Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Proposition of Improved Methodology in Creep Life Extrapolation

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1. Introduction

Modified 9Cr-1Mo steel (ASME Grade 91, hereafter referred to as Gr. 91 steel) is regarded as a promising candidate for structural materials such as steam generators (SG), intermediate heat exchangers (IHX), and hot pipes in sodium-cooled fast reactors (SFR). The selection of Gr. 91 steel is mainly based on its high creep and low cycle fatigue resistance than those exhibited by its counterparts such as 9Cr-1Mo and 2.25 -1Mo steels [1,2].

To design SFRs for a 60-year operation, it is desirable to have the experimental creep-rupture data for Gr. 91 steel close to 20 y, or at least rupture lives significantly higher than 10^5 h. This requirement arises from the fact that, for the creep design, a factor of 3 times for extrapolation is considered to be appropriate. However, obtaining experimental data close to 20 y would be expensive and also take considerable time. Therefore, reliable creep life extrapolation techniques become necessary for a safe design life of 60 y. In addition, it is appropriate to obtain experimental long-term creep-rupture data in the range 10^5~$2x10^5$ h to improve the reliability of extrapolation [3].

In the present investigation, a new function of a hyperbolic sine ("sinh") form for a master curve in time-temperature parameter (TTP) methods, was proposed to accurately extrapolate the long-term creep-rupture stress of Gr. 91 steel. Constant values used for each parametric equation were optimized on the basis of the creep rupture data. Average stress values predicted for up to 60 y were evaluated and compared with those of French Nuclear Design Code, RCC-MRx.

2. Results and Discussion

2.1 Proposition of improved methodology

Many attempts have been made to formulate dependency of creep life to operating temperature and stress. A promising approach has been the use of the TTP method. All of the various developed TTPs consist of a combination of time, temperature and suitable constants. With such parameters and for a given material, a single master curve of stress against the parameter can be obtained and this is of a great value for extrapolating test results.

To accurately achieve the long-term life extrapolation, a "master rupture curve" (hereafter referred to as "master curve") describing the relationships between log (stress) and parameter (*P*) should be suitably determined. So far, a polynomial equation, as the master curve in the TTP methods such as the Larson-Miller (LM), Orr-Sherby-Dorn (OSD), and Manson-Harferd (MH) parameters, has been conventionally used well [4-6]. However, the equations of a polynomial form give the convex or concave curves in the extrapolation of the low stress ranges beyond experimental creep durations. The reason for this is due to intrinsic characteristics of polynomials. As the results, the predicted curve is unstable in the low stress region beyond experimental data. In particular, the predicted life was overestimated or underestimated according to the degree of orders of polynomial forms. To overcome this problem, a "sinh" function instead of the polynomial form is newly proposed herein, as follows.

$$P(t_r,T) \Rightarrow f(\sigma) \tag{1}$$

$$P = b_1 log(\sigma) - b_2 log(\sigma)^2 - b_3 log(\sigma)^3 + .. b_n log(\sigma)^n \tag{2}$$

$$P = b_1 + b_2 \sinh(b_3 \log\sigma) - b_4(\log\sigma) \tag{3}$$

In the above equations, the time-temperature parameter (*P*) is expressed as a function of stress as Eq. (1). The parameter can be used for the polynomial form of Eq. (2), and the "sinh" function of Eq. (3). Eq. (3) can be used instead of Eq. (2).

It is identified that the master curve of Eq. (3) is stable in extrapolation without a sharp bent in the low stress ranges beyond the experimental test durations, but the polynomial equations of 2nd, 3rd, and 4th orders are sharply bent as convex or concave curves, as shown in Fig. 1. For example in the 2nd order polynomial, the predicted curve at 700°C is sharply bent down, and the other temperature curves are overestimated, as shown in Fig. 2.

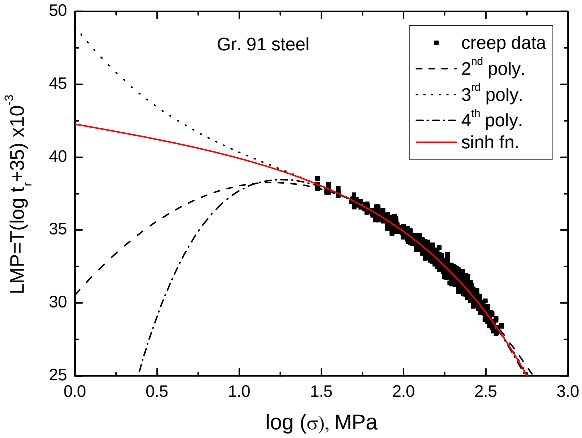


Fig. 1. Comparison of the master curves for the polynomials and "sinh" function in the extrapolation of the low stress ranges beyond experimental creep data (Gr. 91 steel).

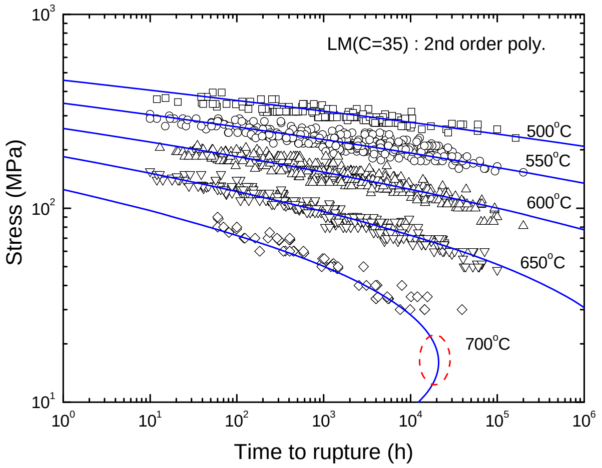


Fig. 2. Predicted curve results of the 2nd order polynomial at each temperature (Gr. 91 steel).

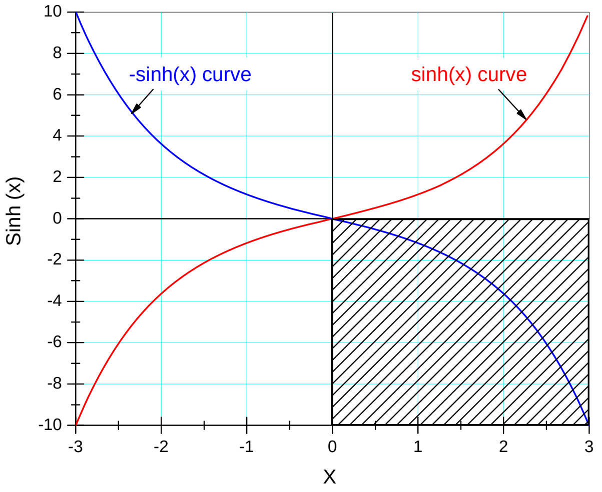


Fig. 3. The curve shapes of the "sinh" function, and the shaded portion indicates the range used for extrapolation.

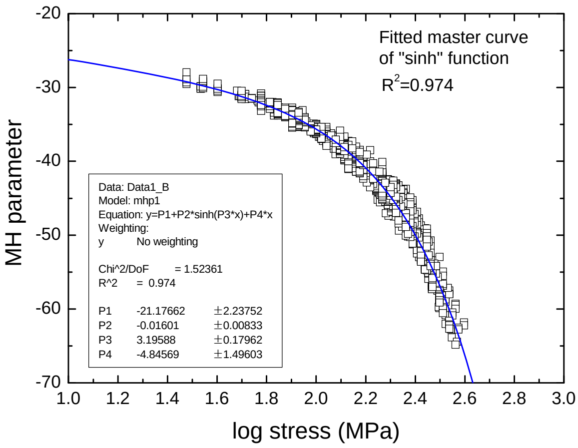
2.2 Result of improved methodology

The "sinh" function can be given as

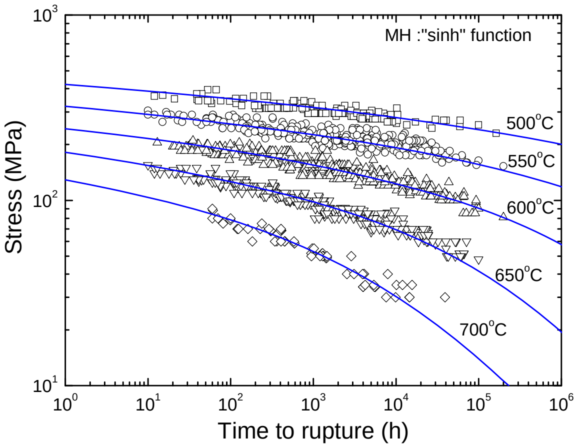
$$\sinh = \frac{1}{2}(e^x - e^x) \qquad (4)$$

The curve shape can be plotted, as shown in Fig. 3. In the figure, the shaded portion indicates the range used for extrapolation in Eq. (4). In Eq. (3), b_1, b_2, b_3, and b_4 are the parameters (or constants). Where, b_1 is the intercept value at x=0 as the parameter indicating the magnitude of y-axis, b_2 is the parameter determining the curve shape, and b_3 and b_4 are the parameters determining the magnitude of x-axis. It is noted that the curve slope is sharply changed with an increase in the b_2 value. The values of the 4-parameters were optimized by the best-fit regression of experimental creep data.

Fig. 4 shows typical results of creep-life prediction obtained using the "sinh" function in the MH method for Gr. 91 steel. In the figure, (a) indicates a master curve, and (b) indicates the predicted curves at each temperature. As shown in Fig.2 and Fig. 4, the predicted curves make a considerable difference in the stress values at given rupture time. The reason for this is that the differences in the master curves between the 2nd order polynomial and "sinh" function. In particular, it can be seen that the predicted stress makes significant difference between the 2nd order polynomial and "sinh" function in the LM and MH at 700°C. Accordingly, it is identified that the "sinh" function is reasonable in creep-life extrapolation compared with polynomial forms, which have been used conventionally until now.



(a) A master curve fitted by the "sinh" function



(b) Life prediction curves

Fig. 4. Plots of (a) a master curve and (b) the rupture stress curves predicted for the "sinh" function in the MH method for Gr. steel.

3. Conclusions

Improved methodology using the "sinh" function in creep-life extrapolation was newly proposed. The results showed that the master curve of the "sinh" function was a wider acceptance with good flexibility in the low stress ranges beyond the experimental data. It was clarified clarified that the "sinh" function was reasonable in creep-life extrapolation compared with polynomial forms, which have been used conventionally until now. It is suggested that the improved methodology can be utilized to accurately extrapolate the long-term creep life or strength of Gen-IV nuclear materials which will be designed for life span of 60 years.

Acknowledgements

This study has been carried out as a part of the Innovative R&D Project of Korea Atomic Energy Research Institute.

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