be the use of creep rate data wher the time of start of third-stage creep might be uncertain as discussed in the previous section. It also assumes that due consideration has been given to geometrical effects from prior creep as well as surface deterioration effects and recovery phenomena.

There seems to be little real proof of theoretical soundness for the life-fraction rule. However, mounting evidence suggests that this rule comes closer to predicting performance than other suggested means for integrating creep under varying stress and temperature conditions. The life-fraction rule apparently does better than the time-hardening rule or the equal-deformation rule for rationalizing creep under varying conditions.

Creep Damage and Heat Treatment

It has previously been mentioned that there is a general opinion that creep life cannot be prolonged by heat treatment. There is, however, a lack of good supporting evidence in the literature. The opinion seems to be largely based on unreported experiments in various laboratories in which there has been a remarkable lack of success indicated for the ability heat treatments to prolong life.

One of the authors has attempted many times to heat treat materials after prolonged service and has never been successful in showing a significant increase in creep-rupture life. A limited number of experiments have been conducted in which creep-rupture specimens were run for 1/3 of their normal life, removed from the creep-rupture unit, heat treated, and then continued to rupture. The results have always shown the life after heat treatment to be closer to 2/3 of the original life than to 100 percent. In the experiments conducted, however, the materials selected for study have been quite structurally stable.

It is possible to raise short-time strength in spheroidized low-alloy steels by heat treatment after services. Unfortunately, however, the extrapolated strengths for prolonged time periods usually are not changed. In other cases the strength has actually been reduced because the heat treatment removed what appeared to be strain hardening that had accumulated during prior creep and thus the material was weakened when again subjected to creep.

The authors have also heard discussions of studies on relatively pure materials where the data indicate that void formation was accompanied by lack of response to heat treatment after creep. If, however, creep was restricted to conditions where rupture would normally occur transgranularly and there was no evidence of void formation, creep life could be restored by heat treatment.

Cr - Mo - V steel which underwent loss in creep-rupture life at 1000°F as a result of prior creep at 1100°F (ref. 4) could be restored by heat treatment. The damage was largely temperature induced although accentuated by creep. Presumably heat treatments were successful because the damage was largely structural, although no carbide changes were observed. This is supported by the fact that damage to 1100°F properties was very slight from prior exposure to creep at 1000°F. This further suggests that the major factor at 1100°F was structural deterioration and possibly a change in the mode of deformation between the two temperatures.

Creep Damage and Extrapolation of Properties

Successful extrapolations of short-time data must necessarily predict damage effects in the future. This would presumably not be difficult if the mode of deformation did not change, the structure was stable and there were no surface deterioration from environment. Usually, all of these requirements are not met. This, therefore, complicates extrapolation and tends to make the success of any extrapolation procedure dependent on the particular alloy, its heat treatment and the test conditions. It is unreasonable to expect any one type of extrapolation to include all possible effects. To be exact, the extrapolation procedure must take into account the particular damages occurring. Examples of such complications are:

1. Recrystallization of creep-strain monel during creep tests complicated by intercrystalline crack growth and oxidation was shown by Grant and Bucklin (ref. 6) to abnormally decrease long-time properties.

2. Cellular precipitate formation at grain boundaries induced by creep was associated with premature rupture in Mg-Al alloys (ref. 7). Continuous grain boundary films formed by precipitation were used to explain similar effects (ref. 8). Alloy depletion from the matrix adjacent to grain boundaries by precipitation in the grain boundaries has been offered as another structural change causing premature, brittle failures (ref. 8).

3. Ludahn (ref. 9) encountered difficulty from strain aging in prediction of creep behavior by tension tests. Also, reference is made to prior history effects (ref. 10) even in metallurgically stable materials.

4. Lubahn in reference 10 postulates that the temperature of prior deformation affects current behavior, but that rate of strain may not. Sherby and Dorn (ref. 11), on the other hand, developed a method for prediction of long-time behavior of alpha solid solutions based on the observation that substructures developed at a given creep stress are functions of creep strain independent of test temperature.

5. Orr, Sherby and Dorn (ref. 12) discuss a method for correlation of rupture data based on a constant heat of activation for a given metal independent of stress, temperature, grain size, sub-grain structure, minor alloying additions and dispersed phases.

6. A number of methods for correlating and predicting performance from a relatively few number of short-time tests have been presented in recent years. Most of these involve empirical or semi-empirical correlations of data with the structural change effects taken into account by the actual test data to varying degrees. The best known of these is the Larson-Miller parameter (ref. 13). Others have been proposed by Manson and Halford (ref. 14) and McGregor and Fisher (ref. 15 and 16). The success of any of these methods depends on how well the data used to predict behavior at other time periods, temperatures and stress levels is affected by the various instabilities which can occur. In addition, there are assumptions made which may not hold for all conditions. The use of a single constant of 20 in the Larson-Miller parameter is an example of this.

Relationship of Creep Damage to Other Properties

There exists considerable data in the literature of an empirical nature which gives properties of material after various amounts and conditions of creep. Most of this type of data is too extensive, specific in nature and restricted by so many qualifying conditions that it cannot be adequately treated in this survey. Some typical examples are discussed below.

Sachs and Brown (ref. 17) reviewed creep damage literature and showed that prolonged creep tests at 932°F on alloy steels in Europe indicated that notched-bar impact tests were a sensitive indicator of creep damage when tension, bending and hardness tests did not indicate damage. The damage was a function of the alloying elements in the steel as well as the test conditions. Cr - Ni and Cr - Ni - Mo steels were embrittled while Cr - Mo steels were not. Heating embrittled Cr - V steel with little effect from stress. The stress effect was large in Cr - Ni - Mo steel compared to the temperature effect. Cr - Mo - V steel showed both temperature and stress embrittlement. Armco iron underwent rapid and severe embrittlement. When stress-induced damage occurred it tended to increase with decreasing stress and increasing time to a maximum value and then decrease for still lower stresses and longer times. It was not clear if this represented a recovery from damage due to prolonged heating or a reduction in the creep damage from low creep rates. Heat treatments after embrittlement improved Cr - Mo - V and stainless steels and the other steels, provided the amount of damage was not too great. There appeared, however, to be a level of damage where heat treatments would not relieve embrittlement. The tendency for embrittlement seemed to be associated with the conditions leading to low ductility and notch sensitivity in rupture tests.

Prior heat treatments influence observed results. For instance, it is well known that after creep a hardened steel will usually show a reduction in tensile strength due to tempering. The same alloy in the annealed condition will usually show an increase in tensile properties due to "strain hardening" accumulated during creep. There are an infinite number of ramifications of such effects.

Impact tests are often used to measure creep damage effects because they seem to be more sensitive than other tests.

There is often concern over changes in fatigue strength accompanying creep damage. While it is now well documented it appears that in the absence of other significant structural changes, there is usually no effect on fatigue strength until third-stage creep starts. Clauss, (ref. 18), however, found that prior creep significantly reduced the resistance of S816 alloy to thermal shock while it somewhat improved Inconel 550 alloy. It was not clear whether this represented a creep damage in one case and not in the other, although he accounted for it on the basis of the greater amount of ductility expended in the case of S816.

It has been previously pointed out that changes in the mechanism of deformation may show little or no influence of the prior creep when materials exposed to creep are subject to other mechanical tests. Sherby and Dorn (ref. 11) reported improved tensile properties in aluminum after extensive prior creep, with the amount being directly related to the true creep strain.

It was shown that even the presence of cracks from third-stage creep apparently did not damage some properties of Cr - Mo - V steel (ref. 4).

Many attempts have been made to relate creep damage to physical properties such as electrical resistivity, damping capacity, density, etc. For instance, increased internal friction from prior creep strain was reported for aluminum (ref. 19). In most cases, and especially in engineering materials, the complications of thermally induced changes in the structure combined with the creep have usually defeated attempts to relate these properties to creep damage.

Very little information is available concerning the response of materials to notches introduced after prior creep. Creep-rupture considerations for notched specimens are covered in another review. It would seem, however, that the main consideration would be the influence of the prior creep on properties which control response to notches in creep-rupture tests. Notch sensitivity might be increased if the prior creep increased yield strength; reduced primary creep (as might be expected) and otherwise reduced rates of relaxation of stress concentrations; used up available ductility so that there was insufficient ductility to allow stress redistribution; lowered fracture stress in some manner; or reduced creep-rupture strength under the effective stress of the notch; etc. There is little doubt that in most practical cases the structural changes will be the predominant factor rather than effects introduced by creep alone. It is a field, however, where there is need for more information.

The Materials Laboratory, WADC is currently sponsoring at the University of Michigan an investigation of changes in mechanical properties of three sheet alloys during creep. Samples are being exposed to total deformations up to 3 percent in time periods up to 100 hours at three temperatures. The specimens are then removed from creep units and subjected to short-time tensile, compressive tests and tension-impact tests at room temperature and the creep-exposure temperature. The results to date show both increases and decreases in these mechanical properties as a result of the creep over and above the changes due solely to exposure to temperature without stress. The explanations are not yet well established. A major factor may be the influence of creep on structural changes. It may not be possible to separate effects due to creep alone from the concurrent thermally induced structural changes. It is, however, clear that creep in the amounts considered can improve as well as reduce the short-time mechanical properties.

Voids and Microcracks

Void formation followed by growth of the familiar transverse, intercrystalline cracks seems to be the mechanism leading to a larger percentage of creep-induced fractures. It follows, therefore, that void formation is important to creep damage. The theories and mechanisms proposed are too numerous to cover in this survey. It is worthwhile, however, to point out certain special aspects of reported research.

1. There is mounting evidence that excess phases or at least certain types of excess phases have profound effects on formation and growth of voids. The removal of ZnO particles from α-brass (ref. 20) reduced the start of cracks in creep and greatly increased elongation before fracture. The second phase particles of ZnO were considered to act as heterogenious nucleators of voids and cracks. Mackin (ref. 21), proposed that voids must be originally present from solidification stresses or

as a result of prior plastic work, gas pockets, cracked inclusions, etc. to account for observed cracks where their presence could not be accounted for on the basis of vacancy condensation. A number of Russian investigators have proposed that cracking develops by the pile-up of dislocations at low melting point excess phases in grain boundaries. Frey (ref. 22) suggested thermal stresses at excess phases as being important in brittle fracture.

2. Compositional and structural changes which tend to strengthen grains relative to grain boundaries seem to accelerate crack growth and probably the original void formation. Thus, alloys are usually more prone to cracking than "pure" metals. Various theories are advanced to account for the compositional effects on crack formation and growth. Grant and co-workers (ref. 8) indicate the essential feature to be the resistance to deformation by the grains for relief of the stress concentrations. Alloying strengthens the grains and thereby increases the stress concentration effects at the grain boundaries causing crack formation and growth. Excess phases present in some forms in the grain boundaries not only interfere with the recovery mechanisms that relieve stress concentrations, but also act as sources of stress concentrations.

3. Changes in mode of deformation are involved (ref. 21). Increasing temperature and decreasing strain rate usually shifts the mode of deformation from slip and allied processes in the grains to grain boundary phenomena. This apparently favors void formation and crack growth with reduced ductility. At still higher temperatures it is easier for the relief of stress concentrations to occur. More cracks form but they do not grow as readily. Consequently, fractured samples usually show far more cracks than at lower temperatures when the relief of the stress concentrations is more difficult. Grant (ref. 23) discussed the temperature effect for a number of alloys and related exceptions to compositional and structural factors affecting relief of stress concentration at the grain boundaries.

4. Certain elements present in trace amounts appear to have profound effects on void and crack formation and growth. Small additions of zirconium to phosphor bronze and aluminum brass (ref. 24) reduced cracking during creep to a remarkable extent. A similar effect has been reported for small additions of boron and/or zirconium to Ti + Al hardened nickel base alloys (ref. 25). Another case is reported in reference 26.

5. While the preponderance of the literature seems to point to creep damage arising from voids and their growth to cracks, the emphasis varies from the Russian investigators (ref. 27, 28, 29, 30 and 31) who attribute the creep almost entirely to voids to Sully (ref. 32) who doubts that they have much effect and shows that micro-cracks are not always a cause of third-stage creep. Others (ref. 33, 34) have pointed out the prior correlations between the stages of creep and cracking. Voids during second-stage creep were reported in reference 35 while voids formed during first-stage creep were reported in reference 36. Most writers, however, indicate that voids do not form until third-stage creep (ref. 37, 38, 39).

Discussion

It became clear from this review of the literature that there have been very few critical investigations of creep damage. Considerably more information is probably scattered through the literature of creep than were found in this survey. Unfortunately, these pieces of information relating to creep damage are usually buried in articles primarily devoted to some other subject and their presence is not evident in the titles and abstracts. Furthermore, it became evident that many of the generalities are based on experience and unpublished experiments. Considerable recourse was, therefore, taken to general impressions, discussions of the subject with other investigators, and personal experience. It is amply evident that a considerable amount of critical experimental work would be desirable to clarify the subject creep damage.

Thermally induced structural changes generally accompany creep. In almost every article reviewed, reason was found to question whether or not damage from the creep process and from structural deterioration were properly correlated.

It is suggested that one of the most significant aspects of creep damage may be the indication that creep life cannot be rejuvenated by heat treatment. This should be a very useful field for research. The objectives could include:

1. Determination of the validity of the belief that creep life is permanently lost.

2. Relation of mechanisms of creep to response to heat treatment. In particula the taking into account of the stage of creep, recovery effects and creep under conditions which would and would not lead to intergranular cracking.

3. Establish whether or not void formation is responsible for permanent creep damage. Careful metallographic and electron microscope techniques ought to be fruitful in such studies.

A most important problem is the development of methods for estimating the effect of prior service on future service. There seems to be no reason to mistrust test results after prior service provided care is exercised to be sure the test results are applicable. For instance, the tests should not involve different modes of deformation than will occur in service. Better basic data supporting the validity of test data as a basis for estimating future performance without tests would, however, be useful. A program of conducting tests for part of their creep-rupture life and then remachining specimens for retesting should provide useful information. Special attention should be directed to the problem of estimation of start of third-stage creep after partial service. This would be considerably strengthened by a cooperative program in industry providing for the removal and testing of samples after partial service under known conditions. All experiments should be planned to establish principles by the inclusion of the necessary supporting structural studies.

There is little doubt that ultimate clarification of creep damage is dependent on clarification of the creep mechanisms and their relationships to microstructure. It appears that a careful review of experimental and theoretical studies of creep from the viewpoint of creep damage would be valuable. This could lead to considerable progress in the field and suggest clarifying experiments. The General Research Panel might profitably organize a continuing group to review creep mechanism studies from this viewpoint.

This review suggests certain generalities regarding creep damage as summarized in the initial portions of this review. It seems apparent that most of the concepts are not very well supported by good data. In addition, there are probably many limitations related to initial structures in metal, conditions of creep and concurrent structural changes which are not understood and could lead to errors when the attempts are made to apply these concepts.

Very little consideration has been given to damage resulting from surface deterioration. There are certainly cases where creep and corrosion, as well as acceleration of intergranular corrosion could be particularly important. It should also be recognized that surface corrosion, particularly of a localized nature, could also be cause for retirement of equipment from service even though creep damage was minor. Alloy depletion from the surface as well as contamination of the alloy by elements introduced from the environment are often controlling factors in service change.

Geometrical instabilities introduced by creep can often accelerate failure by increasing stress even though the total creep damage at the time the instability occurs may be rather small. For instance, column buckling is mainly controlled by this type of problem.

Thus, it is readily evident that the concept of creep damage is a complex inter-play of metal structure, the creep process itself, and environmental and service factors.

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