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PREDICTION OF LONG-TERM CREEP RUPTURE LIFE OF GRADE 122 STEEL BY MULTI-REGION ANALYSIS

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ABSTRACT

Conventional time-temperature-parameter (TTP) methods often overestimate long-term rupture life of creep strength enhanced ferritic steels. Decrease in activation energy Q for rupture life in long-term creep is the cause of the overestimation, since the TTP methods cannot deal with the change in Q. Creep rupture data of a heat of Gr.122 steel (up to 26200h) were divided into several data sets so that Q was unique in each divided data set. Then a TTP method was applied to each divided data set for rupture life prediction. This is the procedure of multi-region analysis of creep rupture data. The predicted rupture lives have been reported in literature. Long-term rupture lives (up to 51400h) of the same heat of the steel have been published in 2013. The multi-region analysis of creep rupture life can predict properly the long-term lives reported. Stress and temperature dependences of rupture life show similar behavior among different heats. Therefore, database on results of the multi-region analyses of various heats of the steel is helpful for rupture life estimation of another heat.

INTRODUCTION

Allowable stress of structural materials at elevated temperature is usually determined by the stress that causes creep rupture at 10^5h. The creep rupture strength is evaluated by extrapolation of short-term creep rupture data on the basis of a time-temperature-parameter (TTP) method. It is widely known that the conventional TTP methods often overestimate rupture life of creep strength enhanced ferritic (CSEF) steels (1-5). Kimura et al. (6) have proposed the following way to avoid the overestimation. In their data analysis they chose creep rupture data tested at stresses lower than a half of 0.2% proof stress for evaluating long-term rupture life ($\sigma_{0.2}/2$ criterion).

In Japan 10^5h creep rupture strength of Gr.122 steel has been re-evaluated in 2004 (7,8). Creep rupture data used for the life evaluation were selected following the $\sigma_{0.2}/2$ criterion. Due to the removal of short-term data points, 10^5h creep strength of the steel was reduced from the one estimated with the whole data points. As a result, 10^5h rupture strength of the steel has been lowered (7,8). Not only the reduction in Japan, European Creep Collaborative Committee has re-evaluated 10^5h rupture strength of Gr.91 steels, and has also reduced it slightly at temperatures from 510 to 650°C (9). After seven years from the first reduction in 2004, 10^5h rupture strength in Japan was reduced again (5), since the rupture strength evaluated with the $\sigma_{0.2}/2$ criterion in 2004 overestimates actual data points obtained later. In order to avoid the repeated reduction of the rupture strength, we should understand causes of the overestimation and propose an appropriate methodology for preventing the overestimation.

The conventional TTP methods, such as Orr-Sherby-Dorn (OSD) and Larson-Miller methods are based on a crucial assumption that the TTP constant, such as Q in OSD method (see Eq. (1)) is unique for a set of creep rupture data to be analyzed. In other words, temperature T dependence of rupture life t_r, namely $d\ln t_r/d(1/T)$ should not change in the data set. However, this assumption is not always valid. Maruyama et al. (10) have pointed out that a change in $d\ln t_r/d(1/T)$ is the major cause of the overestimation, and have proposed a multi-region analysis of creep rupture data. In the analysis a set of creep rupture data is divided into several data sets so that Q is unique in each divided data set. Detailed procedure of the multi-region analysis is explained in the next section (4,10). The multi-region analysis was initially applied to austenitic stainless steels (10,11) in which values of Q for rupture life decreases in longer term due to change in fracture mechanism. Decrease in Q in long-term creep has been confirmed in CSEF steels (1,4,12,13) also.

Long-term rupture life of a heat of Gr.122 steel has been predicted by the multi-region analyses in Ref.(12). In the literature (12) its rupture life has been estimated also by using the data points selected by the $\sigma_{0.2}/2$ criterion. The longest test duration was 26,200h at that time. Longer-term rupture lives up to 51,400h of the same heat have been reported recently (14). The predictions made in 2005 (12) are assessed in the present paper with the longer-term data, and it is discussed how to predict long-term rupture life properly. Heat-to-heat variation is also examined by comparing stress and temperature dependence of rupture life with another heat of the steel. These examinations will assist valid estimation of long-term rupture life of CSEF steels.

CAUSE OF OVERESTIMATION

When estimating long-term creep rupture life, we first

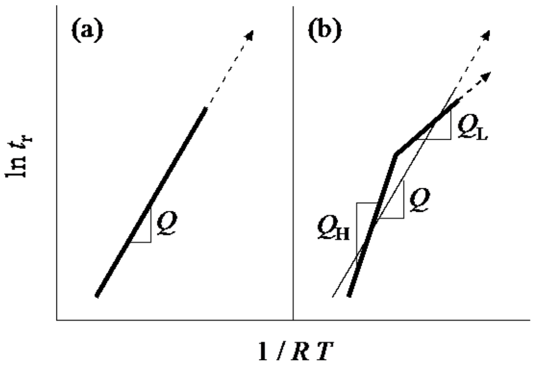

Figure 1: Correlation between data band (thick solid line) and its regression line (thin solid line) determined by the OSD analysis of creep rupture data.

formulate stress and temperature dependence of rupture life t_r on the basis of short-term data measured. The following ODS equation is often employed in the formulation:

$$t_r = f(\sigma) \exp(Q / R T) \quad (1)$$

where $f(\sigma)$ is a function of stress σ, R is the universal gas constant, and T is the absolute temperature. The activation energy Q characterizes temperature dependence of rupture life. A polynomial of $\ln\sigma$ is generally used for $f(\sigma)$, for example:

$$\ln f(\sigma) = a_0 + a_1 \ln\sigma + a_2 (\ln\sigma)^2 + a_3 (\ln\sigma)^3 + a_4 (\ln\sigma)^4 + a_5 (\ln\sigma)^5 \quad (2)$$

where a_0 to a_5 are constants giving the best fit of a regression curve to data points. The stress function is flexible enough, and no difficulty arises in describing stress dependence of rupture life. Therefore, the stress function is not responsible for overestimation of long-term rupture life. However, Eq.(1) is quite rigid in terms of temperature dependence of rupture life. The value of Q in Eq.(1) is assumed to be unique in a whole data set to be analyzed. If this assumption does not hold in the data set, Eq.(1) cannot properly formulate rupture life of the data set, bringing about over or underestimation of rupture life.

Figure 1 represents temperature dependence of rupture life at a given stress. The thick solid line is a band of experimental data, and the thin solid line is a regression line of Eq.(1) for the data band. If Q is unique as is the case in Fig.1(a), the regression line coincides with the data band. The straight extrapolation of the regression line (dotted line) can correctly predict long-term rupture life. On the other hand, let us suppose that there are two regions with different values of activation energy Q_H and Q_L as shown in Fig.1(b), and Q takes a lower value, Q_L, in the long-term region. Direct application of Eq.(1) to such a data set gives the regression line represented by the thin solid line. The extrapolation of the regression line results in overestimation of long-term rupture life. It is obvious that change in temperature dependence of rupture life is critical in correct estimation of long-term rupture life by means of a TTP method.

In order to avoid the overestimation, the multi-region analysis of creep rupture data (4,10,12) has been proposed. In the analysis, creep rupture data are divided into several data sets, so that Q in Eq.(1) is unique in each divided data set. Then a conventional analysis based on Eq.(1) is applied to each divided data set. This analysis gives several equations formulating rupture life as functions of stress and temperature. Taking the shortest life among the equations when Q and n decrease with increasing rupture life, then one can formulate the whole data. The multi-region analysis is necessary to avoid the overestimation in a material with the decrease of Q in long-term creep.

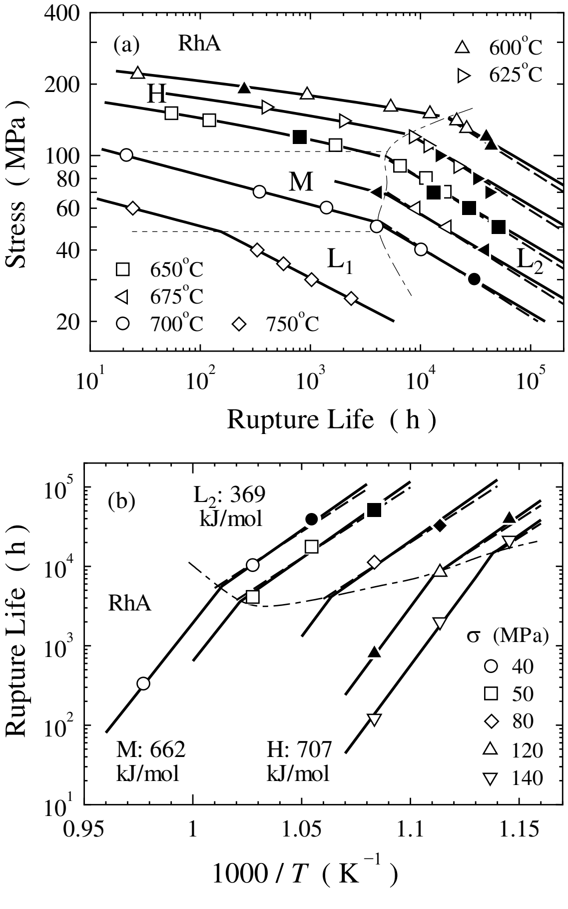

Figure 2: (a) Stress and (b) temperature dependence of rupture life of Heat RhA. The solid lines are regression curves determined by the multi-region analysis taking account of the change in activation energy Q between Region L_2 and other regions.

ASSESSMENT OF PREDICTED RUPTURE LIFE

MULTI-REGION ANALYSIS

Creep rupture data of Heat RhA (plate steel) of Gr.122 steel reported in Ref.(15) are plotted in Fig.2(a) with open marks. Some of the data are plotted against reciprocal

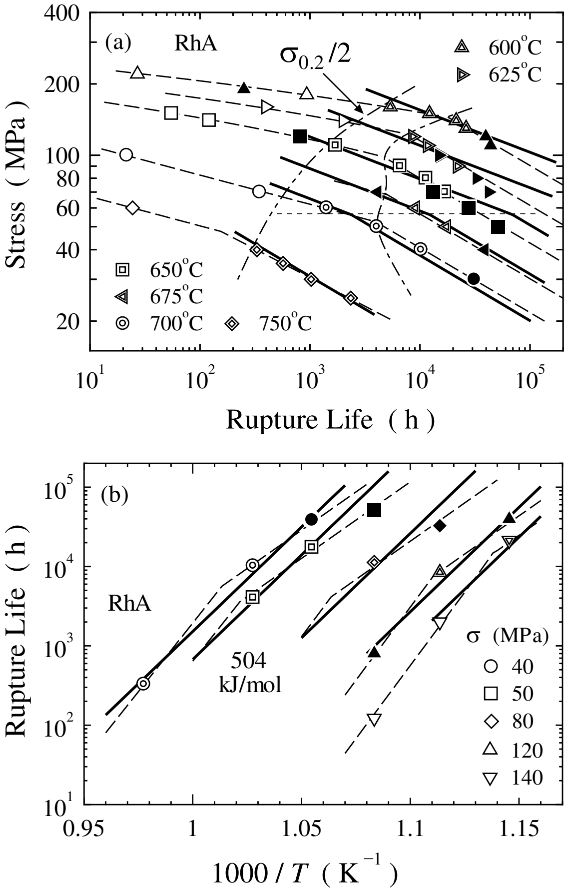

Figure 3: Comparison of long-term rupture data (solid marks) of Heat RhA to the regression curves (solid lines) determined from the data points selected by the $\sigma_{0.2}/2$ criterion (double marks). (a) Stress and (b) temperature dependences.

temperature in Fig.2(b). The data points represented with the open marks (referred to as old data hereafter) were analyzed by the multi-region analysis in 2005 (12). The longest test duration was 26,200h at that time. The OSD method based on Eq.(1) requires a unique value of Q to the data to be analyzed. Since the open data points in Fig.2(b) do not fulfill this requirement, the creep rupture data was divided into two groups at the dash-dot curve in Fig.2, so that Q is unique in each divided data set: short-term region and long-term region (L_2). Then the data set was subjected to the OSD analyses based on Eq.(1). The analyses allowed the following exponential and power laws only for the stress function $f(\sigma)$:

$$\ln f(\sigma) = \ln t_o - m\,\sigma \tag{3}$$

$$\ln f(\sigma) = \ln t_o - n \ln\sigma \tag{4}$$

where m, n and t_o are material constants. The values of Q, m, n and t_o are determined by a least square regression analysis, so that they give the best fit of regression curves to the data points analyzed. Once the constants are determined, one can readily estimate t_r at any σ and T. Since the slope of $\log\sigma$ vs. $\log t_r$ curves in Fig.2(a) increases with decreasing stress, the stress dependence of t_r cannot be described by a single value of n or m. However, the data analysis in the previous paper did not allow the use of a polynomial of $\log\sigma$. To make up for the limited forms of stress function allowed in the paper, the short-term data set was further divided into three regions bounded by the thin dotted lines in Fig.2(a): Regions H, M and L_1. The stress dependence of rupture life in Region H was described by the exponential law, and in Regions M and L_2, by the power law. The apparent activation energies giving the best fit of regression curves were Q_H = 707 kJ/mol in Region H, Q_M = 662kJ/mol in Region M, and Q_{L2} = 369 kJ/mol in the long-term region L_2. The values of Q giving the best fit are slightly different even within the short-term regions. The value of Q could not be determined in Region L_1 because of the lack of data at other temperatures than 750°C. The solid lines drawn in Fig.2 are the regression curves determined by the multi-region analysis.

Newly obtained creep rupture data of the same heat of the steel have been added recently in NIMS Creep Data Sheet (14). The added data points are plotted in Fig.2 with the solid marks. The longest test duration is 51,400h, and the test duration increases by 25,000h. The regression curves can predict very well the added data points. The thick dashed lines in Fig.2 are obtained by the OSD analysis of all the data point in Region L_2 (the old data together with the newly added data). They are close to the original prediction from the open marks. Slight decrease in Q and n values takes place after the addition of the new data: from 369kJ/mol to 340 kJ/mol (8% reduction) for Q, and from 3.66 to 3.40 for n.

$\sigma_{0.2}/2$ CRITERION

It is not always easy to divide data into several data sets based on the change in Q. Kimura et al. (6) have proposed the $\sigma_{0.2}/2$ criterion as the boundary for dividing creep rupture data, and have used the data points tested at stresses lower than $\sigma_{0.2}/2$ when estimating long-term rupture life. The proof stress is measured by a conventional tensile test at creep temperatures.

The $\sigma_{0.2}/2$ criterion was applied to the old data of Heat RhA in Ref.(12). The proof stresses reported by Masuyama (16) at creep temperatures were taken to determine the boundary in the analysis, and the dash-two dots curve in Fig.3 corresponds to the boundary of $\sigma_{0.2}/2$. The data points (double marks) located in the right hand side of the boundary were subjected to the OSD analysis assuming a unique value of Q. The data set was further divided into two sub-regions with different n values to describe them with the power law (Eq.(4)), and the horizontal dotted line in Fig.3(a) is the boundary. Figure 3(b) shows temperature dependence of the rupture lives together with the regression (solid) lines. The double marks represent the data points tested at stresses lower than $\sigma_{0.2}/2$ also in this figure, whereas the open marks were tested at stresses higher than $\sigma_{0.2}/2$. The dashed lines in the figures are the regression curves obtained in Fig.2. Deviation of the regression curves (solid lines) from the data point (double marks) was not evident at that time.

The data set used in this analysis includes eight data points belonging to Regions H, M and L_1 in addition to 13 data points within Region L_2. They take higher values of Q than that in Region L_2 (369kJ/mol). Due to the contribution of those data points with high Q values, the apparent activation energy obtained by this analysis is 504kJ/mol, being larger than the correct value of Q_{L2} = 369kJ/mol. The Q value larger than the correct Q_{L2} points out overestimation of long-term rupture life in the estimation based on the $\sigma_{0.2}/2$ criterion. The data points newly added in Ref.(14) are indicated with the solid marks in Fig.3. The value of Q larger than 369kJ/mol results in the upward deviation of the regression lines in Fig.3(b) from the solid marks. This overestimation is evident also in Fig.3(a). This example explains the story of the second reduction of 10^5h rupture strength made in Japan in 2011 (5).

The $\sigma_{0.2}/2$ criterion is easy in data selection but not appropriate for preventing the overestimation. On the other hand, the original multi-region analysis can always predict long-term rupture life properly. This fact points out that we should pay special attention to the change in temperature dependence of rupture life when selecting data points for long-term life estimation.

Table 1: Stress exponent n and activation energy Q for rupture life in each region of Heats RhA and RHQ

	H		M		L_1	L_2
RhA	n = 16 Q = 714 kJ/mol		7.9 714		4.1 563	3.4 336
RHQ	n = 19		5.9		3.3	2.8
	H_S Q = 1002 kJ/mol	H_L 747	M_S 634	M_L 516	507	254

HEAT-TO-HEAT VARIATION

Independently from the analyses made in Ref.(12), Ref.(17) has performed another multi-region analysis of creep rupture data of the same Heat RhA (plate steel) reported in Ref.(18). In the literature some data points up to 32,700h were added to the data of Ref.(15). The following power low equation combined with the OSD equation was used in the regression analyses:

$$\ln t_r = \ln t_o - n \ln\sigma + Q/R\,T \qquad (5)$$

The material constant t_o, the stress exponent n and the activation energy Q are determined by a least square regression analysis, so that the three parameters give the best fit of regression curves to data points. The procedure of the multi-region analysis has been reported in more detail in Ref.(17). In the present paper this improved procedure of multi-region analysis was applied to the whole data of Heat RhA up to 51,400h reported in Ref.(14). The result is given in Fig.4(a). Since there are four regions with different values of n, the data points are divided into four regions H, M, L_1 and L_2. The solid lines are regression curves, and the dotted lines are boundaries between neighboring regions. The values of n and Q are summarized in Table 1. Rupture lives of Heat RhA at four stress levels are plotted against reciprocal temperature in Fig.5 together with their regression curves. The decrease of Q in the long-term creep is evident in the figure also. Because of the modification of the procedure of the analysis, the boundaries between Regions H and M and Regions L_1 and L_2 move to some extent from those in Fig.2(a). However, Fig.4(a) is essentially the same as Fig.2(a).

Another result of the multi-region analysis on Heat RHQ (pipe steel) of Gr.122 steel is shown in Fig.4(b) and summarized in Table 1. Creep rupture data of the steel have been reported in Ref.(14). There are four regions, H, M, L_1 and L_2 with different values of n. The values of n and Q decrease at longer term. The values of Q in Region L_2 are close to that for lattice diffusion in ferritic steel (300kJ/mol) in the temperature range of interest. These facts are common to both heats. This fact suggests that accumulation of results of multi-region analyses on many heats of the steel can be useful in creep life estimation of other heats of the steel. However, there are differences between the two heats. The absolute value of rupture life, locations of the boundaries, and values of n and Q

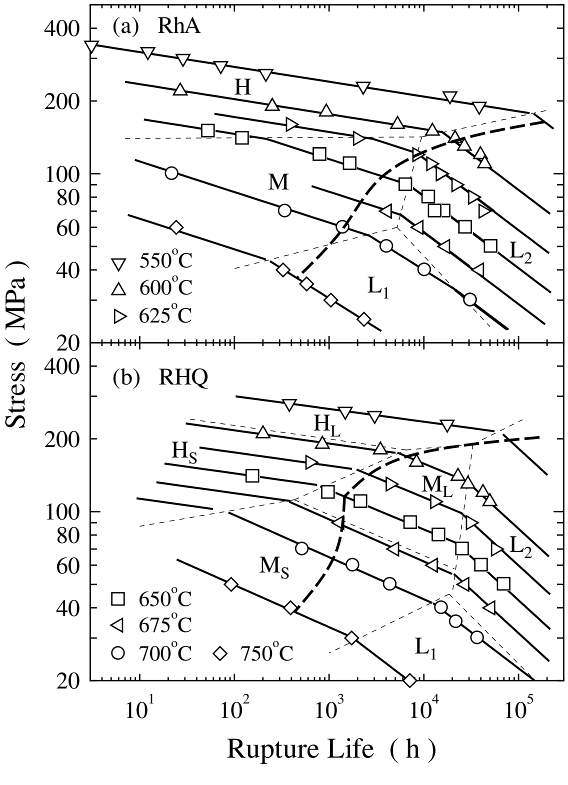

Figure 4: Stress-rupture data of Heats (a) RhA and (b) RHQ together with their regression (solid) curves. The thick dashed curves are the boundary corresponding to $\sigma_{0.2}/2$.

are different between the two heats. Within Regions H and M the Q value change from a high value at higher temperature to a low value at lower temperatures as shown in Table 1. Therefore, Regions H and M in Heat RHQ are further divided into a short-term region (S) with a greater value of Q and a long-term region (L) with a smaller value of Q. The result of Heat RHQ is a little complicated as compared to that of Heat RhA.

In the rupture data analysis based on the OSD method (Eq.(4)), long-term rupture life is primarily estimated by extrapolation of $\ln t_r$-$(1/T)$ line in Region L_2 to longer term. Temperature dependences of rupture life in the two heats are compared in Fig.5. The upward (RhA) and downward (RHQ) arrows indicate the boundary to Region L_2. The value of Q_{L2} determining the slope in Region L_2 varies from heat to heat. The rupture lives are longer in Heat RHQ in the time range from 10^4 to $5x10^4$h. The rupture lives extrapolated to 10^5h are similar in both heats. The extrapolation to $3x10^5$h may give longer rupture lives in Heat RhA. We should be aware that the rupture life estimation is not regression analysis but extrapolation to longer term (11). The slope of $\ln t_r$-$(1/T)$ line can be different in each heat.

The values of $\sigma_{0.2}$ have been reported on the two heats in Ref.(14). The thick dashed curves drawn in Fig.4 are the boundaries corresponding to $\sigma_{0.2}/2$. The location of the boundary moves from heat to heat. Overestimation of creep life in Region L_2 is a concern from engineering point of view. As mentioned in Introduction, decrease in activation energy Q in Region L_2 is the cause of overestimation of rupture life. Therefore, the $\sigma_{0.2}/2$ criterion is required to foretell the boundary to Region L_2. However, the thick dashed boundaries in Fig.4 do not accord with the boundaries to Region L_2. In the case of Heat RHQ the region below the $\sigma_{0.2}/2$ boundary includes 16 data points belonging to Regions M_S, M_L and L_1 in addition to nine points belonging to Region L_2. The fraction of data points outside Region L_2 is larger in Heat RHQ than in Heat RhA. This fact together with the values of Q given in Table 1 suggests that the $\sigma_{0.2}/2$ criterion make more significant overestimation in Heat RHQ than that in Heat RhA.

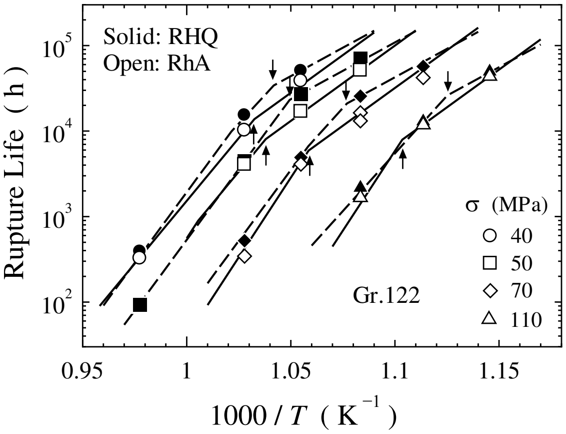

Figure 5: Temperature dependence of rupture lives together with their regression curves: solid curves for Heat RhA and dashed curves for Heat RHQ.

SUMMARY

(a) Activation energy Q for rupture life of Gr.122 steel decreases from a high value of short-term creep to a low value of long-term creep. This decrease is the major cause of the overestimation of long-term rupture life predicted by conventional time-temperature parameter (TTP) analysis of short-term data.

(b) Creep rupture data should be divided into several data sets, so that Q is unique in each divided data set. Then a conventional TTP analysis can be applied to each divided data set for estimating long-term rupture life. This is the basic idea of the multi-region analysis.

(c) The multi-region analysis on Heat RhA made in 2005 can predict properly long-term data points reported recently.

(d) A half of 0.2% proof stress ($\sigma_{0.2}/2$) is not appropriate criterion when selecting data points for creep life estimation, since the region below $\sigma_{0.2}/2$ always includes data points with larger Q values. The Orr-Sherby-Dorn analysis of the data below $\sigma_{0.2}/2$ overestimates long-term rupture life.

(e) Creep rupture data of both Heats RhA and RhQ show similar behavior in terms of their stress and temperature dependence. Therefore, database on results of multi-region analyses of various heats of the steel is helpful for rupture life estimation of another heat.

(f) The location of the boundary to Region L_2 and Q_{L2} in the region vary from heat to heat. We should remember these heat-to-heat variations when high accuracy is required to a predicted rupture life.

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