

The Role of Welding in the Power Generation Industry*

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Abstract

Welding was in the past, is at present and will also be in the future the key fabrication technology for the realisation of production of electrical energy in power plants. The challenges coming from the power plant industry enforced the development of suitable materials and welding technologies. Examples of that developments, problems arisen and solutions evolved are given from the viewpoint of the author's experience for penstocks of hydro power stations, large components of water cooled nuclear power plants and advanced materials of USC thermal power stations.

Preface

Edouard Houdremont was a scientist and research manager of highest international stature. His name is indispensable in connection with the term of special steels. Aside of more than 100 publications, his "Handbuch der Sonderstahlkunde", first appeared in 1935, then 1943 and 1956 was for generations of metallurgists, material specialists and engineers "the bible" in materials science of steels. This was also valid for the personal experience of the author when he became a student of metallurgy at the University of Mining and Metallurgy in Leoben in 1958.

His CV is strongly connected with the history of the time when he lived:

Born in 1896 in Luxembourg, he studied metallurgy and mechanical engineering from 1916 to 1920 at the famous Faculty of Metallurgy at Berlin-Charlottenburg Technische Hochschule and received his Dr. Ing. in 1921 with honours. In the same year he joined Krefelder Stahlwerk AG which later became the Deutsche Edelstahlwerke AG and worked there in the field of physical-metallurgy developments. Because of his splendid performance, in 1926 he was invited to join Fried. Krupp AG, where he made an extraordinary career as researcher and also as research manager. His main scientific achievement was his contribution to the understanding and systematisation of the laws of interconnections between the manifold various steel properties and crystal and atomic structures on the one hand

and the thermal and mechanical treatments and alloying elements on the other hand. This approach is still valid today: the way from the empiric approaches to science based approaches which we try to understand nowadays by the use of modelling and simulation. Houdremont can be called as one of the pioneers of modern science of steels.

His career with Fried. Krupp was impressive: from assistant of steel production he became manager of a newly formed "center of steels" in 1932 and director of Krupp Forschungsanstalten in 1936. He became an international highly accepted expert in special steels and received a call as honorary professor at Aachen Technische Hochschule and gave lectures also at TH Berlin.

In 1941 he became deputy member of the Board of Directors, and in 1943 a full member of Krupp BoD. In this position he was, of course, heavily involved in the Krupp armament production during World War II but he tried as much as he could to distance himself from the political system. He stated in a letter to his college in Cambridge: "I must say that ...I include myself in believing that politics... are nothing for normal metallurgical brains".

His main scientific and technical concern was the development of so called "savings steels" with customized properties by minimizing rare and expensive alloying elements. An approach which nowadays has at least the same global importance as it had during WWII.

However, he was in his capacity as Krupp CEO, sentenced to prison by the Nuremberg War Criminal Court of 1948 and released in 1952.

From there on he involved himself in many technical and scientific, as well as cultural activities with great devotion. Because of his scientific competence as well as his outstanding personality, he was much respected in the national and international community and shared his knowledge and experience worldwide. He involved himself in the reconstruction of the German steel industry and German steel research which owes him great respect.

He was appointed Chairman in 1954 of IIW Commission IX "Behaviour of metals subjected to welding". In 1956 he was elected Vice-President of the IIW and as such played a prominent role in the 1957 Annual Assembly, among other things presiding at the Public Session on "Welding Metallurgy".

Professor Houdremont's career with the IIW illustrates his outstanding talents, not only as a materials scientist but also as a leader. He was a man of great charm and wide culture and his expert interest and enthusiasm were an inspiration to the young people whose work he encouraged and supported; these were not only metallurgists but also musicians, Professor Houdremont being himself an excellent violinist. He passed away in 1958 [1].

IIW respects and honours this outstanding personality by sponsoring the Houdremont Lecture. It is the greatest honour and also the summit of the professional career of the author to be appointed, to deliver this year the lecture in commemoration of this great man.

Introduction

The full availability of electric energy is today one of the basic requirements of civilized societies and a backbone of wealth and prosperity. Although, the use of industrial electric power generation is only about 100 years old, the development of this industry was in the past and is still extremely dynamic. While from beginning in the history of power generation small units with a capacity of several kilowatts were used, the increased demand of energy called for bigger units. As a consequence, the required larger components in general could only be realized by the use of joining methods like riveting and screwing of single parts together. The appearance of industrial usable welding processes finally made the successful development of the power industry possible and is the basis for their today's indispensable contribution for a better life of mankind.

On the other hand, the challenges coming from the power industry on materials science and welding technology enabled the breathtaking progress which in turn led to the appearance of suitable, safe, sustainable and economic materials and welding technologies and this development will definitely be continued in the future. Of course, these achievements have often been accompanied with some painful experiences. On the other hand, with learning the lessons properly, these failure cases contributed positively to the continuous evolution of materials and welding technologies for power generation.

IIW delivered essential contributions to those developments and progress and, most importantly, the dissemination of the expertise generated amongst the IIW members, which is the main goal of our IIW.

In the following sections, some representative examples of material developments in connection with welding and their impact on the fabrication and service behaviour of welded components for Hydro, Nuclear –and Thermal Power plants will be discussed.

Hydro Power

In the field of hydro power the application of welding

technology significantly enabled today's existing state of the art in this prominent and historically most important branch of power-generation. By the example of the component penstock and shafts the role of welding will be discussed. With increasing capacity and water head of the storage hydro power plants the demand for high strength steels also increased. Fig. 1 describes the development of the yield strength and steel grades used for penstocks and shafts in Europe in the last century [2].

Watergas welding

As the first penstocks had been riveted in the late 1920s welding appeared as the most appropriate fabrication method for the pipes. The so called Water-gas welding procedure developed by Mannesmann Röhrenwerke appeared and was widely used. During and after WWII arc welding processes were introduced progressively.

Water-gas-welding is a forge welding process where a watergas -burner is serving as the heat source. Removal of oxidant, overheating of the edges, inhomogeneous heating and the lack of veritable quality assurance measures appeared as problems by using this process [3].

Many power stations in the alpine region have been equipped by watergas-welded pipes and some of them are still in use [4]. Fig. 2 shows a cross section of such a weld seam and Fig. 3 shows the load bearing and fracture behaviour of water-gas welds with and without flaws [5]

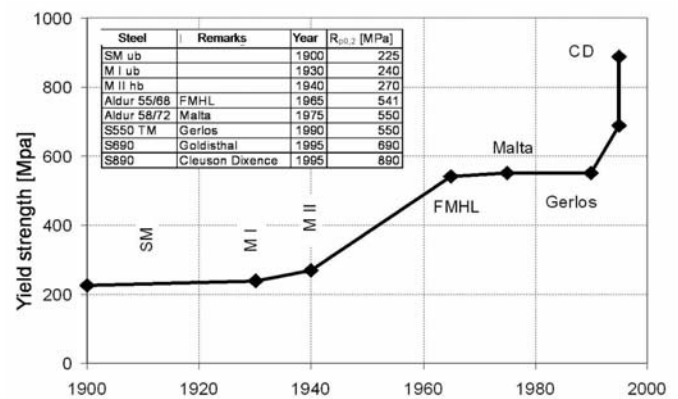


Fig. 1 Development of high strength steels for penstocks and shafts [2].



Fig. 2 Cross section of water gas weld [5].

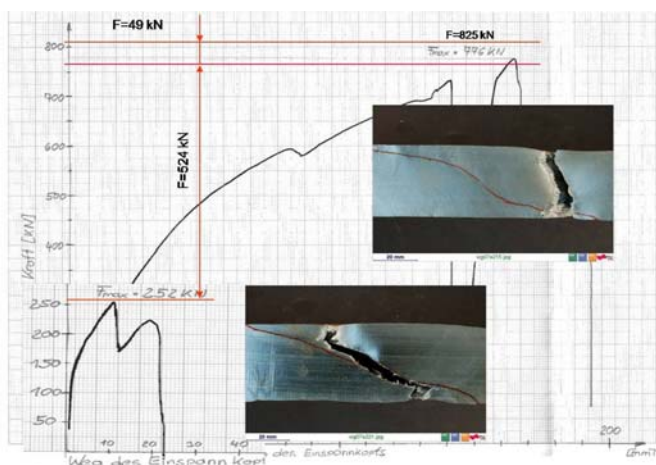


Fig. 3 Water gas weld, load bearing capacity [5].

Quenched and tempered fine grain steels

When the application of the quenched and tempered (Q+T) fine grain steels started in the late 1950s, hydrogen induced cold-cracking in the HAZ, the so called type IV-cracking, appeared as the main problem when welding this type of steels, see Fig. 4. The maintenance of proper pre- and post-heating procedures in the cases of cold-cracking was widely underestimated, also the necessity of the use of sensitive non-destructive testing methods [6].

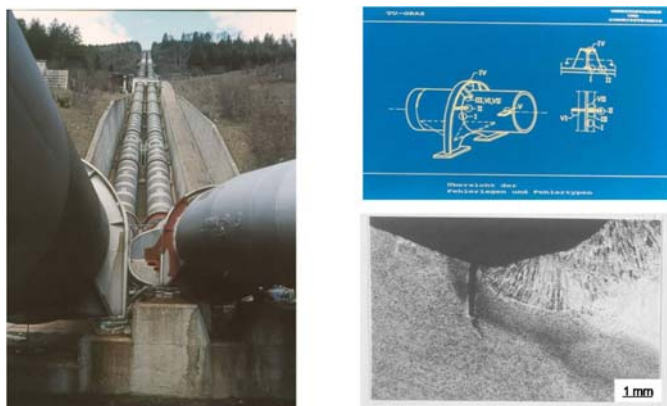


Fig. 4 Type IV cold cracking on penstock Q+T fine grain steel [6].

High strength steels

The application of high strength steels, types S690, and in the last decade also of S890 Q+T raised another welding problem, which is still not satisfactorily solved today: the hydrogen induced cold-cracking in the high strength steel weld metal. The development of high strength weldable steels made great progress in the last 20 years by the application of the combination of lean alloying concepts with the thermo-mechanical treatment of the materials. As a result of this successful development, steel grades showing excellent strength and toughness properties, but also good weldability appeared on the market. The risk of H – induced

cold-cracking in the HAZ was dramatically reduced which, as a consequence, leads to the reduction of applied preheating temperatures. By the use of the traditional fusion welding procedures SMAW and SA, the required strength in the weld deposit adequate to that of the base material can only be reached by the application of a higher amount of alloying elements in the consumables. By this, the risks of the appearance of H - induced cold-cracking moved from the HAZ region of the base material, triggered, as mentioned for the lower preheating temperatures, towards the weld deposit. The H –induced weld metal –cold cracking appeared mostly as transversal –but also as longitudinal cracks in the weld deposit as shown in Fig. 5. These types of cracks were unexpected and therefore in many cases not detected by the applied traditional NDT methods.

The cause of these cracks is – as in the traditional HAZ-type IV cold-cracks, the combined interaction of microstructure, H-content and residual stresses. The maintaining and control of the necessary pre- and post-heating temperatures – and durations, the control of the H-intake by the consumables, are in combination with the application of proper NDT-methods in the case of using high strength steel grades of even greater importance as it was in the past.

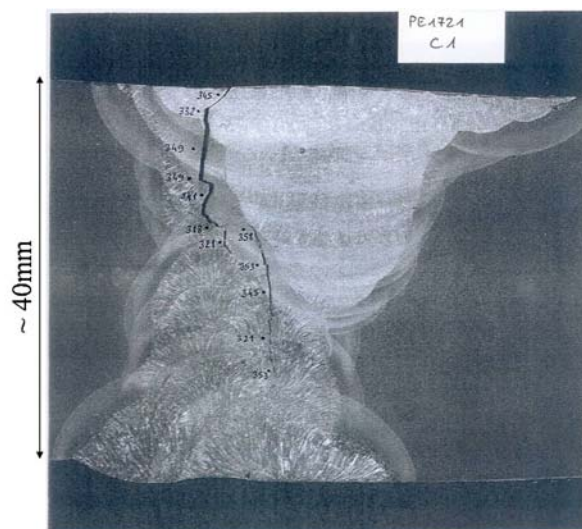


Fig. 5 H-induced cold crack in S890 steel weld deposit [7].

The Cleuson Dixence Case

One landmark of the underestimation of these basic requirements when using new high strength grades is the Cleuson Dixence case in Switzerland, which happened in December 2000. A brand new shaft, 3.5 m diameter and 36 mm wall thickness made from steel S890 fractured catastrophically by the formation of a crack in the longitudinal weld of the shell, penetrated into the base materials of the both adjacent shells and stopped in the next circumferential welds (Fig. 6). The mud caused by the water leakage went down the mountain and caused heavy damage, three people were killed. Extensive investigations performed

by different competent European laboratories devoted to that failure case came to the conclusion that this catastrophic failure initiated from an existing cold-crack in the weld deposit. The detailed results of these investigations are described in Ref.[8]. Other postulated failure mechanisms, like stress corrosion cracking, could not be confirmed by these investigations.

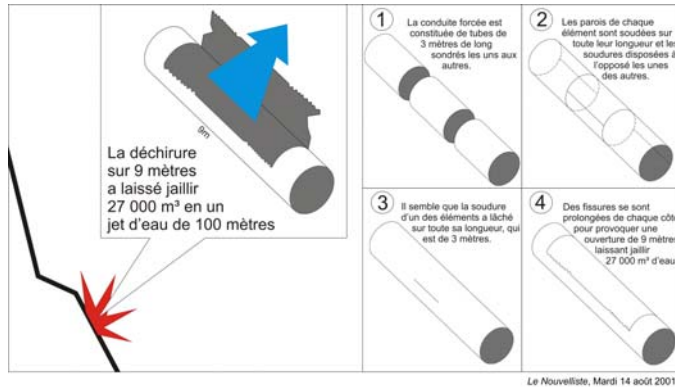


Fig. 6 Cleuson Dixence: Crash appearance [9].

The selected reconstruction concept is based on the introduction of a new sleeving pipe in the existing pipe, made of steel grade S690. The reconstruction works started in 2007 and will be finished at the end of 2009 [10].

The overall conclusion about this case is the following statement, which not only for penstocks but for other components is also applicable:

when welding new grades of materials, for installations with high risk potential for public safety a fully reconsidering of the existing approaches has to be undertaken - this shall include:

- the quantitative determination of the load bearing capacity of the base materials and of the welds (strength and toughness)
- the welding procedures
- the pre- and post-heating conditions
- the consumables and the their proper treatment
- the implications from the environmental and geometrical conditions from the site for fabrication, welding and NDT testing and most important
- the NDT-procedures to be applied.

For the reconstruction – for the first time two fully different NDT-philosophies were applied:

- a consequent traditional manual Ultrasonic Testing (UT) and
- the application of a fully automatic Time of Flight Diffraction (TOFD) method.

The results of these two methods are compared and in the case of differences in the results additional investigations will become mandatory.

It is the hope that this example will open a new, better, more

quantitative view on interpreting of UT-NDT results which will made the decisions more objective.

Thermal Power Plants

Mainly because of their physical properties thermal conductivity and thermal expansion coefficient ferritic steel grades are highly valued for the fabrication of components in thermal power generation industry. Beside of low Chromium ferritic/bainitic steels for turbine and boiler components like waterwalls or for sub-critical steam piping and headers, steels with a Chromium content in the range of 9-12% for ultra-super critical (USC) power plants are of great interest. Welding in all its variety is still the major joining and repair technology for those power plant components [11, 12].

By repair welds of casting defects, fabrication welds, joints of similar and dissimilar steel grades, connections of small cross-sections e.g. tube to tube welds, or of large cross-sections e.g. pipe to pipe or pipe to casting welds, the microstructure of the joined materials is strongly influenced by the welding process and whereby their mechanical properties are altered. As for all components exposed to high temperatures during service, the 100000 hour creep rupture strength of base material (BM), weld metal (WM) and cross-welds is still the major design criteria.

Long lasting experience with creep exposed welded structures has shown, that the heat affected zone (HAZ), a narrow zone of base material adjacent to the weld fusion line altered by the weld thermal cycle, is, in respect of the creep strength, often regarded as the weakest link in welded constructions.

The awareness of the importance of knowledge on creep behaviour of welded structures increased continuously within the last decades. In the 1990's several failures of welded steam piping systems, some of them in catastrophic manner, have backed the need for investigations on the creep behaviour of welded structures [13].

Weldments of ferritic steels exposed to high temperature creep loading show very similar behaviour in tendency, irrespective of the chemical composition and other parameters like welding procedure, groove preparation etc. Numerous creep tests of cross-weld samples showed that at lower temperatures there is no big difference between the base metal and cross-weld creep strength [14]. This difference becomes more prominent as the temperature increases and the applied stress level is lowered. The time of deviation of cross-weld creep strength from base metal mean creep strength is varying with creep testing conditions, material grades and welding prerequisites e.g. stress level, temperature, welding procedure, postweld heat treatment (PWHT) parameters, etc.

Fig. 7 compares the creep rupture strength of cross-welds with the mean line of base metal creep rupture strength of 9% Cr steel grade E911.

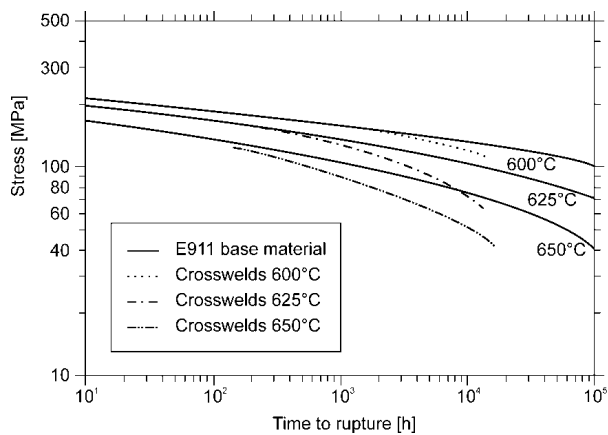


Fig. 7 Comparison of cross-weld creep rupture strength to mean base material creep rupture strength of E911 steel at different temperatures [12].

At higher stress levels and lower testing temperatures the location of failure is rather randomly distributed between BM, WM and HAZ. At lower stress levels and higher testing temperatures the HAZ of creep resistant steels appears to be the weakest link, diminishing the creep strength of weldments up to 50%. Generally, as derived from numerous long running creep tests, the creep rupture time is longer in the order of weld metal, base metal, cross-welds and fine grained simulated HAZ material [15]

Implications for industries using welded creep resistant steels Above, it was shown that creep rupture strength of base metals and weldments can differ significantly. Therefore, it is of great importance to consider a weld strength factor (WSF) during the design stage of new components and residual life evaluation of existing structures [16][17]. In design codes for nuclear power plants weld strength reduction factors are already implemented. The WSF is defined as the ratio of creep rupture stress at a certain time and temperature between weldments and base material.

The European Creep Collaborative Committee (ECCC) defined WSF and SRF (Stress reduction factor) in their ECCC Recommendations – Volume 2 Part IIb as follows [18]:

$$WSF(t, T) = \frac{R_{u(w)/t/T}}{R_{u/t/T}} \quad (1)$$

where $R_{u/t/T}$ is the creep rupture strength of base material samples at a time t and temperature T and $R_{u(w)/t/T}$ is the creep rupture strength of cross-weld samples at a time t and temperature T . Lack of long-term creep rupture data makes the determination of accurate WSF very difficult. Extrapolation of WSF from short term creep rupture tests holds the risk of over estimation of long term creep properties and is not recommended. This emphasizes the necessity for long-term creep rupture data of base material and welded joints.

In Fig. 8, WSF for several steel grades at different

temperatures are shown [19]. A reduction of up to 50% in creep rupture strength of weldments compared to base material creep rupture strength emphasises the importance of further research in this field and a correct consideration of WSF during design stage of new structures

The reason for the breakdown of crossweld creep strength – Type IV cracking

Type IV cracking is defined as the formation and propagation of failures in the fine grained (FG) HAZ and the intercritically heated (IC) region of the HAZ (Fig. 9). A strict differentiation between ICHAZ and FGHAZ is generally difficult because of very similar microstructural features in both regions. At that time, Type IV cracking is considered as the major “end of life” failure mechanism for ferritic creep resistant steel weldments in power generating industry. Therefore, this failure mechanism is of great interest and many researchers have investigated this life limiting phenomenon in welded components so far. Type IV cracking has been reported in low alloy ferritic/bainitic steels ($\frac{1}{2}\text{Cr}\frac{1}{2}\text{Mo}\frac{1}{4}\text{V}$, 1CrMo, 1CrMoV, $\frac{1}{4}\text{Cr}\frac{1}{2}\text{Mo}$, 2CrMo, T/P22, T/P23, T/P24), as well as in ferritic/martensitic 9-12%Cr steels (P91, X20CrMoV121, P92, P122, E911).

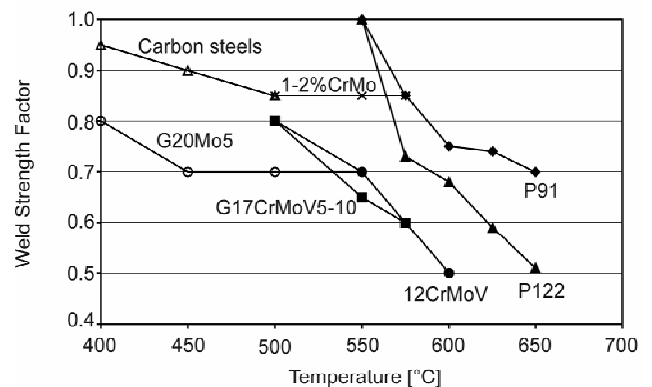


Fig. 8 Weld strength factors for the 100000 hours creep rupture strength of different steel grades [19].

Different from creep failures in ferritic weldments at high stress levels taking place randomly either in BM, WM or the HAZ, fracture location of weldments exposed to lower stress levels is shifted into the very narrow FGHAZ or intercritical HAZ region. Generally, Type IV cracking can be seen as the result of a microstructural zone of material weak in creep strength surrounded by materials that are stronger in creep. This mismatch in creep properties leads to highly complex material behaviour. The failure mechanism of Type IV cracking is governed by creep cavitation. Creep voids generally initiate at sub-surface and grow by a diffusive mechanism. Fig. 10 shows the formation of a very narrow band of voids in the outer region of the HAZ in a cross-weld sample prepared from an E911 pipe welded with matching filler and creep tested for 14000 hours at 600°C.

The combination of voids forms micro-cracks which in turn

coalesce to form macro-cracks finally leading to a premature failure. As mentioned earlier, Type IV damage initiates as creep cavitation subsurface at about halftime of the expected life of that of the base material. However, cracks may form relatively late in life of the component and crack growth once initiated may however be very rapid [20]. Remaining life for propagation throughout the wall can be less than 10000 hours. Surface bearing cracks do not appear until late in life. Therefore, surface examination of creep exposed weldments by application of replica techniques, penetration testing or eddy current testing can be misleading and severe damage in subsurface regions can be overlooked [21]. A sound residual life investigation on weldments can only be performed by advanced ultrasonic (UT) inspections or highly sophisticated methods like Time Of Flight Diffraction (TOFD) with which creep voids and micro cracks can be detected even at a life ratio (t/tr) of 0.5. In any case, life assessment methods for weldments vulnerable to Type IV cracking have to include a qualitative damage classification scheme and a cavity density based model [22].

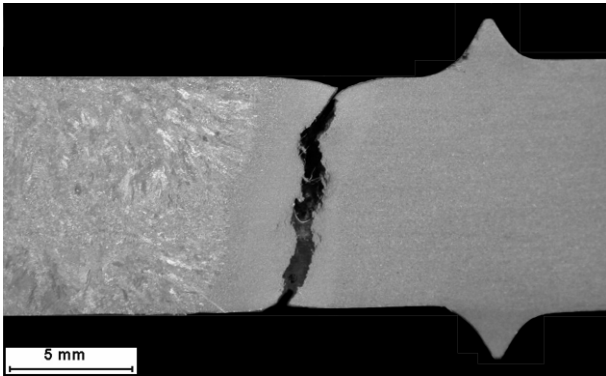


Fig. 9 Cross-weld sample prepared from E911 pipe welded with matching filler and creep tested at 600°C for 18000 hours. The macroscopic low deformation fracture is located in the FGHAZ close to the unaffected base material [12].

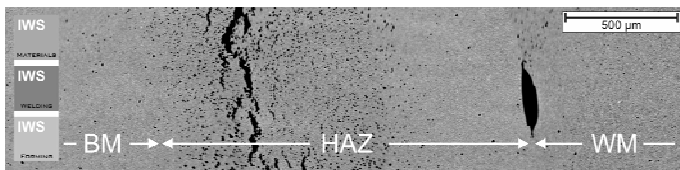


Fig. 10 Cross-weld sample prepared from E911 pipe welded with matching filler and creep tested at 600°C for 14000 hours. Localised formation of voids and their coalescence to macro cracks at the outer region of the HAZ observed by SEM led to final fracture [12].

Future trends

Up to the present, inferior long term creep properties of weldments of heat resistant steels can only be taken into account during the design stage of thermal power plant components. The awareness of designers, engineers and operators of the risk of extrapolating results of short term

creep tests to longer times has already contributed to an increase in safety. General acceptance of the necessity of long term creep testing data of cross-welds, weld metal and base metal for a reliable material selection is inevitable [23]. Within the last decades suppliers of welding consumables have improved their filler materials in terms of cleanliness, weldability and mechanical properties. As a consequence, weld metal cracking has almost disappeared.

In most cases the HAZ was identified as the weakest link in welded structures of creep resistant steels. Shifting of welds to lower creep stressed regions may improve the short time performance of welded components but failures cannot be avoided in the long range. The use of most advanced non-destructive testing (NDT) methods is necessary to detect damage as soon as possible to react with appropriate countermeasures.

The HAZ, as part of the base metal, has to be taken into consideration already in the design of new steel alloys. Weldability studies using HAZ simulation techniques can provide useful information on possible bottlenecks. Recently, in Japan at the National Institute for Materials Science (NIMS) a 9Cr-3W-3Co steel with reduced Nitrogen level and controlled addition of Boron was developed. Contrary to all up to now used creep resistant steels, this steel does not show the formation of a fine grained region within the HAZ. Fig. 11 shows results of an electron backscatter diffraction pattern (EBSP) analysis of the grain size, as a function of distance from fusion line, of conventional P92 steel versus the new 9Cr-3W-3Co material [24]. By the elimination of fine grains in the HAZ the formation of creep damage by Type IV mechanism, which is strictly limited to fine grained regions, should be avoided. Up to a duration of 10000 hours, creep tests at 650°C are very promising and no difference in creep strength between cross-weld specimen and base material is shown.

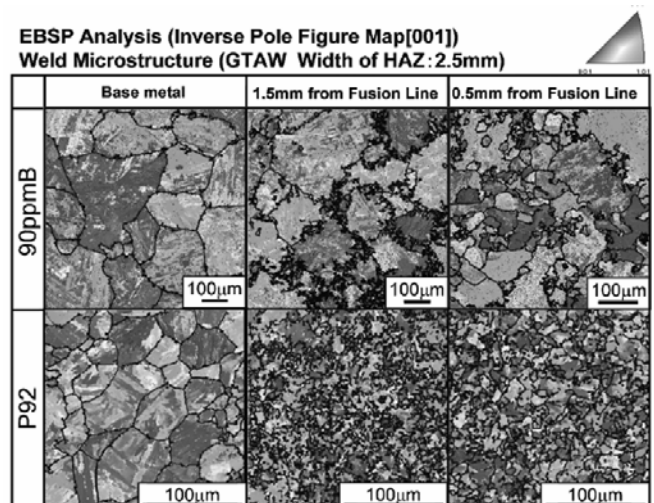


Fig. 11 Electron backscatter diffraction pattern (EBSP) analysis results for 9Cr-3W-3CoNB steel and P92 steel HAZ microstructures [24].

Although the mechanisms active in this steel are not fully

understood, this might be a possible approach for the prevention of Type IV cracking in ferritic creep resistant steels.

Nuclear Power

The peaceful use of nuclear reactions for power generation would have not been possible without the application of welding. While in other main branches of power generation industry, i.e. hydro and thermo-power, started before the welding technology could be used industrially, the evolution of nuclear power generation is indispensably connected with welding technology. In this sense it is to mention that the development of nuclear power generation triggered and supported the evolution of materials science and welding technology dramatically. It may be stated that today the overall status of materials science and welding technology would not nearly have reached that level as it is visible now. This is mainly caused by the standards of safety and reliability applied on the welded nuclear installations. From the appearance of nuclear power industry on, many unknown and unexpected challenges towards materials science and welding technology appeared. This finally has led worldwide to the following developments in the view of materials and welding:

- research in material science and technology emerged to an essential part in the entire development of nuclear power industry
- materials were developed and optimized towards better weldability
- welding processes and consumables were investigated, optimized and developed
- failure cases were investigated in detail not known before and countermeasures introduced
- new testing methods – mechanical tests – mainly in the field of fracture mechanics as well as in NDT has been developed
- the system of quality assurance, today standard in many industrial welding applications, has been developed based on the experience made in welding of nuclear power plant components.

IIW Commissions have been deeply involved in these breathtaking developments and made important indispensable contributions to it.

For the components of Nuclear Power Plants (NPP), especially for the so called Nuclear Steam Supply System (NSSS) of light water cooled reactor systems, due to the design, service and safety aspects special requirements are placed on the materials and weldings. These are essentially:

- huge components with extreme wall thickness
- corrosion resistance on all inner surfaces exposed to the coolant
- through hardenability for heavy sections

- highest toughness requirements
 - resistance against neutron embrittlement
 - resistance against formation of radioactive isotopes
 - NDT testability with sufficient sensitivity for the failure detection for the fabrication as well as for in-service inspection procedures
 - economic fabricability
- and most important:
- weldability

For the weld deposits the same basic requirements are valid for every volume element of the butt welds as well as for the cladding.

Materials used

In the western world mainly two grades of steel were developed which, after modification and optimization, fulfilled the above mentioned basic requirements: 22NiMoCr37 – A508C12 and 20MnMoNi55 – A533GrB, A508C13

Basically at first A508C12 was used as forging grade while A533GrB was used as material for plates. The corrosion resistance of the components for the NSSS is secured by the application of weld cladding of austenitic stainless steel on the entire inner surface [25-28].

Fig. 12 gives the wall thicknesses to be butt welded for reactor pressure vessels (RPV) for different types of pressured water reactors (PWR) designed by SIEMENS /KWU company. The huge dimensions and the risk which have been generally considered in connection with welds led in general to the decision of that company to reduce the number and length of welds dramatically by increasing the size of the forged parts to be welded together. Fig. 13 reveals the dramatic reduction of welds which was also to consider in connection with the reduction of tests necessary. Decisive also was the reduction of the time needed to perform the mandatory NDT – in service inspection of RPV welds. By this it helps to reduce the shutdown period to perform the tests and increase the availability of the plant [29, 30].

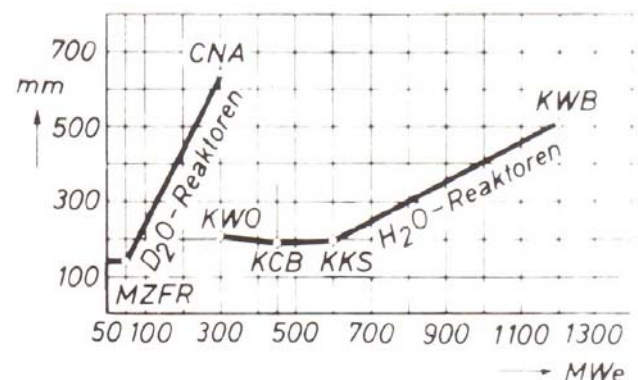


Fig. 12 Dimensions and wall thickness to be welded [25].



Fig. 13 Reduction number of welds and tests when increasing the size of forgings. [30]

Underclad Cracking

As mentioned above, all components of the NSSS have to be clad by the application of austenitic stainless steel weld cladding to assure the corrosion resistance requested. Occasionally in the late 1960s in the coarse grain region of the HAZ below strip claddings on NSSS components the systematic appearance of intergranular cracks had been detected. This observation led to worldwide recognition and intensive discussions [31].

The appearance of those cracks is shown in Fig. 14 and Fig. 15. The size of the cracks observed was limited to the max. depth of the HAZ coarse grain zone caused by strip cladding, which is max. 2.5 mm. The length was found to be typically 10-20 mm in average. The direction of the cracks was found to be perpendicular to the weld direction.

Intensive investigation started to fulfil two goals:

- 1) to investigate the mechanism and cause of the crack formation with the goal to develop appropriate counter measures to prevent it
- 2) to quantify the significance of this type of cracking in respect to safety and reliability of the components of the NSSS.

The second goal led, at least in Germany, to the establishment of the very extensive safety program “Forschungsprogram Komponentensicherheit, FKS” which were managed by MPA Stuttgart under the responsibility of Prof. Karl Kussmaul. The results of that project-work were appreciated and used worldwide. It finally led to the very successful so called German “basis safety concept for NPP’s” [32].

As mentioned, the first goal was to prevent the formation of underclad cracks UCC. The results of the investigations revealed, that UCC formation is caused by the mechanism of relaxation cracking, which is limited to the coarse grain HAZ region of the steel type A508c12 (22NiMoCr37) and occurs during the 600°C post-weld heat treatment (PWHT) applied on the component.

Fig. 16 and Fig. 17 explain that effect on the example of hot tensile tests applied on different HAZ simulated microstructures on material 22NiMoCr37, (A508c12). The material representing HAZ coarse grain microstructure shows a loss of ductility (elongation and reduction of area) at about 600°C. This is the PWHT temperature of that component.

Fine grain HAZ microstructures did not show that effect, as shown in Fig. 17.

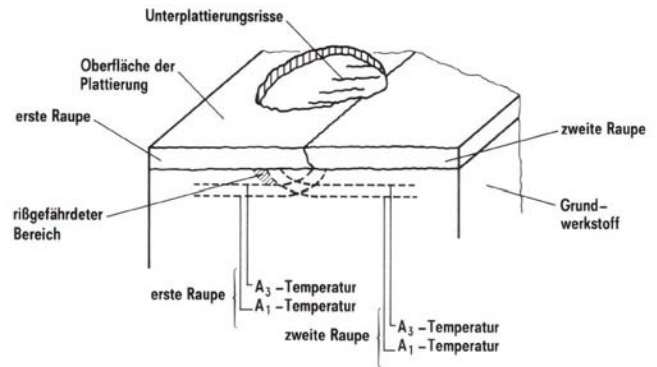


Fig. 14 Principle of the appearance of underclad cracks beyond strip cladding (acc. [27])

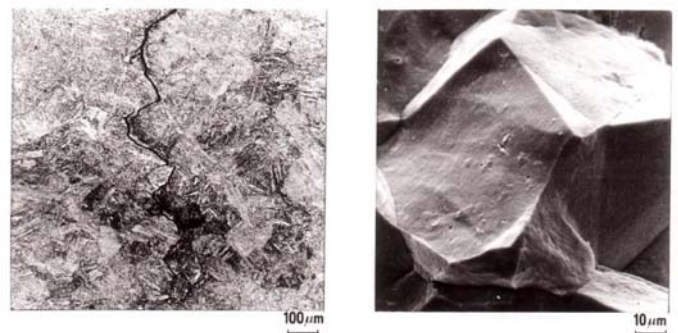
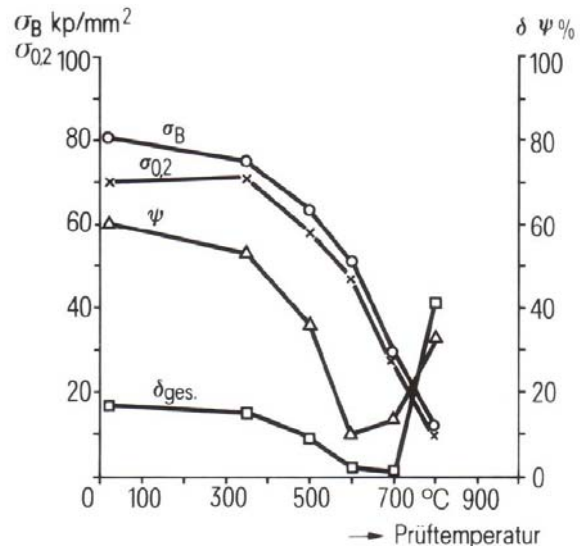


Fig. 15 Underclad cracking, light microscopy (left) and SEM (right) (acc. [27])

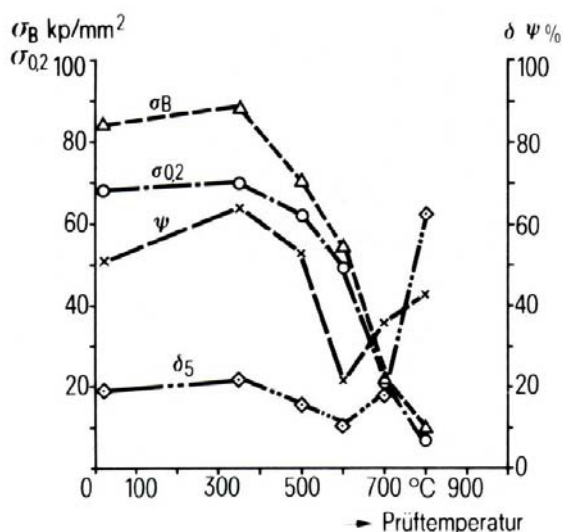


Analyse:	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al
	%	%	%	%	%	%	%	%	%	%	%
	.21	.25	.66	.012	.010	.39	.69	.89	.02	.012	.018

Fig. 16 Tensile tests of HAZ coarse grain microstructure (steel 22NiMoCr37) [33].

Based on those results, the first very successful countermeasure could be applied by the use of a double layer strip cladding process to enforce the transformation of the coarse grain HAZ, produced by the first layer in a fully fine grain HAZ by a controlled application of a second strip cladding layer. Most important, in this case, is that the second layer has to be applied before PWHT after the first layer welding (Fig. 18).

This appearance of very small and limited relaxation cracking was observed not only as UCC but also, in much smaller size, detected on butt weld coarse grain HAZ regions of multilayer butt welds and sometimes also as stress relief cracks (see Fig. 19). As a consequence obviously this problem can only be solved by the application of a material which shows less sensitivity against this relaxation cracking.



Analyse:	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al
	%	%	%	%	%	%	%	%	%	%	%
	.21	.25	.66	.012	.010	.39	.69	.89	.02	.012	.018

Fig. 17 Tensile test of simulated HAZ coarse grain plus fine grain recrystallized microstructure (steel 22NiMoCr37) [33].

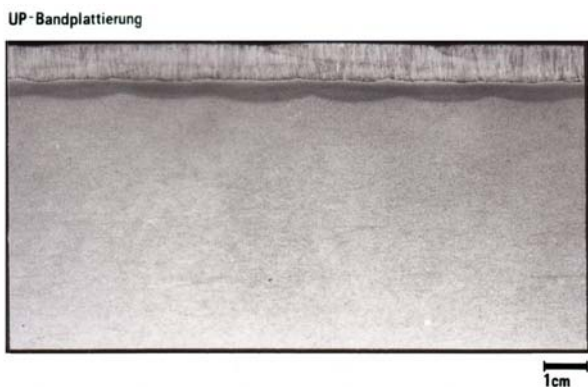


Fig. 19 Two layer strip cladding by controlled refining of the HAZ coarse grain caused by the first layer by the controlled

application of the second layer [33].

The steel type A533GrB was also investigated by the same methods with the result that this material shows, much less sensitivity against that effect, Fig. 20.

In consequence of this observation the qualification of that grade of steel for heavy forgings started in 1973, including the optimization of the chemical analysis and the fabricability of heavy forgings.

It is to report that this grade, called after German standards 20MnMoNi55, which is equivalent to grade A508C13, is nowadays worldwide applied successfully for the components of the NSSS of water-cooled reactors.

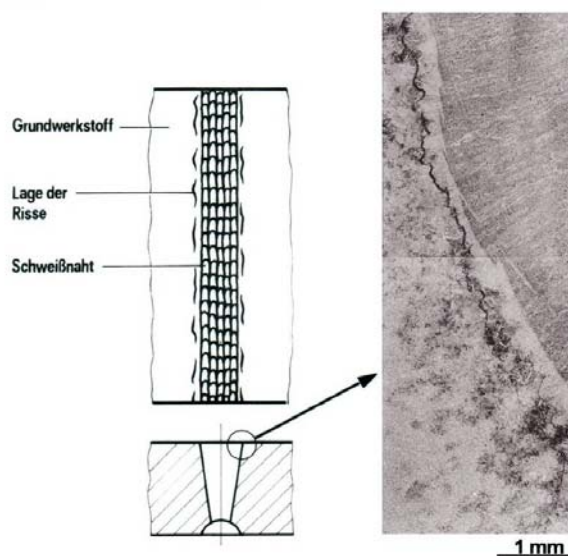
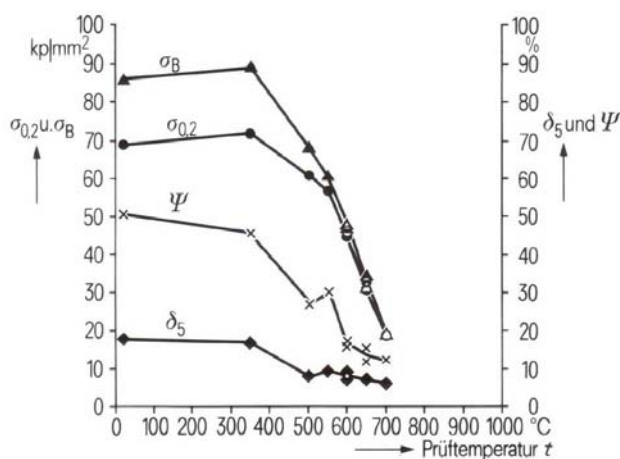


Fig. 19 Stress relief cracks in butt welds of steel 22NiMoCr37 [33].



Analyse:	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al
	%	%	%	%	%	%	%	%	%	%	%
	.205	.250	.420	.011	.010	.530	.620				

Fig. 20 Hot tensile test on HAZ coarse grain simulated microstructure of steel 20MnMoNi55 (A533GrB) [28]

CAN II RPV closure-head welding

The realisation of the circumferential closure-head weld for the RPV of the heavy water PWR NPP Atucha II (CNAII), in Argentina was at that time –in the late 1970s, the decisive technology for the realisation of the entire project.

The basic technology for the realization of that weld was developed at the KWU welding laboratory in Erlangen, Germany. The weld had to connect the calotte with the head flange ring with a weld thickness of 650mm, Fig. 21. The analysis performed led to the decision to select a narrow gap weld design. All pros and cons were evaluated: Many detailed investigations and tests were performed. This finally led to the very successful completion of that weld, consisting of 699 single layers, each ~ 25m long, which were welded in a row in six weeks continuously by GHH Company in Oberhausen Sterkrade in Germany [34].

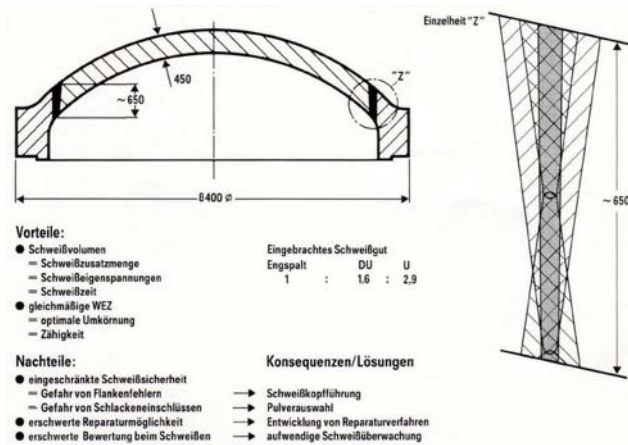


Fig. 21 CNA II RPV closure head weld design [34].

Conclusion

Welding was in the past and is still the dominant fabrication technology in the power generation industry. The development of power generation in all its branches enforced not only the development of new and optimized welding processes that were able to fulfil the requirements of optimized and economical fabrication. The today's worldwide applied system of quality assurance is based essentially on the requirements coming from the power generation industry, mainly the nuclear power industry. Most important in that respect is the role of the behaviour of the materials to be welded. When reviewing examples from it, it is obvious that the understanding of the behaviour of materials subjected to welding is one of the key issues of realizing safe, economic, reliable and sustainable energy production.

The role of welding, especially the contribution of IIW towards the power industry to improve the quality of life worldwide must be highlighted.

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