Proceedings of the ASME 2018 Symposium on Elevated Temperature Application
of Materials for Fossil, Nuclear, and Petrochemical Industries
ETAM2018
April 3-5, 2018, Seattle, WA, USA

ETAM2018-6734

CREEP LIFE ASSESSMENT OF USC BOILER TUBES

Keiji Kubushiro
IHI Corporation
Yokohama city, Japan

ABSTRACT

CSEF (creep strength enhanced ferritic) steels and austenitic steels are widely used for USC boiler tubes. It is important to evaluate creep life of these parts because metal temperature is indeterminable in superheater and reheater tubes. Almost investigations were conducted under higher stress, short time creep tests, but the pressure for the boiler pipe and tube at actual plant were very low. It is therefore necessary to establish creep life method under long time region time test at various stresses. The purpose of this work is to establish creep life evaluation in high Cr ferritic steels and austenitic steels with long time creep ruptured data. The creep life evaluation methods are based on hardness and microstructure changes

INTRODUCTION

Steam temperature of thermal power plants has been increased to decrease CO_2 gas emission. The USCs where the steam temperature is higher than 600°C have already been developed and widely operated in the world [1]. There are many USC plants in Japan and their operation time is more than 25 years [2]. CSEF (creep strength enhanced ferritic) steels and austenitic stainless steels are used in superheater tubes and reheater tubes. Inspections of the tubes and their life assessments are very important for the safety operation, but the metal temperature of them can't be measured during plant operation. It makes the life assessment difficult. Additionally, the allowable stress of the materials has been revised recently [3-6]. It makes some plants lifetime shorter than designed one. The quick and easy inspection is needed to evaluate the life assessment of the tube accurately.

The hardness method is well known for the life assessment of ferritic steels. However, the methodology is based on the test results in relatively shorter time or under higher stress [7-10]. The longer test results under lower stress give us the more accurate life assessment methodology, but it takes longer time. Moreover, although the hardness of the virgin material is needed in the hardness method, ferritic steel hardness can be changed by heat treatment condition and fabrication condition [11]. Then, the method is inappropriate.

For austenitic stainless steels, the methodologies where creep voids and cracks are evaluated are discussed [12-14]. Unfortunately, all of the data is obtained from the test samples with the shorter time than actual plant operation time. Then the creep behavior under actual plant operation remains unclear. Some researchers pointed out that the incubation time and amount of creep void are changed by stress condition.

The life assessment method based on the longer creep tests is strongly hoped to evaluate the more accurate life time assessment as mentioned above. There are many NIMS creep data sheets and some reports fortunately, the effective method can be developed if they are utilized. For ferritic steel, we might be able to develop the evaluation method by using the difference of the hardness from the ruptured creep specimens because initial hardness is strongly influenced by heat treatment condition and fabrication condition in the virgin materials. In this paper, the hardness method for ferritic steels and the novel method for austenitic stainless steels by microstructure evolution are developed by NIMS data sheets.

LIFE ASSESSMENT FOR HIGH CR FERRITIC HEAT RESISTANT STEEL.

For creep life assessment with hardness, the method must satisfy following qualifications.

1. It is possible to evaluate in the case of not only higher stress test but also lower stress.
2. It is possible to evaluate if hardness in virgin specimens is unknown.

To satisfy these qualifications, the hardness method based on the hardness of ruptured specimens was discussed. Hardness data was referred to NIMS and our previous results. [15-17]

Hardness and stress after rupture.

The relationship between hardness of ruptured specimens (HV_{final}) and creep applied stress at various temperature is shown in Figure 1. HV_{final} decreased as applied stress was low. The relationship was explained with formula (1).

$$HV_{final} = a\sigma^2 + b\sigma + c \qquad (1)$$

This result means that the hardness value become lower while creep test as applied stress is low, i.e., microstructure recover and recrystallize, then dislocation density decreases during creep. Therefore, last hardness must be changed with applied stress.

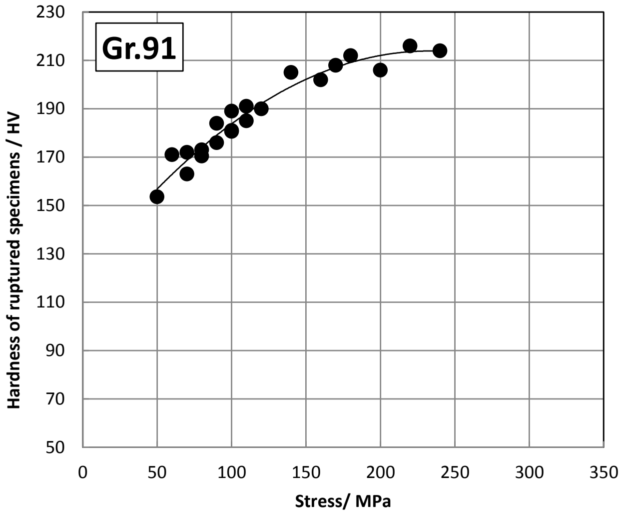

Figure 1. Hardness of ruptured specimens change in applied stress at various temperature for Gr.91.

The change in hardness during creep

It was unveiled that the degree of decreasing hardness value was different with applied stress. Figure 2 shows the relationship between the creep life ratio and HV_{final}. Hardness change curve could be divided into three regions, 1. decreased rapidly at initial creep stage, 2. decreased slightly at middle creep stage, 3. decreased rapidly at later creep stage. It is seemed that these regions correspond to transient creep region, steady state creep region, and accelerating creep region. The relationship between creep rate and life time at representative stress is shown in Figure 3, referred to NIMS creep data sheet [18].

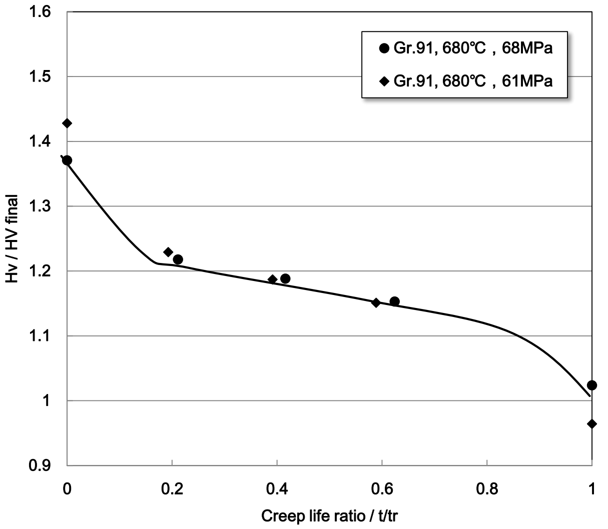

Figure 2. The relationship between hardness change ratio and creep life ratio in Gr.91

There are transient creep, steady state creep, and accelerating creep in the relationship between creep rate and life time for Gr.91 steel. These divisions are almost same without depending on applied stress. Some reports mentioned that the hardness of CrMoV steel decreases rapidly in transitent creep region, and decrease of creep rate led to decrease of dislocation density [19]. Hence, the rapid decrease of hardness at initial stage results from the decrease of hardness with transient creep. At steady state creep region, the width of lath increases in microstructure [20]. Therefore, it is considered that slight microstructure changes result in slight decrease of hardness. At accelerating creep region, recovery of microstructure leads to formation of sub-grain and coarsening of lath, and hardness decreases rapidly with microstructure development [21]. Thus, hardness change curve corresponds reasonably to structure changes of ferritic steel.

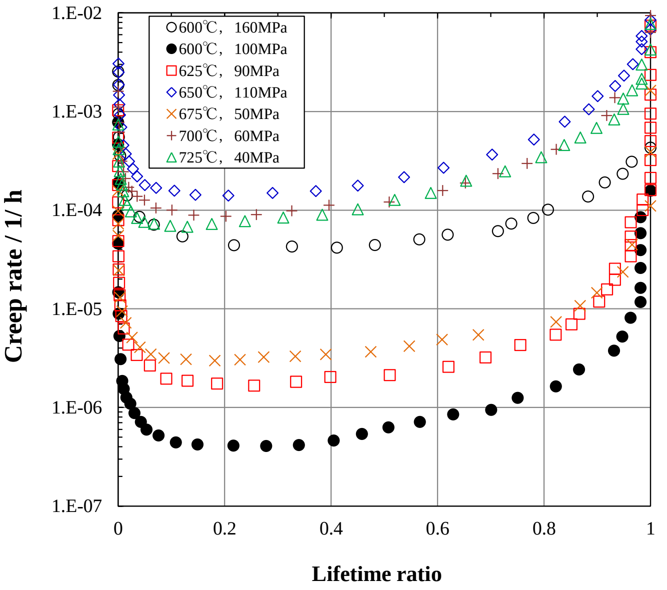

Figure 3. Creep rate- life time ratio curves under various creep conditions.

Life assessment for high Cr ferritic heat resistant steel by the hardness method

Remaining creep life assessment flow with hardness is shown in Figure 4. First, for evaluated tube, applied stress and design temperature are calculated. HV_{final} is calculated from formula (1) and Figure 1 with calculated stress. Next, hardness measured from actual tube or extracted tube and hardness after rupture lead to the hardness change rate. This rate and Figure 2 result in life time consumption rate, and then it is possible to evaluate lifetime for ferritic heat resistant steel. However initial hardness are strongly affected by heat treatment and cold work, so creep life assessment by this method are desirable in the range of t/tr > 0.6.

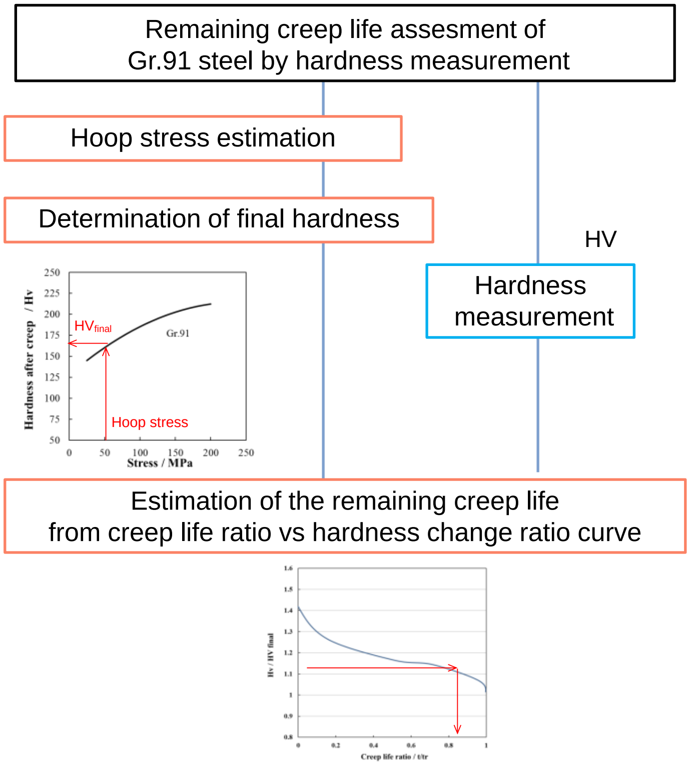

Figure 4. Creep life assessment of Gr.91 by the hardness change ratio.

LIFE ASSESSMENT FOR AUSTENITIC STEEL

For ferritic steel, the hardness assessment and the void assessment are usually utilized. For austenitic steel, however, these assessments are not suitable because the hardness of austenitic steel changes with not creep deformation but precipitation of carbides in many cases [22-24]. As for void and crack, it was reported that creep voids occurred slightly in recent austenitic steel with high creep strength due to small deformation compared with standard austenitic steel, shown in Figure 5. Therefore, life assessment for austenitic steel must be carried out without the hardness and the void measurement. It is possible to assess lifetime for heat transfer pipes with existing creep rupture strength data. Thus, microstructure changing was focused for estimation of temperature.

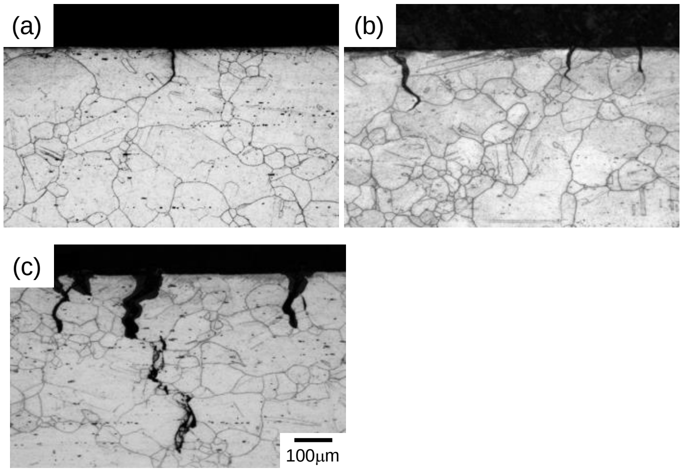

Figure 5. Crack development at surface with increasing creep time in SUPER304H at 650 °C, 240MPa, (a) lifetime ratio 0.47 specimen, (b) lifetime ratio 0.70 specimen, (c) the ruptured specimen at 10mm away from ruptured area.

Precipitation of σ phase in SUPER304H

Figure 6 shows the microstructure after rupture by internal pressure creep test at 750 °C [25]. **σ** phase was precipitated at grain boundary, the number and the size of **σ** phase increased with longer test time.

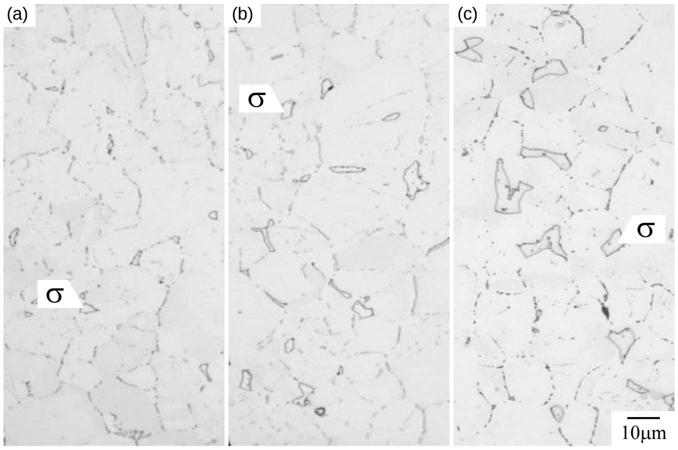

Figure 6. Optical micrographs of ruptured specimens after internal pressure creep tests under following conditons (a) 750 °C / 100 MPa, (b) 750 °C / 80 MPa and (c) 750 °C / 60 MPa.

According to NIMS creep data sheet [26], precipitation nose of **σ** phase is around 750 °C, coarsening rate is high with high temperature. Figure 7 shows that the average particle size of **σ** phase organized by LMP, the function of temperature and time, is explained with only shingle line. This line was explained with formula (2), (3).

$$\sigma phase \cdot size = aLMP^{2} + bLMP + c \qquad (2)$$

$$LMP = (Logt + C) \times T(K) \qquad (3)$$

The diameter of the σ phase particles at grain boundaries was measured by means of five optical micrographs at a magnification of 500×, which were assumed to be a sphere of equivalent value.

In addition, the particle size was same to compare the head part with the gauge part. Generally, the precipitation of **σ** phase is accelerated with stress aging and so on. In the case of SUPER304H, however, the particle size of **σ** phase was not changed.

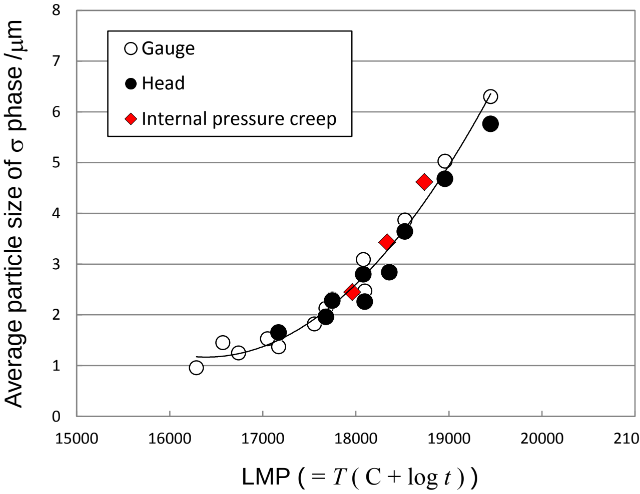

Figure 7. Change in particle size of **σ** phase with LMP.

Life assessment for austenitic steel by coarsening of σ phase

Life assessment flow with microstructure observation of SUPER304H is shown in Figure 8. First, for the assessed tube, applied stress and design operation temperature are calculated. Microstructure observation can reveal whether there are creep cracks and σ phase or not. If there is no creep crack, it is predicted that life consumption is no more 50%. Next, temperature can be calculated by the particle size of σ phase. LMP is calculated by the measured particle size of σ phase and formula (2). It is possible to estimate the temperature of heat transfer tube with operation time and

LMP. Formula (3) can calculate remain creep life with obtained temperature, design stress, and operation time. Without depending on stress, this method can be applied to superheater tube and reheater tube.

As stated above, microstructure observation with the particle size of σ phase leads to estimation of temperature. One formula cannot estimate temperature for all kinds of steels because the precipitation start time of σ phase is different in various steels [27, 28]. However, if the particle sizes of σ phase for various steels are grasped, this method can be applied to various steels.

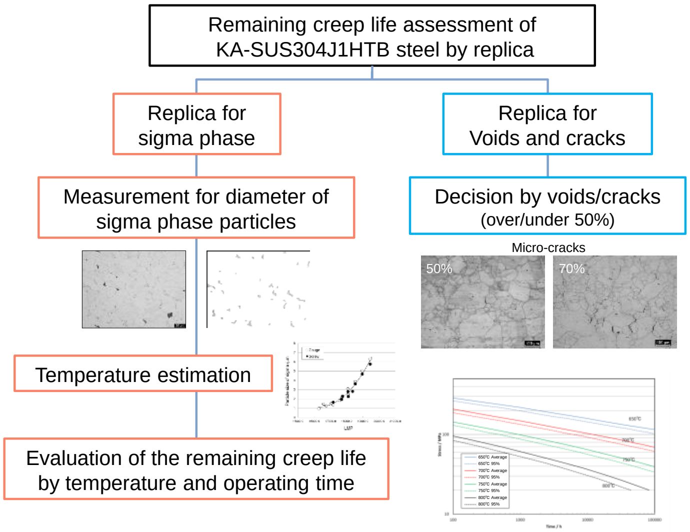

Figure 8. Creep life assessment flow of SUPER304H by microstructure.

CONCLUSION

For creep life assessment, the hardness method in ferritic steels and the novel method in austenitic stainless steels by microstructure evolution are developed by NIMS data sheets. The following conclusions were reached.

In ferritic steel, HV_{final} depends on applied stress and this relationship as shown in formula (1) could be revealed. And then, hardness changing ratio (HV/HV_{final}) corresponds to life consumption.

In austenitic steel, the particle size of σ phase could be organized by LMP and this relationship as shown in formula (2), (3) could be revealed. Creep temperature could be estimated with this relationship.

These creep life assessment methods have already been used in actual plants.

REFERENCES

[1] JCOAL World Coal Report., 2013.
[2] Makino, K., 2014, “Importance of the Coal Fired Power in Electric Power Energy”, THE THERMAL AND NUCLEAR POWER, Vol.65, pp.713-721 (in Japanese).
[3] Kimura, K. and Takahashi, Y., 2012, “EVALUATION OF LONG-TERM CREEP STRENGTH OF ASME GRADES 91, 92, AND 122 TYPE STEELS”, Proceedings of the ASME 2012 Pressure Vessels & Piping Conference, PVP2012-78323.
[4] Yaguchi, M., Matsumura, T. and Hoshino, K., 2012, “EVALUATION OF LONG-TERM CREEP STRENGTH OF WELDED JOINTS OF ASME GRADES 91, 92 AND 122 TYPE STEELS”, Proceedings of the ASME 2012 Pressure Vessels & Piping Conference, PVP2012-78393.
[5] Kimura, K. and Yaguchi, M., 2016, “RE-EVALUATION OF LONG-TERM CREEP STRENGTH OF BASE METAL OF ASME GRADE 91 TYPE STEEL”, Proceedings of the ASME 2016 Pressure Vessels & Piping Conference, PVP2016-63355.
[6] Yaguchi, M., Nakamura, K. and Nakahashi, S., 2016, “RE-EVALUATION OF LONG-TERM CREEP STRENGTH OF WELDED JOINT OF ASME GRADE 91 TYPE STEEL”, Proceedings of the ASME 2016 Pressure Vessels & Piping Conference, PVP2016-63316.
[7] Endo, T., Masuyama, F. and Park, K.S., 2003 “Change in Vickers Hardness and Substructure during Creep of a Mod.9Cr–1Mo Steel”, Materials Transactions, Vol.44, pp. 239 -246.
[8] Armaki, H. G, Chen, R., Kano, S., Maruyama, K., Hasegawa, Y. and Igarashi, M., 2011, “Microstructural degradation mechanisms during creep in strength enhanced high Cr ferritic steels and their evaluation by hardness measurement” Journal of Nuclear Materials, Vol.416, pp.273–279.
[9] Masuyama, F. and Nishimura, N., 2004, “PHASE TRANSFORMATION AND PROPERTIES OF GR.91 AT AROUND CRITICAL TEMPERATURE”, PVP2004-2574.
[10] Endo, T., Masuyama, F. and Park, K. S., 2002, “Change in Hardness and Substructure during Creep of Mod.9Cr-1Mo Steel”, Tetsu-to-Hagane, Vol.88, pp.526-533 (in Japanese).
[11] Shioda, Y., Kubushiro, K. and Murata, Y., 2017, “Difference in the effect of cold working and tempering

on microstructure of Mod.9Cr-1Mo steel", Netsu Shori, Vol.57, pp.343-350 (in Japanese).

[12] Niu, L. B., Katsuta, A., Kobayashi, M. and Takaku, H., 2003, "Initiation and growth behavior of creep voids in an austenitic steel with high ductility under multi-axial stresses", ISIJ International, Vol.43, pp.251-255.

[13] Tanaka, H., Murata, M., Abe, F. and Yagi, K., 1997, "Effects of Grain Boundary Precipitates on Long-Term Creep Rupture Properties of SUS347H Steel", Tetsu-to-Hagane, Vol.83, pp.72-77 (in Japanese).

[14] Tanaka, H., Abe, F., Yagi, K. and Sugita, T., 1998, "Evaluation of Creep-damaged Microstructure in Austenitic Stainless Steels by Surface Observations", Tetsu-to-Hagane, Vol.84, pp.303-308 (in Japanese).

[15] Kimura, K., Sawada, K. and Kushima, H., 2010, "CREEP RUPTURE DUCTILITY OF CREEP STRENGTH ENHANCED FERRITIC STEELS", Proceedings of the ASME 2010 Pressure Vessels & Piping Conference, PVP2010-25297.

[16] Ito, T., Inzen, A. and Nonaka, I., 1999, "Creep damage evaluation of Mod.9Cr-1Mo steel by hardness change ratio", Proceedings of the 54th symposium on strength of materials at high temperature, Vol.37, pp.71-75 (in Japanese).

[17] Sawada, K., Kushima, H., Tabuchi, M., Kimura. K., 2011, "Microstructural degradation of Gr.91 steel during creep under low stress", Materials Science and Engineering A 528, pp.5511–5518.

[18] NIMS, "Atlas of Creep deformation property", 2007, No.D-1.

[19] Matsuo, T., Kimura, K. and Kikuchi, M., 1987, "Transient Creep in Cr-Mo-V Steel", Denki Seiko, Vol.58, pp.94-103 (in Japanese).

[20] Sawada, K., Maruyama, K., Komine, R. and Nagae, Y., 1987, "Microstructural Changes during Creep and Life Assessment of Mod.9Cr-1Mo Steel", Tetsu-to-Hagane, Vol.83, pp.466-471 (in Japanese).

[21] Sawada, K., Takeda, M., Maruyama, K., Komie, R. and Nagae, Y., 1988, "Residual Creep Life Assessment by Change of Martensitic Lath Structure in Modified 9Cr-1 Mo Steels", Tetsu-to-Hagane, Vol.84, pp.580-585 (in Japanese).

[22] NIMS, "Metallographic Atlas of Long-term Crept Materials", 1999, No. M-1.

[23] NIMS, "Metallographic Atlas of Long-term Crept Materials", 2004, No. M-3.

[24] NIMS, "Metallographic Atlas of Long-term Crept Materials", 2006, No. M-5.

[25] Kimura, T., Shioda, Y., Nomura, K. and Kubushiro, K., 2017, "Growth and coarsening of sigma phase due to creep of KA-SUS304J1 HTB steels", CAMP-ISIJ Vol.30, p.412 (in Japanese).

[26] NIMS, "Metallographic Atlas of Long-term Crept Materials", 2016, No. M-11.

[27] Minami, Y., Kimura, H. and Ihara, Y., 1986, "Microstructural changes in austenitic stainless steels during long-term aging", Materials Science and Technology, Vol.2, pp.795-806.

[28] Sourmail, T., 2001, "Precipitation in creep resistant austenitic stainless steels", Materials Science and Technology, Vol.17, pp.1-14