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Weld Behavior of Martensitic Steels and Ni-based Alloys for High Temperature Components

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Abstract

High efficient steam power plants are being designed to operate at temperatures higher than 700°C and pressure up to 350 bar. Due to this increase of the steam parameters Ni-based alloys are required for the realization of the plants. However, modern martensitic steels and their welded joints can also be consideded in these new high efficient power plants at locations where the temperature is below 700°C . This paper describes the investigations on the behaviour of components made of Ni-based Alloy 617 mod. and ferritic / martensitic steels T24, T/P92 and VM12; the materials currently being considered for these plants. Results of basic qualification programs with standard specimens including welded joints show the suitability of these materials for the intended applications. Beside results of creep rupture tests of base materials and welded joints, Weld Strength Factors (WSF) are also discussed in this paper. Microstructural investigations to obtain information on precipitation and dislocation state in the virgin and aged conditions are also presented.

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Keywords: Martensitic steel; alloy 617: weldment: creep; WSF

1. Introduction

For future coal fired steam power plants, a more resource-saving application is possible by use of new technologies providing a significant increase of efficiency and thereby a considerable reduction of pollution. These new technologies are primarily based on increase of the steam parameters, pressure and temperature. Materials used up to now in coal fired power plants are not appropriate; hence the use of nickel based alloys has to be intensified in the future plants. Increase in temperature sets considerable demands on proof of long-term stability, corrosion/oxidation resistance, strength and ductility of the structural materials. Moreover the state of the material in the component e.g. in welded joints or cold formed tubes has also to be considered. Programs currently running for material optimisation for 700°C power plants [1, 2] put their focus on the provision of technology for future high performance power plants. The critical components of boilers for the

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700 °C technology are the membrane and furnace walls, the final superheater and reheater stages, boiler tubes (hot sections), in- and outlet headers (hot sections) as well as the thick-walled components, mainly the high-pressure outlet headers and the piping to the turbine. The materials currently being proposed and and under extensive chacterisation for the boiler components future power plants are summarized in Table 1 along with their chemical compositions.

Table.1. Chemical composition of materials for power plant components.

Material	C	Cr	Mo	W	Ti	Co	Others	Material application limit
2 – 2.5 % Cr -steels:								
T24	0.05 - 0.10	2.2 - 2.6	0.9 - 1.1	-	0.05 - 0.10	-	V, N, B	540 ℃
9 – 12 % Cr -steels:								
T92	0.07 - 0.13	8.5 - 9.5	0.3 - 0.6	1.5 - 2.0	-	-	V, Nb, N, B	580℃ -600℃
P92	0.07 - 0.13	8.5 - 9.5	0.3 - 0.6	1.5 - 2.0	-	-	V, Nb, N, B	625℃
VM12	0.10 - 0.14	11.0 - 12.0	0.2 - 0.4	1.3 - 1.7	-	1.4 - 1.8	V, Nb, N, B	580℃ -600℃
Ni-based alloys:								
Alloy 617 mod.	0.05 - 0.08	21.0 - 23.0	8.0 - 10.0	-	0.3 - 0.5	11.0 - 13.0	Ni, Al, Cu, N, B	750 ℃
Alloy 740	0.03	25.0	0.50	-	1.8	20.0	Ni, Al, Nb	770℃
Alloy 263	0.04 – 0.08	19.0 – 21.0	5.6 – 6.1	-	1.9 - 2.4	19.0 – 21.0	Ni, Al, Ti, Cu, B	735℃

2. Ferritic / Martensitic steels

Special consideration of welded joints is needed for this material since the heat affected zone (HAZ) formed as a result of the heat input by the welding shows different properties, especially the creep behaviour is different from those of base material and weld metal. The welding of the martensitic steels can cause major problems in service due to the formation of a heat affected zone with low creep resistance (fine grained or intercritical zone). It represents the weakest link in weldments and can lead to premature failure of the component.

For the temperature field between 490 °C and 535 °C of the 700/720 °C high efficient power plant the bainitic steel *T/P24 (7CrMoVTiB10-10)* is considered so far. The typical fields of application for T/P24 steel are membrane water walls, superheaters and reheaters. To increase the creep rupture strength V, Ti and N was added to form carbides, nitrides and/or carbonitrides (type MX) and cause fine precipitations in the matrix. After welding there was originally no need of post-weld heat treatment (PWHT) [3], but nowadays this subject is more and more in discussion. In [4] and [5] it is recommended to perform PWHT for T/P24 only for thick-walled components. However, extensive studies of the manufacturability and weldability including cold bending and determination of Charpy impact values for base and weld material as well as heat affected zones show acceptable results [6]. In Fig. 1 the results of creep rupture tests of base material, crossweld specimens (TIG) and weld metal specimens at main test temperature 525°C are shown. It can be seen, that the base material is in the upper range of the scatterband. The creep rupture of pure TIG-weld metal is partially under the lower scatterband limit. It should be noted that in the weld metal for T24 Ti (as in this investigation) is now replaced by Nb. The crossweld specimens are all in the scatterband of the base material. These welds were produced without heat treatment. For comparison, results from the project AVIF A129 are also shown [6] in the figure. After the change of fracture location from BM to HAZ, which occurs earlier for the specimens with heat treatment, a decrease in the scatterband limit can be seen. The creep rupture time of welds without PWHT is slightly higher.

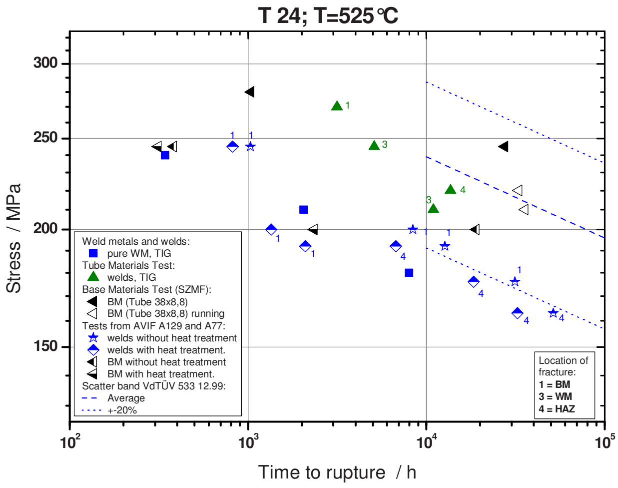

Fig. 1. Creep rupture behavior of T24-steel and their welded joints at T=525°C.

An increase in creep strength of *9 – 12 wt.% Cr-steels* is realized by reducing the amount of molybdenum and the addition of boron and tungsten and additionally a precise adjustment of the carbon content. With this improved properties the martensitic steel P/T92 turned into an interesting material for boiler and tubing components for temperatures up to 625 °C. But the development of these modern steels cannot be considered to be completed at present. There is still potential to increase creep strength and improve oxidation behaviour[7]. The big challenge is the determination of the ideal chromium content. In order to improve the oxidation behaviour the 12 % Cr steel VM12 was developed. The creep properties of this material turned out to be slightly lower than that of P92 [8, 9] but still shows rupture times around the scatterband of the 9%Cr steel E911. Its excellent oxidation properties ,make this 12%Cr steel a strong candidate material for boiler components. The results of creep rupture tests of base material, crossweld specimens and weld metal specimens for T/P92 at main test temperature 625°C are shown in Fig. 2. All creep test results on base material including that from specimens taken from an inductive bend are near the mean value for P92. At lower stresses a decrease of creep rupture strength of crossweld specimens was observed. In these experiments, the fracture occurs in the heat affected zone. This is in coincidence with other findings and the reason for investigations on optimisation of chemical composition to avoid a decrease in creep rupture strength due to the formation of a weak heat affected zone [10]. The SMAW-welded joints are also within the lower scatterband limits. Only the experiment performed at 95 MPa is below this limit. The fracture locations are in the heat affected zone and partly in the weld metal.

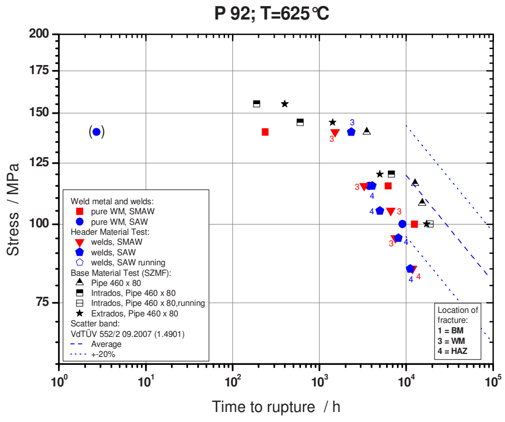

Fig. 2. Creep rupture behavior of P92-steel and his welded joints at T=625°C.

In Figure 3 the results of creep rupture tests of the material VM12/VM12-SHC at 625°C are shown. In addition, the scatterband of the 9% Cr steels E911 according to ECCC at 625°C is given. VdTÜV-sheet values for VM12 exist only up to 600°C. The VM12 has a nearly identical creep strength like E911 steel. At 625°C the tests on base material (pipe and tube) are all within ± 20% scatterband limits of the E911 material. The SMAW- and SAW-welded specimens from pure weld metal are located in the lower scatterband. The crossweld specimens from the pipe (SMAW and SAW), and the tube (TIG) show, after occurring change of fracture position (5,000 h duration), a significant decrease of creep strength.

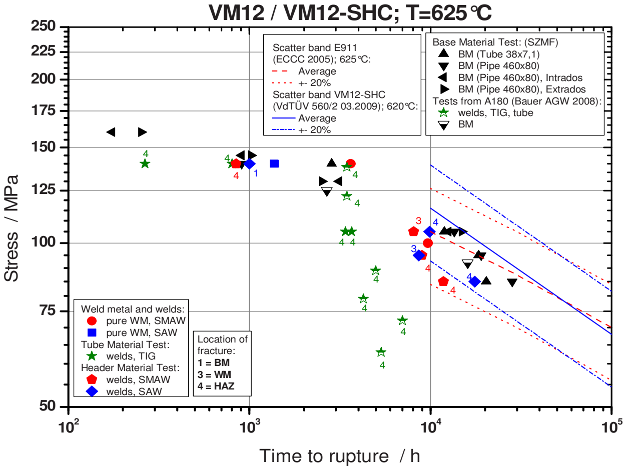

Fig. 3. Creep rupture behavior of VM12-steel and their welded joints at T=625°C

3. Modified nickel-based Alloy 617.

Due to their excellent corrosion resistance and creep properties at high temperatures nickel base alloys are currently applied in combustion chambers of turbines, high-temperature heat exchangers and high-temperature gas-cooled reactors. However, the reported properties make these materials for a usage in boiler components of a fossil fired power plant at temperatures above 625 °C as well. For this field of application the nickel base alloy Alloy 617 (type NiCr22Co12Mo) is of special interest. This alloy is a solid-solution strengthened and carbide-hardened material. It is characterized by high resistance and creep properties and a good resistance against carbonisation as well as oxidation resistance at temperatures up to 1100 °C. For Alloy 617 mod. a reasonably good long term data base exists for base material and welded joints of tubes and pipes obtained by crossweld tests [1, 11-13]. In Fig. 4 the results of creep rupture tests on base material Alloy 617 mod. and its welded joints at 700°C are shown [12]. In addition, the scatterband estimated from the data available from project MARCKO-DE2 [1] is also given. The creep ruptures of the different pure weld metal specimens differ. The results of pure TIG-weld metal are located almost in the middle of the scatterband, the results of pure SMAW- weld metal are in the lower scatterband range. The creep rupture of the SAW-weld metal, persumably due to the melting loss of aluminium, is below the scatterband. The results of the crossweld specimens are generally within the scatterband. The results for the alternative technique used v-TIGp (orbital) are also within the scatterband, these scatter however strong. For comparison, the base material specimens were prepared from a thick-walled tube. The tests are both in the upper area of the scatterband. A last, still ongoing test, exceeded the average scatterband already. Despite very good high temperature properties nickel based materials tend to generate hot cracking during or immediately after welding in the weld metal and/or in the heat affected zone.

In Fig. 5 the micrograph of a crossweld specimen from a welded pipe made of Alloy 617 mod ruptured after long term creep (26,700 h at 700°C/140 MPa) is shown. Different zones of the specimen are shown: base material, heat effected zone and weld metal. The crack appeared in the weld metal, formation of creep cavities on grain boundaries could be observed in HAZ, near the fusion line, perpendicular to the direction of loading.

In the weld metal, interdendritic cavities are visible but also cavity chains and micro cracks. Grain boundaries are covered with precipitates. The hardness increases from about 210HV10 in as-received condition to 270 HV10 (BM) and 286 (HAZ). In WM the hardness is 345 HV10. Due to different kinetics of precipitations on grain boundaries and within the grain, the TEM investigations were performed on these both positions, Fig. 5.

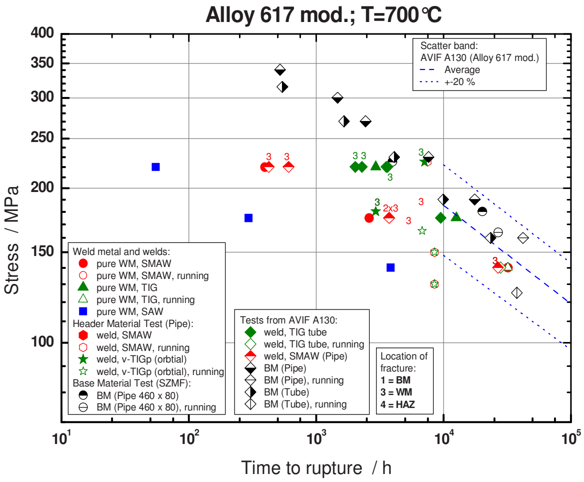

Fig. 4. Creep rupture behavior of Alloy 617 and their welded joints at T=700°C

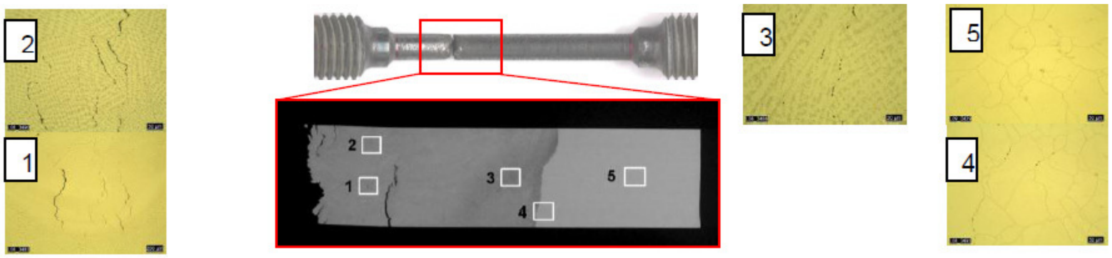

Fig. 5. Uniaxial creep rupture specimen (crossweld) after creep, Alloy 617 mod. (pipe).

The microstructural investigations for the material conditions of the pipe and also the tube made of nickel-based Alloy 617 mod. can be summarized as follows (Fig. 6): in the initial state $M_{23}C_6$ precipitates occur within the grain and at the grain boundaries, in the tube only at the grain boundaries. Dislocation density, particle size and number of $M_{23}C_6$ precipitates within the grain are increasing with time. The number of $M_{23}C_6$ precipitates at the grain boundaries decreases with time, their size is increasing. The dislocation density in the shank of the specimens after creep are over the double that of the initial state for both product forms (tube and pipe). Furthermore, after creep γ' phase and M_6C particles were identified. This could clearly be identified using diffraction pattern and EDX analysis. In weld metal γ’ phase is large (112 nm) compared to those present in the base metal. For the pipe specimen size of γ’ phase is about 90 nm and 60-70 nm for the tube specimen. Size of γ’ phase did not vary much between the head and guage porton of the creep sepcimen, respectively of aged and crept state. In the pipe-weld only able M_6C particles are found. $M_{23}C_6$ could not be detected. The dislocation density is highest in weld metal (pipe) with $11.8 \pm 3.8 \cdot 10^9 cm^{-2}$.

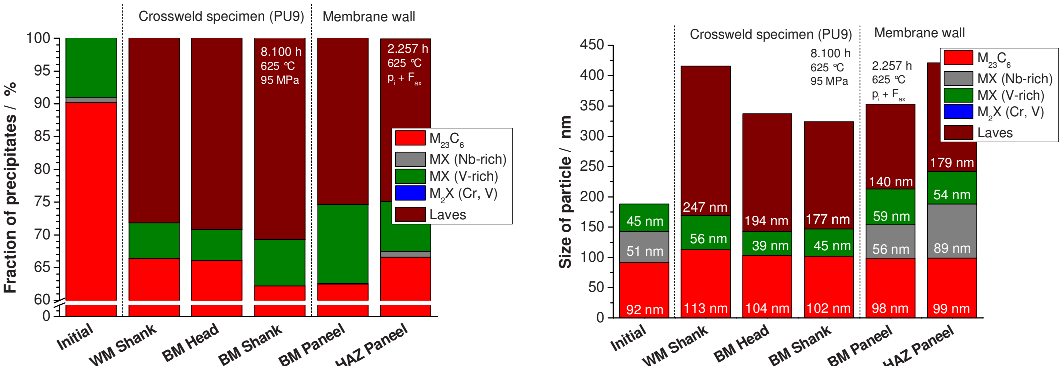

Fig. 6. a) Number and b) size of particles in Alloy 617 mod. in initial condition state and after creep (Grain- within the grain; GB- grain boundary).

4. Weld strength factors (WSFs)

The weld strength factor is defined as the relationship of creep rupture strength of the welded joint divided by the creep rupture strength of the parent material. Fig. 7 shows weld strength factors for 100.000 h creep rupture strength for different materials. Especially the martensitic steels show a strong influence due to their complex microstructure and their specific heat treatment. Whether these factors, obtained from small scale specimen with loading direction perpendicular to the welding direction, can be transferred to components is under detailed investigation at the moment. Results of recent crossweld tests for different materials are compared with weld strength factors evaluated for 100,000 h in [14-16]. For martensitic steels the scatterband of test results is in reasonable agreement with the values given for 100,000 h. However, here it has to be noted, that the scatterband is based on tests from crossweld tests with rupture times ranging from 10,000 h to 50,000 h. For the martensitic steels the value given in 0 is fully confirmed, in principle this is also the case for the bainitic steel T24, even if for these materials the scatterband is around the given value. For Alloy 617 mod. the scatterband is around the proposed WSF of 0.85.

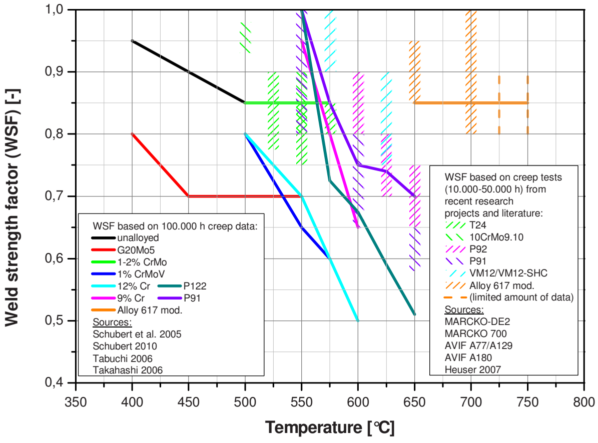

Fig. 7. Weld strength factors for 100.000 h creep rupture strength [14-16] and comparison with recent results from research projects and literature on the basis of creep tests (rupture times 10,000 h to 50,000 h).

5. Summary

Based on experiences with field tests and couple of research projects the development of power plants with 700°C technology is well under way. Design and material needs are described and the requirements for all materials used are outlined. These materials are ranging from low alloyed T24 to martensitic and austentitic steels, finally Ni-based alloys are needed. Extensive qualification programs are under way and with the first results, production of components using Ni base alloys and weldability of these alloys could be demonstrated. Alloy 617 mod., thanks to good mechanical properties and oxidation resistance, has great potential to be employed at operating temperatures over 700°C as components like pipes, membrane walls etc. However, special effects such as e.g. inverse creep, dynamic strain aging or the tendency for creep crack embrittlement and the danger of the formation of not only hot cracks but also relaxation cracks during annealing can complicate the application and therefore have to be checked more intensively. Extensive creep data on welds have been generated on welds of 617. From intensive microstructural investigations a database is going to arise which can be used for the optimisation of weldments and the evaluation with regard to lifetime by findings on the change in precipitation and dislocation structure.

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