A Study on the Tensile Properties of Materials at Elevated Temperature in RCC-M

Lifeng Guo, Yuxin Wang and Zhe Li

Abstract The tensile properties of materials at elevated temperature shall be ensured for PWR (pressurized water reactor) nuclear components as the components normally are used in elevated temperature applications. ASME BPVC and RCC-M provide tensile properties at elevated temperature which are used to derive the allowable design stress for high-temperature service. However, it always confuses the code user to notice verification of elevated temperature tensile properties is required in RCC-M, while such requirement never appears in ASME BPVC. In this article, technical basis of the temperature-dependant tensile properties in ASME (Table U and Table Y-1 in Section II Part D) and RCC-M (Annex I Table ZI 2.0 and Table ZI 3.0 in Section I Subsection Z) is investigated, followed by an analysis on the effectiveness of verification tests in RCC-M. It is found that basically, the temperature-dependent tensile properties in RCC-M come from ASME BPVC, which is based on a so-called ratio-trend-curve method. The values given by this method are derived from the trend curve of the material and are different from the specified minimum properties at high temperature in EN standard, which are mandatory requirements for the material. Verification of tensile properties at certain temperature in RCC-M will improve the confidence to ensure the actual tensile results at high temperature will not be less than those listed in Table ZI 2.0 and Table ZI 3.0 (a 10% decrease for S_u need to be accounted); nevertheless, it does not mean the tensile properties in the whole range of elevated temperature can be guaranteed in RCC-M as those in EN standards, which provide a high confidence level and normally result in a decreased specified tensile properties at high temperature. Finally, suggestion for localization of nuclear code on requirements of temperature-dependent tensile properties is given.

Keywords Tensile properties · Elevated temperature · RCC-M

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1 Introduction

The tensile properties, including ultimate tensile strength and yield strength, are critical material characteristics for design of pressure-retaining components. These properties are not only determined by the materials itself, but also are influenced by temperature, and time in some circumstances [1], which further results in creep and rupture strength. As the nuclear components for PWR are designed under the material "creep" range, only the effect of temperature needs to be taken into account.

Figure 1 demonstrates typical behavior of temperature-dependent tensile properties for carbon steel. It is noticeable that yield strength decreases with the increase in temperature, while ultimate tensile strength increases initially within a moderate range of temperatures and then decreases. The shape and the size of the tensile properties vs. temperature curve may be different for various steel grades. For austenitic stainless steel and nickel alloy, the behavior may be significantly different from that of carbon steel. To assure a reasonable design, the temperature-dependent strength properties of various materials shall be thoroughly investigated, and provide for the establishment of allowable design stress. In ASME BPVC (Boiler and Pressure Vessel Code), the tensile strength S_u and yield strength S_y at elevated temperature are tabulated in Table U and Table Y-1 of Section II Part D, and in RCC-M, the values are provided in Annex I Table ZI 2.0 and Table ZI 3.0 in Section I Subsection Z, respectively.

It is interesting to note there are specified minimum tensile properties at high temperature in RCC-M, whereas such requirements never appear in ASME BPVC. This fact always confuses the code user. This article will review the technical basis of the S_u and S_y values in ASME and RCC-M and analyse the verification tests at high temperature in RCC-M, with the aim to promote deeper understanding on this topic and give suggestion on the nuclear codes and standards in China.

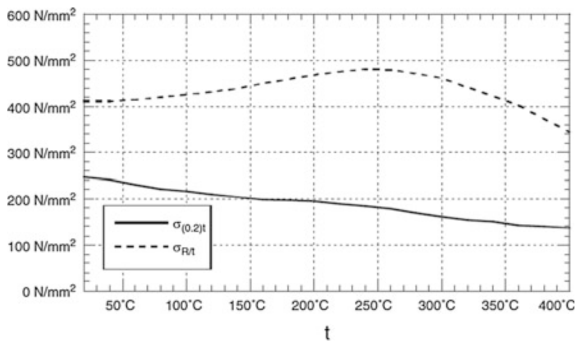

Fig. 1 Typical behavior of temperature-dependent tensile strength and yield strength for carbon steel [1]

2 Technical Basis of S_u and S_y in ASME BPVC

In the USA, the evaluation of tensile properties at elevated temperature can be traced back to the work by ASTM-ASME Joint Committee on Effect of Temperature on the Properties of Metals in some decades ago [2, 3]. The committee sought to offer best possible assessments of various properties of materials as the basis to establish allowable stresses in design. The testing data were collected from different industries, government, institute, and university laboratories in the USA and generally did not represent systematic or coordinated test programs; i.e., the testing were conducted independently. The data were processed by a "ratio-trend-curve" method to evaluate the behavior of the temperature-dependent properties. To illustrate the basic principle of the method, an example is given below to evaluate yield strength of type 304L stainless steel.

The original data included testing data of type 304L from different lot and different product form (bar, plate, pipe, etc.). As the data were not generated by systematic test programs, it is not usually feasible to develop the trend curve for yield strength with temperature by simply passing a curve through the averages of the data at different temperatures. Such a curve would be subject to local distortion by limited data representing lots differing from the average. Therefore, the original data were normalized in terms of ratio of strength at temperature to the strength at room temperature, on the premise that a lot of material which exhibits relatively high strength at room temperature may reasonably be expected to exhibit high strength at elevated temperatures. By this treatment, it becomes possible to utilize all of the available data at high temperature if corresponding test data at room temperature are available [2].

Figure 2 shows the strength ratio vs. temperature for type 304L. Some data (identified with "x" mark) appeared to lie outside the general scatter band and were excluded from analysis by the committee. The excluded data were invariably on the high side for conservative purpose. Trend curve was derived for the remaining data by polynomial regression analysis. The regression process terminated at the polynomial degree for which there was no further reduction in the sum of the squares of the residuals. The best fit curve developed by the regression analysis is given in Fig. 2.

The derived strength ratios trend curve is believed to be the best estimation of the behavior of the temperature-dependent yield strength of type 304L. Therefore, specified minimum yield strength at room temperature may be computed directly with the ratio-trend-curve method to obtain the most probable value of the yield strength at temperature for a product whose yield strength at room temperature is equal to the specified minimum yield strength at room temperature. Figure 3 provides the curve of yield strength versus temperature when the specified minimum yield strength is 25 ksi at room temperature. The curve of tensile strength versus temperature is determined with the same approach.

In ASME BPVC, yield strength S_y in Table Y-1 of Section II Part D at ambient temperatures is based on the published values in the applicable material

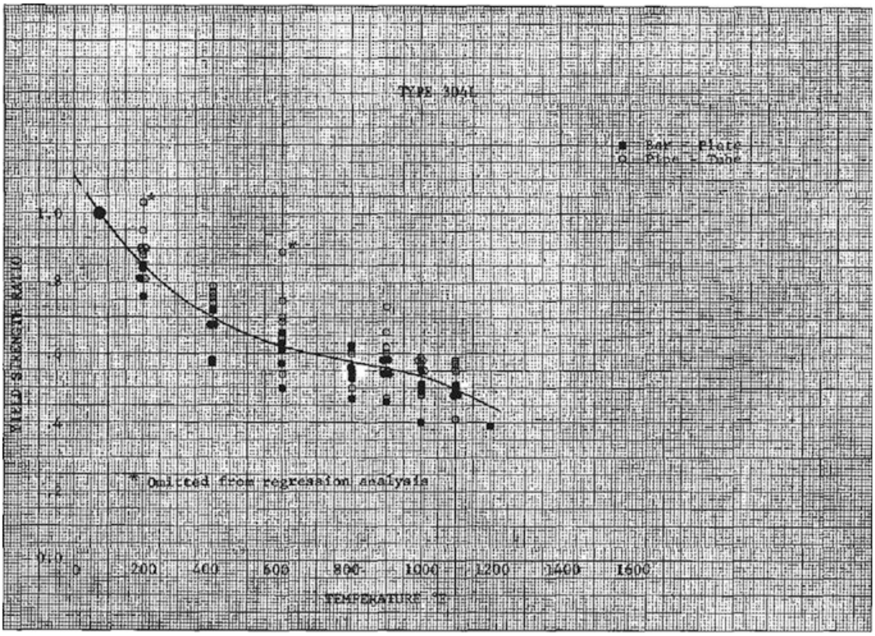

Fig. 2 Ratio versus temperature and derived trend curve for type 304L stainless steel [2]

specification, i.e., specified minimum yield strength; those at elevated temperatures are determined by the "ratio-trend-curve" method mentioned above. Tensile strength S_u in Table U is obtained with the same manner except at temperatures above the ambient temperature, the value are increased up to 10% as long as they do not exceed the specified minimum tensile strength at ambient temperature [4]. In the general note of Table Y-1, the ASME Committee states S_y do not corresponds exactly to "minimum" or "average" value of the material. Neither the ASME Section II nor Section III requires yield strength testing at high temperature for production material used in component fabrication. It is not intended that results of such tests, if performed, be compared with S_y for acceptance/rejection purpose. There is a similar description in the general notes of Table U.

The ASME process avoids the need for material organization to collect or guarantee elevated temperature strength of material. The process was developed at a time when there was substantial participation by material producers in the ASME code process, and they objected to having collected such data. Since the ASME process is a consensus process (rather than one determined by a government agency), a method was developed to avoid the necessity of collecting such data except when a new material is proposed to enter into the Code [5].

Supporting material cannot be found in the literature to justify why component designed with ASME BPVC is still safe even the actual material strength at elevated temperature, in some cases, may be lower than $S_u/1.1$ or S_y from which the

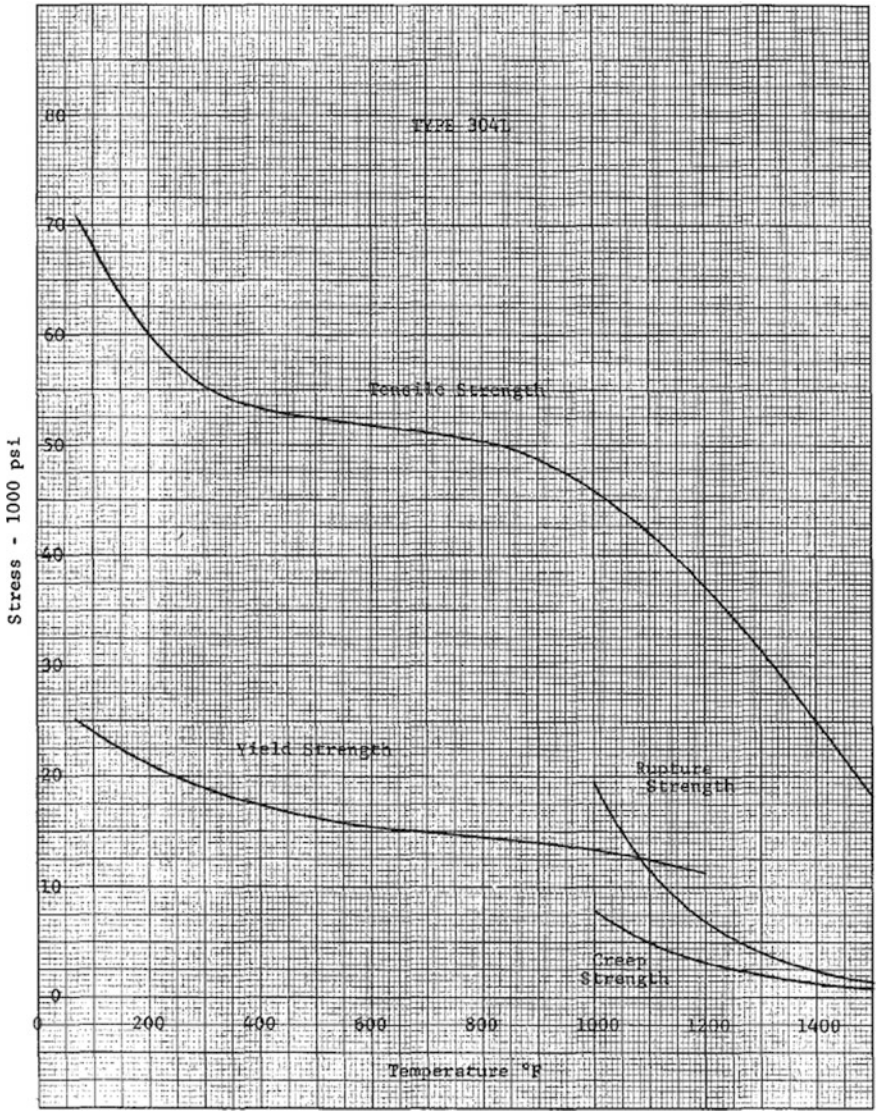

Fig. 3 Yield strength versus temperature for type 304L when the yield strength at room temperature is equal to 25 ksi. Other curves are also given in this plot [2]

allowable stress is derived for design calculation. It is assumed that enough margins have been provided by the ASME Committee by other mechanisms such as design factor, and as the approach has its historical reason, ASME Committee does not allow question previous practices which have good experience feedback.

3 Source of S_u and S_y in RCC-M

It is well known that RCC-M is established on the basis of ASME BPVC, with the combination of French industrial practice, feedback, and regulatory requirements. The S_u and S_y in RCC-M Annex I Table ZI 2.0 and Table ZI 3.0 of Section I Subsection Z are also strongly dependent on the ASME BPVC Section II Part D. The mechanical properties and allowable stresses of the materials were taken from the ASME Code whenever the requirements of RCC-M met the requirements of the ASME Code for a given grade (chemical composition and specified mechanical properties) [6]. A typical example is 16MND5 in RCC-M, an equivalent grade for SA-508 Gr.3 Cl.1. Table 1 shows their specified properties at room temperature and S_y values at elevated temperature. For S_u, the two materials are all equal to 552 Mpa at elevated temperature below creep range.

Table 1 shows although 16MND5 has raised the specified minimum yield strength at room temperature (R_e) from 345 MPa of its ASME counterpart to 400 Mpa, the S_y at high temperature is still anchored to S_y at 20 °C, which is equal to R_e of SA-508 Gr.3 Cl.1. There are minor differences for S_y at elevated temperature between the two materials, which may be caused by following reasons:

- Various editions of ASME Code may have minor differences on S_y in Table Y-1, which reflects continuous efforts of the ASME Committee on assessment of material behavior in the later edition with increasing testing data. The ASME edition referred by RCC-M 2007 is not the 2010 edition used in Table 1.
- Difference occurs during rounding when conversion from U.S. Customary Units to SI Units, as only customary data were available in earlier edition of ASME Code. Furthermore, in earlier edition, the S_y value is only given at integer interval in Fahrenheit temperature like 200 °F, 300 °F, 400 °F. To obtain the values at integer Celsius degree like 100 °C, 150 °C, 200 °C, interpolation will be needed and may bring additional conversion error.

Table 1 Specified tensile properties at room temperature and S_y value for some ASME BPVC and RCC-M materials [7, 8] (MPa)

Grade	R_e	R_m	S_y at 20 °C	S_u at 20 °C	50 °C	100 °C	150 °C	200 °C	250 °C	300 °C	350 °C
M2111 16MND5	400	550	345	552	340	326	318	311	308	303	299
SA-508 Gr.3 Cl.1	345	550	345	550	[a].	323	314	305	299	292	285
M3304 Z2CN18.10	175	490	173	483	165	145	131	121	113	108	104
SA-213 TP304L	170	485	172	483	[b]	146	132	121	114	108	104

[a]No data available at 50 °C. S_y at 65 °C is 332 MPa
[b]No data available at 50 °C. S_y at 65 °C is 157 MPa

Nevertheless, the design stress intensity value S_m is same (184 MPa) for the two materials, thanks to S_m actually depends on the S_u for these two materials.

Table 1 also provides an example for stainless steel seamless pipe RCC-M M 3304 Z2CN18.10 and its ASME equivalent grade SA-213 TP304L. The data are highly consistent with each other and conform to yield strength curve in Fig. 3, which was derived by Dr. G. V. Smith some decades ago.

When the RCC-M grade has no equivalent in the ASME BPVC, the values of specified minimum yield strength at elevated temperature given in the NFA or EN standards were chosen as values of S_y. The value of S_u was taken equal to the specified R_m value at room temperature, until this value reaches 110% of the tensile strength value given in the standard [6]. An example is RCC-M M1131 P265GH carbon plate, which is widely used for fabrication of classes 2 and 3 components. Table 2 shows S_y values of M1131 P265GH with $t \le 30$ mm is basically the same as that specified yield strength $R_{p0.2}$ at temperature in EN standard for $40 < t \le 60$ mm. AFCEN does not take the value for $16 < t \le 40$ mm in the standard. It demonstrates the Code Committee (here AFCEN) has arbitrary judgment during determination of S_y based on the published material property data, and the decision is carried out in a conservative way.

SA/EN10028-2 P265GH has been approved by ASME BPVC 2013 Edition in Part D. It is interesting to compare S_y between ASME and RCC-M for this material. Table 2 shows a marked increase in S_y in ASME BPVC, for instance, around 18% greater than that of RCC-M at 300 °C. The difference is because the S_y value given in ASME is still based on the "ratio-trend-curve" method, other than the specified minimum yield strength value in the standard. The example clearly shows that S_y obtained by "ratio-trend-curve" method has significant difference from the specified minimum yield strength value of the material.

In RCC-M Section II, the material specification stipulates tensile properties at certain elevated temperature, i.e., at 300 °C for carbon steel, and at 350 °C (in certain circumstances 360 °C) for stainless steel and nickel alloys. The required tensile strength and yield strength are based on the value in Annex I Table ZI 2.0 and Table ZI 3.0, and a 10% decrease of S_u is taken into account. Unlike ASME, this verification test is used for material acceptance/rejection. Obviously, this additional requirement will increase the confidence level that the actual tensile properties of the lot to be tested will be no less than the value used to derive the data for design calculation in Annex I.

4 Analysis of the Verification Test at Elevated Temperature in RCC-M

Before RCC-M 2000 Edition, only yield strength is required to be verified at high temperature, and tensile strength at high temperature is only for information purpose. For welding material, verification of tensile strength at high temperature is not a mandatory requirement till today. As the allowable stress is derived from yield

Table 2 Specified tensile properties and S_y value for P265GH in different codes and standard (MPa)

Grade	Thickness (mm)	R_e	R_m	S_y at 20 °C	S_u at 20 °C	50 °C	100 °C	150 °C	200 °C	250 °C	300 °C	350 °C
EN10028-2:2003 P265GH	16 < t ≤ 40	255	410			247	232	215	197	181	166	154
EN10028-2:2003 P265GH	40 < t≤ 60	245	410			237	223	206	190	174	160	148
M1131 P265GH	t ≤ 30	245	410	245	410	234	223	206	191	176	157	142
SA/EN10028-2 P265GH	t ≤ 60	245	410	245	410	[a]	223	217	210	202	191	180

[a]No data available at 50 °C. S_y at 65 °C is 230 MPa

strength and tensile strength at room and elevated temperature, and tests at room temperature are always required, the code user may doubt about the effectiveness of verifying yield strength at high temperature only. To evaluate the verification test at elevated temperature in RCC-M, the parameter dominating the allowable stress is analyzed among R_m, R_e, S_u, and S_y. If the allowable stress is not determined by S_y, the verification test of S_y is not critical as even S_y is not satisfied; the allowable stress may not be influenced.

For RCC-M Class 1 components (and Class 2 components using the design method in RCC-M C3200) other than bolts, the allowable basic stress intensity S_m is determined by:

$S_m = \min(1/3R_m, 1/3S_u, 2/3R_e, 2/3S_y)$ for ferritic steels,
$S_m = \min(1/3R_m, 1/3S_u, 2/3R_e, 0.9S_y)$ for stainless steels and nickel alloys.

The value of $\min(1/3R_m, 1/3S_u)$ minus $\min(2/3R_e, 2/3S_y)$ for ferritic steel and $\min(1/3R_m, 1/3S_u)$ minus $\min(2/3R_e, 0.9S_y)$ for austenitic steel and nickel alloys is calculated at room and high temperature for 4 typical material grades, M1131 P265GH ($t <= 30$ mm), M2111 16MND5, M3304 Z2CN18.10, and M4103 NC15Fe, which are representative of carbon steel, low alloys steel, stainless steel, and nickel alloy. The plot is given in Fig. 4. The value below zero corresponds to the region where S_m is controlled by S_u, as S_u cannot be greater than R_m, and they have the same reduction factor. On the other hand, when the value is above zero, R_e or S_y will dominate the S_m. For ferritic steel, the controlled parameter will be S_y as R_e and S_y have the same reduction factor and S_y is not greater than R_e. For stainless steel and nickel alloys, the temperature-dependent value of $2/3R_e$-$0.9S_y$ is plotted in Fig. 5 to determine which one plays a critical role on S_m.

Figures 4 and 5 clearly demonstrate S_m is governed by different parameters for different types of materials:

- For M2111 16MND5, S_m is invariably governed by S_u. Actually, S_u is equal to R_m within the temperature range in RCC-M for carbon steel and low-alloy steel, which conforms the characteristic of increased tensile strength at elevated temperature shown in Fig. 1. Verification of S_y and S_u has little contribution to guarantee S_m value for M2111 16MND5; this is particularly true as R_e has increased to 400 MPa, instead of 345 MPa used for S_u at room temperature in RCC-M,
- For P265GH, S_m is initially governed by S_u. With the increase in temperature, the effect of S_y becomes more dominant and the controlled parameter is changed to S_y at around 150 °C. Verification test of S_y is normally conducted at 300 °C. At this point, $1/3S_u$-$2/3S_y$ is more than 30 MPa, i.e. S_u has more than 90 MPa margin before it can influence S_m. Verification of S_y is normally enough for material properties at 300 °C.
- For Z2CN 18.10, S_m is initially governed by R_e, and the controlled parameter is changed to S_y at around 150 °C. Verification of S_y is normally carried out at 350 °C. At this point, $1/3S_u$-$0.9S_y$ is more than 35 MPa which corresponds to

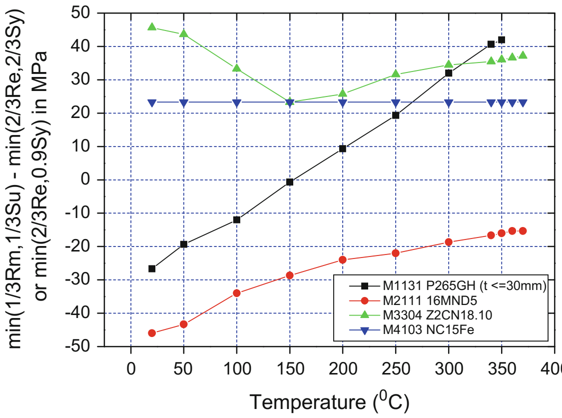

Fig. 4 The temperature-dependent difference between tensile strength and yield strength at room and high temperature with reduction factor for S_m

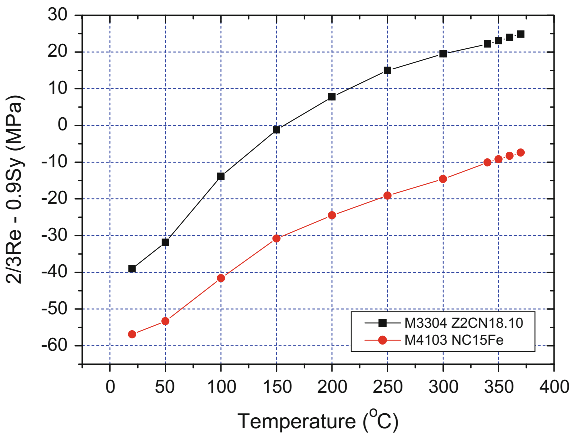

Fig. 5 The temperature-dependent difference between yield strength at room and high temperature with reduction factor for S_m

nearly 100 MPa margin for S_u before it can influence S_m. Verification of S_y is normally enough for material properties at 350 °C.

- For NC 15 Fe, S_m is always governed by R_e. Verification test at high temperature has no contribution.

For RCC-M Class 2 (except those designed by RCC-M C3200) and Class 3 components other than bolts, similar analysis can be conducted for allowable basic stress S, which is governed by:

S = min(1/4R_m, 1/4S_u, 2/3R_e, 2/3S_y) for ferritic steels,
S = min(1/4R_m, 1/4S_u, 2/3R_e, 0.9S_y) for stainless steels and nickel alloys

As 16MND5 and NC 15Fe are rarely used for classes 2 and 3 components, only P265GH and Z2CND18.10 are analyzed, and the results are given in Fig. 6. For

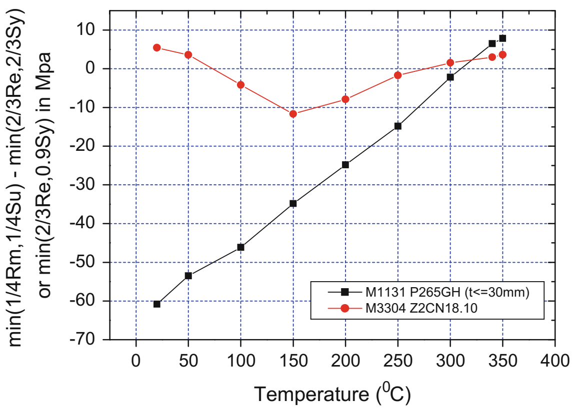

Fig. 6 The temperature-dependent difference between tensile strength and yield strength at room and high temperature with reduction factor for S

allowable basic stress S, P265GH and Z2CN 18.10 are all dominated by S_u within the majority of temperature range in RCC-M until at around 300 °C. The result is not surprising as a quite big reduction factor of 4 is adopted by RCC-M 2007 Edition (the value is reduced to 3.5 in 2012 Edition). However, the differences between $1/4S_u$ and $2/3S_y$ (for carbon steel) or $0.9S_y$ (for stainless steel) are quite small at the typical verification temperature 300 °C and 350 °C, respectively, which means only verification of S_y may not be enough to guarantee S. The revision about verification of both S_u and S_y from 2000 Edition becomes reasonable for the two materials. Besides, there is actually no work added as tensile test at high temperature can measure both tensile strength and yield strength.

The analysis shows that although verification of tensile tests at high temperature will, in general, improve the confidence level that the actual tensile properties of the lot to be tested will be no less than the value used to derive the data for design calculation in RCC-M Annex I, its effectiveness cannot be overemphasized. For 16MND5 and NC15Fe, the verification has little contribution. Moreover, the verification is only conducted at a single high temperature. There is no evidence to support an acceptable verification test at a single high temperature can assure same conclusion can be obtained for the whole temperature range. If a specific design needs measured tensile properties of the materials to be guaranteed at the service temperature, it is suggested to conduct verification test at that specific service temperature, instead of the temperature stipulated in the material specifications in RCC-M Section II.

Meanwhile, if the actual tensile properties within the whole temperature range need to be assured, a method similar to that adopted in EN standard is suggested. For instance, EN 10314 can derive elevated tensile properties data with a confidence level of 98% [9]. Nevertheless, this method will bring a reduced value for tensile properties at elevated temperature, and when adopted by design code, the wall thickness calculated will be greater than that based on “ratio-trend-curve” approach, which means cost will increase.

5 Conclusions

(1) S_u and S_y in ASME BPVC are based on "ratio-trend-curve" method. The ASME Committee does not require verification tests at high temperature and does not consider the result of such tests can be used to reject the material, probably due to good feedback of previous practice.
(2) S_u and S_y in RCC-M are essentially the same as that in ASME BPVC when material has the equivalent in ASME. In addition, some materials use the value specified in EN or NFA standard to establish S_u and S_y. Verification of tensile tests can improve the confidence level that the actual tensile properties of the lot to be tested will be no less than the value used to derive the data for design calculation in Annex I.
(3) However, the effectiveness of verification tests cannot be overemphasized. If a specific design needs measured tensile properties of the materials to be guaranteed at the service temperature, it is suggested to conduct verification test at that specific service temperature. Moreover, if the actual tensile properties within the whole temperature range need to be assured, a method similar to that adopted in EN standard is suggested.

The data of material properties are the foundation of the design code. For localization of nuclear code, it is suggested to establish specific organization which is responsible for collection, processing, and publication of property data (including tensile properties at high temperature). The data from ASME BPVC can be used, but it does not mean further analysis is not necessary. The material properties data shall be continuously obtained, analyzed, and reflected by the update in the later edition of the code, to improve the accuracy and reliability of the data used for design.

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