Basic Aspects of the Weldability of 9-10% Cr-Steels for Advanced Power Generation

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ABSTRACT

There are strong environmental and economic demands to increase the thermal efficiency of fossil fuel fired power stations, and this has led to a steady increase in steam temperatures and pressures resulting in worldwide plans for ultra-supercritical power plants. Modern life martensitic 9-10% Cr-steels are used widely to fulfil the requirements resulting from the design aspects.

Basic investigations on the weldability of modern 9-10% Cr creep resistant steels which are presently in use and planned to fulfil this requirement were performed on pipes P91, E911 and a W-containing cast steel G-X 12 CrMo WVNbN 10 1 1. Gleeble simulation representing the manual metal arc welding process were applied to produce HAZ-simulated microstructures. After different post weld heat treatments they were tested using hardness tests, metallographic investigations, constant strain rate tests, creep and toughness tests.Main attention was given to the softening effect in the HAZ and its influence on the creep resistance of the welded material. This decrease shown by simulated and manufacturing welded samples, seems to be less pronounced of the W-modified versions than observed at P91 material.

INTRODUCTION

There is a substantial and growing interest in operating thermal power plants at relatively high temperatures and /or pressures for improving thermal efficiency that bring lower CO_2 emission. Materials with ferritic/martensitic microstructure are preferred, because of their favourable physical properties such as good thermal conductivity and low coefficient of thermal expansion, coupled with higher resistance to thermal shock (1, 2). These are some of the advantages relative to austenitic stainless steels. For these reasons, there has been a growing demand for high-strength, high-chromium ferritic steel, which has resulted in the development and application of several kinds of 9 to 12%

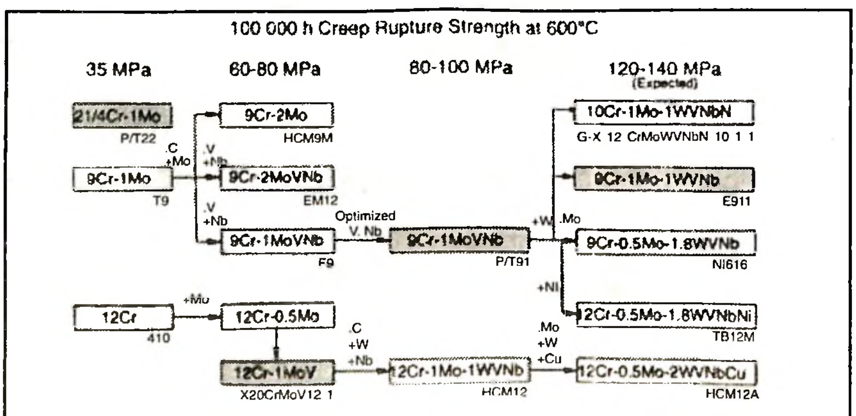

Fig. 1 : Development progress of 9-12% Cr creep resistant steels, (3)

Table I : Chemical composition in wt. - % of materials investigated.

Material	C	Si	Mn	P	S	Cr	Ni	Mo	W	V	Nb	N
X 10 CrMo VNb 9 1 (P91)	0,099	0,385	0,40	0,017	0,004	8,75	0,128	0,96	0,03	0,204	0,07	0,058
E 911	0,11	0,18	0,40	0,015	0,003	8,61	0,21	0,92	0,99	0,19	0,089	0,065
G-X 12 CrMoW VNb 10 1 1	0,12	0,29	0,62	0,027	0,003	10,51	0,93	0,99	0,99	0,22	0,08	0,048
Cromocord 10M	0,09	0,24	1,00	0,012	0,007	9,60	0,9	1,05	1,03	0,2	0,06	0,05

chromium steels. The development of these materials as a function of the 100.000 hours creep rupture strength at 600°C can be seen from Fig 1 (3). The main steps in the development are different in various countries, such as in the US, the European nations and Japan. In Europe, particularly in Germany the gap between the application range of the ferritic steel P22, German designation 10 CrMo 9 10, and the austenitic stainless steels regarding their creep resistance were successfully bridged in the past by using the 12% chromium steel X20 CrMo V 12 1 (4). Since 1975 a new modified 9% chromium steel has been developed in the US under the leadership of ORNL and standardised i.e. as P91 in ASTM A 335, (German designation X10 CrMo V Nb 9 1) in the early 1980's This development led to the application of tungsten containing 9-12% chromium steels, which showed higher creep resistance, compared to the type P91.

Within the framework of the European COST 501 programme (Development of Materials for Advanced Steam Cycles [5]) a cast version of a tungsten modified 10% Cr-steel for castings and later a 9% Cr version for pipes and forging, called E911, was designed to fulfil the increased demands on the creep strength for advanced design values for fossil fired power plants.

For a successful service application and acceptance in practice, the weldability and the long time behaviour of the newly developed materials is one of the most important aspects. The creep rupture strengths of the parent materials P91 and X20 CrMo V 12 1 are compared to the creep rupture strengths of cross welds specimens (1). It can be observed, that the creep rupture strength of cross weld samples is at higher temperature remarkably lower than that of the base material.

EXPERIMENTAL PROCEDURE

Investigated Materials

As for the material P91, the investigations for the study were performed on a seamless pipe, produced by pilgermill rolling process, dimension 149 mm outside diameter and 20 mm wall thickness. The newly developed COST steel E911, comes from Mannesmannrohren- Werke, Germany. The tests were realised on a seamless pipe with 336mm outside diameter and 62mm wall thickness. For the casting material G-X 12 CrMoWVNbN 10 1 1, the material investigated comes from the valve body trial casting produced by Georg Fischer Schaffhausen, Switzerland. The manufacturing weld was carried out by Voest Alpine Stahl Linz Foundry, Austria, in the framework of COST 501 Round II. As for the welding rod, Cromocord 10M produced by Oerlikon Welding Ltd., Switzerland, was used. Table I shows the chemical composition of the materials investigated.

HEAT-AFFECTED ZONE - SIMULATION

The different microstructures appearing in the heat-affected zone (HAZ) of fusion welds show different properties, depending on their thermal history (6). The simulation of weld thermal cycles is a powerful method to investigate HAZ-microstructures. Compared to the HAZ-microstructure of real joints, simulated microstructures can be produced in relatively large volumes. This leads to a transparent variation of welding parameters and helps to reduce scatter in testing results which is caused by inhomogeneities in real welded microstructures. Effects of local gradients in microstructure, properties and residual stresses are not taken into account when using HAZ simulation technique.

For simulation a GLEEBLE 1500 machine was used. The weld thermal cycles which are needed as input for the simulation process were calculated from D.Rosenthal's solution of Fourier's heat conduction equation in a simplified version derived by N.N.Rykalin (7). These equations allow the representation of the weld thermal cycles by the cooling times between two temperatures (respectively the cooling time between 800°C and 500°C -$t_{8/5}$), the peak temperature (Tp), the preheat temperature and the plate thickness. For this investigation the thermal cycles applied were selected to represent a manual shielded metal arc welding process with heat input of 225°C kJ/cm and a preheat temperature of 225°C. These conditions led to a corresponding cooling time between 800°C and 500°C of 21,6 seconds, see figure 2 (8).

INVESTIGATIONS ON HAZ-SIMULATED AND WELDED MATERIALS

Using real welds from material P91, E911 and G-X 12 CrMoWVNbN 10 1 1, metallographic investigations, hardness tests and creep rupture tests were performed. The results of P91 investigation were presented in (1), the results of cast steel investigation were summarised in (5). Concerning Gleeble HAZ-simulated samples from material P91, E911 and G-X 12 CrMoWVNbN 10 1 1 special attention was given to the evaluation of the soft zones in the HAZ by metallographic investigations, using light microscopy and TEM, hardness tests, toughness tests as well as constant strain rate tests. Additionally, creep rupture tests were performed to investigate the creep strength behaviour of the soft zone at the HAZ region.

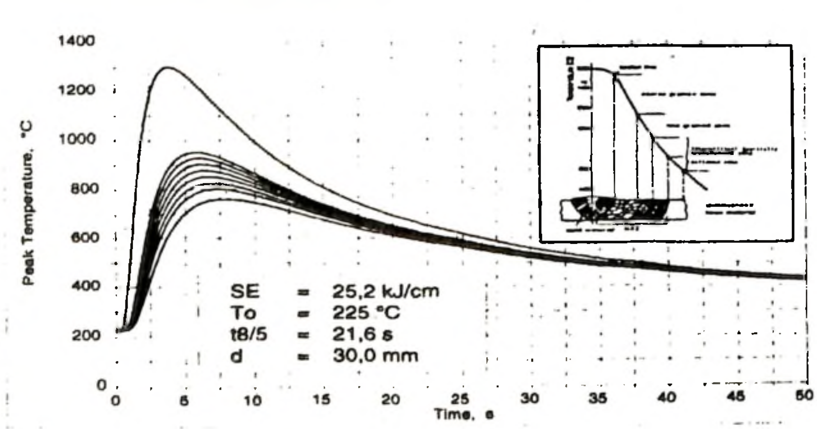

Fig. 2 : Thermal cycles calculated for various peak temperatures between 1300°C and 760°C (SE...heat input, To....preheat temperature, $t_{8/5}$....cooling time between 800°C and 500°C, d...wall thickness), (8).

RESULTS AND DISCUSSION

Hardness

In hardness tests across a weld seam of material P91, it can be observed that these types of steel show a tendency to form a soft zone in the fine grain HAZ after post weld heat treatment (PWHT), figure 3. The hardness in the zones was found to be = $20HV_{10}$ lower than that of the unaffected base material. The hardness profile across a weld seam of E911 and G-X 12 CrMoWVNbN 10 1 1 show a similar curve to that of P91, Figure 3. To define the zone in which maximum softening occurs, specimens were subjected to HAZ-simulation at different peak temperatures in the range between 760°C and 950°C according to figure 2. The hardness was tested in the "as welded", simulated and in the simulated and tempered condition. The tempering conditions after welding were 750°C/2h air cooled for P91, respectively 760°C/2h for E911 and 730°C/12h for material G-X 12 CrMoWVNbN 10 1 1.

The results of the hardness tests performed on the weld simulated microstructures of the three

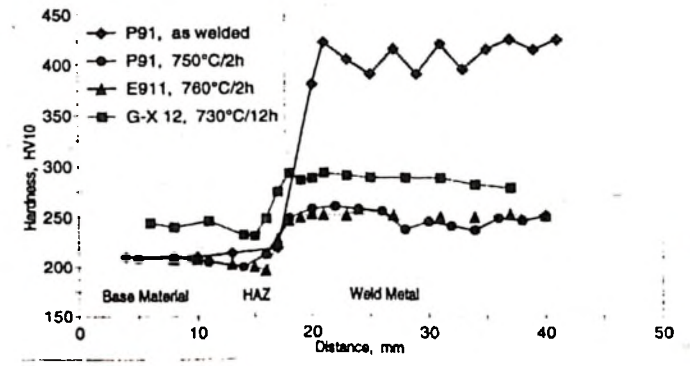

Fig. 3 : Hardness of weld seam in as-welded condition and after various post-weld heat treatments of P91, E911 and G-X 12 CrMoWVNbN 10 1 1, (1,5)

materials are presented in figure 4 as a function of the peak temperature for both tempered and "as welded", condition. The hardness of the base materials tested is shown on the left side of the diagram figure 4. It is not influenced by thermal cycles with peak temperatures up to about 850°C. The beginning a/g-transformation as a function of heat cycles can be observed by the increase of hardness in the "as-welded" condition. After stress relieving, the hardening effect disappears in the materials as can be observed from figure 4. In the range of peak temperatures between 900°C and 950°C in the materials, a minimum hardness can be observed. The hardness here is about 10 HV_{10} lower than the remaining values.

CONSTANT STRAIN RATE TESTS ON HAZ-SIMULATED MATERIALS

Constant strain rate tests at 600°C using a constant strain rate of $e = 10^{-5}\ s^{-1}$ were applied on specimens which have been subjected to HAZ-simulation and subsequent tempering to investigate the principal influence of the HAZ-softening effect on the creep resistance. This test method was first applied on this type of steel in (9). The maximum stress gives indications on the creep resistance of the microstructures tested. The results of these tests, performed at 600°C applied on microstructures, produced by weld simulation with different peak temperatures, are shown in figure 5. For the unaffected base material P91 a maximum stress of 280 MPa and for G-X 12 CrMoWVNbN 10 1 1 a stress of 260 MPa was measured. For peak temperatures in the range of 875 to 920°C, there is a significant decrease in the maximum stress, analogous with the decrease in hardness. The minimum in the stress versus peak temperature curve is for the material P91 at 250 MPa and 920°C, for the material G-X 12 CrMoWVNbN 10

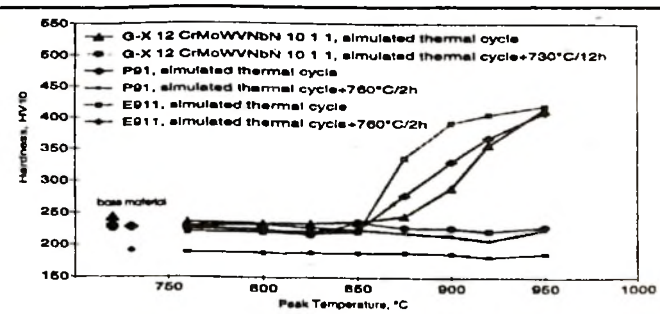

Fig. 4 : Results of hardness measurements on specimens of P91, E911 and G-X 12 CrMoWVNbN 10 1 1 subjected to weld thermal cycle simulation treatments (softening behaviour of HAZ)

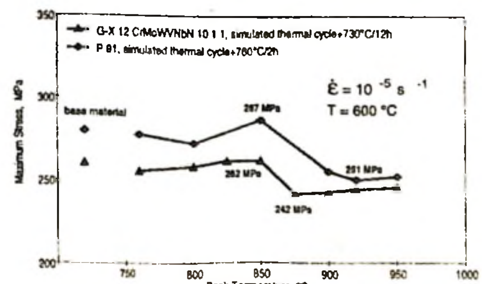

Fig. 5 : Results of constant strain rate tests on specimens of P91 and G-X 12 CrMoWVNbN 10 1 1 subjected to weld thermal cycle simulation treatment followed by tempering (HAZ-softening)

1 1 at 240 Mpa and 875°C. The measured minimum of stress is about 10% lower than that measured for the unaffected base material. The investigation of material E911 is in progress.

Toughness Tests

For the investigation of the toughness behaviour in the different areas of the heat-affected zones of welded material P91 and G-X 12 CrMoWVNbN 10 1 1 toughness tests on HAZ-simulated microstructures using Charpy V-notch samples were performed. The HAZ-simulations were applied according to the heat cycles described in figure 2, using peak temperatures of 1300°C, representing a coarse grain region of the HAZ and a double cycle with a peak temperature of 1300°C followed by a second thermal cycle with a peak temperature of 900°C. This double cycle represents a fine grain transformation of a coarse grain, which can occur in the multilayer welding.

For the optimisation of the influence of PWHT different annealing conditions were selected and are described in the figs. 6 and 7.

Figure 6 shows the Charpy V-notch toughness as a function of testing temperature for the different HAZ microstructures and PWHT conditions for the material P91. Figure 7 shows the toughness behaviour in the HAZ of the cast material G-X 12 CrMoWVNbN 10 1 1. In all investigations, the toughness of the unaffected base material is plotted for comparison. As can be seen from these diagrams, the toughness behaviour of HAZ weld simulated microstructures, can in these kinds of steels be expected in about the same level as those of the base materials, when the HAZ microstructures will be annealed after welding. Although, the wrought material P91 shows a much higher basic toughness compared to the cast material G-X 12 CrMoWVNbN 10 1 1. The influence of the thermal cycles caused by welding on the microstructure and on the toughness is similar. The lower level of toughness observed in the casting material is mainly the result of the different grain size and the presence of a certain amount of "Delta-Ferrite" in the microstructure in the casting. Improvements in optimising the chemical analysis have been applied in the meantime to successfully enhance the toughness level. Therefore it can be expected from this investigation, that the toughness level in the heat-affected zone will also increase when the toughness level of the base material is improved.

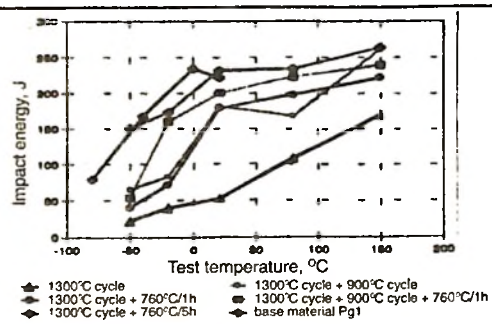

Fig. 6 : Material P91, Charpy V-notch toughness of simulated heat-affected zone (cooling time $t_{8/5}$ = 22s), (9)

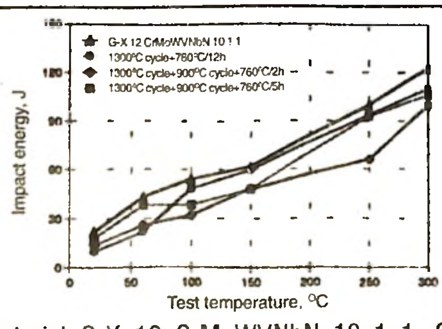

Fig. 7 : Material G-X 12 CrMoWVNbN 10 1 1, Charpy V-notch toughness of simulated heat-affected zone (cooling time $t_{8/5}$ =21s)

CREEP RUPTURE TESTS ON HAZ-SIMULATED MATERIALS

Creep rupture tests on samples which were designed to represent material containing microstructures caused by a peak temperature of 900°C to 920°C were performed. The results are

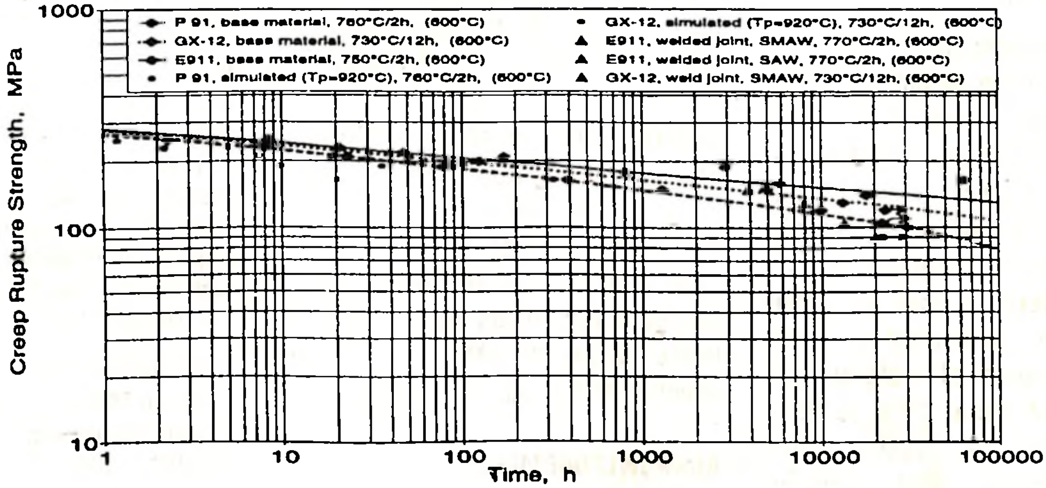

Fig. 8 : Results of creep rupture tests of P91, E911 and G-X 12 CrMoWVNbN 10 1 1 base material, welded joint and soft zone HAZ simulated materials (5)

shown in figure 8 and are compared with results obtained on creep samples made from uninfluenced base material and welded joints. As can be seen from figure 8 the creep resistance of plain HAZ simulated materials falls for all investigated materials, remarkably below the creep resistance of the uninfluenced base material. Comparing the behaviour of the material P91 to the material E911 and G-X 12 CrMoWVNbN 10 1 1 it can be revealed that the softening effect in the W-modified material in the creep behaviour, at high stress levels, is lower than that of material P91. Creep test of original welded and stress relieved samples of the cast steel show a similar curve.

Creep rupture tests on cross weld samples

The current status of the creep tests at 600°C with a testing time of 30.000 hours is shown in figure 8. The cast steel G-X 12 CrMoWVNbN 10 1 1 and pipe version E911 appears to have a creep strength which is at least as high as that of modified 9% CrMo steel P91. At high stress levels the fracture is located in the base material. As the applied stress decreases and the rupture time increases, the fracture location shifts near to the fine grain region in the HAZ. Microstructural investigation of broken creep rupture samples is shown in fig. 9.

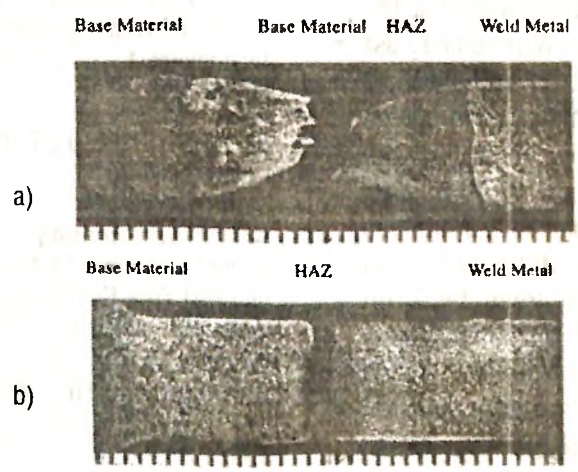

Fig. 9 : Fracture location at cross weld samples, G-X 12 CrMoWVNbN 10 1 1 / Cromocord 10M
a) (150 MPa, 600°C, 3.919h) b) (75 MPa, 600°C, 20.175h)

CONCLUSIONS

Previous investigations (1,9) have shown, that the weldability of the heat resistant material P91 can be described as very satisfactory. Although in a heat affected zone, a drop in the creep resistance can be observed. Compared to the base material a loss of creep resistance measured in cross weld samples of welded P91 material of about 20% to 25% have to be taken into account.Basic investigations using mainly the Gleeble HAZ-simulation tecnnique revealed that this drop in the creep resistance occurred in the fine grain area of the heat affected zone, where the peak temperature reached a level of about 900 to 950°C. The aim of this study was to investigate whether newly developed W-containing materials with higher creep resistance than P91 material show similar behaviour in the welded condition. The results obtained revealed that the behaviour of the W-modified cast material G-X 12 CrMoWVNbN 10 1 1 and pipe material E911 shows similar behaviour regarding the creep resistance in the heat-affected zone than P91. Hardness tests, constant strain rate tests and short time creep tests on HAZ-simulated microstructures showed that also in W-modified 9-10% Cr-steels creep resistant steels a drop of the creep strengths in the welded area has to be taken into account. The first results of HAZ-simulated short time creep tests showed that this drop is less than observed in P91 pipe material. At stresses lower than 150 MPa, the fracture location shifts from the base material into the softened fine grain HAZ, At 600°C the data points of the weldments are below those of the base material by more than 25%. In the design of welded components made from these types of materials, this effect must be taken into account.

ACKNOWLEDGEMENTS

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