böhler welding
by voestalpine

Lasting Connections

WELDING SOLUTIONS FOR GRADE 91

voestalpine Böhler Welding
www.voestalpine.com/welding

voestalpine
ONE STEP AHEAD.

LASTING CONNECTIONS

As a pioneer in innovative welding consumables, Böhler Welding offers a unique product portfolio for joint welding worldwide. More than 2000 products are adapted continuously to the current industry specifications and customer requirements, certified by well-respected institutes and thus approved for the most demanding welding applications.

Böhler Welding shares its experience and knowledge and co-operates closely with industrial customers and distributors. In doing so, Böhler Welding offers joining solutions that have been developed together with customers and partners and successfully proven in practice.

Especially for P91 material welding know-how is of utmost importance. Our weldTECH Application Services with highest expertise in joint welding provide customers with professional support.

Our clients benefit from a partner with

» the highest expertise in joining, rendering the best application support globally available
» specialized and best in class product solutions for their local and global challenges
» an absolute focus on customer needs and their success
» a worldwide presence through factories, offices and distributors

voestalpine Böhler Welding has provided welding solutions for thermal power stations since 1926. Whenever high temperature and creep resistance properties are essential, voestalpine Böhler Welding is the competent partner and supplier. Therefore, it was not surprising that voestalpine Böhler Welding filler metals where chosen for the first application of P91 in the thermal power industry back in 1990.

Today with more than twenty years' experience researching these types of filler metals to meet and exceed this industries ever more demanding applications, voestalpine Böhler Welding has moved forward in line with the principle material manufacturers to introduce new filler metals for alternative pipes and tubes.

In Addition the high integrity welds produced, using our filler metals, are supported by many thousands of hours proofed creep properties of all weld metal and real welds. Therefore, we are not surprised but delighted that our reputation for high quality filler metals has resulted in our products being used for numerous new build power plants worldwide.

voestalpine Böhler Welding products are used in various thermal power plant projects in execution, in particular in China, India, South East Asia and United States of America.

We are proud that our customers rely on quality assured products. voestalpine Böhler Welding filler metals are engineered to produce high integrity Joints.

They have been developed from years of careful formulation backed by factual technical research and testing to enable our customer to enjoy the confidence that our products can offer during many years of in plant service.

CONTENT

DEVELOPMENT OF GRADE 91

Grade 91 is a creep strength enhanced ferritic steel used for high temperature applications in modern thermal power stations and petrochemical units. The benefit of this modified 9Cr-1Mo steel is the outstanding creep, good oxidation and corrosion resistance to traditional power plant steel grades like.

The nominal composition of grade 91 includes carbon, chromium, molybdenum, vanadium, niobium and nitrogen. The excellent creep resistance is a result of finely dispersed vanadium and niobium carbo-nitrides throughout the tempered martensitic matrix along with chromium carbides stabilizing the microstructure. Molybdenum improves high temperature strength through solid solution. The high chromium content leads to oxidation and high temperature corrosion resistance.

Grade 91 has been developed in the 1970´s and 80´s by the Oak Ridge national Laboratory in the US. In 1983 it has been standardized in ASTM A 213. Since then it has been recognized in various national and international standards.

First industrial applications of the grade 91 as super-heater tube and steam header came up in the US in the 1990´s. Since then, grade 91 has been used for super and re-heater tubing as well as for header and steam piping system in hundreds of conventional and combined cycle thermal power stations around the globe. Beside the application as tube and pipe material as tube and pipe material grade 91 is available as cast material for steam turbine parts such as valve bodies.

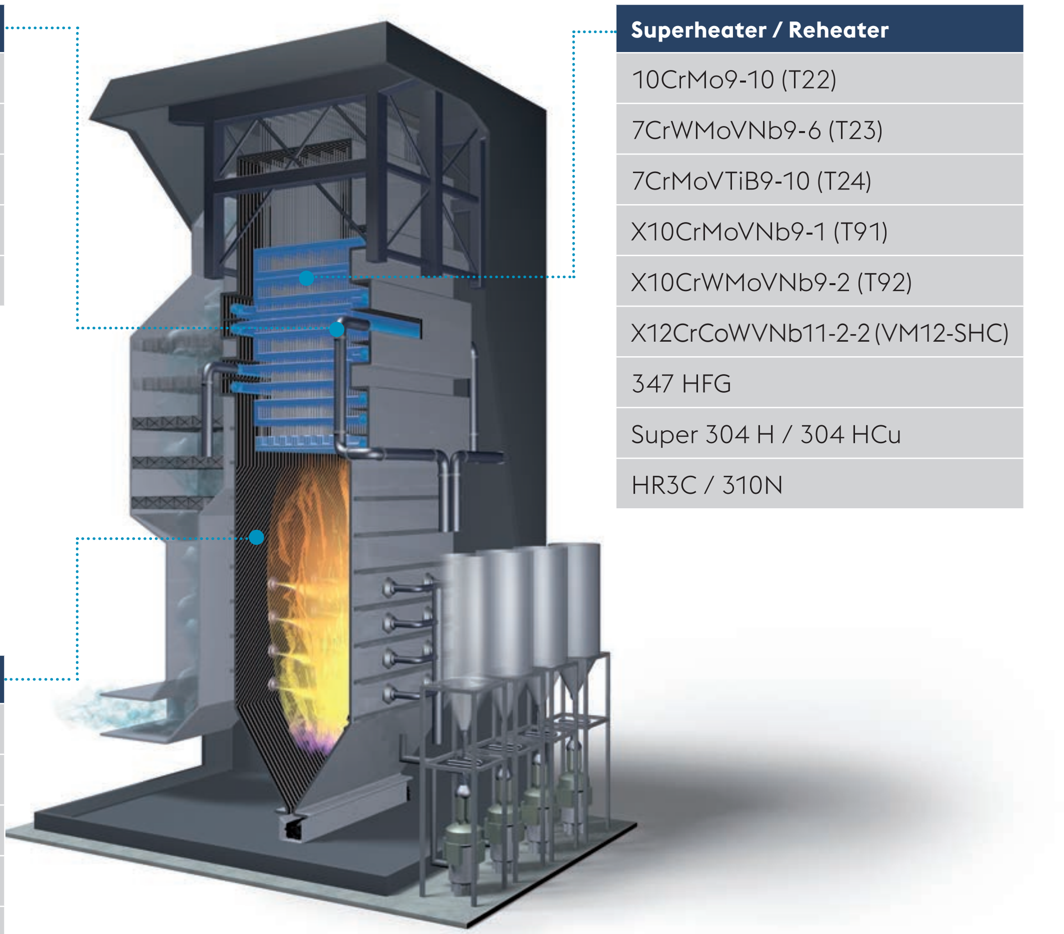
Table 1: Nominal Composition of Grade 91 (wt. %)

C	Si	Mn	Cr	Ni	Mo	V	Nb	N
0.1	0.3	0.5	9.0	0.2	1.0	0.2	0.06	0.04

Table 2: Modified 9Cr-1Mo grade in international standards

Standard	Country	Grade
ASTM / ASME	USA	91, T91, P91, F91, FP91, WP91, C12A
British Standard (BS)	UK	91
European Standard (EN)	Europe	X10CrMoVNb 9-1, GX12CrMoVNbN 9-1
Guobiao Standards (GB)	China	10Cr9Mo1VNbN
South African National Standard (SANS)	South Africa	X10CrMoVNb 9-1
Japanese Industrial Standard (METI)	Japan	STPA28, STBA28

Header / Piping
15NiCuMoNb5-6-4 (WB36)
10CrMo9-10 (P22)
X10CrMoVnb9-1 (P91)
X 11 CrMoWVNb 9-1-1 (E911)
X10CrWMoVNb9-2 (P92)



Superheater / Reheater
10CrMo9-10 (T22)
7CrWMoVNb9-6 (T23)
7CrMoVTiB9-10 (T24)
X10CrMoVNb9-1 (T91)
X10CrWMoVNb9-2 (T92)
X12CrCoWVNb11-2-2 (VM12-SHC)
347 HFG
Super 304 H / 304 HCu
HR3C / 310N

Water wall
Grade A1
15Mo3 (T1)
13CrMoV4-5 (T12)
7CrWMoVNb9-6 (T23)
7CrMoVTiB9-10 (T24)

WELDING

Despite its complex alloy system, grade 91 has good weldability as a result of its moderate carbon content and favorable properties. However, during fabrication inadequate mechanical properties as well as cold and hot cracking issues may arise. Therefore, precaution must be taken before, during and after welding.

Grade 91 can be welded with all common welding processes. SMAW still belongs to the most applied welding processes especially for on-site construction purposes. Due to the high productivity SAW is used for workshop fabrications especially of thick walled components. The application of GMAW and FCAW are well established today especially as a result of the ease of handling as well as the advantage with respect to productivity increase during positional welding.

Manual GTAW is commonly used for joint welding of small diameter tubes as well as for root pass welding. The advantage of GTAW for root pass welding is the highest quality weld metal as well as the absence of slag. The latter is important in the case that the slag cannot be removed e.g. due to the bevel geometry. Furthermore, semi mechanized GTAW processes like narrow gap GTA orbital welding is used for the fabrication of thick walled components.

WELDING CONSUMABLE

voestalpine Böhler Welding provides high quality and approved welding solutions for grade 91 meeting the requirements of international and national standards and individual customer specification.

Table 3: Overview on voestalpine Böhler Welding grade 91 welding consumables

Welding Process	Product Name	AWS classification	EN ISO classification	Product Feature
SMAW	BÖHLER FOX C 9 MV	E9015-B91 H4	E CrMo91 B 42 H5	» Core wire alloyed covered electrode with basic coating. » Low diffusible hydrogen content.
	BÖHLER FOX C 9 MV LNi	E9015-B91 H4	E ZCrMo91 B 42 H5	» Core wire alloyed covered electrode with basic coating. » Mn+Ni ≤ 1.0 wt. %. » Low diffusible hydrogen content
	Thermanit Chromo 9 V	E9015-B91 H4R	E CrMo91 B 42 H5	» Covered electrode with basic coating. » Low diffusible hydrogen content.
	Thermanit Chromo 9 V mod	E9015-B91 H4R	E ZCrMo91 B 42 H5	» Covered electrode with basic coating. » Mn+Ni ≤ 1.0 wt. %. » Low diffusible hydrogen content.
GTAW	Thermanit MTS 3	ER90S-B9	W CrMo91	» Welding rod or wire for gas tungsten arc welding.
	Thermanit MTS 3 LNi	ER90S-B9		» Welding rod or wire for gas tungsten arc welding. » Mn+Ni ≤ 1.0 wt. %.
GMAW	Thermanit MTS 3	ER90S-B9	G CrMo91	» Solid wire electrode for gas metal arc welding.
	Thermanit MTS 3 LNi	ER90S-B9		» Solid wire electrode for gas metal arc welding. » Mn+Ni ≤ 1.0 wt. %.
FCAW	FOXcore C 9 MV RC	E91T1-M21PY-B91-H4	T ZCrMo9VNb PM1	» Rutil-basic flux cored wire for gas metal arc welding. » Mn+Ni ≤ 1.0 wt. %. » Low diffusible hydrogen content.
MCAW	FOXcore C 9 MV MC	E91T15-M12PY-B91-H4		» Metal cored wire for gas metal arc welding. » Low diffusible hydrogen content.
SAW	Thermanit MTS 3 Marathon 543	F9PZ-EB91-B91	S S CrMo91 FB	» Solid wire electrode and welding flux for submerged arc welding.
	Thermanit MTS 3 LNi Marathon 543	F9PZ-EB91-B91	S S ZCrMo91 FB	» Solid wire electrode and welding flux for submerged arc welding. » Mn+Ni ≤ 1.0 wt. %.

More detailed information on welding parameter ranges for the individual welding process can be found in the respective product data sheet.

PURGING

For welding of grade 91 it is mandatory to apply purging devices during root pass welding and at least for the hot pass. Purging gas should be in pure argon quality (100%Ar).

TEMPERATURE MANAGEMENT

The temperature cycle for manufacturing grade 91 is illustrated in Figure 2. An explanation is given in the following paragraphs.

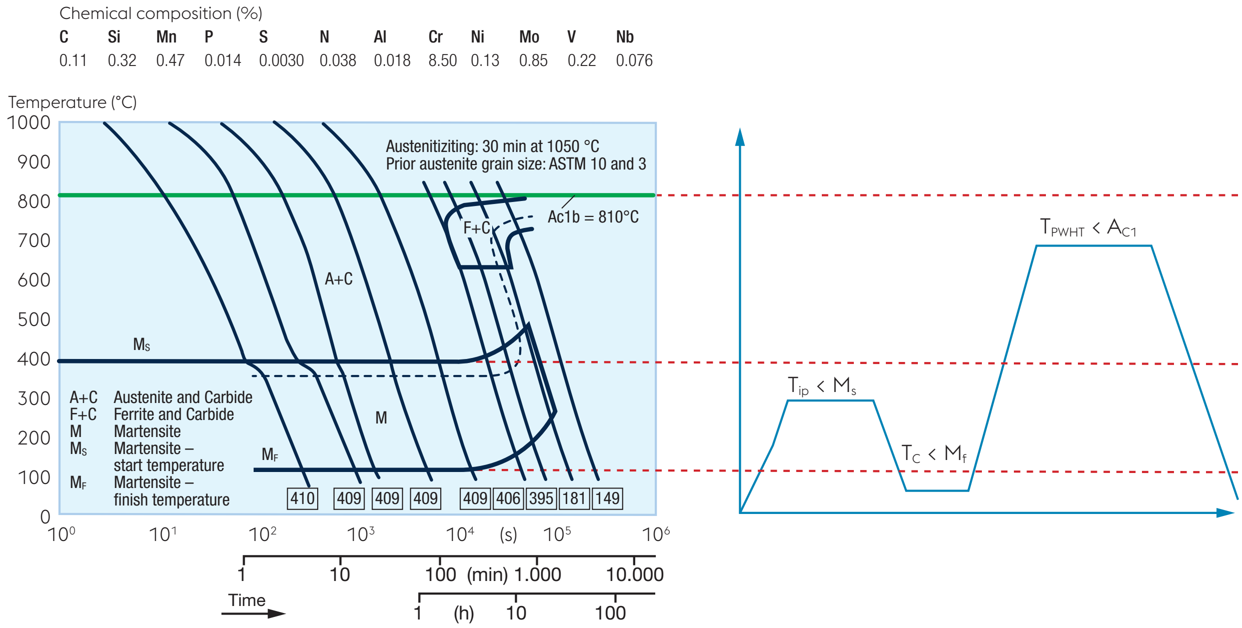


Figure 2: Continuous Cooling Transformation (CCT) diagram of grade 91 and the derived temperature management before, during and after welding.

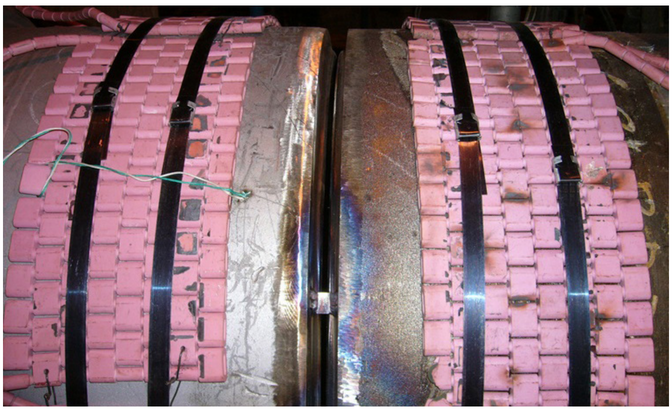
Preheating

After cooling down from peak temperatures above the A_{c3} point during welding, grade 91 exhibits a fully. This microstructure is susceptible to hydrogen induced cracking which is additionally influenced by residual welding stresses, preheat temperature and level of diffusible hydrogen. The residual welding stresses are a function of the component geometry to be welded and the bead sequence. A careful design might be able to decrease the level of residual stresses but for the welding process itself the key factor to be controlled is the preheat temperature as well as elimination of any hydrogen source apart from an optimized bead sequence. Thus, use of low hydrogen welding consumables as well as re-baking of SAW flux and SMAW electrodes are essential. All surfaces around the weld preparation must be carefully cleaned from oil, dirt, grease and rust.
Preheating is necessary in order to evaporate any water-based fluid prior to welding and slow down cooling rate after welding. Furthermore, at temperatures above 150 °C the hydrogen mobility is significantly increased allowing hydrogen to diffuse out of the weld area.

A preheat temperature of 200 °C as recommended by most standards is reasonable in order to minimize the probability for hydrogen induced cracking. For GTA welding of thin components preheating of ≥ 150 °C can be accepted.

If the welding process needs to be interrupted, the weld seam must be maintained at preheat temperature.

Figure 3: Proper preheating of grade 91 using ceramic heating mats



Interpass temperature

In principle, the interpass temperature for grade 91 is limited to 350°C. To limit the interpass temperature below the martensite start temperature is based on the idea to allow each layer to transform partially into martensite. The advantage is that during welding of the subsequent layer the previous layer as well as the heat affected zone is tempered through the heat input during welding. This leads to reduced hardness and improved toughness of the weld seam. Another aspect is, that exceeding the recommended interpass temperature might lead to hot crack formation, especially for high heat input welding processes like SAW. This effect is linked to the chemical composition of the weld metal. Many fabricators apply a maximum inter pass temperature of 300 °C which is recommended in order to increase quality and reliability during fabrication.

Cooling after Welding

After welding is completed the weld seam must be slowly cooled below the martensite finish temperature in order to generate a 100 % martensitic microstructure prior to post weld heat treatment. Best practice for thick walled components is to hold the component for 2 h at a temperature between 80 °C and 100 °C to ensure that the microstructure throughout the complete wall thickness is transformed into martensite. For complex components with high residual stresses it is recommended to stop cooling at 80 °C and holding at this temperature before dehydrogenating or post weld heat treatment.

Post weld heat treatment (PWHT)

All tempered martensitic steels require a post weld heat treatment after welding. a) because the martensitic microstructure is very sensitive to stress corrosion cracking and b) because PWHT is essential for reducing the hardness level and to obtain reasonable level of impact toughness. Furthermore, the outstanding high temperature mechanical properties like creep resistance is a consequence of the microstructure which is established during the tempering process. Figure 5 shows high resolution TEM images of grade 91 weld metal. After welding, the microstructure exhibits 100 % martensite and high dislocation density (Figure 5a).

Dehydrogenating treatment (DHT)

For very complex components or in the case that it is not feasible to carry out post weld heat treatment subsequent to completed welding it might be recommended to apply a dehydrogenating treatment (DHT) between 260 and 400 °C for grade 91 components in order to reduce the risk for hydrogen assisted cracking. Holding time should be at least 2 h for components thicker than 25 mm. It can be recommended to carry out DHT after cooling down below martensite finish temperature. This practice carries the advantage that the diffusible hydrogen level can be reduced to a minimum.

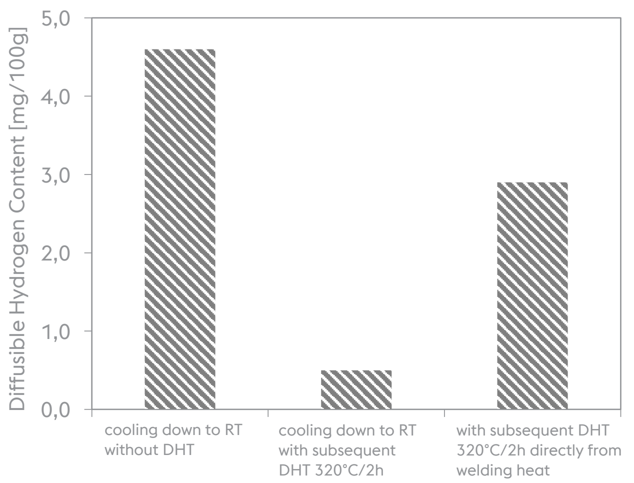


Figure 4: Impact of intermediate cooling after welding and DHT on diffusible hydrogen content of Thermanit MTS 3 / Marathon 543 submerged arc weld metal

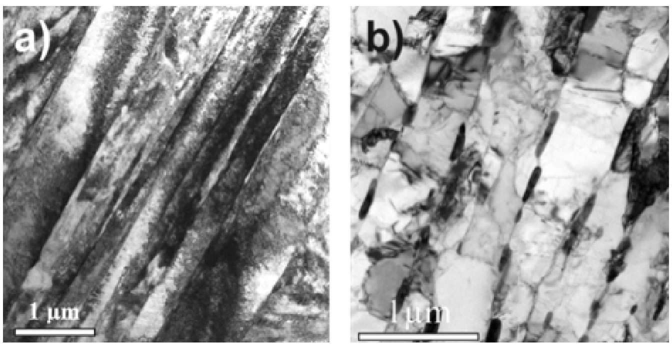


Figure 5: Microstructure of grade 91 weld metal a) directly after welding and b) after post weld heat treatment

During PWHT the martensite transforms into a subgrain microstructure due to the dislocation rearrangement. Thus, the dislocation density decreases as a function of PWHT temperature and time leading to reduced hardness and increased Charpy impact values (Figure 6).

Beside the recovering process, various types of particles precipitate within the microstructure. Vanadium and niobium rich carbo-nitrides precipitate within the martensite lath. Chromium carbides precipitate along prior austenite grain and martensite lath boundaries (Figure 5b). These precipitation reactions within the subgrain microstructure are essential in order to employ the desired creep rupture strength.

The upper temperature limit is restricted by the ferrite to austenite transformation temperature A_{c1} which is a function of the chemical composition (see paragraph on weld metal metallurgy). Exceeding the A_{c1} temperature of either the base material or weld metal during PWHT must be avoided in order to maintain the desired microstructure. According to the fabrication codes and standards grade 91 material should be post weld heat treated between 730 °C (740 °C) and 770 °C. In order to achieve reasonable impact energy and strength level the recommended PWHT temperature is 760 °C ± 10 °C. The holding time depends on the component thickness and welding process.

PWHT should be carried out using furnace, electrical induction or electrical resistance heating devices and must be properly monitored and controlled. The use of oxy-flame devices is not recommended. In order to reduce thermal stresses and promote a homogenous temperature distribution throughout the wall thickness heating and cooling rates for grade 91 welded components range from 80-120 °C/h and 100-150 °C/h, respectively. For thinner wall thickness higher heating and cooling rates are possible. The following temperature management can be recommended for the fabrication of grade 91 components (Figure 7).

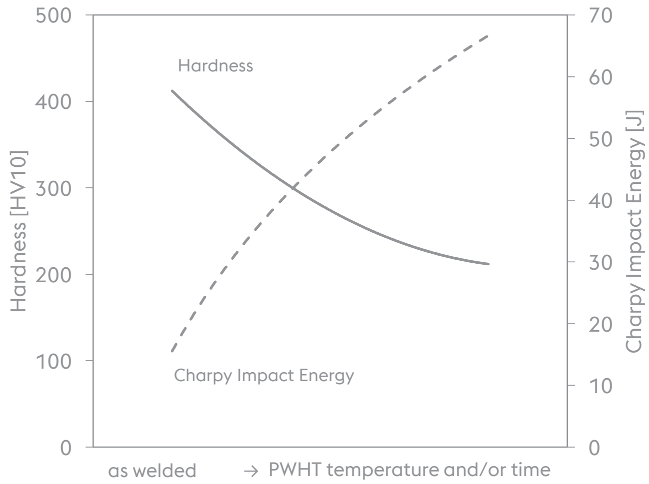


Figure 6: Impact of PWHT on hardness and impact energy of submerged arc welding consumable Thermanit MTS 3 / Marathon 543

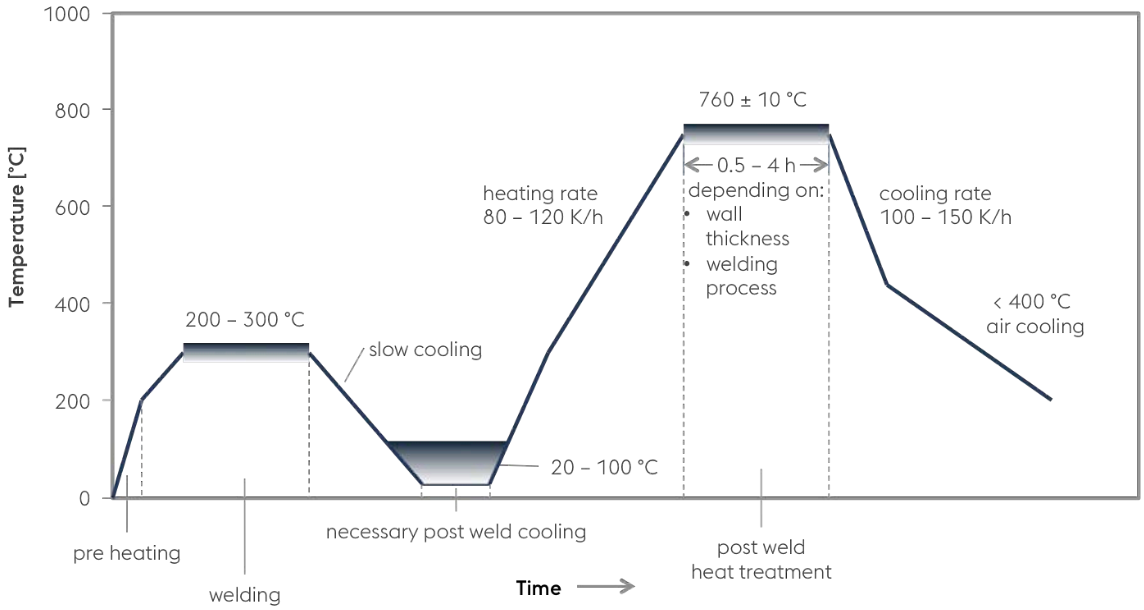


Figure 7: Recommended temperature management for welding of grade 91 components

WELD METAL PROPERTIES

WELD METAL METALLURGY

The weld metal chemical analysis of voestalpine Böhler Welding grade 91 welding consumables are optimized in order to fulfil standard and customer specifications as well as to guarantee an optimum of high temperature mechanical properties like creep rupture strength and impact toughness.

The weld metal chemical analysis is slightly different to the base material. Especially manganese (Mn) and nickel (Ni) differ from the base material analysis. Mn is added for deoxidation purposes and significantly influences impact toughness. Ni is also known to improve weld metal impact toughness. From a metallurgical point of view Mn and Ni are both austenite stabilizing elements. Therefore, a certain amount of Mn and Ni are essential in order to avoid the formation of delta ferrite which is detrimental to mechanical properties. However, both elements impact the ferrite to austenite transformation temperature A_{c1}. As shown in Figure 8, Mn+Ni in grade 91 weld metal decrease the transformation temperature. According to the European and AWS standards the manganese plus nickel content of grade 91 weld metal is limited to 1.4 wt. %. However, more and more customers request a Mn+Ni content ≤ 1.0 as recommended by the Electric Power Research Institute (EPRI) in the USA.

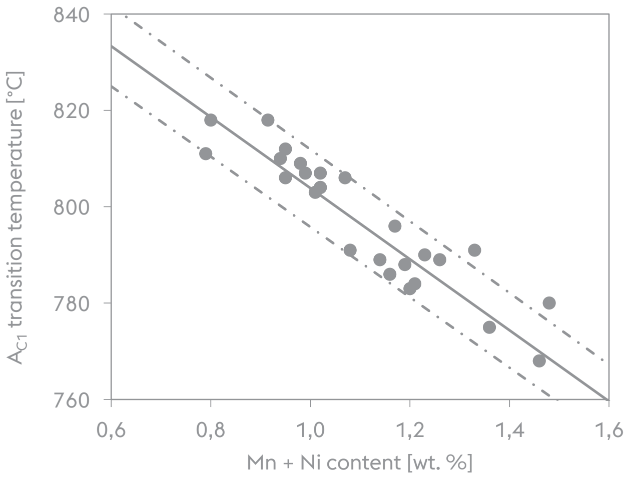


Figure 8: Impact of manganese plus nickel on A_{c1} transformation temperature in vaBW B91 type weld metal

At Mn+Ni content of 1.2 wt. % , which is the upper limit of the standard product range, the Ac1 transition temperature is above 780 °C. BÖHLER FOX C 9 MV LNi or Thermanit Chromo 9 V mod with limited Mn+Ni content of ≤ 1.0 show increased transformation temperature above 800 °C. The application of these new welding consumables increases the process window for the fabricators during PWHT.

Table 4: Chemical composition of voestalpine Böhler Welding grade 91 welding consumables

Welding process	Product name	C	Si	Mn	Cr	Mo	Ni	V	Nb	N	Mn+Ni	X-factor
		[wt. %]										
SMAW	BÖHLER FOX C 9 MV	0.1	0.2	0.6	8.5	1.0	0.5	0.2	0.05	0.04	≤ 1.2	≤ 15
	BÖHLER FOX C 9 MV LNi	0.1	0.2	0.8	9.0	1.0	0.1	0.2	0.05	0.04	≤ 1.0	≤ 15
	Thermanit Chromo 9 V	0.1	0.2	0.6	9.0	1.0	0.5	0.2	0.05	0.04	≤ 1.2	≤ 15
	Thermanit Chromo 9 V mod	0.1	0.2	0.8	9.0	1.0	0.1	0.2	0.05	0.04	≤ 1.0	≤ 15
GTAW	Thermanit MTS 3	0.1	0.3	0.5	9.0	1.0	0.5	0.2	0.05	0.04	≤ 1.2	≤ 15
	Thermanit MTS 3 LNi	0.1	0.3	0.7	9.0	1.0	0.1	0.2	0.05	0.04	≤ 1.0	≤ 15
GMAW	Thermanit MTS 3	0.1	0.3	0.5	9.0	1.0	0.5	0.2	0.05	0.04	≤ 1.2	≤ 15
	Thermanit MTS 3 LNi	0.1	0.3	0.7	9.0	1.0	0.1	0.2	0.05	0.04	≤ 1.0	≤ 15
FCAW	FOXcore C 9 MV RC	0.1	0.2	0.7	9.0	1.0	0.2	0.2	0.04	0.04	≤ 1.0	≤ 15
MCAW	FOXcore C 9 MV MC	0.1	0.3	0.6	9.0	1.0	0.7	0.2	0.05	0.04	≤ 1.4	≤ 15
SAW	Thermanit MTS 3 / Marathon 543	0.1	0.2	0.7	9.0	1.0	0.5	0.2	0.05	0.04	≤ 1.2	≤ 15
	Thermanit MTS 3 LNi / Marathon 543	0.1	0.2	0.8	9.0	1.0	0.1	0.2	0.05	0.04	≤ 1.0	≤ 15

MECHANICAL PROPERTIES AT ROOM TEMPERATURE

According to the AWS or EN classification for grade 91 all weld metal the minimum requirement on yield and tensile strength as well as Charpy impact energy depends on the welding process.

Irrespective to the weld metal classification which only reflects the all weld properties under defined conditions the mechanical properties of the weld metal must match the minimum required mechanical properties of the base material in a real welded joint. The mechanical properties of a real welded joint are influenced by the welding process, welding parameter as well as by the post weld heat treatment condition. Depending on the component, various post weld heat treatment practice or multiple post weld heat treatments can be applied. For the fabricator it is important to know how the weld metal will be influenced by prolonged or multiple post weld heat treatment. At vaBW a large number of test results are available in order to assess reliably the performance of our products. The performance of vaBW grade 91 welding consumables on yield and tensile strength at room temperature as a function of post weld heat treatment is illustrated in Figure 9.

Table 5: requirements on mechanical properties of grade 91 welding consumables according EN & AWS classification

	SMAW		GTAW / GMAW		FCAW		SAW	
	AWS 5.5	**EN ISO 3580-A**	**AWS 5.28**	**EN ISO 21952-A**	**AWS 5.36**	**EN ISO 17634-B**	**AWS 5.23**	**EN ISO 24598-A**
Classification	E9015-B91	E CrMo91	ER90S-B9	WCrMo91	E91T1-M21PY-B91	T69T1-1M-9C1MV	F9PZ-EB91-B91	SCrMo91
Yield Strength [MPa]	530	415	410	415	540	610	540	415
Tensile Strength [MPa]	620	585	620	585	620	690	620	585
Elongation [%]	17	17	17	17	17	14	17	17
Charpy Impact Energy [J]	–	47	–	47	27	–	–	47
PWHT	760 ± 15 °C 2-3 h	760 ± 15 °C 2 h	760 ± 15 °C 2 h	755 ± 5 °C 2 h	760 ± 15 °C 2 h	745 ± 15 °C 1 h	760 ± 15 °C 2 h	755 ± 5 °C 3 h

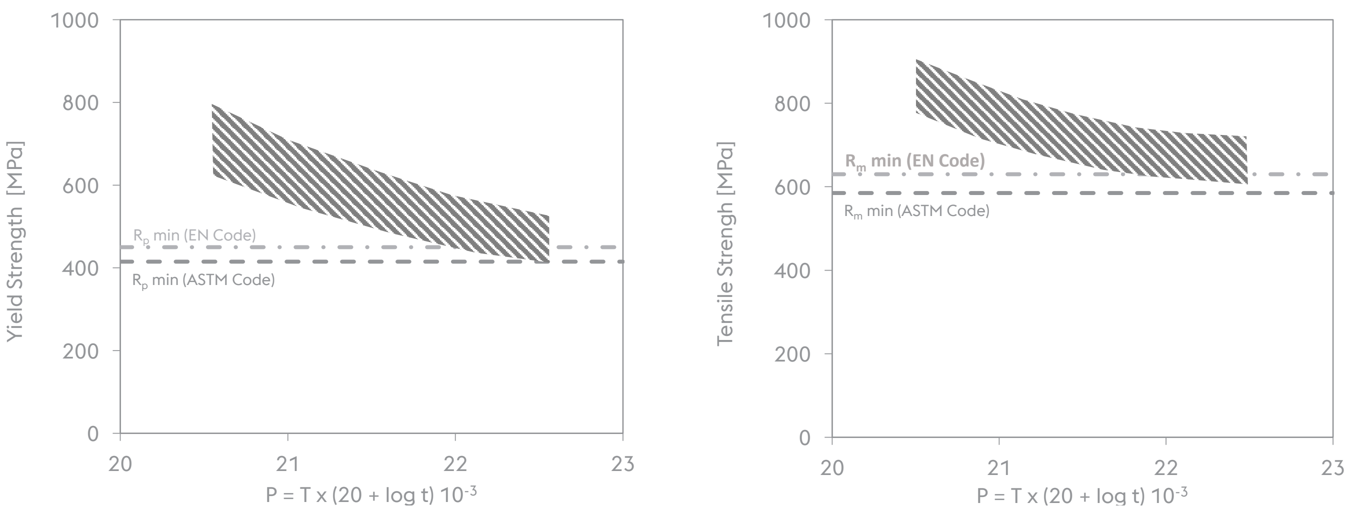


Figure 9: Impact of post weld heat treatment on yield and tensile strength of voestalpine Böhler Welding grade 91 SMAW, FCAW, GMAW, GTAW and SAW consumables

With increasing PWHT temperature or time (increasing time-temperature parameter P) the yield and tensile strength decreases as a result of tempering effects. However, vaBW welding consumables are optimized in order to withstand multiple PWHT cycles. Up to time-temperature Parameter P ≤ 21.8, which is equivalent to a holding time of 12 h at 760°C, the yield and tensile strength is certainly above the minimum requirements for the base material according to EN and ASTM code.

The Charpy impact energy is much more sensitive to tempering and the welding process than strength. The best impact energy values are typically achieved by GTAW as a result of the very low oxygen content. At similar PWHT conditions the impact energy increases from FCAW/GMAW over SAW and SMAW to GTAW (Figure 10).

Depending on the welding parameter, weld metal chemistry, bead sequence, layer thickness, base material quality, etc. a scattering of 15 to 30 % is possible. Thus, a welding process specific PWHT is required in order to guarantee a minimum in impact energy (e.g. 47J according to EN standard).

In order to optimize impact toughness of grade 91 weld metal during multi pass welding a welding technique that ensures small layer thickness of maximum 2 mm should be applied. This can be realized by applying a stringer bead or minor weaving and/or increased welding speed. Furthermore, heat input should be limited to a maximum of 1.8 kJ/mm (Figure 11).

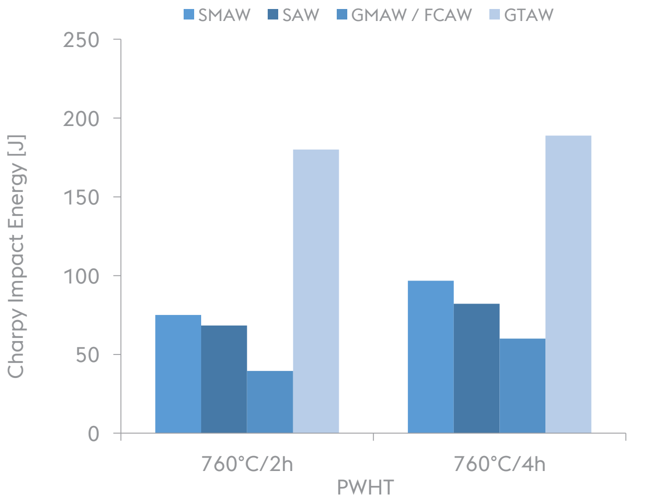


Figure 10: Charpy impact energy of B91 welding consumables after PWHT 760°C/2 h and 760°C/4 h

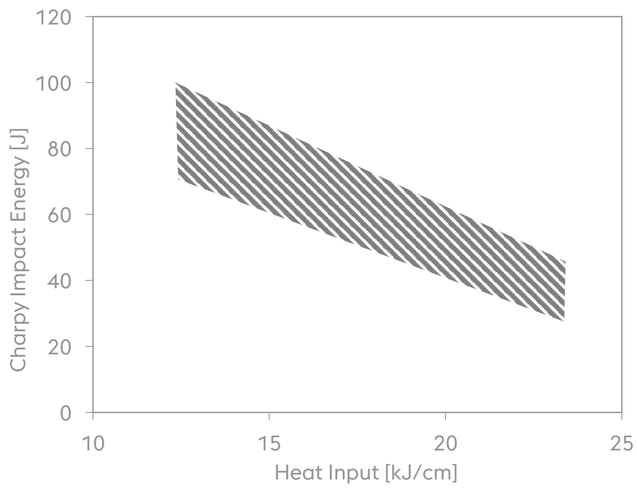


Figure 11: Effect of heat input on impact energy of Thermanit MTS 3/ Marathon 543 wire flux combination

Table 6: recommended PWHT for voestalpine Böhler Welding grade 91 welding consumables

Welding process	SMAW	FCAW / GMAW	SAW	GTAW
PWHT	760 °C / ≥ 2 h	760 °C / ≥ 3 h	760 °C / ≥ 4 h	760 °C / ≥ 2 h

HARDNESS

Hardness can be used as an indicator to check the quality of grade 91 steel. As other mechanical properties hardness can be influenced by chemical composition as well as thermal history of the material. The hardness of grade 91 base material (as-delivered condition) should be in the range of 190 HB to 250 HB (200 to 260 HV). For the weld metal and component hardness after proper PWHT values up to 280 HB (295 HV) should be acceptable. Within the heat affected zone locally higher and lower hardness values are possible due to the metallurgical feature of the coarse, fine grain and intercritical heat affected zone, respectively.

MECHANICAL PROPERTIES AT ELEVATED TEMPERATURE

Grade 91 is intended to be used for high temperature applications operating at service temperatures between 500 and 600 °C or even above. Therefore, the mechanical properties at high temperatures are an essential characteristic of the weld metal. Nevertheless, short term properties as measured by a conventional tensile test do not reflect the long term performance under creep conditions.

For tempered martensitic 9 % Cr steels like grade 91 the creep regime starts at temperatures above around 500 °C. A large number of high temperature tensile tests are carried out up to a test temperature of 660 °C. The scatter field as indicated in Figure 12 reflects the various welding processes, welding parameter, typical PWHT conditions (760 °C / 2-4 h) as well as batch to batch variations.

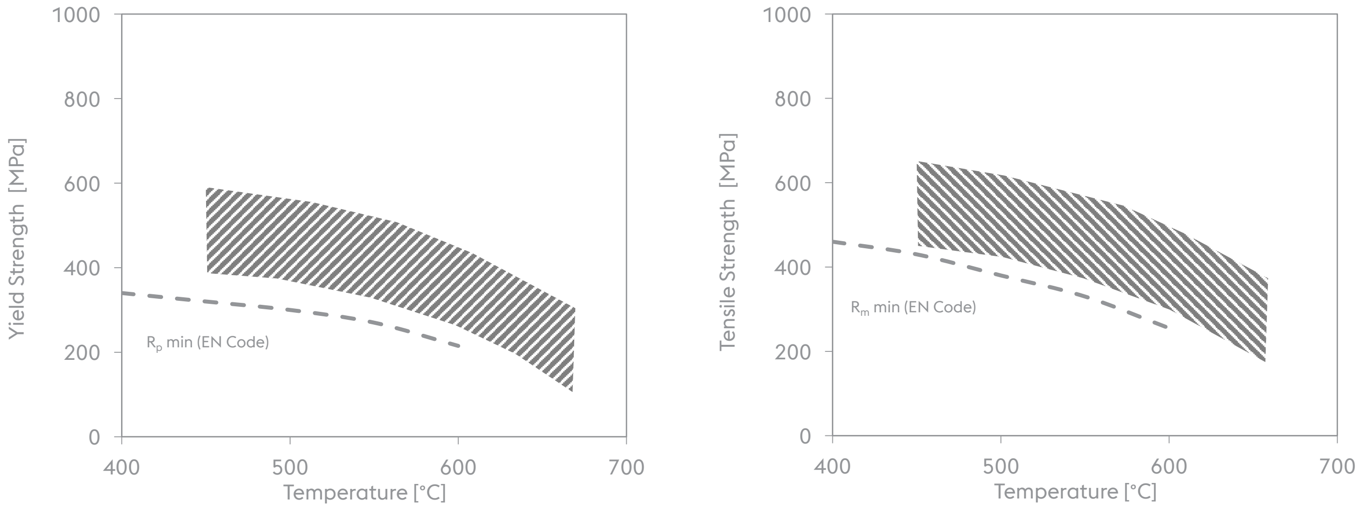


Figure 12: High temperature tensile test data for SMAW, GMAW, FCAW, GTAW and SAW all weld metal

All test results are well above the minimum requirement of the base material. Tensile test on welded joints in transversal direction commonly show failure location in the base material. The impact of post weld heat treatment on the high temperature tensile test performance at 550 °C is shown in Figure 13. Again, the scatter field includes test results on SMAW, GMAW, FCAW, GTAW and SAW all weld metal and reflects various welding conditions.

voestalpine Böhler Welding grade 91 welding consumables can withstand prolonged or multiple PWHT. Up to a time-temperature parameter P ≤ 21.8 the minimum requirement on tensile and yield strength according to the EN codes are fulfilled.

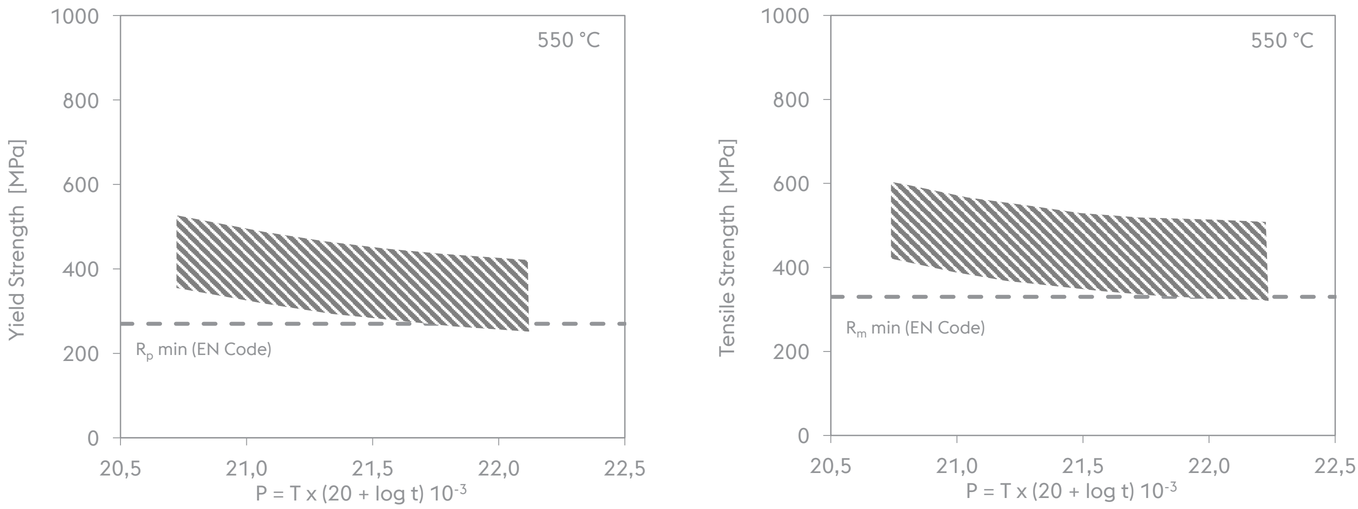


Figure 13: Impact of PWHT on high temperature tensile test result at 550 °C for SMAW, GMAW, FCAW, GTAW and SAW all weld metal

CREEP RUPTURE PERFORMANCE

Creep rupture test are essential in order to evaluate the long term performance of high temperature service products like sheets, tubes, pipes and welding consumables. It is a common practice to perform creep rupture tests at various test temperatures and proof stresses and apply extrapolation techniques to evaluate the long term creep rupture strength e.g. for 100.000 h. Since the extrapolation factor is limited to a maximum of 3 (e.g. ECCC recommendations) creep rupture test data with a minimum test duration of 30.000 h are necessary for reliable extrapolations. It has always been the philosophy of voestalpine Böhler Welding to generate large creep rupture data sets in order to qualify our products for long term service under severe conditions. Today, we have more than 2.7 million accumulated creep test hours available. Both on all weld metal and welded joints. The longest still ongoing test on a welded joint passed 200.000 hours at 600 °C in 2020.

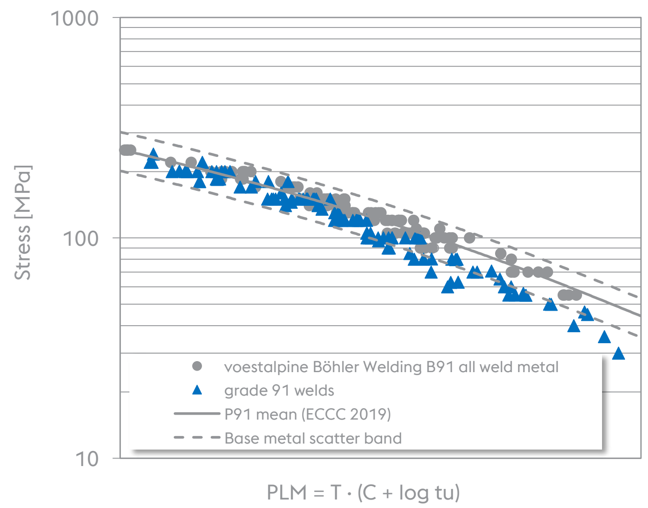


Figure 15: results of creep rupture test on voestalpine Böhler welding B91 all weld metal & grade 91 welded joints

A comprehensive illustration of creep rupture tests on voestalpine Böhler Welding grade 91 welding consumables is shown in Figure 14. The Larson-Miller diagram includes creep tests on all weld metal from 550 – 650 °C with single test duration of more than 56.000 h.

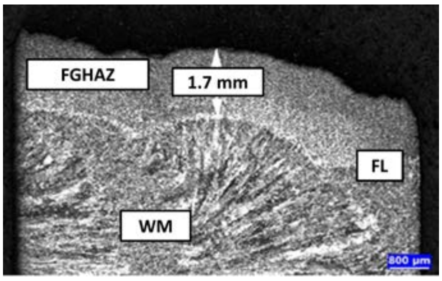


Figure 16: Location of fracture within fine grained heat affected zone of P91 weld creep test sample (600°C/50MPa/55.438h)

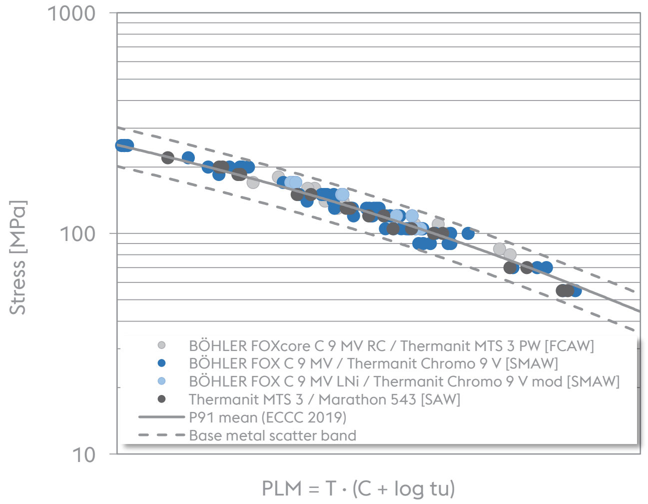


Figure 14: Results of creep rupture tests on voestalpine Böhler Welding B91 all weld metal

All data points are within the scatter band of the base material according to the 2019 ECCC creep rupture data assessment. There is no significant difference between the creep rupture strength of the various welding processes. Furthermore, the creep rupture strength of the low nickel products BÖHLER FOX C 9 MV LNi and Thermanit Chromo 9 V mod is on the same level as for the standard products.

It is well known that creep strength enhanced ferritic steels like grade 91 suffer from premature failure within the heat affected zone during long term testing under creep conditions (Figure 15 and 16). This phenomenon is sometimes called Type IV cracking and is a metallurgical consequence of the welding process and cannot be avoided. For the design of high temperature components it has to be taken into consideration as far as high stresses are distributed in transversal direction to the weld seam e.g. in longitudinally welded pipes.

Long term tests on welded joints with test duration of more than 200.000 h confirmed that voestalpine Böhler Welding grade 91 welding consumables show sufficient creep rupture strength and do not promote premature failure within the weld metal.

Figure 17: Grade 91 tee-connection manufactured by shielded metal arc welding

DISSIMILAR WELDING GRADE 91

During the fabrication of high temperature components numerous dissimilar welds have to be completed during the workshop and on-site fabrication. Possible are dissimilar welds between different ferritic steels like grade 22 to grade 91 or dissimilar welds between grade 91 and austenitic steels or nickel alloys. The choice of the right welding consumable is essential in order to produce high quality dissimilar welds. The metallurgical behavior, mechanical properties as well as physical properties of the base materials and weld metal have to be taken into consideration. Furthermore, preheat, interpass temperature and post weld heat treatment practice must be aligned to the specific base materials and welding consumables

WELDING GRADE 91 TO UN- AND LOW-ALLOYED STEELS

As a general rule of thumb for welding dissimilar ferritic to ferritic steels it can be recommended to use a welding consumable that matches the lower alloyed partner. Although using a higher alloyed welding consumable is possible and has the advantage of significant improved significant improved toughness properties and improved weldability.

The biggest challenges for welding grade 91 to low alloyed steels are the different post weld post weld heat treatment temperatures. Depending on the applicable code and wall thickness different minimum PWHT holding temperatures are mandatory. E.g. ASME BPVC Section I requires a minimum PWHT holding temperature of 705°C for dissimilar welds involving filler metals with less than 3% chromium. However, this is above the maximum holding temperature for un-alloyed and most low-alloyed steels due to the significant reduction in strength during high temperature PWHT.

Furthermore, carbon migration from the low to the high alloyed metal might lead to decarburized soft zones in the lower alloyed metal and to carburized hard zones in the higher alloyed metal. This effect cannot be avoided but minimized through an aligned PWHT. It becomes clear that the PWHT temperature is a compromise and should be carried out at the lowest temperature as recommended for the higher alloyed material.

A very common dissimilar weld is grade 91 to grade 22. Here, a B3 or B91 type welding consumable has been approved in many welding procedure specifications. Using the B3 type welding consumable bears the advantage of superior toughness compared to the B91 type. A PWHT at 710 – 730 °C is sufficient to temper the P91 HAZ without over-tempering the P22 material or weld metal. Using a B91 type welding consumable might require slightly higher temperatures (730-750°C) in order to achieve sufficient impact energy values of the weld metal. Long-term creep rupture testing on P91-P22 welded with B3 and B91 filler metal reveals negligible variation in rupture life.

Dissimilar welding of grade 91 to un-alloyed or low alloyed steels with less than 2.25% chromium is not recommended due to the fact that the PWHT temperature of at least 705 °C will over-temper the un- or low alloyed steel. Here, a transition piece or a special buffer technique involving low alloyed or nickel based welding consumables in combination with specific PWHT is required.

WELDING GRADE 91 TO OTHER TEMPERED MARTENSITIC 9-12 % CR STEELS

Welding grade 91 to other tempered martensitic 9-12 % Cr steels like grade 92, X20, TP122 or VM12-SHC is comparatively simple due to the metallurgical similarities and similar PWHT practice. In any case, B91 welding consumables can be recommended.

WELDING GRADE 91 TO AUSTENITIC STEELS AND NICKEL ALLOYS

For welding dissimilar welds between grade 91 and austenitic steels or nickel alloys it is mandatory to use nickel base welding consumables. Due to embrittlement effects during PWHT or elevated temperature service above 300 °C, it is not recommended to use austenitic welding consumables like 309 type, which are commonly used for dissimilar ferritic to austenitic welds for ambient temperature applications. Nickel base welding consumables commonly suffer from hot cracking tendency. They should be welded with controlled heat input as cold as possible. However, grade 91 requires a minimum preheat practice of at least 150 °C.

It is common practice to apply pre-heating to the grade 91 component, only. For thick walled components it is recommended to butter the grade 91 side with the nickel base welding consumable Thermanit Nicro 82 or Thermanit Nicro 182 followed by an ordinary PWHT. Then, the welding to the austenite or nickel alloys can be performed by using the same nickel base welding consumable as used for the buffering. Thin walled components can be directly welded using Thermanit Nicro 82 or Thermanit Nicro 182 as long as the austenitic steel is not negatively affected by PWHT.

Precaution must be taken in order to limit the heat input e.g. through application of stringer beads, welding parameter (HI ≤ 1.2 kJ/mm), and use of thin electrode diameter for SMAW process.

In general, all welding processes can be applied for dissimilar welding of grade 91 to austenitic steels or nickel alloys. Table 7 gives an overview on voestalpine Böhler Welding GTAW filler metals only, for the sake of convenience.

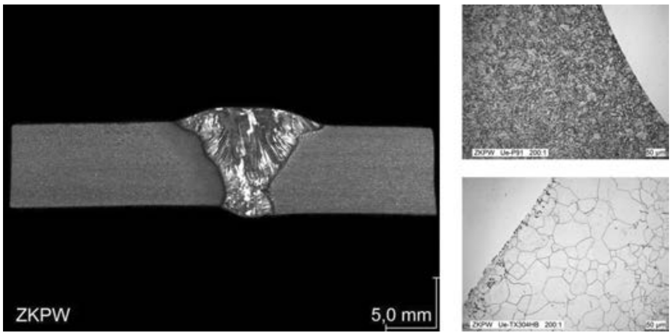


Figure 18: Grade 91 to Super 304H dissimilar joint welded with Thermanit Nicro 82

Table 7: Welding consumable selection guide for welding dissimilar welds involving grade 91

Grade 91 welded to	Filler metal type	Product name (GTAW)	Preheat temperature [°C]	Interpass temperature [°C]	PWHT holding temperature [°C]
Grade 22	B3	**Böhler CM2-IG**	≥ 200	≤ 300	710-730
Grade 23	B23	**Union I P23**	≥ 200	≤ 300	730-750
Grade 24	B24	**Union I P24**	≥ 200	≤ 300	730-750
Grade 91	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 300	750-770
Grade 92	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 300	750-770
Grade 93	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 280	750-780
X20	B9	**Thermanit MTS 3 (LNi)**	≥ 250	≤ 300	750-770
Grade 122	B9	**Thermanit MTS 3 (LNi)**	≥ 250	≤ 300	750-770
Thor 115	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 280	750-770
VM12-SHC	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 280	760-780
Super VM12	B9	**Thermanit MTS 3 (LNi)**	≥ 200	≤ 280	760-780
Austenitics	ERNiCr-3	**Thermanit Nicro 82**	≥ 180	≤ 250	740-770
Nickel alloys	ERNiCr-3	**Thermanit Nicro 82**	≥ 180	≤ 250	740-770

APPROVALS

voestalpine Böhler Welding puts high effort into validating the promised properties of our welding products. Beside our production plant quality assurance program most of our welding consumables for high temperature applications are approved by third party authorities like VdTÜV. Approved welding consumables are mandatory for the erection of pressure vessels within Europe and some other countries.

The approval procedure involves a complex test program on weld metal properties and welded joints including long term creep rupture tests and annual re-qualification.

It is our customers benefit to be delivered with reliable and approved welding consumables.

Table 8: List of approved grade 91 welding consumables (status: April 2020)

Welding process	Product name	Approval
SMAW	**BÖHLER FOX C 9 MV**	VdTÜV (09168), CE
SMAW	**Thermanit Chromo 9 V**	VdTÜV (06173), IBR, CE
GTAW (welding wire and rod)	**Thermanit MTS 3**	VdTÜV (06166), CE
FCAW	**FOXcore C 9 MV RC**	VdTÜV (19235)
SAW (wire flux combination)	**Thermanit MTS 3 / Marathon 543**	VdTÜV (06527), CE

The range of approvals (NAKS, IBR, etc.) might be extended on request.

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The Management System of voestalpine Böhler Welding Group GmbH, Peter-Mueller-Strasse 14-14a, 40469 Duesseldorf, Germany has been approved by Lloyd's Register Quality Assurance to: ISO 9001:2015, ISO 14001:2015, OHSAS 18001:2007, applicable to: Development, Manufacturing and Supply of Welding and Brazing Consumables.
More information: www.voestalpine.com/welding

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