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A. ZIELIŃSKI*, G. GOLAŃSKI**,#, J. DOBRZAŃSKI*, M. SROKA***

# CREEP RESISTANCE OF VM12 STEEL

This article presents selected material characteristics of VM12 steel used for elements of boilers with super- and ultra-critical steam parameters. In particular, abridged and long-term creep tests with and without elongation measurement during testing and investigations of microstructural changes due to long-term impact of temperature and stress were carried out. The practical aspect of the use of creep test results in forecasting the durability of materials operating under creep conditions was presented. The characteristics of steels with regard to creep tests developed in this paper are used in assessment of changes in functional properties of the material of elements operating under creep conditions.

## 1. Introduction

The development of new grades of creep-resisting steels is stimulated by development of the power industry, and particularly it is dictated by both economical and environmental considerations and improvement in thermal efficiency of power units ultimately by 50%.

As a result of numerous research projects, new grades of martensitic steels, including, but not limited to, T/P91, T/P92 and E911, were developed and implemented. High-chromium martensitic steels were developed as a result of modification and optimisation of the chemical composition of steels used in the power industry so far. These steels are characterised by high mechanical properties; among other things, their creep strength is higher by approx. 20÷25% than creep strength of steels used so far [1÷4]. However, 9% chromium content in these steels restricts their use up to a temperature of 580÷600°C. Hence, higher chromium content of approx. 12% is required to ensure oxidation and gas corrosion resistance at the operating temperature above 600°C. To meet these requirements in Europe, a steel containing approx. 12%Cr, designated as X12CrCoWVNbN12-2-2 and commonly known as VM12, was developed. Originally, this steel was to be characterised by creep strength higher than that of T/P92 and oxidation and gas corrosion resistance comparable to that of PT304/PT347 austenitic steel [5÷8]. The aim of this paper is present the results of creep tests and structural changes as well as their practical use in forecasting the durability of materials operating under creep conditions. The characteristics of steels with regard to creep tests and structure investigations developed in this paper are used in assessment of changes in functional properties of the material of elements operating under creep conditions.

Chemical composition of VM12 steel under investigation for use in boiler elements with super- and ultra-supercritical steam parameters, which are the subject of research, is presented in Table 1 with reference to chemical composition according to the standard.

## 2. Research methodology

The chemical composition of the VM12 steel is presented in Tables 1. The creep tests were carried out in single-sample six-stand machines constructed in Institute for Ferrous Metallurgy. They were equipped with three-zone heaters with the control and regulation system based on high quality PLC drivers and extensometers used for elongation measurements performed by a high-resolution inductive distance sensors. These machines have compound lever ensuring constant load that are placed in heating chambers ensuring constant temperature conditions on the total length of sample and throughout duration of tests with accuracy of 1°C for temperature up to 800°C.

TABLE 1

Chemical composition of VM12 steel, wt.%

| Steel grade | Chemical composition [%] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Ni | Mo | V | W | Nb | Co | Others |
| VM12 | 0.13 | 0.48 | 0.22 | 11.4 | 0.19 | 0.27 | 0.22 | 1.30 | 0.05 | 1.20 | B:0.003<br>N: 0.05 |

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* INSTITUTE FOR FERROUS METALLURGY, K. MIARKI 12-14, 44-120 GLIWICE, POLAND

** INSTITUTE OF MATERIALS ENGINEERING, CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, 19 ARMII KRAJOWEJ AV., 42-200 CZĘSTOCHOWA POLAND

*** INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS, SILESIAN UNIVERSITY OF TECHNOLOGY, 18 A KONARSKIEGO STR., 44-100 GLIWICE, POLAND

# Corresponding author: grisza@wip.pcz.pl

Abridged creep tests were conducted at constant stress level corresponding to the required operating one, i.e. 100 and 120 MPa and at five different test temperature levels that were higher than expected exploitation temperature i.e. 620, 640, 660, 680, 700°C.

Long-term creep tests with elongation measurement during testing were performed at 575, 600 and 625°C with periodically changed stress level: at 575°C with stress level 130, 150, 160 and 180 MPa; at 600°C stress level 100, 125, 150 and 180 MPa and at 625°C with stress level 70, 80, 100 and 125 MPa.

## 3. Creep tests

### 3.1. Abridged creep tests

One of the elements of characteristics that describe material's creep strength is the so-called abridged creep tests, conducted at constant stress level corresponding to the required operating one and at different test temperature level higher than the operating temperature [7, 9]. With extrapolation method, they are used for determination of creep strength for temperature levels corresponding to the expected operating ones.

The determined characteristics of abridged creep tests in the form of relationship log $t_r = f(T_e)$ at $\sigma_b$ = const for VM12 steel at constant stress level $\sigma_b$ = 100 and 120 MPa are shown in Fig. 1

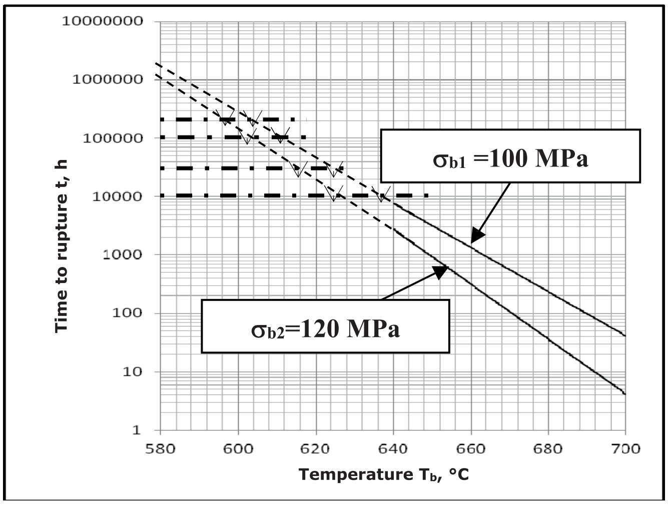

Fig. 1. Results of abridged creep tests of VM12 steel conducted at a temperature higher than the expected operating one and at constant stress level with different values ($\sigma_{b1}$ = 100 MPa; $\sigma_{b2}$ = 120 MPa)

Estimated by extrapolation, the life time with regard to temperature level corresponding to the expected operating one is summarised in Table 2.

Based on prepared characteristics of abridged creep tests, temperature levels were determined for the required times to rupture of 10, 30, 100 and 200 thousand hours at stress corresponding to the operating one. The obtained results are summarised in Table 3.

TABLE 2

Life time due to creep of VM12 steel at a temperature and stress corresponding to the expected operating ones, estimated based on abridged creep tests

| Test temperature $T_{b}$, °C | Test stress $\sigma_b$, MPa | |
|---|---|---|
| | 100 | 120 |
| | Estimated life time $t_r$, h*10$^3$ | |
| 580 | 1 800 | 1 100 |
| 590 | 700 | 400 |
| 600 | 300 | 150 |
| 610 | 100 | 50 |
| 620 | 45 | 20 |

TABLE 3

Forecast temperature for time to rupture of VM12 steel corresponding to 10, 30, 100 and 200 thousand hours at stress of 100 and 120 MPa

| Test stress $\sigma_b$, MPa | |
|---|---|
| 100 | 120 |
| forecast temperature for time to rupture of 10,000 h; °C | |
| 638 | 628 |
| forecast temperature for time to rupture of 30,000 h; °C | |
| 622 | 615 |
| forecast temperature for time to rupture of 100,000 h; °C | |
| 612 | 603 |
| forecast temperature for time to rupture of 200,000 h; °C | |
| 603 | 598 |

### 3.2. Long-term creep tests

The obtained results of VM12 steel creep tests, conducted both with and without elongation measurement at constant temperature and stress parameters for several test temperature levels and several test stress levels, were used to build the temporary creep strength characteristics as parametric curves.

The developed parametric creep strength curves in the form of relationship log$\sigma_b$ = f(L-M), where L-M is the Larson-Miller parameter, are shown in Fig. 2.

By knowing the design temperature $T_o$ and design stress $\sigma_o$ (arising from element's geometry and design pressure po) of service from the parametric Larsson-Miller curve, the time to rupture tr upon which the element destruction should be expected can be determined.

The creep tests with elongation measurement during testing conducted at constant temperature and stress allowed the creep curves to be drawn in the form of relationship between the quantity of constant strain $\varepsilon$ and creep time $t$. The practical value determined in these tests is the time at the end of stage II of material creep process, called the disposable life $t_b$, which is a part of the life time, i.e. time to rupture $t_r$. The time at the end of stage II of creep process is a temperature and stress level-dependent value characteristic of each of the tested grades of material. The obtained sets of creep curves in the form of relationship between plastic strain and time to rupture of sample $t$, $\varepsilon = f(\sigma)$ for several test stress levels at constant test temperature $T_b$ are shown graphically for VM12 steel at constant temperature $T_b$ = 575°C in Fig. 3, at $T_b$ = 600°C in Fig. 4 and at $T_b$ = 625°C in Fig. 5.

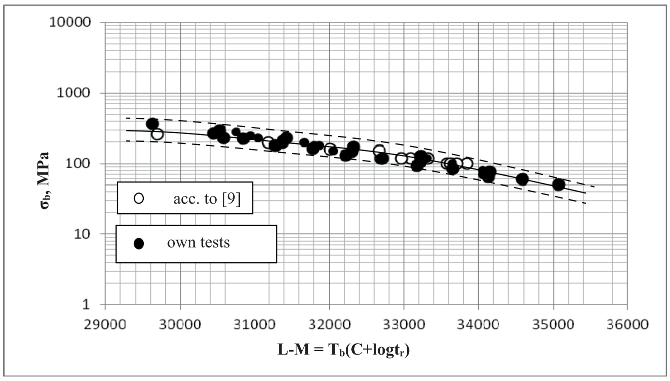

Fig. 2. Parametric average temporary creep strength curve in the form of relationship log $\sigma_b$ = f(L-M) for VM12 martensitic steel under investigation. where: L-M is the Larson-Miller parameter; L-M = $T_b(C + \log t_r)$, $\sigma_b$ – test stress, $t_r$ – time to rupture, $T_b$ – test temperature in K, C = 37 – material constant

The determined values of the end of secondary creep $t_{II}$, time to rupture $t_r$ and share of secondary creep in duration of the creep rupture test ($tII/t_r$) are summarised for the assumed temperature levels of $T_b$=575, 600 and 625°C in Tables 4, 5, 6, respectively.

The obtained values of the share of secondary creep in duration of the creep rupture test ($tII/t_r$), which are also the value of life exhaustion extent defined as duration of the creep test $t$ up to the time to rupture $t_r$, for various stress levels at constant test temperature, allowed the relationship between $tII/t_r$ and test stress $\sigma_b$ at constant test temperature $T_b$ ($tII/tr=f(\sigma_b)$ for $T_b$=const.) to be formed.

These relationships for VM12 steel at test temperature $T_b$=575°C are shown in Fig. 6a, at test temperature $T_b$=600°C in Fig. 6b and at test temperature $T_b$=625°C in Fig. 6c. The extrapolation of outlined curves for specific temperature and stress corresponding to the expected operating one allows the estimation of life exhaustion extent corresponding to the end of secondary creep to determine the end of safe service life.

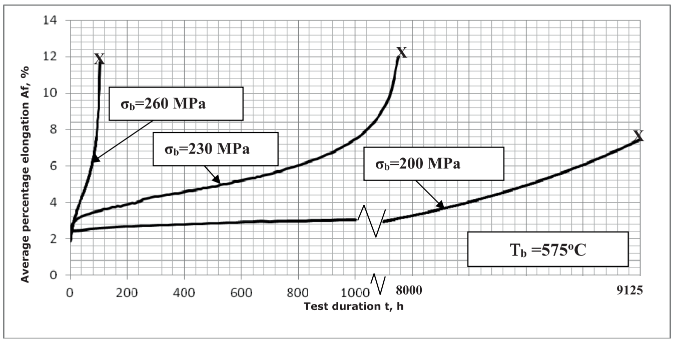

Fig. 3. Comparison of results of creep test with elongation measurement during testing in the form of creep curves ε = f($t$) for different test stress levels σb at constant test temperature $T_b$ = 575°C for VM12 steel

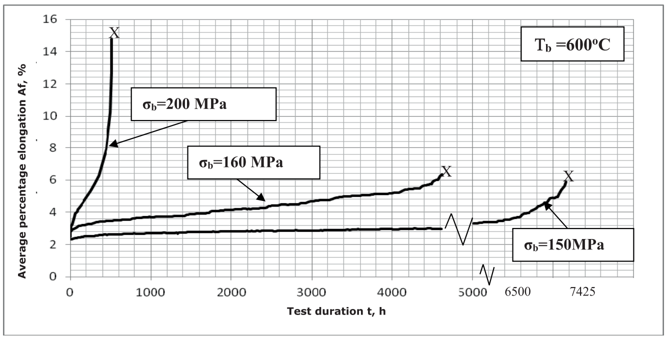

Fig. 4. Comparison of results of creep test with elongation measurement during testing in the form of creep curves ε = f(t) for different test stress levels $\sigma_b$ at constant test temperature $T_b$ = 600°C for VM12 steel

To evaluate the suitability and validate the evaluation of exhaustion extent by the method using the life-time fractions rule, creep tests with measurement and recording of elongation during testing at cyclically changed stress level and constant temperature and at cyclically changed temperature level and constant stress level were carried out.

These tests represent the behaviour of material under real conditions. During the operation, its performance changes and such changes have a substantial impact on the extent and intensity of changes occurring in the material of boiler elements operating under creep conditions, thus significantly reducing the real life time.

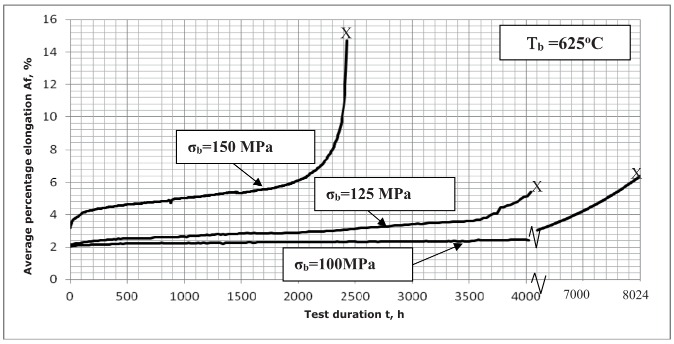

Fig. 5. Comparison of results of creep test with elongation measurement during testing in the form of creep curves ε = f($t$) for different test stress levels $\sigma_b$ at constant test temperature $T_b$ = 625°C for VM12 steel

TABLE 4

Time to end of secondary creep $t_{II}$, time to rupture $t_r$ and share of secondary creep in time to rupture $t_{II}/t_r$ for VM12 steel depending on test stress at constant test temperature $T_b$=575°C

| **Test temperature $T_b$=575°C** | | | **VM12 steel** |
|---|---|---|---|
| **Test stress $\sigma_b$, MPa** | | | |
| 260 | 230 | 200 | |
| 104 | 1154 | 9125 | **Time to rupture $t_r$, h** |
| 68 | 790 | 6 370 | **Time to end of secondary creep $t_{II}$, h** |
| 0.65 | 0.68 | 0.70 | **Share of $t_{II}$ in $t_r$, $t_{II}/t_r$** |

TABLE 5

Time to end of secondary creep $t_{II}$, time to rupture $t_r$ and share of secondary creep in time to rupture $t_{II}/t_r$ for VM12 steel depending on test stress at constant test temperature $T_b$=600°C

| **Test temperature $T_b$=600°C** | | | **VM12 steel** |
|---|---|---|---|
| **Test stress $\sigma_b$, MPa** | | | |
| **200** | **160** | **150** | |
| 516 | 4 626 | 7 425 | **Time to rupture $t_r$, h** |
| 330 | 3 145 | 4 980 | **Time to end of secondary creep $t_{II}$, h** |
| 0.63 | 0.68 | 0.70 | **Share of $t_{II}$ in $t_r$, $t_{II}/t_r$** |

TABLE 6

Time to end of secondary creep $t_{II}$, time to rupture $t_r$ and share of secondary creep in time to rupture $t_{II}/t_r$ for VM12 steel depending on test stress at constant test temperature $T_b$=625°C

| **Test temperature $T_b$=625°C** | | | **VM12 steel** |
|---|---|---|---|
| **Test stress $\sigma_b$, MPa** | | | |
| **150** | **125** | **100** | |
| 2 410 | 4 152 | 8 024 | **Time to rupture $t_r$, h** |
| 1 640 | 2 910 | 5 980 | **Time to end of secondary creep $t_{II}$, h** |
| 0.68 | 0.70 | 0.74 | **Share of $t_{II}$ in $t_r$, $t_{II}/t_r$** |

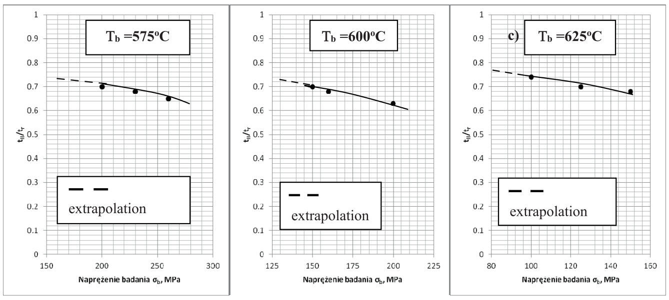

Fig. 6. Share of secondary creep $t_{II}$ in life time tr depending on test creep level at constant test temperature a) $T_b$=575°C, b)$T_b$=600°C, c)$T_b$=625°C for VM12 steel based on creep tests with elongation measurement during testing

The obtained results of creep tests for constant temperature levels $T_b$ and cyclically changed stress level $\sigma_b$ for VM12 steel are presented in Fig. 7 for $T_b$=625°C, respectively, and of tests carried out at constant stress level $\sigma_b$ and cyclically changed test temperature $T_b$ – in Fig. 8 for $\sigma_b$ = 150 MPa.

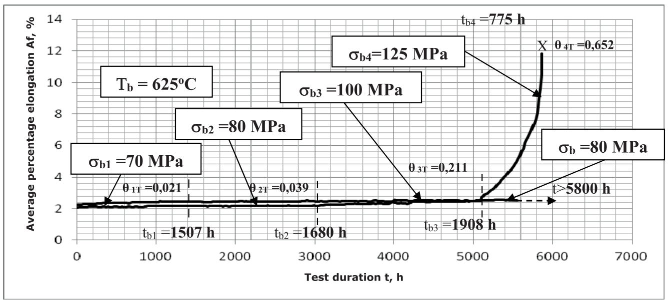

Fig. 7. Comparison of results of creep test with elongation measurement during testing in the form of creep curves $\varepsilon$ = f($t$) for various periodically changed levels of test stress $\sigma_b$ at constant test temperature $T_b$ = 625°C to creep test conducted at constant temperature and stress parameters ($\sigma_b$ = 80 MPa; $T_b$ = 625°C) for VM12 steel

The share of Robinson life-time fractures in creep tests carried out for this steel at constant temperature $T_b$=600°C and 625°C and cyclically changed stress level $\sigma_b$ are summarised in Tables 6 and 7, respectively, and of tests carried out at constant stress $\sigma_b$ = 150 MPa and cyclically changed test temperature $T_b$ – in Table 8.

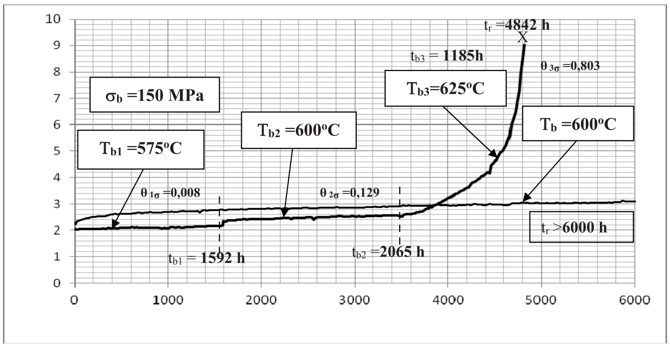

Fig. 8. Comparison of results of creep test with elongation measurement during testing in the form of creep curves $\varepsilon = f(t)$ for different cyclically changed test temperature levels $T_b$ at constant test stress level $\sigma_b$ = 150MPa to creep test conducted at constant temperature and stress parameters ($\sigma_b$ = 150 MPa; $T_b$ = 575°C) for VM12 steel

TABLE 7

Share of Robinson life-time fractures in creep test for VM12 steel conducted at constant temperature $T_b$=625°C and cyclically changed stress level $\sigma_b$

| **Test temperature Tb=625°C** | | | | **VM12** | |
|---|---|---|---|---|---|
| **i** | **$\sigma_{bi}$T, MPa** | **$t_{rbi}$ to L-M, hours** | **$t_{bi}$, hours** | **$t_b$, hours** | **$\Theta_{iT}$ ($t_{bi}$/ $t_{rbi}$)** |
| 1 | 70 | 71 764 | 1 507 | up to 1 507 | **0.021** |
| 2 | 80 | 43 571 | 1 680 | from 1 507 to 3 187 | **0.039** |
| 3 | 100 | 9 055 | 1 908 | from 3 187 to 5095 | **0.211** |
| 4 | 125 | 1 189 | 775 | from 5095 to 5 870 | **0.652** |
| Total: | | | | | **0.923** |

TABLE 8

Share of Robinson life-time fractures in creep test for VM12 steel conducted at constant stress level $\sigma_b$=150 MPa and cyclically changed temperature $T_b$

| | | | | | |
|---|---|---|---|---|---|
| **Test stress $\sigma_b$=150 MPa** | | | | **VM12** | |
| **i** | **$T_{bi\sigma}$, °C** | **$t_{rbi}$ to L-M, hours** | **$t_{bi}$, hours** | **$t_b$, hours** | **$\Theta_{i\sigma}$ ($t_{bi}$/ $t_{rbi}$)** |
| 1 | 575 | 200 394 | 1 592 | up to 1 592 | **0.008** |
| 2 | 600 | 16 033 | 2 065 | from 1 592 to 3 657 | **0.129** |
| 3 | 625 | 1 476 | 1 185 | from 3 657 to 4 842 | **0.803** |
| Total: | | | | | **0.940** |

where:

*i* – number of test stress degrees $\sigma_{biT}$ corresponding to constant test temperature $T_b$,

$\sigma_{biT}$ – stress corresponding to the ith degree for test conducted at constant test temperature $T_b$,

$t_{bi}$ – test time at the ith stress level at constant test temperature $T_b$,

$t_{rbi}$ – time to rupture of tested steel for $\sigma_{biT}$ at test temperature $T_b$ based on determined parametric Larson-Miller average temporary creep strength curve,

$t_b$ – time of testing at constant temperature $T_b$,

$\Theta_{iT}$ – relationship between the time $t_{bi}$ of applied ith test stress $\sigma_{biT}$ during the test and time to rupture $t_{rbi}$

The obtained sum of life-time fractures in steel tests is between 0.900 and 1.000. Values different than 1 are the result of adopted times to rupture for individual temperature and stress parameters from the parametric average temporary creep strength curve.

Thus, the use of this method is useful when preliminary condition assessment of critical boiler elements operating under creep conditions is made based on the real values of basic performance parameters recorded on-line. However, for safety reasons the remaining time of operation for declared further service parameters should be determined in relation to the sum of life-time fractures equal to 0.95, not 1.

TABLE 9

Creep limit 1% for 10, 30 and 100 thousand hours for VM12 depending on test temperature $T_b$

| **VM12 steel** | **Test temperature $T_b$, °C** | | |
|---|---|---|---|
| **Creep limit, MPa** | **575** | **600** | **625** |
| $R_{1/10\,000}$ | $156^{1)}$ | $115^{1)}$ | $85^{1)}$ |
| $R_{1/30\,000}$ | $112^{1)}$ | $83^{1)}$ | $62^{1)}$ |
| $R_{1/100\,000}$ | $68^{1)}$ | $50^{1)}$ | $35^{1)}$ |

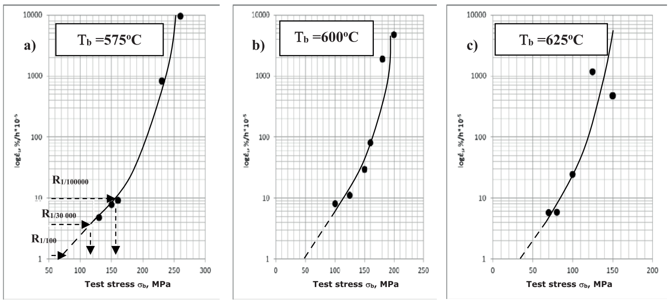

Fig. 9. Steady-state creep rate $\dot{\varepsilon}_s$ as a function of test stress level σ at constant test temperature Tb of VM12 steel: a) at $T_b$=575˚C; b) at $T_b$=600˚C; c) at $T_b$=625˚C

Based on the results of the test with elongation measurement during testing obtained for selected test temperature and stress parameters ($\sigma_b$, $T_b$) from recorded creep curves in the form of relationship $\varepsilon = f(t)$ at constant stress, the creep rate was determined too. It is the tangent of the inclination angle of determined steady-state creep curve. To determine the creep rate for present test stress level $\sigma_b$ at test temperature $T_b$, the time between approx. 1000 and approx. 3000 hours, depending on test parameters, was assumed as sufficient test duration. The determined creep rates allowed the relationship between creep rate εs and test stress level $\sigma_b$ at constant test temperature $\boldsymbol{T_b}$ (log $\varepsilon_s$=f($\sigma_b$) at $T_b$=const.) to be constructed. Built in this way, the graphic characteristics of changes in steady-state creep rates $\varepsilon_s$ depending on stress level at constant temperature $T_b$ for VM12 steel at $T_b$=575, 600 and 625°C are presented in Fig. 9. Based on prepared characteristics, the forecast creep limit of 1% for 10 000, 30 000 and 100 000 hours was determined for selected test temperature levels. The forecast creep limit $R_{1/10000}$, $R_{1/30000}$ and $R_{1/100000}$ for VM12 steel at $T_b$=575, 600 and 625°C is presented in Table 9.

## 4. Summary

The literature review and own investigations on VM12 austenitic steel for critical elements of boiler in the form of steam superheater coils have allowed the following conclusions to be formulated:

1. The time to end of secondary creep determined in creep tests with elongation measurement has a practical value, which is the disposable residual life tb. The disposable residual life is the maximum time of safe service.
2. The method for evaluation of exhaustion extent using the life-time fractures rule is useful in preliminary condition assessment of critical elements operating under creep conditions based on the real performance parameters recorded on-line. However, for safety reasons the remaining time of operation for the adopted further service parameters should be determined in relation to the sum of life-time fractures equal to 0.95, not 1.
3. The constructed characteristics in the form of relationship between creep rate and stress level at constant test temperature (log $\varepsilon_s = f(\sigma_b)$ at $T_b$=const.) allow the forecast creep limit of $R_{1/10000}$, $R_{1/30000}$ and $R_{1/100000}$ at 575, 600 and 625°C to be determined.

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