Topics

Development of 500,000-hour material strength standards of 9Cr-1Mo-V steel for next-generation innovative high-temperature reactors

Kazuhiro Kimura[1]

[1] Research Center for Structural Materials

In response to the 60-years design life of the next generation innovative high temperature reactors, material strength standards up to 500,000 hours for the design of high-temperature structural components have been developed for 9Cr-1Mo-V steel in ASME Boiler and Pressure Vessel Codes, Section III, Division 5, some of which have been approved by the U.S. Nuclear Regulatory Commission in 2023.

1. Introduction.

On February 10, 2023, the Cabinet approved the "Basic Policy Toward the Realization of GX (Green Transformation): A Roadmap for the Next 10 Years," based on the results of discussions at the GX Executive Council established in the Cabinet Office.[1)] The roadmap clearly states the policy to work on the development and construction of next-generation innovative reactors that incorporate new safety mechanisms as part of the decarbonization efforts toward GX, which is based on the major premise of ensuring a stable energy supply. Furthermore, plans for five types of nuclear power generation systems were set as goals and strategies: advanced light water reactor, small modular reactor, fast reactor, high temperature gas cooled reactor, and nuclear fusion. In contrast to light water reactors that operate at relatively low temperatures, fast reactors, high-temperature gas reactors, and nuclear fusion, which are operated at high temperatures, require the evaluation of long-term creep strength characteristics to establish material strength standards for high-temperature structural components. This topic introduces recent trends in material strength standards for high-temperature structural components of next-generation innovative high temperature reactors.

2. Material Strength Standards for Next Generation Innovative High Temperature Reactors

*E-mail: kimura.kazuhiro@nims.go.jp

2.1 500,000-hour material strength standards

While a long-term creep strength property evaluation of 100,000 hours (about 11 years and 5 months) is required to establish material strength standards for non-nuclear components such as thermal power plants, an extremely long-time creep strength property evaluation up to 500,000 hours, corresponding to the 60-years design life of a nuclear reactor, is required to establish material strength standards for design and construction of high temperature components for next-generation innovative reactors. In Japan, the Japan Society of Mechanical Engineers (JSME) Committee on Standards for Power Plants has been studying the evaluation of ultra-long term creep strength properties necessary to establish material strength standards for high temperature structural components of fast reactors and high temperature gas cooled reactors. Standardization in this field is being pioneered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Committee. The allowable stress in the creep temperature range for non-nuclear components in the ASME Boiler Pressure Vessel Standard is determined by the minimum of the following three conditions.

(1) 100% of the average stress to produce a creep rate of 0.01% / 1,000h
(2) 100 F_{avg} % of the average creep stress to cause rupture at the end of 100,000 h (F_{avg} = 0.67 below 815°C)
(3) 80% of the minimum stress to cause rupture at the end of 100,000 h

On the other hand, in order to develop material strength standards for 60-year design of high-temperature components for nuclear power plants, it is necessary to evaluate the long-time creep strength properties shown below for up to 500,000 hours at each temperature.

(a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%

(b) 80% of the minimum stress to cause initiation of tertiary creep

(c) 67% of the minimum stress to cause rupture

The above requirements are equivalent to the material strength standards in Japan. In order to evaluate the stress at which creep rupture occurs after an extremely long term of more than half a century (500,000 hours) as well as the stress at which 1% total strain is reached and accelerated creep initiates, it is necessary to extrapolate the short-time creep test data to the long-term resime with high accuracy. Reliable extrapolation of creep test data to the long term is recognized to be up to about three times, and further extrapolation beyond three time is considered to below accuracy and unreliable, so creep test data up to 20 years in maximum is necessary, even if it is a short time.

2.2 Interpretation of Technical Standards for Thermal Power Plants for Power Generation

In June 2004, steam leakage from high-temperature reheat pipe occurred at the operating ultra-supercritical thermal power plant. As a result of the investigation into the cause of the damage and the study of measures to prevent recurrence, it was concluded that the creep strength of the high-strength ferritic creep resistant steel used in the damaged part was lower than the estimated strength when the design allowable stress was established. Subsequently allowable tensile stress was lowered based on the re-evaluation of creep strength using the "Region Splitting Analysis method [2] " proposed by Kimura.[3]。 Furthermore, for the maintenance of existing facilities, a life evaluation formula was developed.[4] This life evaluation formula was set based on the 99% confidence limit of the creep rupture life evaluated using the "Region Splitting Analysis method [2]) ". The allowable tensile stress and life evaluation formulas for high-strength ferritic creep resistant steels have been revised several times since then. In both reviews, creep strength evaluation based on the "Region Splitting Analysis method [2] " proposed by Kimura was used.

2.3 ASME Boiler Pressure Vessel Standard

Since the publication of the standard for power boilers in 1914, ASME has developed a number of standards for boilers, pressure vessels, and nuclear power plant equipment, as shown in Table 1. The ASME Boiler Pressure Vessel Codes is utilized in many countries and is the basis for technical standards and various standards related to the Electricity Business Act, Gas Business Act, High Pressure Gas Safety Act, and Industrial Safety and Health Act in Japan.

Table 1 Composition of the ASME Boiler Pressure Vessel Standard (BPVC)

Section I	Rules for Construction of Power Boilers
Section II	Materials
Section III	Rules for Construction of Nuclear Facility Components
Section IV	Rules for Construction of Heating Boilers
Section V	Nondestructive Examination
Section VI	Recommended Rules for the Care and Operation of Heating Boilers
Section VII	Recommended Guidelines for the Care of Power Boilers
Section VIII	Rules for Construction of Pressure Vessels
Section IX	Welding, Blazing and Fusing Qualifications
Section X	Fiber-Reinforced Plastic Pressure Vessels
Section XI	Rules for Inservice Inspection of Nuclear Reactor Facility Components
Section XII	Rules for Construction and Continued Service of Transport Tanks
Section XIII	Rules for Overpressure Protection

At the request of the Nuclear and Industrial Safety Agency, Kimura attended the ASME Boiler Pressure Vessel Code Committee meeting in August 2005 and provided information on the re-evaluation of creep strength and reduction of allowable stress for high-strength ferritic creep-resistant steel conducted in Japan. Since then, I have been attending the standard committee meetings held four times a year, and at present I am a member of the Standard Committee on Materials (BPV II), WG Creep Strength Enhanced Ferritic Steels, WG Data Analysis, SG High Temperature Reactors, and WG Allowable Stress Criteria. I mainly participate in the development of standards related to material strength criteria.

The ASME Standards Committee studied material strength criteria for non-nuclear components using the "Region Splitting Analysis method" and proposed a material strength criterion value for 9Cr-1Mo-V steel up to 500,000 hours, corresponding to high-temperature components for nuclear power plants[5]. After several years of deliberations, the proposed revisions to the existing material strength standard values up to 300,000 hours and the proposed new material strength standard values for 500,000 hours were approved and established in ASME BPVC Section III, Division 5, 2019 Edition. Technical review by the U.S. Nuclear Regulatory Commission was conducted on material strength standard values up to 500,000 hours for 9Cr-1Mo-V steel established in the 2019 edition of the standard, and those were endorsed in 2023[6]. The weld strength reduction factors up to 500,000 hours for the same steel grade was also approved by the ASME Standards Committee and established in the 2023 edition of the same standard.

3. Summary

The contents described in this paper have been reflected in the formulation of Japanese standards for fast reactors and are expected to contribute to the formulation of standards for high-temperature gas-cooled reactors in the future.

References

1) https://www.cas.go.jp/jp/seisaku/gx_jikkou_kaigi/pdf/kihon.pdf
2) Kimura, Kushima, Abe, J Society Materials Science Japan, 52 (2003), 57-62.
3) Interpretation of Technical Standards for Thermal Power Plants for Power Generation, Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry, December 14, 2005, NISA-234c-05-8.
4) Life Evaluation Formula for High Chromium Steels in Thermal Power Plants for Power Generation, Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry, December 14, 2005, NISA-234c-05-9.
5) K. Kimura, Proc. ASME PVP2017 July 16-20, 2017, Hawaii, USA, (2017) PVP2017-65522.
6) U.S. Nuclear Regulatory Commission, Regulatory Guide 1.87, Revision 2, Acceptability of ASME Code, Section III, Division 5, “High Temperature Reactors”, (2023).