CREEP DAMAGE ASSESSMENT AND RESIDUAL LIFE ESTIMATION BY MECHANICAL TESTING

V. Bicego *

The possibility to extend the lives of many existing old plants beyond the original lives considered in designs demands a number of analyses to be done, including integrity assessments and residual life evaluations based on results obtained from mechanical tests on specimens of material sampled from the plant components in the actual damage state. Due to a generally limited material availability for the specimens, a number of problems exist; test procedures must be carefully designed and test results properly interpreted, in order to provide high quality and fully valid results. Aspects of experimental activities for the determination of creep, toughness, low cycle fatigue resistance and cracking behaviour of material sampled from serviced high temperature components of industrial plants are considered in this work.

INTRODUCTION

A trend is evident in the field of energy-production, petro-chemical and chemical industries towards extending lives of plants, well beyond the time figures considered in the original designs. Convenience of purshuing maximum possible profit from already existing old plants is favoured by several factors opposing construction of new plants, the most important being the need to comply with increasingly severe safety and environmental regulations, difficult political decisions about localization of new plants in opposition to local public opinions, high financial costs. On the other hand, Life Extension (LE) of old plants is economically possible because of lack of substantial improvements in plant engineering during the last decades (the efficiency of an old design is often not far from that of a more recent design). In terms of economic convenience, the cost of renuvation of an old plant has been evaluated 1/10 of the cost of a new plant (Tremmel (1)), which rises to 1/3 when consideration is given to the additional surveillance actions for the extended phase of the old plant (Towsend (2)). Finally, LE is now technically feasible due to development and increasing use in industry of a number of modern methods suitable to quantify the extent of damage and to predict the Residual Life (RL).

* CISE S.p.A. Segrate (Milano)

RESTLIFE ESTIMATION

A large amount and variety of materials data, specific for components in the actual damaged state, are required to evaluate and predict the extent of damage. The problem of creep is normally the most important aspect affecting the RL of high temperature components in industrial plants. On the other hand it is recognized that the creep damage which has occurred in a material can also considerably reduce other mechanical characteristics of the material with respect to virgin condition considered in design, such as toughness, fatigue and stress corrosion properties. The creep damaged areas of components are therefore also the parts to which experimental activities for the determination of the other relevant mechanical resistance parameters have to be concentrated. The problem of identifying the critical locations of creep damage in a high temperature plant relies at a preliminar level on residual life estimates derived from nominal creep rupture curves usually reported in codes, material manufacturer specifications etc., eventually expressed in parametric forms (Larson-Miller being a popular method). Such creep rupture data are representative of virgin materials, and are typically given in forms of bands representative of broad classes of alloys. Large uncertainties are involved when applying these data for predicting the life of a particular component made of a certain alloy, due to the large data variability of creep strengths within the same class of alloys (fig.1). Therefore studies are growing aimed at precisely locating the actual component material within the band of the same class of alloys, e.g. from values of hardness (Kuwabara et al. (3)) or from considerations of chemical compositions of minor phases (Afrouz et al. (4)). Despite the many problems involved, nevertheless use of life calculations from these creep rupture curves is a typical preliminar step in the identification of critical items of a plant to which further analyses should be addressed. For the steels of most common use, expecially austenitic and ferritic steels and some Nickel base alloys, existing creep rupture data banks are substantially adequate, at least for normal material conditions. In the case of the heat affected zones (HAZ) near welds and fusion lines, creep data are lacking. A safety reduction factor of 0.8 applied to the stress is sometimes considered, which may be too conservative. Obviously the creep resistance of the HAZ may be not a critical issue when "leak before break" occurs in HAZ's of pressure pipes of fossil fuelled power plants. Here moderate amounts of steam leakages may be tolerated, as they are soon discovered and the failed component repaired; convenience of weld reparation in place of pipe replacement depends on the expected residual creep duration of the sound pipe material, which shifts the relevance of creep rupture data from the welded regions to the base metal. The situation is different when explosive ruptures may occur, or when leakage of an aggressive or toxic fluid from a chemical plant is involved. In these circumstances better knowledge of creep rupture characteristics of HAZ's is important in view of safe life extension strategy. As creep data bases for HAZ's rarely exist, the need of undertaking laboratory test programmes specifically aimed at characterizing creep rupture behaviour of HAZ's for the most common types of welds is recognized.

Once the critical regions of a plant have been identified, progressively deeper analyses are made using life estimates based on actual operational plant data, f.e.m. calculations, NDI, surface replication and finally, if applicable, mechanical tests on material sampled from the component. In order to maintain component ability to work after sampling, only moderate amount of material is normally available for the specimens of the mechanical test. In case of thick components (large turbine rotors of land based units) deep cylindrical plugs 20mm in diameter are taken commonly, with no subsequent component reparation needed when the plugs are taken according to appropriate directions to minimize the disturbance to the component stress state. In other cases boat samples are taken, which can be followed by weld pass reparation or not. For thinner components, like piping and tubing, a section of the pipe can be removed to obtain material for the mechanical tests, and the lacking part is then replaced with a new part. The particular choice of form and orientation of sampling, and questions about post sampling component repair, depend on a number of factors, such as costs, time of outage available for this job, accessibility to certain locations, importance of stress directions and presence of preferential orientations of damage. In any case, the experimentalist is generally faced with two solutions in making his tests on the serviced material: use of miniature specimens or use of conventionally-sized composite specimens, i.e. built by joining together (frequently by welding) pieces of material available in small amounts.

ASPECTS OF MECHANICAL TESTING

Particular equipment and expertise in defining test procedures and in interpreting tests data are involved when carrying out mechanical tests for RL scopes: few amount of material is normally available, which allows obtainment of only small specimens and in limited number. Valid data should be derived from a minimum number of tests made in short time, as a limited quantity of material is typically available for the specimens and the plant engineers demand definite answers about material's state of damage in stringent times. All these aspects must be clearly considered by the experimentalist. The author's company, CISE, starting from a multidisciplinary experience in the fields of plant monitoring, f.e.m., NDI, corrosion and mechanical studies, has been increasingly involved during recent years in activities for assessing the integrity and evaluating the RL of components in plants which have exceeded or near to exceed their nominal design lives. In this work considerations derived from this experience are presented, with the discussion focussed on problems of mechanical tests aimed at evaluating material's creep resistance, toughness, crack growth properties and resistance to elastic-plastic fatigue from tests made on miniature and conventionally-sized composite specimens; the typical geometries considered are summarized in fig.2.

Creep

Creep rupture tests (not necessarily involving the measurement of specimens elongations during the tests) performed on material in the actual damaged state are in principle the most straightforward way to define the residual lives of components, when creep is the relevant life limiting factor. Unfavourable aspects of any experimental creep activity for RL evaluations are material and time wastage: these problems may be reduced to some extent by performing the tests on miniature specimens, eventually with the shoulders made of a different material, and using accelerated test conditions, namely higher stresses and temperatures with respect to service conditions.

Methods for determination of RL using experimental data from accelerated tests have been largely based in the past on Robinson's Linear Damage Summation (LDS) rule (5):

$$\frac{t_{ser}}{t_{ser}+RL} + \frac{t_{r,acc}}{t_{r,acc,vir}} = 1 \qquad (1)$$

with:

t_{ser} = service time of the component,

$t_{r,acc}$ = the creep life as determined from an accelerated creep test on the damaged material of the component,

$t_{r,acc,vir}$ = the life from a similar test made on virgin material (eventually obtained by heat treatment regeneration of the damaged material).

In eq.1 RL is the unknown, the residual life of the material of the component which is assumed to continue its operation under conditions for σ and T identical to the past. To improve the estimate of RL, several accelerated tests of this type may be performed. In any case, problems in this approach are the often poorly known stress and temperature histories during past operation (which may have been non-stationary), non availability of virgin material for the tests (re-generation by heat treatment being uneffective when excessive oriented cavitation damage is present), and intrinsic uncertainty of the LDS model, as the constant in the second member of eq.1 is often different from unity. As far as this last point is concerned, a large number of different formulations of the LDS rule have been proposed; in particular the methods of Bendick and Weber (6) and of Fee Wen (7) may be mentioned for application to RL evaluations, the former considering an initial non-damaging life period for the serviced material not entering in the LDS balance, and the latter utilizing a "strain ductility exhaustion" version of the LDS rule.

Apart from LDS approaches, a different prodedure for RL estimation based on data from accelerated creep tests involves use of Time-Temperature parameters, such as Manson-Haferd (8), Orr-Sherby-Dorn (9) and Larson-Miller (10). According to the last method, RL is obtained from:

$$(T_{ser}+273)\ (C+\log_{10}RL) = (T_{acc}+273)\ (C+\log_{10}t_{r,acc}) \qquad (2)$$

with C = a constant (usually taken 20 for ferritic steels and 15 for austenitic steels) and the indexes of temperatures (T_{ser}, T_{acc}) and time ($t_{r,acc}$) having the usual meanings of service and accelerated test conditions as above. It is seen that, differently from the LDS approaches, the use of a Time-Temperature parameter do not rely on availability of virgin material accelerated creep rupture data for RL predictions. A problem in use of parametric forms such eq.2 relies however on the uncertain degree of validity of Time-Temperature parameters particularly when large extrapolations are involved (service values of σ and T quite different from values used in the accelerated tests: in order to keep durations of such tests within few thousands hours, stresses about 50% higher and temperatures about 100°C higher than service are used at least). Different creep rupture mechanisms may also be involved.

To overcome difficulties in the methods above, in the last years the isostress creep rupture tests method has got increasing popularity for RL evaluations. The method (Stubbe and Van Melsen (11)), essentially based on a Manson-Haferd parametric correlation, provides an RL estimate from extrapolating to the actual value of service temperature a best fit drown through the data of tests (usually not less than 5 tests) performed under accelerated conditions for the temperature and with a stress equal to the service stress: fig.3. Typically to derive good RL estimates this method considers creep rupture data spanning 3 decades of times (test durations from a few hours up to a few thousands hours), at different temperatures over a 100°C interval starting from a minimum temperature (for the longest test) which, having indicatively fixed the desired duration of the test at 10^3h, essentially depends on the extent of damage present in the material: as an example, when a residual service life of 10^5h is retained (this is of course the quantity to be determined, not known in advance), the lowest temperature in the accelerated tests is around T_{ser}+100°C. Upper limit of test temperature is related to the minimum time fixed for the tests: time should be the lowest, to provide a well defined best fitting curve to be confidently extrapolated to service condition, and minimum durations of the order of one hour are frequently considered. However it is sometimes observed (Cane and Williams (12)) that the maximum temperatures for the isostress tests are physically limited by phenomena of microstructural evolutions of minor phases, which change the creep mechanisms with respect to the service situation (new types of carbides are observed to form in steels above certain limits of temperature). Therefore too high temperature data should not be used. Usually however the maximum temperature level allowed by such physical considerations is too stringent for a practical application of the isostress method (an upper temperature of 600°C has been indicated in the case of a low alloy ferritic steel,(Felix and Geiger (13)) and this limitation is therefore generally nonconsidered; this is a question which should merit deeper study, to better clarify consequences in RL predictions and perhaps to reconsider more realistically the problem of the maximum test temperatures. In any case the temperatures used in the isostress tests are quite above the values at which these materials are used in plants while retaining adequate properties of resistance to environmental degradation, and therefore in order to prevent severe oxidation of the specimens from the laboratory air the tests are frequently done in an inert atmosphere, usually vacuum or argon. Actually a high purity atmosphere is out of scope, as the interaction of creep and oxidation does occur in the component, so that only massive oxidation of the specimens is to be avoided. Though the diminution of resisting cross sections of specimens in the isostress tests made in air can be modeled to a certain extent and the RL predictions analytically corrected for this effect (Cane (14)), however use of an inert atmosphere is recommended, particularly when the tests are performed on miniature specimens. At present the use of miniature specimens, often also built of different parts welded together (in which case only the central portion of the specimens is made of the actual material of the component, while a different alloy can by used for the threaded ends, furtherly reducing material consumption), is increasingly adopted in isostress activities for RL estimation, particularly when the material is available in forms of small plugs or boat samples taken from thick components which must subsequently retain their ability to work (eventually after a minor weld reparation of the sampled region). A value of 60 for the ratio of specimen diameter to material grain size dimension is generally considered as a minimum value, to avoid problems of creep strengths influenced by particular orientations of cristallographic planes in the the few grains sampled by the very small specimen. Complete recording of the creep elongation curve is not normally the output of a miniature specimen test, due to technical difficulties in accurately measuring the strains. Approximate methods are sometimes suggested, whose adequacy is not clear: in addition to provide elongation data useful for engineering scopes, the importance of having accurate strain data might be to support use of advanced models of Continuous Damage Analysis (Lemaitre (15)), providing numerical information of the extent of creep damage parameter D in the material which explicitly enters in these models. In addition to the problem of massive oxidation in the miniature specimens,demanding use of inert atmospheres, still at an experimental level the possible inaccuracy in results brought by poor load axis alignement has to be carefully considered. Whenever applicable, as in the case with standard creep tests made on conventionally-sized specimens, use of a couple of extensometers provides the opportunity for checking, at least orientatively, the degree of initial alignement of the specimen axis. In the isostress tests for RL evaluations the undesired role of bending seems a major potential problem, as it is enhanced by the combination of for unfavourable features typical of these tests, namely a) the quite low loads used (service loads), b) the high stiffness of the specimens, as the specimen gauge lengths are short to reduce material consumption (low ratio of length vs. diameter), c) non use of extensometers pairs which might provide some indication of the initial extent of bending and of the way to reduce it, and d) materials to be tested which are often in a brittle condition, resulting from the prolongued operation. These features are all present when testing with the isostress method miniature specimens made of 1CrMo steels from plug or boat samples taken from thick components such as rotors and casings, which have undergone severe temper embrittlement during service; in case of piping of 2 1/4 Cr Mo steel entire sections of pipes can be removed to machine conventionally-sized specimens, and only the first condition a) applies. Whenever the degree of misalignement is suspected to be a problem, special precautions in test set up, such as adopting more efficient coupling systems in the loading apparatus, together with sistematical preliminar verifications using resistive strain gages bonded at 120 intervals around specimen sections, should be considered. It may also be of interest to quote ASTM creep tests standard practice E139-83: "The Subcommittee on Test Methods of the ASTM-ASME-MPC Joint Committee on the Effect of Temperature on the Properties of Metals urgently requests factual information on the effect of nonaxiality of loading on test results. ... In testing of brittle materials even a bending strain of 10% may result in lower strength than would be obtained with improved axiality. In these cases, measurements of bending strain on the specimen to be tested may be specifically requested and the permissible magnitude limited to a smaller value."

Toughness

Knowledge of toughness of materials of plant components in the actual damage state allows determination of critical sizes of cracks, already present at the beginning or which have been subcritically growing during service. Toughness data provide the upper values of crack lengths in the integration of the crack growth rate expressions for the growth mechanism involved (i.e. fatigue, corrosion or creep), from which the RL is estimated. Apart from this use, material toughness properties are an essential ingredient for integrity assessment studies of components (the other ingredient being knowledge of stress and temperature distributions). Therefore cracks and any other type of microstructural defects as revealed by NDI are evaluated in relation to the capability of the component to resist the severe events which may occur during service. Typical examples of routinely occurring severe events in thick walled components are the large thermal transients during plant start up and shut down. Critical situation for existing cracks are when large stresses are in correspondance with a temperature in the lower branch of material toughness vs. temperature transition curve. For old plants made of ferritic steels the problem of the integrity of large components during transient operations is of growing importance during life, due to temperature embrittlement which shifts the FATT (Fracture Appearence Transition Temperature) towards higher values, thus extending the potential for brittle fractures.

Conventional as well as composite specimens, CV or precracked CV type, are used in impact tests for assessing the extent of the embrittlement in high temperature components made of low alloy steels. In order to minimize material consumption for the tests, a convenient procedure consists in carrying out one first test on a normal specimen, subsequently utilizing the two broken halves to provide the central portions for two additional specimens, having the shoulders made of a different steel; the attachements are made by butt resistance welding. With this procedure three tests are made using the material of one specimen. In case of toughness testing, the two possibilities of using composite specimens or sub-sized specimens exist, fig.2. According to CISE experience with composite specimens, convenient results are obtainable by the front-reconstruction C(T) geometry, case a) in fig.2, with however only a moderate material saving advantage but nevertheless with a convenient use when sampling pipes with at least approximately 12 mm wall thickness as the normal 1TC(T) geometry can be used. When use is made of composite specimens made of the serviced material only in the small cylindrical region surrounding the crack tip, case b) in fig.2, problems of excessive residual stresses at crack tip caused by welding have been recognized and this solution has not been purshued furtherly at CISE (Bicego et al. (16)); however an interesting and simple solution for correcting apparent Kic values determined from such tests affected by residual stresses into appropriate toughness values has been proposed by Klausnitzer (17). Main effort is presently devoted in author's company towards utilization of miniature specimens, namely with Disk Shaped C(T) geometry with 18 mm diameter, suitable to be obtained from cylindrical plugs. Testing such miniature specimens requires particular attention to certain experimental aspects, such as precracking, which must be interrupted as soon as the minimum appropriate crack length is reached to save a large portion of the residual ligament for the subsequent test, and measuring with appropriate accuracy the load line displacements: in lack of miniature gages an indirect procedure for measuring displacements has been proved convenient, Bicego and Lucon (18). Crack extensions are measured by a sophisticated version of Potential Drop system (Catlin et al. (19)). Recently a special test procedure aimed at measuring material toughness utilizing circumferentially cracked cylindrical specimens loaded in tension (Gray (20)) is also under study at CISE. In any case, it is observed that existing guidelines and standard recommendations may be unsufficient to comply with the peculiar characteristics of the tests on the miniature specimens, and a great expertise in conducting the tests and analyzing the results is essential. All these aspects are considered in a specific paper presented at this same Conference (21), therefore they will not be discussed in detail here. Only, a final point merits to be raised about aspects of validity (and therofore significance of using the test results for assessing integrity of components) of data obtained in tests for the determination of J-Resistance curves, when the specimen dimensions severely restrict the field in which the J-Integral is the appropriate correlating parameter for stress and strain crack tip fields. It is believed that the importance of obtainining data for the plant material, often under difficult experimental conditions which demand adoption of nonconventional test procedures, should not lead to underestimate aspects of validity requirements. An illustrative example is given in fig.4, reporting fracture resistance data obtained by Liaw et al. (22) is tests on a low alloy steel, here re-analyzed to show regions in which validid data cannot be obtained according to ASTM E813-87 and ASTM E1152-87: it is seen that definite conclusions when commenting behaviours of materials analyzed should be taken with caution.

Subcritical Crack Propagation

The measurement in laboratory tests of the growth rates of cracks which propagate under conditions of fatigue, stress corrosion and creep provide the means for deriving, by integrating the crack growth laws determined, the RL of components subjected to these forms of damage.

As far as tests for the determination of Stress Corrosion Cracking (SCC) data are concerned, these tests in most circumstances can be conveniently done utilizing the miniature DS C(T) specimens with 18mm diameters previously mentioned. SCC is a phenomenon in which the rate of crack propagation ($\dot{a}$) is a constant (for a certain combination of temperature and environment) over a large interval of the applied stress intensity factor K, from a minimum level of K below which a threshold is present, up to a high K level above which the SCC rates increase drastically. In many cases of components subjected to SCC only the threshold values of K and the stationary values of ȧ are of interest, and the tests can be conveniently done on quite small specimens because the levels of K are moderate with respect to the K-capacity of the specimens (LEFM conditions met). A simple wedge-type of loading, leading to decreasing K as the crack growth proceeds, can be conveniently used. The definition of the upper limit of SCC, i.e. the K level for crack acceleration, may be more problematic in tests on miniature specimens. Concerning material state of damage, the propagation of a large corrosion crack is generally regarded as a surface or subsurface (at crack tip) phenomenon, in the sense that the bulk material far in front of the crack tip is not degraded by this form of damage. Therefore the phenomenon is essentially the propagation of a crack starting from the surface of a component and than propagating inside, assisted by load and by corrosion, into a material which is essentially "virgin" at the instant it is reached by the advancing front of the crack. Tests on actual serviced materials taken from components are therefore essential when the SCC properties are not known from tests made on the original material, or in particular cases where different forms of damage other than corrosion may be present: temperature embrittlement, hydrogen absorption and aging phenomena in microstructurally unstable steels. On the other hand when other types of bulk damage of mechanical origins, namely creep or fatigue, exist, it is likely that the corrosion crack will keep on propagating fastly governed by such driving forces, not due to SCC.

FCG tests on the small DS C(T) specimens machined from plug samples from components are a quite common activity in the author's laboratory since the last few years. Generally these data are needed because for many components used in service, not only the oldest ones, the FCG materials properties are not known, (and sometimes even knowledge may be lacking of the type of alloy of which a particular component is made) and pieces of similar materials available from other sources do not exist. The FCG data are generally utilized to predict future periods of safe operation of components containing cracks which, once nucleated at surface often in regions of stress concentrations (notches), propagate along regions of negative stress gradients: a long stage of useful working life is still possible before the component looses integrity. Due to the moderate loads usually involved in fatigue tests on specimens under a prevailing bending condition, the K-capacity of the miniature DS C(T) specimens results generally adequate, and threshold values of K and FCG data in the Paris regime are easily obtainable. The tests, which are performed on servo-controlled tension machines, only require accurate measurements of crack lengths; a good PD system is adequate, while the elastic compliance method seems to fail. For a closer description of the many aspects of this test methodology in the author's experimental experience the reader is referred to the already mentioned paper presented at this Conference (21). Some further remarks remain to be given to the rapidly developing field of the small crack studies. It is now well recognized that cracks whose dimensions are inferior to certain magnitudes, depending on a number of factors still not perfectly known, propagate faster than the large fatigue cracks usually modelled in terms of LEFM. For the most common steels of which the high temperature components are made the anomalous behaviour regards cracks with in-depth lengths of a few tenths of mm. As long periods of operation are spent while cracks of this size are present, for which the conventional LEFM-based FCG laws would provide nonconservative predictions, and also in view of the increasing capacity of modern NDI tecniques to provide detections of small cracks, the need of appropriate data and models for the peculiar propagation of the small cracks is of increasing relevance in tecnology, and this has led in the recent years to a great field of research. Beside the aspect of modeling, particular problems exist in adequacy of testing apparatus to accurately follow these cracks in laboratory tests performed at high temperature. Here also the aspect of crack acceleration in materials having suffered bulk damage due to temper embrittlement, fatigue or creep, is also of importance for reliable RL predictions (Sakurai et al. (23)).

LCF

The LCF tests are intended to provide information on ability of components to resist fatigue cycling under elastic-plastic conditions, produced in large components by transient inertial effects in rotational parts or, more frequently, by large strains induced during severe thermal transients (cold start and shut down). This damage is often localized at regions of geometrical strain concentrations, and results in the formation after a certain number of cycles of small cracks in the engineering sense, i.e. with dimensions comparable with the sizes of the plastically yielded zones at notch roots of components. The subsequent period of propagation is normally rapid, and is out of engineering relevance as components cannot be kept in operation once the LCF cracks have formed. The laboratory tests to characterize materials with respect to this form of damage, providing curves of number of cycles to failure vs. values of applied strain ranges, in the same way as components define essentially the duration of the specimens up to small cracks nucleation. The tests relevant for description of thermal fatigue damage in high temperature components are mostly performed under isothermal conditions, at the highest temperature of the real thermomechanical cycle (this being also generally the temperature during steady state operation). As a result of material plastic yielding during transients, residual stresses are introduced which subsequently relax by creep during the steady operation. Therefore the interaction of time dependent (creep) and time independent (plasticity) damage is an essential feature of thermal fatigue and this is accounted in laboratory by running the tests over a large variety of strain rates and by introducing hold periods at peak tensile or compressive strains. Quite long cycle periods would be needed to approach realistic operational times; usually the longest cycle periods considered in LCF tests do not exceed few hours, and therefore these tests are in a certain sense tests accelerated in time. Differently from the accelerated creep rupture tests for the evaluation of the residual creep life of components, use of higher temperatures is not an effective solution in LCF tests. In addition to creep, another essential form of time dependent and temperature dependent damage is oxidation, enhancing surface cracks initiation at brittle oxide films ruptures and oxygen absorption at grain boundaries assisting propagation of microcracks (though in certain circumstances even improved fatigue lives caused by extensive oxidation have been documented). Therefore the final mechanisms of LCF damage are the result of complicated interactions of pure plasticity, creep and oxidation, and there is no soundly established method at present to manage information derived from temperature accelerated LCF tests to provide predictions of LCF lives at lower temperature. The majority of the models dealing with the creep-fatigue-oxidation interaction utilize information from LCF tests accelerated in time, performed at the temperature of the plant steady operation. Tests on miniature specimens for RL evaluations are almost impossible on material sampled from components, due to experimental difficulties in testing too small specimens; instead of relying on results of LCF tests on sampled material in the real damage state, residual lives are evaluated from LCF endurance curves for the virgin material (curves representative of the same class of alloys are often adopted in lack of specific data), and from consideration of the elapsed damage history of the components. Difficulties in LCF testing miniature specimens are caused by enhanced massive oxidation with respect to the small net sections adopted; testing in inert atmospheres would be costly, considering the typical durations of these tests (up to some months typically), and more importantly not representative of the actual damage condition of the component when oxidation is an essential feature affecting LCF life. A further difficulty in testing small specimens is the delicate problem of the strain monitoring apparatus, which has to be accurate and attached to the specimen in a firmly stable condition, as it provides the test control signal. An increasing use is observed in LCF laboratories of longitudinal extensometres mounted on cylindrical specimens. This is surely appropriate in many modern activities aimed at characterizing high strength materials, even with directionally dependent properties, as these advanced alloys have generally a low ductility; when making the LCF tests on the more ductile steels of components of the electrical and petrochemical industry, large repeated plastic strains are involved, which make critical the mechanical stability of the cylindrical specimens during the compressive portions of the cycles. A small value of the gage length vs. diameter ratio would improve specimen stiffness, but this would require use of extensometres having very short gage lengths, not available in the market and also difficult to construct, also considering the characteristics of accuracy and of mechanical stability requested. Use of a hourglass specimen geometry with a diametral extensometer would be advantageous in terms of compressive stability, but here the errors in diametral readings due to oxide growing at the surface of the small hourglass specimen may be quite large. For many reasons therefore the use of miniature specimens in LCF tests results problematic, and rarely made. Some points of an LCF activity utilizing sub-sized specimens (nor really miniature, minimum diameter being 5mm) recently started at the author's laboratory may be here illustrated. This work is aimed at determining the residual LCF resistance of the material from a HP steam unit rotor after 165,000h service and 219 cold starts. The conventional gripping devices used in the lab are suitable for mounting cylindrical specimens with 25mm diameter flat buttom heads (and 9mm minimum specimen diameter). Due to the limited sizes of the pieces sampled from the component, only 10mm were available for the maximum diameter of the specimens extremities, and the simple solution depicted in fig.5 has been attempted. Here the specimen flat buttom heads have been derived from pieces of conventionally-sized specimens of another steel broken in previous LCF tests. After having firmly tightened the screwed connections among the different parts, this composite specimen is then machined up to the final tolerances (in particular, stringent parallelism is requested for the planes of the flat heads as it fixes the degree of axiality of load). After the test the two end connections are re-usable for other tests. Convenience of this solution also relies in the fact that no preliminar work in setting up new equipment and procedure with respect to the normal laboratory style, for matching peculiarities of these sub-sized specimens, has been needed (problems of stringent times allowed for experimental activities of RL evaluations of serviced components via mechanical tests are well known aspects in the experience of anybody working in this field). In fig.6 results obtained in the tests performed so far are shown, in conjunction with LCF curves for virgin material derived from codes (Berg (24)). The technique utilized in these tests seems convenient, the only non-resolved problem being a somehow critical compressive stability (indicated by irregularities in the shapes of the stress-strain histheresis loops) for the specimen tested at the highest strain range, which provided also a reduced LCF life.

REFERENCES

(1) Tremmel, D., Int. Conf. on Life Time Assessment and Life Time Extension, Den Haag, June 13-15 1988, Vol.3, 151-161.

(2) Towsend, R.D., Int. Conf. on Creep, Panel Discussion on RL Assessment of Fossil Fuel Power Plants, Tokyio, Apr. 14-

18, 1986, 9-11.

(3) Kuwabara, K., Nitta, A., Kashima, K., Takahashi, Y., Matsubara, M., Ogata, T. and Hashimoto, K., in ref.(1), Vol.2, 99-105.

(4) Afrouz, A., Collins, M.J. and Pilkington, R., Met. Techn. Dec. 1983, Vol.10, p.461.

(5) Robinson, E.L., Trans. ASME, Vol.74, N°5, 1952, 777-781.

(6) Bendick, W. and Weber, H., in ref.(1), Vol.3, 76-84.

(7) Wu Fee Ven, ASME Conf. on Life Prediction Methods, Albany (NY), 1983, 347-351.

(8) Manson, S.S. and Haferd, A.M., NASA TN2890, 1953.

(9) Orr, R.L., Sherby, O.D. and Dorn, J.E., Trans. ASME; Vol.46, 1954, p.113.

(10) Larson, F.R. and Miller, J., ASME, Vol.74, 1952, p.765.

(11) Stubbe, J. and Van Melsen, C., Symp. on Residual Life of Constructions Operating at Elevated Temperatures, Den Haag, The Nederlands Inst. of Welding, 1977, p.71.

(12) Cane, B.J. and Williams, J.A., Int. Mat. Reviews, Vol.32, N°5, 1987, 241-262.

(13) Felix, W. and Geiger, T., Sultzer Tech. Rev., Vol.3, 1961, p.37.

(14) Cane, B.J. and Hart, R.V., unpublished work, 1984.

(15) Lemaitre, J., Nucl. Eng. and Des., Vol.80, 1984, 233-245.

(16) Bicego, V., Lucon, E. and Ragazzoni, S., EGF Symp. on EPFM: Elements of Defect Assessment, Freiburg, 1989, Oct. 9-12, in press.

(17) Klausnitzer, E., Zeitschrift fur Werkstofftechnik, J. of Mat. Tech., Vol.7, October 1976, 357-392.

(18) Bicego, V., and Lucon, E., 16th Plenary Meeting of EGF - Task Group I, Paris, 1988, Apr. 21-22.

(19) Catlin, W.R., Lord, D.C., Prater, T.A. and Coffin, L.F., ASTM STP 877, 1985, 67-85.

(20) Gray, T.G.F., Int. J. Fracture, Vol.13, N°1, 1977, 65-75.

(21) Bicego, V., Crudeli, R., Fossati, C., Lucon, E. and Ragazzoni, S., "Fracture Toughness and Fatigue Tests on Miniature Specimens for Plant Components Integrity Assessment", this Conference.

(22) Liaw, P.K., Saxena, A. and Schaefer, J., Eng. Fracture Mechanics, Vol.32, N°5, 1989, 675-708.

(23) Sakurai, S., Miyata, H., Iijima, K., Sukekawa, H. and Kaneko, R., in ref.(1), Vol.2, 76-85.

(24) Berg, U., Bertlisson, J.E., Friedl, K.H. and Scarlin, R.B., Workshop Proc. on Rotor Forgings for Turbine and Generators, Palo Alto, Sep.1981, EPRI WS-79-235.

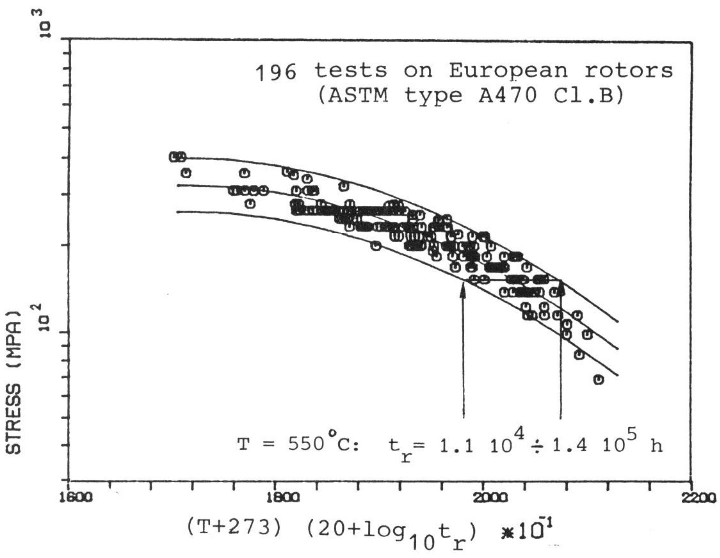

Figure 1 Larson-Miller data of 1CrMoV rotor materials

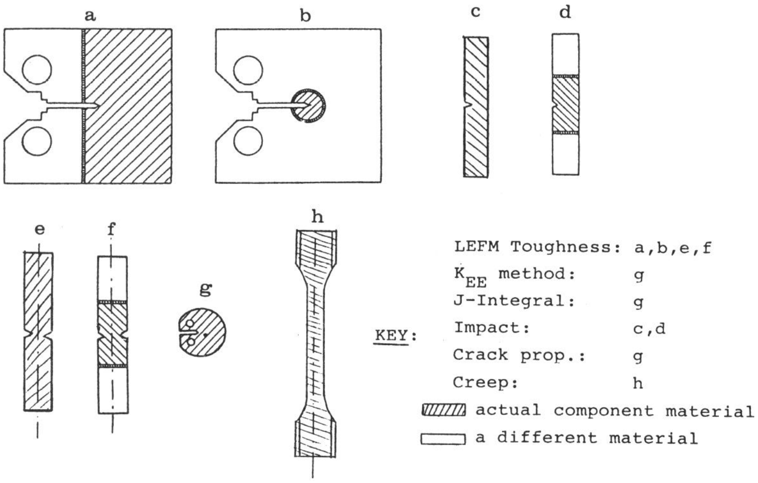

Figure 2 Specimens for the various types of mechanical tests

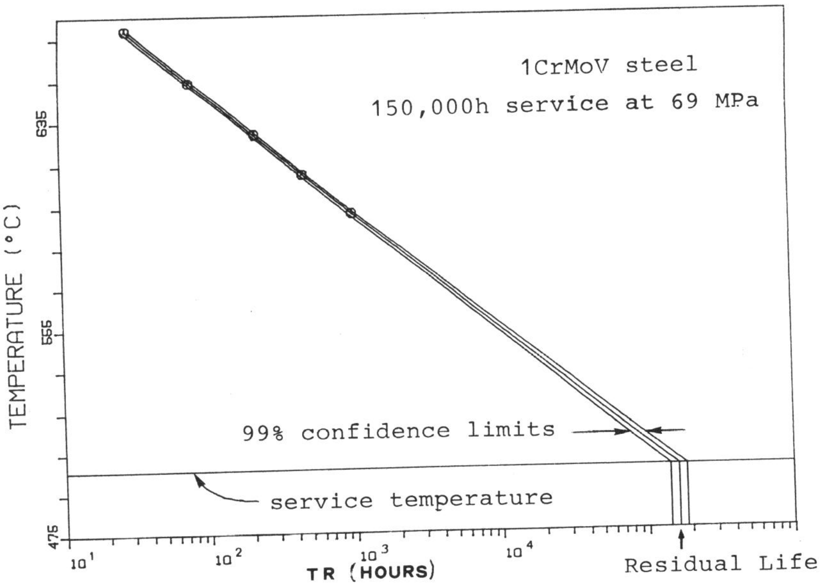

Figure 3 Isostress creep rupture tests data for RL evaluation

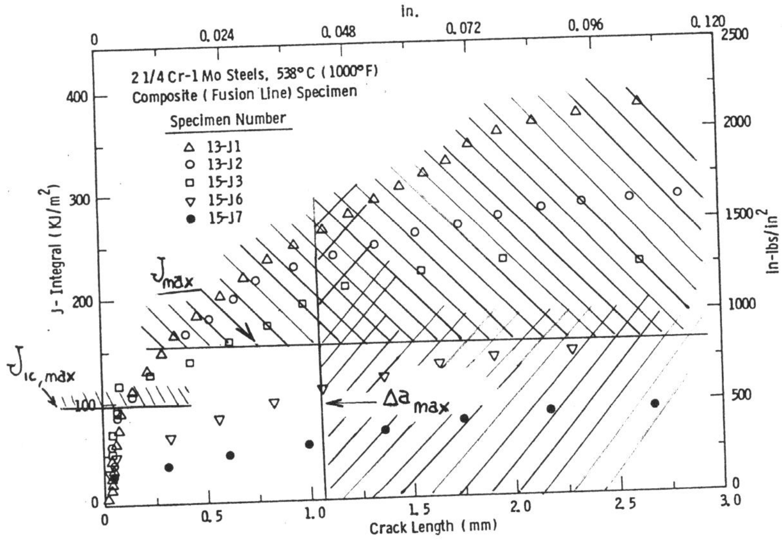

Figure 4 Analysis of J-R data from tests on 1/2T C(T) specimens (from (22))

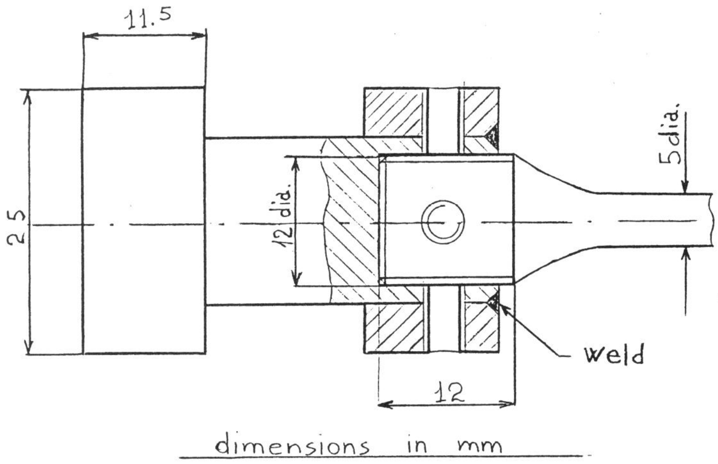

Figure 5 Coupling system for testing small LCF specimens

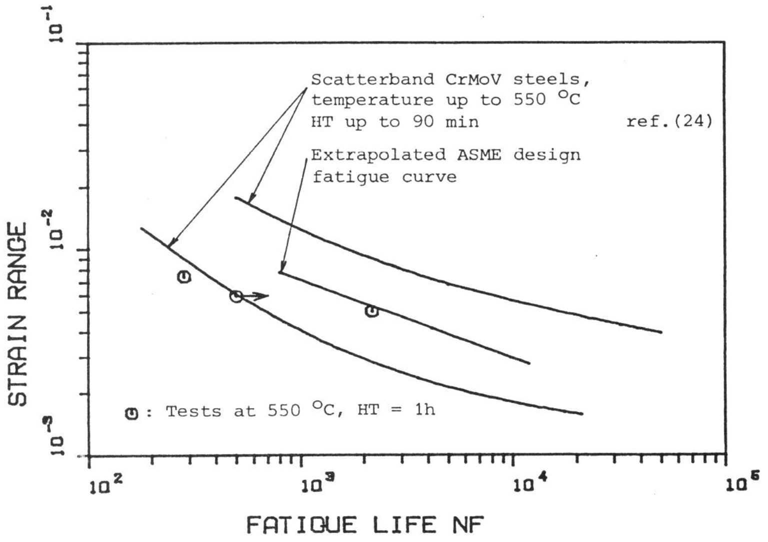

Figure 6 LCF analysis of a serviced rotor material