Research and Development on 9Cr-Steels for Steam Generator of DFBR in Japan

(1) -Fatigue Properties-

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1. INTRODUCTION

A LMFBR steam generator(SG) exchanges heat between sodium and water through heat transfer tubes. The once-through SG which has economical advantages requires the tube material that has enough strength in elevated temperature, high resistance to environmental effect and good fabricability. 9Cr-steels have been considered as the best candidate materials for it.

Research and developments on 9Cr-steels have been performed in many countries. Researches on 9Cr-steels in Japan have been focused on Mod.9Cr-1Mo steel which were developed by U.S. ORNL and domestically developed 9Cr-2Mo steel and 9Cr-1Mo-V-Nb steel. Research committee on applicability of 9Cr-steels to FBR steam generator was organized in Japan Welding Engineering Society (JWES), under the contract of The Japan Atomic Power Company (JAPC). This paper introduces the summary of the overall research and development program of the committee, and describes the fatigue properties of 9Cr-steels obtained by high temperature low cycle fatigue testing both for base metal and welded joints.

2. OVERALL R&D PROGRAM ON 9Cr-STEELS

Long term program of research and developments on SG materials is shown in Table 1. Researches in the committee of JWES were started in 1985 as the 2nd stage 4 years program (FSG subcommittee), taking over the 1st stage study which were performed by utilities and fabricators. In this program, the following tests of material strength in elevated temperature (500 to 600°C) were performed.

a) Test materials: Base metal---tube, plate and forging of Mod.9Cr-1Mo steel, 9Cr-2Mo steel and 9Cr-1Mo-V-Nb steel. Welding method---TIG, SAW and SMAW (SAW and SMAW were applied to only Mod.9Cr-1Mo). Total test pieces came up to 3550 pieces.

b) Tensile tests, fatigue tests, creep rupture tests (max. 8000hrs) and thermal aging tests (max. 6000 hrs), to characterize material strength of welding metals, base metals and welded joints.

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c) Tensile and fatigue tests of tubular specimens, to verify the soundness of welded joints of heat transfer tube.

At present time, data accumulation for material strength standard of Mod.9Cr-1Mo steel has been conducted in the 3rd stage program since 1989. Main research items in each stage are shown in Table 2. Power Reactor and Nuclear Fuel Development Corporation(PNC) has also researched strength characteristics of Mod.9Cr-1Mo steel and environment effect on its strength in corporation with the program of the committee in JWES. Furthermore endurance tests of once-through SG using Mod.9Cr-1Mo steel tube were performed in the joint program of JAPC and PNC.

Table 1. Long Term Program of Research and Developments on SG Materials

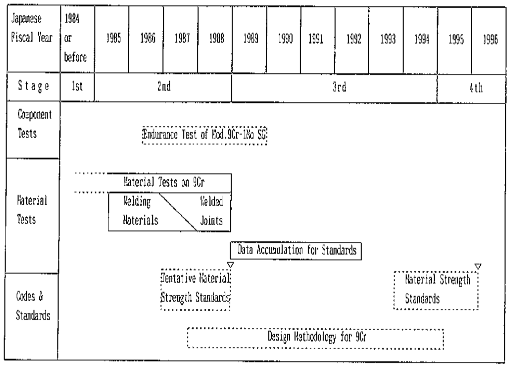

Table 2. Main Researches of SG Materials for DFBR

	1st Stage	2nd Stage		3rd Stage	4th Stage
Elevated Temperature Strength	∘ Selection of Candidate Materials ∘ Basic Strength Data ∘ Fundamental Allowable Stresses	∘ Survey on Current Status ∘ Design Requirement ∘ Long Term Development Program	∘ Creep of Tubes ∘ Forgings	∘ Material Data for MSS ∘ MSS (Material Strength Standard)	∘ Final Specifications of Candidate Materials
Welding Fabricability	∘ Basic Data of Weldability		∘ Welding Materials ∘ Welding Methods	∘ Welded Joint Characteristics	
Environment Effect	∘ Study on Papers		(In Sodium/Water/Steam)		
	1982~1984	1985	1986~1994		1995~

3. FATIGUE PROPERTIES OF 9Cr-STEELS

3.1 Experimental method

Two kinds of 9Cr steels, namely the 9Cr-1Mo-V-Nb grade and the Mod. 9Cr-1Mo variety, were tested. These steels were stress relief annealed (SR) for 8h at 740±10°C and at 710±10°C respectively. Welded joints of plate and forging were made by TIG, SMAW, or SAW, and the weldings of tubular specimen of the Mod. 9Cr-1Mo steel were performed by TIG.

Low cycle fatigue tests were conducted in the strain-controlled triangular wave form. The testing conditions for the plate specimens were a temperature of 500, 550, or 600°C, a strain rate of 0.1%/s, and a total strain range of 0.5 to 2.0%, while those for the tubes were 550°C, 0.1%/s, and 0.5 to 1.2%.

3.2 Prediction of low cycle fatigue life

Three representative methods, the Manson's universal slope method, his 10% rule, and the Diercks' method, which were selected on the past test results of high temperature low cycle fatigue, have been comparatively assessed as to their applicability to the 9Cr steel.

(1) The universal slope method and the 10% rule

According to Manson, room temperature low cycle fatigue life of various metals can be estimated from their tensile behaviors by means of the universal slope equation, which is:

$$\Delta\varepsilon_t=(3.5\sigma_u/E)\cdot N_f^{-0.12}+\varepsilon_f^{0.6}\cdot N_f^{-0.6}, \qquad (1)$$

where $\Delta\varepsilon_t$ is the total strain range; σ_u, the tensile strength; E, the Young's modulus; ε_f, the true fracture ductility to be calculated with the reduction in area at fracture, ψ, as $\varepsilon_f=\ln[100/(100-\psi)]$.

Subsequently, he has demonstrated that the $\Delta\varepsilon_t$-N_f curve, the universal slope equation (1), actually presents the upper limit of fatigue life for the temperature tested. Whereas the following formula (2) with its N_f terms of equation (1) substituted with $10N_f$:

$$\Delta\varepsilon_t=(3.5\sigma_u/E)\cdot(10N_f)^{-0.12}+\varepsilon_f^{0.6}\cdot(10N_f)^{-0.6}, \qquad (2)$$

is the one tenth the fatigue life the formula (1) gives. He proposed to call formula (2) the 10% rule, and has duly shown that the safety lower limit life can be defined by this formula so as to cover such contingencies as an untimely decrease in life due to unexpected rise in operating temperature and acting strain rate.

Fig. 1 presents a comparison of low cycle fatigue test results of Mod. 9Cr-1Mo steel with the calculations according to the universal slope method and the 10% rule method. It is noted that both for base metal and weld metal, the actual life falls between the two prediction curves, and approaches the 10% rule predictions as the temperature is raised.

It has been concluded from these observations that, for both the base metal and the weldments of 9Cr grade steels at a temperature between 500 to 600°C, the actual low cycle fatigue life is somewhere between the universal slope method estimate and the 10% rule estimate, and further that the life predicted by the 10% rule may be considered as safe-side.

(2) The Diercks method

The American FBR development group has collected a large number of high temperature low cycle fatigue data on SUS 304, and, analyzing them by the least squares fitting method, has derived an equation that describes the design master fatigue curve for the ASME Code N-47. This equation, which is called the Diercks formula, is:

$$\begin{aligned}(\log N_f)^{-1/2}=\;&1.20551064+0.66002143\cdot S\\&+0.18040042\cdot S^2-0.00814329\cdot S^4\\&+0.00025308\cdot S^4R+0.00021832\cdot TS^4\\&-0.00054660\cdot RT^2-0.00555671\cdot RH^2\\&-0.00293919\cdot HR^2+0.0119714\cdot HT\\&-0.00051639\cdot H^2T^2,\end{aligned} \qquad (3)$$

where, $S=\log(\Delta\varepsilon_t/100)$; $R=\log\dot{\varepsilon}$; $T=Tc/100$; $H=\log(1+t_h)$; $\Delta\varepsilon_t$ is the total strain range (%); $\dot{\varepsilon}$, the strain rate (%/s); Tc, the temperature (°C); and t_h, the tensile holding time (hr).

Fig. 2 shows the comparison of low cycle fatigue test results of the Mod. 9Cr-1Mo steel with the calculations according to the Diercks formula (3).

The correspondence ascertained for SUS 304 does not hold true for the 9Cr steel.

Thereupon, modification of the Diercks formula was attempted, principally by correcting the temperature term in the trial-and-error approach. It was duly found that a correction of +100°C for the Tc and the life correction factor 1.5 would entail a linearity with a gradient that is satisfactorily close to unity as shown in Fig. 3. The newly developed formula, wherein T=[Tc+100]/100 and $1.5 \cdot N_f$ replaces the existing N_f, appears capable of predicting the low cycle fatigue life of the 9Cr steels with a precision that is as good as that for SUS 304.

3.3 Comparison with other material

To establish a basis for assessing the comparative position of the 9Cr steels among the candidate materials, the fatigue strengths of the two 9Cr steels of this study were compared to the published data of annealed (no SR) 2.25Cr-1Mo steel, which are for 482 to 583°C.

Fig. 4 presents that the low cycle fatigue life at 500° and 550°C of the two 9Cr steels (base metal, SR'ed) are longer than those of the 2.25Cr-1Mo steel (annealed, tested in the 482 to 583°C range) for $\Delta\varepsilon_t$'s larger than 0.6%.

3.4 Fatigue behaviors of tube steel

Fig. 5 presents the results of low cycle fatigue tests conducted for the base metal and the welded joint of tubular 9Cr steel, where the welding was performed in two different practices. Here, the solid line gives the design fatigue criteria, which are calculated based on a safety factor of 20 for the life of the plate steel or a factor of 2 for the strain range.

In the case of the Mod. 9Cr-1Mo steel, the fatigue life of the welded joint specimens was shorter than that of the base metal, probably because the weld metal was harder than the base metal. It was noted also that they all failed in the base metal, and that the fracture surfaces were flat, accompanying little thickness reduction. Fig. 5 also shows that the difference in the welding practice, i.e., with or without the use of the filler for the first pass, does not affect the fatigue life significantly. Here, the rather large dispersion of data for the base metal was probably due in part to the unequal precision of the surface finish in the parallel parts of the tubular specimens, and in other part to the unevenness in the wall thickness of the sample heat transfer tube used.

Fig. 5 also illustrates the relative position of the fatigue strength of Mod. 9cr-1Mo steel tube with regard to its plate counterpart, namely, those obtained with round specimens machined out of plates. It is seen that the fatigue lives of the Mod. 9Cr-1Mo steel heat transfer tube both for the base metal and for the welded joint are shorter than those of the plate, due probably to the difference in the specimen configuration. Since all the fatigue data clear the design fatigue master curve given for plate, there appears to be no problem in using the 9Cr steel heat transfer tube.

4. SUMMARY AND CONCLUSIONS

Research and Developments on 9Cr-steels for SG of DFBR are proceeded steadily in Japan toward authorization of material strength standard.

In conducting high temperature low cycle fatigue tests for the base metal and the welded joint of two representative kinds of the 9Cr steel, both as plate and as heat transfer tube, following conclusions have been obtained:

(1) Evaluation of low cycle fatigue life

a) The low cycle fatigue life data of the 9Cr steels both for the base metal and for the weld metal would fall between those which the universal slope method predicts as the upper limit and those the 10% rule predicts as the lower limit, where the 10% rule estimates may be regarded as the safety lower limit life.

b) The Diercks formula determined for SUS 304 appears to be applicable to the 9Cr steels with the same precision as that for SUS 304 provided it is modified according to this study.

(2) Comparison with other material

a) Compared to the 2.25Cr-1Mo steel, the 9Cr steel has a longer fatigue life in 500° to 600°C range for the total strain range greater than 0.6%.

(3) Fatigue strength of tubular steel

a) The fatigue life of welded joint is somewhat shorter than the base metal.

b) Although the fatigue life of tubes is shorter than that of plates, their fatigue strengths clear well enough the design fatigue master curve specified for plates, indicating that no problems are to be anticipated in using the 9Cr steel heat transfer tube.

Activities in this study has been performed as a part of joint research and development projects for DFBR under the sponsorship of the nine Japanese electric power companies, Electric Power Development Co., Ltd. and the Japan Atomic Power Company.

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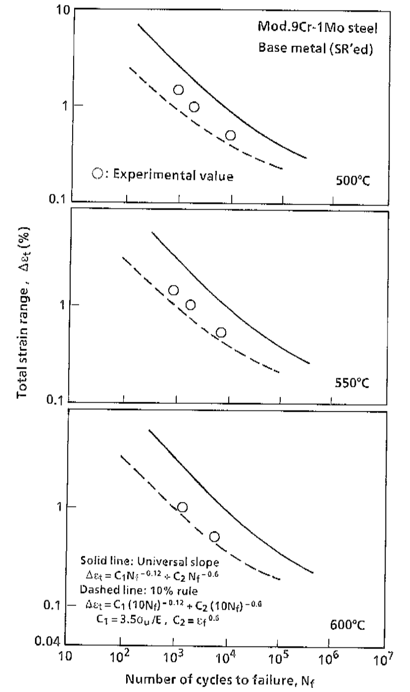

Fig. 1 Comparison of Low Cycle Fatigue Lifetimes of Modified 9Cr-1Mo Steel among the Experimental Determinations, the Universal Slope Method Predictions, and the 10% Rule Predictions

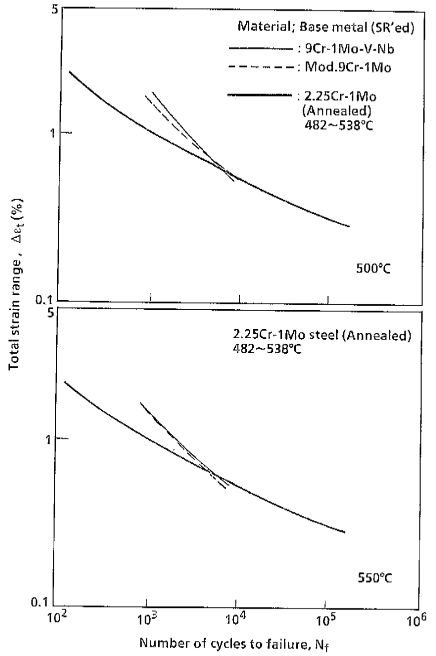

Fig. 4 Fatigue Strengths of Stress Relief Annealed 9Cr Steels in Comparison with Annealed 2.25Cr-1Mo Steel

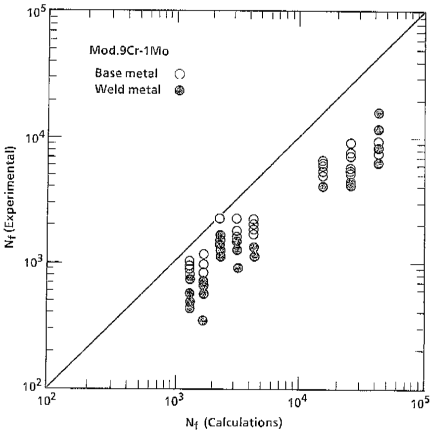

Fig. 2 Applicability of Diercks Formula for SUS 304 to 9Cr Steel

$$\begin{aligned}(\log N_f)^{-1/2} = {} & 1.20551064 + 0.66002143S \\ & + 0.18040042S - 0.00814329S^4 \\ & + 0.00025308S^4 + 0.00021832TS^4 \\ & - 0.00025308ST^2 - 0.00555671RH^2 \\ & - 0.00054660RT^2 + 0.0119714HT \\ & - 0.00293919H^2T^2\end{aligned}$$

$S = \mathrm{LOG}(\Delta\varepsilon_t/100)$, $R = \log \dot{\varepsilon}$
$T = T_c/100$, $H = \log(1 + t_h)$
$\Delta\varepsilon_t$: total strain range (%)
$\dot{\varepsilon}$: strain rate (%/s)
Tc: temperature (°C)
th: tensile holding time (h)

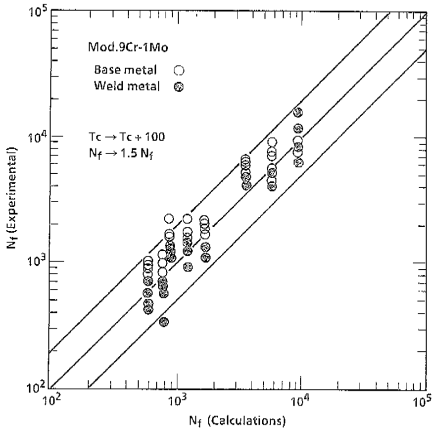

Fig. 3 Applicability of the Diercks Formula, Modified in the Temperature and the Lifetime Terms, to 9Cr Steel

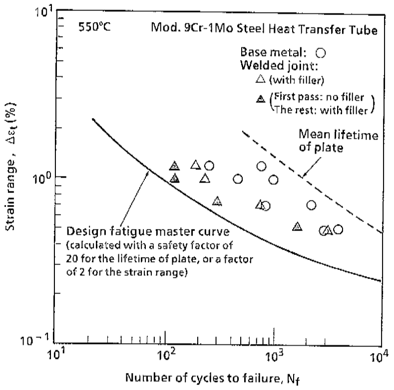

Fig. 5 Results of Low Cycle Fatigue Tests for Modified 9Cr-1Mo Steel Heat Transfer Tube