1 Introduction

K. YAGI, G. MERCKLING, T.–U. KERN

1.1 General remarks

To utilize energy resources efficiently and preserve the global environment, efforts are being made to raise the temperature at which high-temperature equipment is used at power and chemical plants. As a result, the conditions to which the structural components of these plants are exposed have become much more demanding. Structural components have been developed that endure these extreme conditions and some of them are now coming into use. It is therefore necessary to ensure the effective and safe use of these materials, to gain a full understanding of the characteristics of the new structural components, to evaluate their strengths, and to predict their life with greater accuracy. On the other hand, many of the world's high-temperature plants were constructed as long ago as the 1970s and have deteriorated markedly with age. These aged plants are sometimes used under operating conditions different from those planned at the time of their construction. Therefore, the key issue is to be aware of the changes that take place in materials for structural components over time and to predict their remaining life with high accuracy.

With regard to the prediction of the life of high temperature structural materials, the evaluation of their deterioration with time and the prediction of the remaining life of aged materials, it is essential to have a full knowledge of the characteristics of these materials and to be aware of the existence of material data that is a source of that knowledge. Creep characteristics are typical properties of high-temperature structural materials. Because the creep characteristics of structural materials in high-temperature plants are understood to be important in the design of boilers and pressure vessels, creep tests have been actively conducted since the 1930s [1, 2]. Creep data have been systematically obtained and published in the United States and European countries such as UK, Germany and Italy since the end of World War ll. Large-scale facilities and operating funds are required to obtain and register creep data, and in recent years it has become increasingly impractical for single organizations to be tasked with collecting systematic and long-term data. For this reason, it is increasingly important to share basic data and knowledge at the international level

With the beginning of a new Landolt-Börnstein data collection series, the present data book was planned and compiled through the cooperation of European Creep Collaborative Committee (ECCC), German Creep Committee (GCC) and National Institute for Materials Science, Japan (NIMS). The purpose of the data book was to collate previously obtained creep data on major heat resistant steels and alloys as well as knowledge concerning creep characteristics. It could then serve as a basis for technological development to predict the life of structural materials, evaluate their deterioration with age and predict their technically usable life, as well as act as a resource for the design of safe structural components and safe maintenance of plants. More than four years were spent from planning to completion of this data book. However, this is a short period of time compared to the 10 years or more required to obtain service relevant creep data. The editors of this data book hope that it will help in the development of new technology as well as in the design and maintenance of safe power plants and comparable applications.

1.2 Status of creep database

Research institutes, academic societies and private industries have collected and organized up to now creep data independently or through coordination as a group. Because of the need for special facilities and of constraints on funding and time, most long-term creep data have been collected on a national level or through programs run by academic societies. Typical data series published internationally are outlined below.

1.2.1 The ASTM data series

The American Society for Testing and Materials (ASTM) published a collection of data on high-temperature strength as part of the Special Technical Publication (STP) series in the 1950s. Nearly 50 volumes have been published for the Data Series (DS) [3]. The features of this series are that the editors' analyses and the results of their evaluations are included in each volume. The description of data has not followed a prescribed format.

1.2.2 The BSCC high-temperature strength data series

This is a data series compiled by the British Steelmakers Creep Committee (BSCC) in 1972, under the leadership of the British Steel Corporation [4]. The data series shows the results of high-temperature tensile testing and creep rupture testing on representative materials such as carbon steel, alloy steel and austenitic steel and follows a stipulated format.

1.2.3 The long-term data series by the Iron and Steel Institute of Germany

The German Creep Committee with it's secretary of Verein Deutscher Eisenhüttenleute (VDEh) compiled creep data on heat resistant steels in 1968 [5]. Data collection was made by a joint working group of steelmakers and equipment manufacturers. Data on carbon steel, low alloy steel, 12Cr steel and stainless steel are shown in a fixed format. Many years later, a data series on cast steels [6] and heat resistant alloys [7] were jointly published by Forschungsvereinigung Warmfeste Stähle (FWS) and Forschungsvereinigung Hochtemperaturwerkstoffe (FVHT) of VDEh and Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV) in 1986 and 1987, respectively.

1.2.4 European Creep Collaborative Committee (ECCC)

The ECCC was established to jointly acquire, collate and analyze creep data on metallic materials for high temperature plants in the European community in 1992. Actually 14 nations are members of the ECCC, including Germany, United Kingdom, Italy, France, Sweden, Denmark, Finland, Belgium, The Netherlands, Portugal, Austria, Switzerland, Czech Republic and Slovakia. The ECCC aims to harmonise and encourage European creep data generation, provide creep and creep rupture strength data as well as design relevant information to European standards, exchange information on material development, and develop rules for data generation, exchange and assessment [8]. Target materials are carbon steel and low alloy steel, 9-12% Cr steel, austenitic stainless steel, welded joints, bolts, and Ni base alloys. While experimental data have not been made public, the results assessed with proceduralised methods (e.g. BS PD 6605) and validated with the aid of innovative credibility checks [8] were presented to the public in 1999 [9].

Newer European standards, like EN 10028, EN 10216, EN 10222, contain creep strain and creep rupture strength data assessed by ECCC and derived from all over Europe, sometimes all over world collated experimental results.

1.2.5 Report on the mechanical properties of metals at elevated temperatures by the Iron and Steel Institute of Japan

The High-temperature Research Committee (formerly called the Creep Committee) collected data and published five volumes of data series covering low alloy steel, stainless steel, carbon steel and cast iron, heat resistant alloys and welded joints [10].

1.2.6 Creep data sheet published by NIMS (formerly called NRIM)

In 1966, the National Institute for Materials Science (NIMS) launched a 100,000-hour creep rupture strength testing project on domestically produced high-temperature metallic materials. The results of these creep tests series were summarized in 49 kinds of NIMS (formerly called NRIM) creep data sheets and published in 122 volumes up to 2003 [11]. Although still in progress, the project is one of the largest in the world planned to obtain creep test data. A collection of microstructural photographs was also published, showing the microstructure of metal using long-term crept specimens obtained from this data sheet project [12].

1.2.7 Others

Academic societies have been producing data series limited to specific fields only. Those concerned with welded joints [13] and chemical equipment materials [14] have already been published. Creep data on products accumulated by industries have also been published as data series [15, 16].

1.3 Testing procedures for obtaining creep data

To obtain creep test data, a large-scale facility needs to be built. The tests are also time-consuming, making it impossible for one research organization alone to acquire all the required data. It is therefore important to conduct tests based on a shared method so that highly reliable test data can be obtained, exchanged and compared. To meet this need, different countries introduced standards for creep testing and creep rupture testing, and later their respective test standards were incorporated into ISO standards. Because of this background, the standards currently in use around the world are ISO [17], ASTM [18] of the United States and in the last years also the European standards EN [19]. The current ISO 204-1997 will be revised as a result of voting at ISO TC164-SC1. EN 10291:2000 [20] appears to have become the foundation for this amendment. In the revised plan, interrupted tests are allowed and specifications for temperature tolerance and accuracy in measurement of the cross-sectional area are modified.

NIMS creep data have been produced not only in conformity with JIS but also with ISO and ASTM. With regard to temperature and load accuracies in particular, they are found to be better than the relevant standards, allowing the acquisition of data by performing high-accuracy creep tests [21]. During experiments that continue for more than 100,000 hours, there is a risk of exceeding the specified temperature range. In the NIMS creep data sheet, information on this problem is given for each data point. Temperature measurement during creep testing is generally made using a PR thermocouple, but PR thermocouples deteriorate during testing and the thermo-electromotive force declines. These results are published in the paper [22]. This type of information will be helpful in evaluating data and using it effectively.

European creep data were produced according to several standards in the contributing Nations (DIN 50118, BS 3500, UNI 5111, etc.). A widespread overview on all European standards as well as on relevant laboratory intern testing practices formed the basement of the data generation recommendations stated in [19], which then further developed into EN 10291. European data collated in the ECCC programmes according to a specified recording scheme taking account of all testing details (see [19], Volume 4), were assessed for conformity with the minimum testing requirements as stated in Volume 3 of [19] before introduced in general assessment. New data, generated by the ECCC joint programmes, are mandatorily produced with testing procedures conformed to at least EN10291 or to the "high quality" testing recommendations in [19].

1.4 Evaluation and assessment of creep data

The determination of creep strength is a process which requires a high accuracy in the application of the pure testing technique as well as in the handling of the whole process, starting with the specimen manufacture and including the precision in the measurement of length changes during creep as well as the final strength computation. Therefore stringent procedures and specifications are necessary to both guarantee reliable test results and design relevant long-term creep and creep rupture strengths.

The long term strength and creep behaviour of a material is dependent on several factors such as:

- chemical composition,
- way of manufacturing and heat treatment, and
- component size and specimen location.

The reliability of long-term properties of a particular material is fundamentally dependent on the material pedigree and raw test data verification, on the creep strength assessment method, its application procedure and on a critical evaluation of their credibility [23, 24, 25, 26].

The data assessment needs to rely on a sufficiently large data base, which must include a representative number of different casts of the same material grade and – possibly for a big amount of the casts – on several testing results with long durations in the intended application temperature range. Testing times should be sufficiently long to avoid extremely high extrapolations in time, and therefore the stress levels chosen for the specimens have to be well balanced to fulfil the statistical requirements.

In Europe and Japan, the extrapolation rules allow time forecasts of three times the maximum testing time as this was originally suggested by the meanwhile withdrawn ISO 6303, e.g. for an extrapolation of a 100,000h (11.4 years) creep rupture strength, minimum data duration of 30,000h (3.4 years) is required in principle.

If different casts of the same material grade are merged during the assessment, the evaluation with only statistical or mathematical tools does often not mirror the real material behaviour. The single cast trends and behaviour have also to be considered, and the assessment of the whole data population and of its sometimes huge scatter band needs to take this single cast information into account.

Also the pedigree information for the single materials and of each cast of the same material grade needs to be carefully evaluated during the assessment in order to understand particular cast behaviour and to avoid erroneous conclusions based on numerous results belonging to casts with extraordinary surrounding properties.

Europe developed in the last 10 years a quite rational and objective approach to creep data assessment, which bases on some fundamental statements:

- Creep strength is considered reliable only if the available experimental data base conforms to given rules. They require a minimum amount of tested casts, a minimum number of tests per significant casts and a minimum number of tests with design relevant test durations in the range of temperatures and stresses expected to be technically relevant.
- To assess creep strength, different methods for data evaluation are required to be applied contemporaneously to the same multi-cast, big sized and desirably long term test containing data base in order to ensure the true material behaviour from at least two distinct views.
- A credibility check of the assessment results which were derived from test data is required before they are allowed to become strength values in order to ensure that failures and damages do not occur during the design life of the component, taking into account the scatter of properties in technical applications. This credibility check is codified in the ECCC Post Assessment Tests (PAT), which include three categories of physical, numerical and statistical tests, determining the degree of confidence in physical realism, test data description and extrapolation stability of the computed mathematical expression applying for becoming a creep strength prediction tool.

Actually the majority of the creep strength data proposed for the new EN standards bases on this approach.

In Japan, a Manual of Extrapolation Methods for Creep-rupture Strength Based on ISO 6303, in which Larson-Miller, Manson-Haferd and Manson-Brown parameter methods have been introduced as computer-aided extrapolation methods, was published on 1983 [26]. However, it is pointed out that long-term creep strength which is predicted using these current extrapolation methods is critically overestimated for advanced ferritic heat resistant steels. In order to improve long-term life prediction for 9-12Cr ferritic creep resistant steels, a new creep life prediction method is proposed in conjunction with a region partitioning method of stress vs. time to rupture diagrams [27].

The present book includes raw test data in the majority of the presentations. In some cases also computed strength values are included. The latter are determined by the mentioned rules.

Additional statements on minimum data information requirements, testing techniques, minimum acceptability criteria and sound testing rules, data assessment procedures and post assessment tests are available in [23, 24, 28, 29].

1.5 Application of creep data

Design criteria under temperature conditions where creep properties have to be taken account of are determined by data on creep rupture strength, creep deformation rate, creep strain, etc. In ASME Sec. VIII-Div. 1, for example, allowable stress may be calculated from the minimum values obtained from the following:

(1) 67% of the average value of 100,000-hour creep rupture strength
(2) 80% of the minimum value of 100,000-hour creep rupture strength
(3) 100% of the average value of stress that produces a creep rate of 0.01% per 1,000 hours

In Europe and in Turbine and Power Plant industry generally, the recent trend has been to obtain allowable stress from 200,000-hour creep rupture strength.

If a new material is used, creep testing is conducted to obtain its creep strength, from which an allowable stress can be defined. However, long-term creep strength is extrapolated using various methods for life prediction, since it is impossible to obtain data by conducting long-term creep testing under every condition. However, the prediction of creep strength is not simple and extrapolation from short-term creep data is not always reliable. The microstructure of metal changes during creep, and affects creep deformation and rupture life. Many life prediction methods have been proposed, but due to this problem none of them has been ideal. And even if so called Post Assessment Tests have been derived to establish a credibility criterion for data description and extrapolation functions, no mathematical relationship overcomes the need to obtain long-term creep data.

Meanwhile, an additional challenge has appeared due to an increasing number of high-temperature plants which are still in use despite exceeding their design life, which cannot be replaced in short times or shut down. It has become an important task to some National Power Production Balances to keep these plants running by carefully evaluating the remaining life of these plants with a long history of use. In making this evaluation, an increased volume of abundant, more reliable and longer-term test data and microstructural information than those available at the time of plant design is essential. This data should include the changes in the microstructure of the metal during creep, the formation of creep damage and its growth, creep deformation, creep cracking behavior resulting from defects, the strength of welded joints, the effectiveness of multi-axiality on strength and failure, and creep rupture strength.

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DS-6-S1 (1971); 2.25Cr-1Mo steel
DS-5 8(1975); 3 to 9Cr steels
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2 Creep and rupture data of heat resistant steels

2.1 Carbon steels

2.1.1 0.1C steel

2.1.1.1 Introduction

This carbon steel for boiler and heat exchanger tubes is used as water tube, smoke tube, super-heater tube, air-preheater tube, etc. in boiler and as heat exchanger tube, condenser tube, catalyst tube, etc. in chemical and petrolic industries. The carbon steels are used only at temperatures lower than 400 °C, because they have not enough creep strength for higher temperatures.

2.1.1.2 Material standards, chemical and tensile requirements

Table 1. Chemical requirements of 0.1C steel tubes; JIS STB340, ASTM A, BS360 and DIN St35.8

Standards	Designation	Chemical composition [wt%]					Std.No.
		C	Si	Mn	P	S	
JIS	STB340	≤0.18	≤0.35	0.30-0.60	≤0.035	≤0.035	G3461
ASTM	A	0.06-0.18		0.27-0.63	≤0.035	≤0.035	A178
BS	360	≤0.17	0.10-0.35	0.40-0.80	≤0.035	≤0.035	3059-2
DIN	St35.8	≤0.17	0.10-0.35	0.40-0.80	≤0.040	≤0.040	17175

Table 2. Tensile properties of 0.1C steel tubes at room temperature; JIS STB340

Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elongation [%]		
		d ≥20 mm	20>d ≥10 mm	d<10 mm
≥340	≥175	≥35	≥30	≥27

2.1.1.3 Creep properties of 0.1C steel tubes

Information of fact on creep data for 0.1C steels can be obtained from [1], [2] and [3].

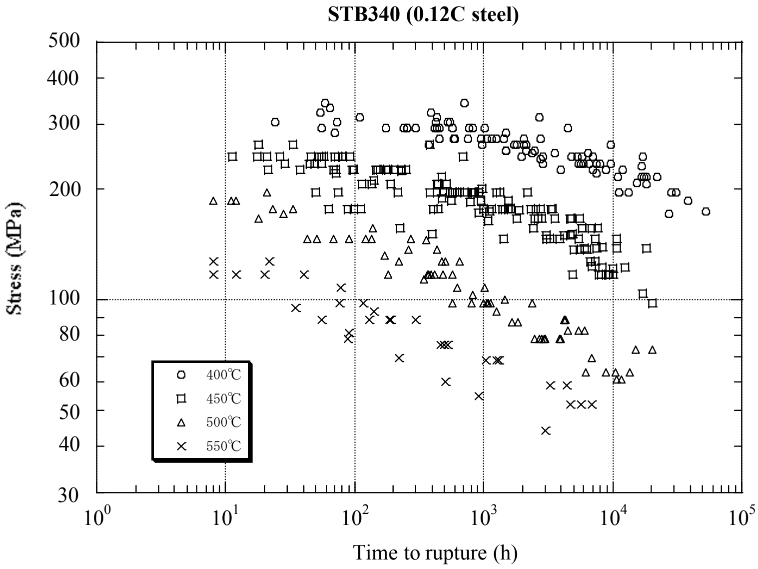

Fig. 1. Creep rupture strength data of STB340; [1].

2.1.1.4 References

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2.1.2 0.2-0.3C steel

2.1.2.1 Introduction

0.2-0.3C steels are used as tubes for heat exchangers, boilers, superheaters and feedwater heaters in power plants, chemical and petrochemical plants. 0.2-0.3C steel plates are used for boilers and pressure vessels in power plants, chemical and petrochemical plants.

Creep strength of the 0.2-0.3C steel is strongly influenced by small amounts of molybdenum through the strengthening effects of Mo-C and Mo-N atomic pairs in solid solution, as will be explained later.

2.1.2.2 Material standards, chemical and tensile requirements

2.1.2.2.1 0.2-0.3C steel tubes for heat exchangers

Table 3. Chemical requirements of 0.2-0.3C steel tubes; JIS STB410, Japanese METI KA STB480, ASTM Gr. C, ASTM Gr. A-1 and ASTM Gr. C2

Standards	Designation	Chemical composition [wt%]					Std. No
		C	Si	Mn	P	S	
JIS	STB410	≤0.32	≤0.35	0.30-0.80	≤0.035	≤0.035	G3461
Japanese METI	KA STB480	≤0.30	≥0.10	0.29-1.06	≤0.048	≤0.058	
ASTM	Gr. C	≤0.35	-	≤0.80	≤0.035	≤0.035	A178
ASTM	Gr. A-1	≤0.27	≥0.10	≤0.93	≤0.035	≤0.035	A210
ASTM	Gr. C	≤0.35	≥0.10	0.29-1.06	≤0.035	≤0.035	A210
ASTM	Gr. C2	≤0.30	≥0.10	0.29-1.06	≤0.035	≤0.035	A556

2.1.2.3 0.2 - 0.3C steel plates for boilers and pressure vessels

Table 4. Chemical requirements of 0.2-0.3C steel plates; JIS SB410, JIS SB480, JIS SGV410

Standards	Designation	Chemical composition [wt%]							Std. No
		Thickness [mm]	C	Si	Mn	P	S	Mo	
JIS	SB410	≤25	≤0.24	0.15 - 0.30	≤0.90	≤0.035	≤0.040	-	G3103
		25 - 50	≤0.27						
		50 - 200	≤0.30						
JIS	SB480	≤25	≤0.31	0.15 - 0.30	≤0.90	≤0.035	≤0.040	-	G3103
		25 - 50	≤0.33						
		50 - 200	≤0.35						
JIS	SGV410	≤12.5	≤0.21	0.15 - 0.40	0.85 - 1.20	≤0.030	≤0.030	-	G3118
		12.5 - 50	≤0.23						
		50 - 100	≤0.25						
		100 - 200	≤0.27						

Table 5. Chemical requirements of 0.2-0.3C steel plates; ASTM Gr. B, ASTM Gr. 60 and ASTM Gr. 70

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<tr><th rowspan="2">Standards</th><th rowspan="2">Desig-
nation</th><th colspan="7">Chemical composition [wt%]</th><th rowspan="2">Std. No</th></tr>
<tr><th>Thickness [mm]</th><th>C</th><th>Si</th><th>Mn</th><th>P</th><th>S</th><th>Mo</th></tr>
<tr><td rowspan="4">ASTM</td><td rowspan="4">Gr. B</td><td>≤25</td><td>≤0.20</td><td rowspan="4">0.15 - 0.40</td><td rowspan="4">≤0.90</td><td rowspan="4">≤0.035</td><td rowspan="4">≤0.035</td><td rowspan="4">0.45 - 0.60</td><td rowspan="4">A204</td></tr>
<tr><td>25 - 50</td><td>≤0.23</td></tr>
<tr><td>50 - 100</td><td>≤0.25</td></tr>
<tr><td>>100</td><td>≤0.27</td></tr>
<tr><td rowspan="5">ASTM</td><td rowspan="5">Gr. 60</td><td>≤25</td><td>≤0.24</td><td rowspan="5">0.15 - 0.40</td><td rowspan="5">≤0.90</td><td rowspan="5">≤0.035</td><td rowspan="5">≤0.035</td><td rowspan="5">-</td><td rowspan="5">A515</td></tr>
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<tr><td>12.5 - 50</td><td>≤0.23</td><td rowspan="4">0.85 - 1.20</td></tr>
<tr><td>50 - 100</td><td>≤0.25</td></tr>
<tr><td>100-200</td><td>≤0.27</td></tr>
<tr><td>>200</td><td>≤0.27</td></tr>
<tr><td rowspan="5">ASTM</td><td rowspan="5">Gr. 70</td><td>≤12.5</td><td>≤0.27</td><td rowspan="5">0.15 - 0.40</td><td rowspan="5">0.85 - 1.20</td><td rowspan="5">≤0.035</td><td rowspan="5">≤0.035</td><td rowspan="5">-</td><td rowspan="5">A516</td></tr>
<tr><td>12.5-50</td><td>≤0.28</td></tr>
<tr><td>50-100</td><td>≤0.30</td></tr>
<tr><td>100-200</td><td>≤0.31</td></tr>
<tr><td>>200</td><td>≤0.31</td></tr>
</table>

2.1.2.3 Creep properties of 0.2-0.3C steel tubes

Information of fact on creep data for 0.2-0.3C steel tubes can be obtained from [1].

2.1.2.3.1 Creep rupture data of 0.2-0.3C steel tubes

The results of creep tests for 9 heats of JIS STB410 steel tubes are compiled in [1]. From this data sheet the data of rupture elongation, reduction of area and microstructures of as-received materials and crept specimens can be also obtained.

Creep rupture strength data for 9 heats of 0.2C steel tubes (JIS STB410) is shown in Fig. 2 [1]. Very large heat-to-heat variation of creep rupture strength is observed over the whole range of creep test conditions from short-term to long-term. Differences in creep rupture strength are caused by differences in small amounts of molybdenum [2, 3]. Creep strength of the 0.2C steel is strongly influenced by small amounts of molybdenum through the strengthening effects of Mo-C and Mo-N atomic pairs in solid solution [4].

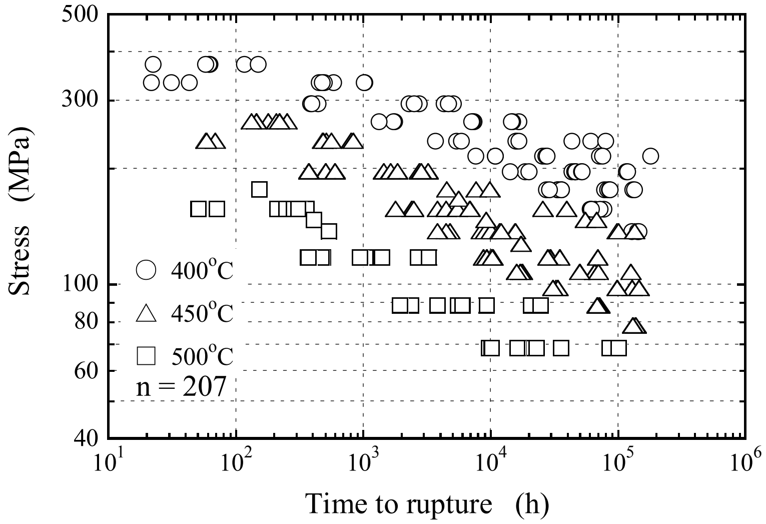

Fig. 2. Creep rupture strength data of 0.2C steel tubes (JIS STB410) according to [1]. *n* indicates the total number of data points.

2.1.2.3.2 Creep rupture strength of 0.2-0.3C steel tubes

Creep rupture strength was analyzed applying the Larson-Miller parameter method to NRIM creep rupture data on 0.2C steel tubes (JIS STB 410). The result is shown in Fig. 3. Sigmoidal inflection with a large scatter band is observed.

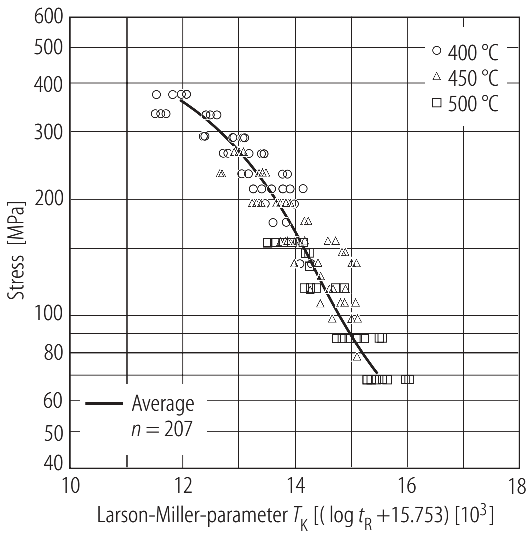

Fig. 3. Master rupture curve obtained by Larson-Miller parameter method for 0.2C steel tubes (JIS STB 410); [1]. *n* indicates the total number of data points.

2.1.2.3.3 Microstructural changes

The typical initial microstructure of 0.2C steel tubes consists of ferritic and pearlitic grains. Optical micrographs of an as-received 0.2C steel tube are shown in Fig. 4. The bright grains are ferritic and the dark grains are pearlitic.

Optical micrographs of 0.2C steel tube specimens creep ruptured after 138,403.7 h at 450 °C and 78 MPa are shown in Fig. 5. Coarsening of carbides within pearlitic grains is observed after long-term creep exposure at 450 °C. Changes in morphology and distribution of carbides within pearlitic grains are used as indicator of degradation of 0.2C steel due to long-term service at elevated temperatures.

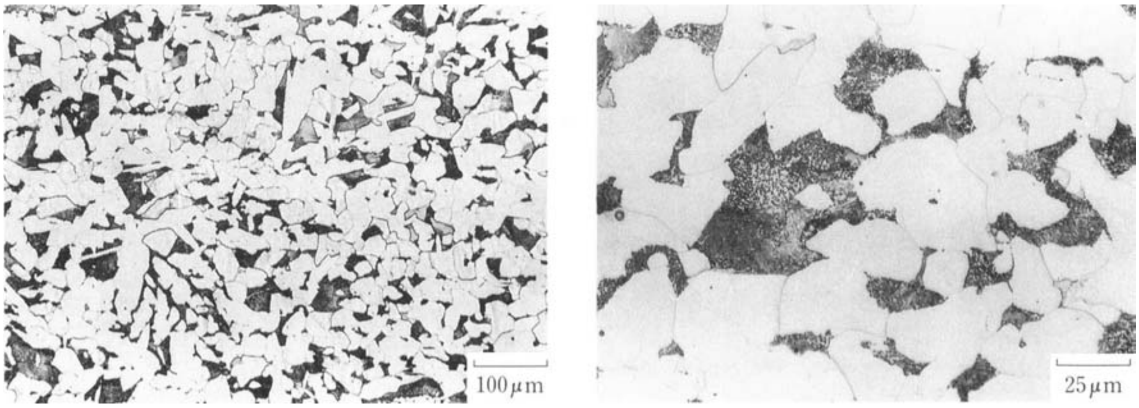

Fig. 4. Optical micrographs of as-received 0.2C steel tubes (etched in 4% nital); [1].

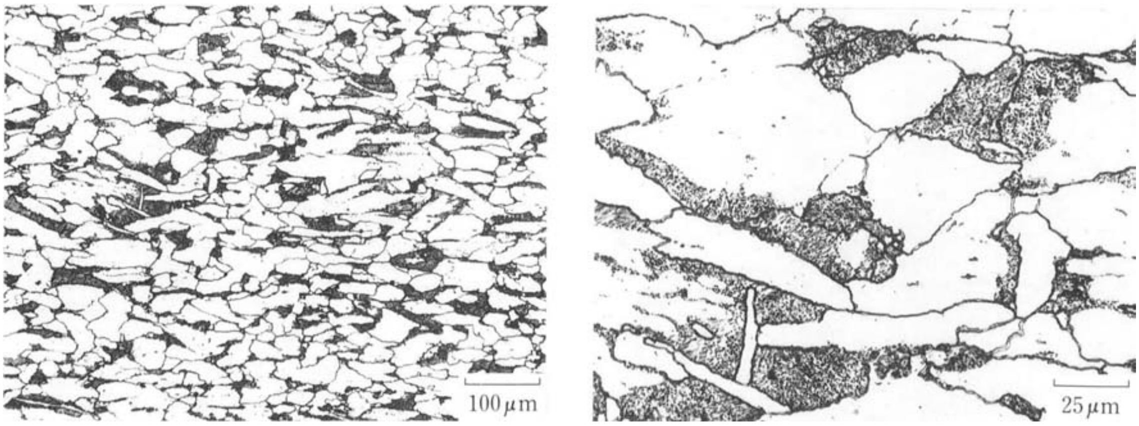

Fig. 5. Optical micrographs of 0.2C steel tube specimens (etched in picral) creep ruptured after 138,403.7 h at 450 °C and 78 MPa; [1].

2.1.2.3.4 Creep deformation behavior of 0.2C steel tubes

The creep deformation behavior of 0.2C steel tubes strongly depends on slight differences in chemical composition, heat treatment and initial microstructure. Creep rate vs. time curves of 0.2C steel tubes at 550 °C and 69 MPa are shown in Fig. 6 [5]. Heat-to-heat variation of creep deformation behavior is clearly observed on these 3 heats of 0.2C steel tubes.

Creep rate vs. time curves of as-received and pre-aged 0.2C steel tubes at 550 °C and 69 MPa are shown in Fig. 7 [6]. Since creep deformation is strongly influenced by microstructural changes during creep exposure, complex creep deformation behavior observed for un-aged steel disappeares by pre-ageing.

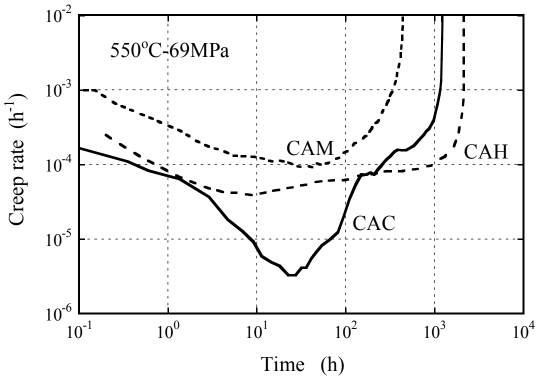

Fig. 6. Creep rate vs. time curves of 0.2C steel tubes at 550 °C and 69 MPa; [5].

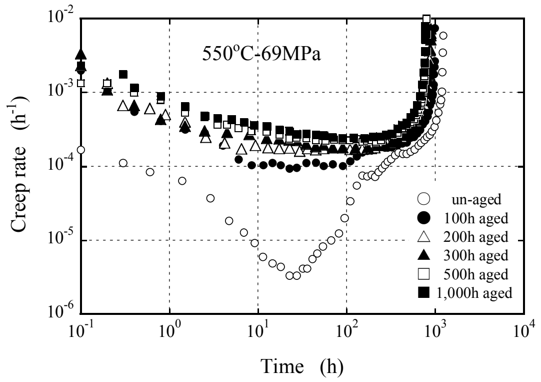

Fig. 7. Effect of pre-ageing on creep deformation behavior of 0.2C steel tube; [6].

2.1.2.3.5 Effect of molybdenum on creep rupture strength

The creep deformation behavior of 0.2C steel tubes is strongly influenced by microstructural changes during creep exposure at elevated temperatures, as mentioned above. Creep strength decreases as a result of microsstructural changes and it becomes an inherent creep strength, which is the creep strength of the ferrite matrix itself, after long-term creep exposure [7, 8].

The inherent creep strength of 0.2C steel tubes is extremely improved by small amounts of molybdenum in solid solution [2, 3]. The very large heat-to-heat variation of long-term creep rupture strength for 0.2C steel tubes, as shown in Figs. 2 and 3, is caused by differences in the inherent creep strength due to a wide variety of molybdenum concentrations, even at low Mo levels of less than 0.02 mass%. Inherent creep strength of 0.2C steel tubes is increased by strengthening effects of Mo-C and Mn-C atomic pairs in solid solution [4].

Inherent creep strength is improved by small amounts of molybdenum, however, this effect is saturated at about 0.03 mass% of molybdenum [2, 3]. Therefore, the inherent creep strength obtained by addition of 0.03 mass% of molybdenum is the highest for 0.2C steel. It has been experimentally found that the inherent creep strength of ferritic creep resistant steels is almost the same independent of chemical composition, heat treatment condition and short-term creep strength [7, 8]. There is a good correspondence between common inherent creep strength for ferritic creep resistant steels and the highest inherent creep strength for 0.2C steel with addition of 0.03 mass% of molybdenum [2, 3].

2.1.2.3.6 Estimated long-term creep strength

The temperature dependence of 0.2% proof stress, tensile strength and creep rupture strength at 1,000 and 100,000 h for 9 heats of 0.2C steel tubes is shown in Fig. 8. The creep rupture strength curves shown in Fig. 8 were obtained by regression analysis using the Larson-Miller parameter.