

GMAW of creep resistant steels

perspectives and limitations

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Flux cored Arc Welding (FCAW) is both an evolving arc welding process and an already very well established process in the field of unalloyed and high alloyed steels – and is now also being adapted for creep resistant steels. This paper focuses on the weldability of creep resistant steels of type P11, P12, P22, P91 and P92 using similar flux cored wires. Using sets of weld-metal data and discussing short-term and long-term creep design, this article points out the advantages of the FCAW process compared to SMAW and GMAW but it shows also the limitations of its application.

Introduction

FCAW has, compared to other welding processes, some general benefits that are very well recognised by welders, such as easy handling, higher productivity and a significant lower risk of defects such as porosity and lack of fusion. This explains its increasing use in joining of un- and high-alloyed standard steel grades. Nevertheless there is also a strong market-driven force for FCAW of more sophisticated steels such as creep resistant steels.

FCAW

Flux cored wires are tiny tubes which are filled with various metallic and non-metallic powders to optimise the metallurgy and chemistry of the weld metal and to produce fluxes which enable some special welding features. The production of flux cored wires is, compared to other electrode types, much more complicated. The most common process route is shown in *Figure 1*. A metal strip is formed into a U-shape before it is filled with specially formulated and mixed powders. Afterwards the shape is completely closed and undergoes several drawing operations to the specified final wire diameter, which is comparable to common solid wires.

In *Figure 2* a rough comparison to stick electrode and solid wire is shown: flux cored wires are delivered on similar baskets as solid wires for use in Gas Metal Arc Welding (GMAW). Similar welding equipment is used to that for solid wire GMAW and the state-of-the-art application in automatic and robotic welding systems is possible.

Additionally, the filling of flux cored wire can provide the

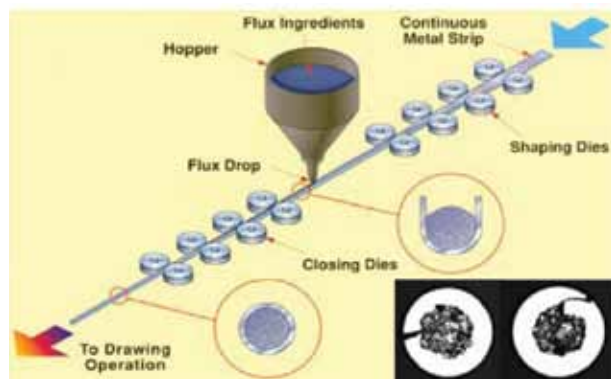


Figure 1: Manufacturing schematic for flux cored wires.

GMAW process with the beneficial effects of the Shielded Metal Arc Welding (SMAW) process: slag metallurgy, protection of the weld pool from the surroundings by the slag covering and improved out-of position weldability.

Additional flux cored wires can be designed with a self-releasing slag as shown in an example in *Figure 3*, which reduces the non-productive time during welding to a minimum.

The special, tube-like design of flux cored wires, in combination with optimised metallurgy and fluxes, provide beneficial properties like a stable arc, higher penetration, spatter-reduced welding behaviour, wider parameter tolerances and higher deposition rates in combination with faster travel speeds.

Economic aspects of FCAW

One of the most often discussed questions in flux cored welding is based on economic considerations. Due to the

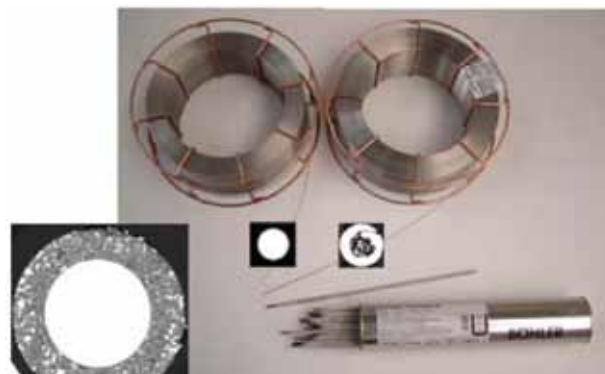


Figure 2: Comparison of the cross-section of stick electrode, solid wires and flux cored wires.



Figure 3: Self-releasing slag design of a flux cored wire – Böhler CM2 Ti-FD (E 91T1-B3M).

with flux cored wires —

more difficult production route and the necessity of using more expensive raw materials, the costs of cored wires are higher compared to stick electrodes or solid wires. Economic evaluation is often only based on the comparison of the purchasing costs for similar amounts of different electrode types. But flux cored wires have welding benefits that also have to be considered, benefits that decrease the time required to complete a joint because of less rework and faster achievable welding speeds. Also the possibility of using common shielding gases or welding machinery without sophisticated pulsed arc technology have to be taken into account.

It's not the aim of this paper to give a detailed view on economic calculations because this depends strongly on the application and available welding infrastructure, but the major points should be pointed out to show the remarkable potential of FCAW.

In general, higher deposition rates and faster travel speeds can be achieved with flux cored wires. In *Figure 4*, a comparison over a given welding time (100 s) between a stick electrode (E8018-B2 Ø4,0 mm; 150 A), a solid wire (ER80SG (Ø1,0 mm; 160 A) and flux cored wire (Böhler DCMS Ti-FD (E81T1-B2M) Ø1,2 mm; 245 A) for out-of position welding (position PF) is shown.

More impressive is the comparison of the welding time required for real joints as shown for welds of length one metre in *Figure 5*. The welding position in this case was also PF, the thickness of the sheet (ASTM A335 Gr.1) was 20 mm, the bevel preparation was 60°C and the root pass was already welded with flux cored wire (Böhler DMO Ti-FD (E81T1-A1M)) on ceramic backing.

The parameter settings were according to common welding procedure for stick electrodes (E7018-A1, Ø3,2 mm; 100 A, Ø4,0 mm; 150 A), solid wire (ER70S-A1 Ø1,0 mm; 125-150 A) and flux cored wire (Böhler DMO Ti-620 FD (E81T1-A1M), Ø1,2 mm; 190-230 A).

These two comparisons give some idea of the savings in welding time that can be achieved when optimised parameters are applied. It is open for the interested reader to offset the savings in reduced welding time against the higher purchasing costs of the flux cored electrodes.

Creep resistant steels

Creep resistant steels are designed to operate at elevated temperatures for very long times. Therefore steel microstructures with high amounts of stable precipitates – carbides and nitrides embedded in a strong bainitic or martensitic matrix – are required. Such microstructures can be achieved with a very well balanced chemistry of carbon, chromium, molybdenum and some special elements like vanadium, aluminium, columbium and/or boron, as shown in *Table 1* for the common grades of creep resistant steels.

But these complex creep resistant microstructures are very sensitive to any kind of heat treatment, which also has to be considered in the design for filler materials and in the selection for a necessary post weld heat treatment required to improve the mechanical properties of the weld or for stress relieving reasons. All changes in the microstructure, however,

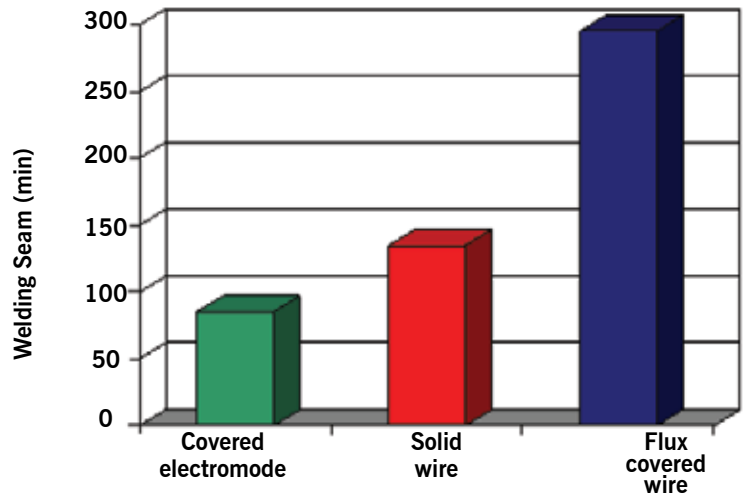


Figure 4: Achieved weld seam length ($a=8$ mm) for a welding time of 100 s, welding position PF, base metal ASTM A335 Gr. P11.

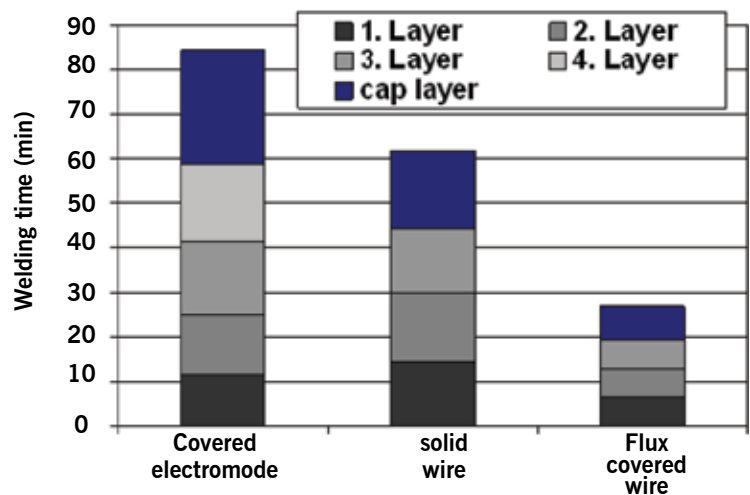


Figure 5: Welding time for a one metre joint, base metal, ASTM A335 Gr.1; welding position: PF.

have to be evaluated with regard to their influence on the long-term high temperature behaviour of the weld.

Low alloyed Chromium-Molybdenum steels with bainitic microstructures like P11 or P22 were the first to be able to cope with steam temperatures above 500°C. Their creep rupture strength is mainly based on the formation of stable chromium carbides. In the design of rutile flux cored wires for these Cr-Mo alloys, the influence of a post weld heat treatment (PWHT) on the mechanical short-term properties is one of the most dominant features – especially the toughness, but also the tensile and yield strengths of the weld are strongly influenced by the annealing temperature and holding time. For a general description of the influence of a PWHT, the Larson-Miller parameter (LM-parameter) can be used. In this equation, T represents the annealing temperature in Kelvin and t, the holding time in hours.

$$LM = T \times (20 + \log t) / 10^3 \quad (1)$$

This parameter appears useful for describing the influence of a PWHT on the mechanical short term properties of a weld

ASTM Grade	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	Other
T/P1	0,12-0,20	< 0,35	0,40-0,90	< 0,30	< 0,30	0,25-0,35	-	-	-	-
T/P12	0,08-0,18	< 0,35	0,40-1,0	0,7-1,15	-	0,40-0,60	-	-	-	-
T/P22	0,08-0,14	< 0,50	0,40-0,80	2,0-2,5	-	0,90-1,10	-	-	-	-
T/P91	0,08-0,12	0,20-0,50	0,30-0,60	8,0-9,5	< 0,40	0,85-1,05	0,18-0,25	-	0,06-0,10	N 0,030-0,070
T/P92	0,07-0,13	< 0,5	0,30-0,60	8,5-9,5	< 0,40	0,30-0,60	0,15-0,25	1,5-2,0	0,04-0,09	N 0,03-0,07 B 0,001-0,006

Table 1: Main alloying elements in standard creep resistant steel types [1].

Steel	Flux cored wire				
	Brand (Bohler)	Brand-T-PUT	AWS A5.29	EN ISO 17634-A	EN ISO 17634-B
P1	DMO Ti-FD	UNION TG MO R	E81T1-A1M	T MoI P M 1	-
P11	DCMS Ti-FD	UNION TG CrMO R	E81T1-B2M	T CrMo1 P M 1	
P12	DCMS Ti-FD	UNION TG CrMO R	E81T1-B2M	T CrMo1 P M 1	
P22	CM2 Ti-FD	UNION TG CrMO 910 R	E91T1-B3M	T ZCrMo2 P M 1	
P91	C9MV Ti-FD	Thermanit MTS 3 PW	E91T1-B9M	T CrMo9VNb P M 1	T 69 T1-1M-9C1MV
P92	P92 Ti-FD	Thermanit MTS 615 PW	E91T1-GM	T CrMo9VNb P M 1	T 69 T1-1M-9C1MV

Table 2: Flux cored wires for creep resistant Bainitic/Martensitic steels.

metal but it does not suit all creep resistant weld metals – a scientific discussion that is beyond the scope of this article.

Higher creep rupture strength could be realized by increasing the chromium content above 7% which leads to a steel group with a martensitic microstructure characterised by a high dislocation density and a fine martensite lath structure, which is stabilised by M23C6 precipitates. Fur-

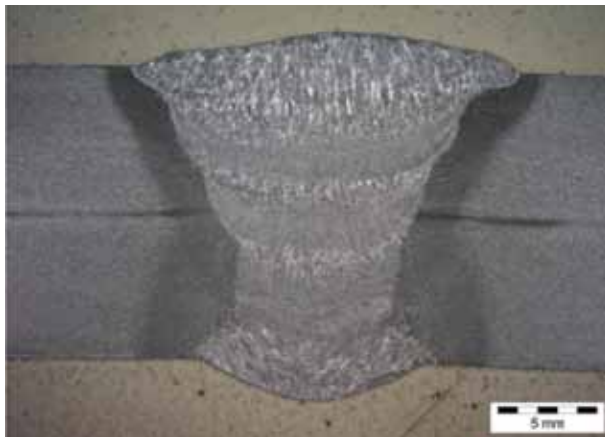


Figure 6: The cross section of a P1 joint welded with Böhler DMO Ti-FD (E81T1-A1M) flux cored wire and the Ar 18% CO₂ shielding gas mixture.

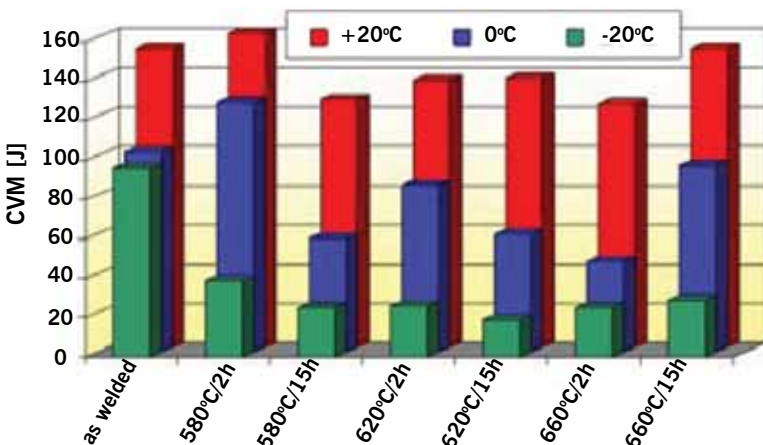


Figure 7: Influence of various PWHTs on the toughness of flux cored all weld metal produced using Böhler DMO Ti-FD (E81T1-A1M) wire.

ther improvement of creep strength has been achieved by alloying with vanadium and niobium in P91 based on the precipitation of finely dispersed Nb/V-carbonitrides of type MX. P91, introduced about 30 years ago in the USA, is a well known steel and is applied in power plants all over the world that operate

at pressures of up to 300 bar and temperatures of 600°C.

P92 was originally developed in Japan as NF616. It contains about 2% tungsten and is additionally alloyed with boron. To avoid the formation of δ-ferrite, the molybdenum content has been reduced to about 0,5%. It was first believed that tungsten acts mainly as a solution hardener but it has since been discovered that most of the tungsten precipitates as Lave’s phases during service operation. The benefit of boron is believed to decrease the coarsening rate of carbides.

These steels are standardised in ASTM and their chemical composition is listed in Table 1. As the bainitic/martensitic CrMo-steels tend to temper and are susceptible to creep embrittlement, a loss of toughness over time under service conditions is experienced. The metallurgical reason for this embrittlement is the diffusion of certain elements to the grain boundaries. Many solutions were attempted to keep this detrimental phenomenon under control. The most well established is the J-factor according to Watanabe.

$$J = (Mn+Si) \times (P+Sn) \times 10^4 \quad (2)$$

The J-factor was originally developed for the base material as Mn and Si tend to co-segregate with P and Sn, which was blamed for the loss in toughness. To prevent this a maximum allowable J-factor was defined.

As Mn and Si are needed in weld metal metallurgy to achieve acceptable mechanical properties and weldability and because of the different solidification of weld metal, the transfer of knowledge gathered from base material investigations regarding the J-factor to the weld metal has to be handled carefully [2]. Nevertheless some specifications require a J-factor < 150 or even < 120 derived from the base metal specifications. More significant for the description of the chemistry of weld metal is the X-factor according to Bruscatto [3]. Elements used in this formulation are expressed in ppm.

$$X = (10P+5Sb+4Sn+As) \times 10^{-2} \quad (3)$$

A further popular characteristic for evaluation of temper embrittlement susceptibility is the so-called 54J transition temperature concept at -20°C or even -40°C after a step cooling process – also called step age heat treatment. The test

specimen has to undergo a specially defined PWHT which should simulate embrittlement during long term service. The toughness at the mentioned low temperatures is then measured and compared to the toughness after a standard PWHT.

Flux cored wires for creep resistant steels

As earlier discussed, FCAW is similar to GMAW with the solid wire electrode being replaced by a flux cored wire. As known from GMAW, various shielding gases can be used. Due to the presence of a slag the influence of the shielding gas on the mechanical properties, penetration and the wetting behaviour of the weld metal is not that strong when compared to solid wire welding, but some effects are evident.

Hence, in contrast to solid wire welding, FCAW relies mainly on two shielding gas compositions: Ar/CO₂ mixtures with 15-25% CO₂ and pure CO₂.

In the case of creep resistant flux cored wires, the mixed gases provide significantly better mechanical weld metal properties and should always be selected for such applications. As can be seen in Figure 6, the mixed gas provides very good penetration and very smooth wetting without any tendency to lack of fusion.

To achieve the general benefits of FCAW as described earlier, the creep resistant flux cored wires are designed primarily as rutile wires, but to achieve the mechanical properties, the amount of basic components is increased.

For the standard creep resistant bainitic/martensitic steels, a set of flux cored wires are available. Brackets around

the classification show that the very high all weld metal toughness, specified by the classification after a very short annealing time, cannot be completely achieved.

The 'Z'-classification in EN ISO 17634-A should point out that these wire-types are, as yet, not included in this standard.

Properties of creep resistant FCAW weld metal 0,5% Mo

As already mentioned, PWHT has an important influence on the mechanical properties, especially on the toughness. As can be seen in Figure 7 this influence is clearly visible at lower temperatures. It can be traced back to the rutile system and is also well known from stick electrode welding.

This issue could be overcome by using basic flux cored wires, but this, on the other hand, reduces some of the big advantages of FCAW, like out of position weldability, easy slag removal, economic benefits, spatter-free welding and easy handling.

1% Cr 0,5% Mo

In Figure 8 and Figure 9, the influence of a PWHT on the mechanical properties of the flux cored weld metal of Böhler DCMS Ti-FD (E81T1-B2M) for joining of 1% Cr0,5% Mo steels is shown.

It can be seen that a very good correlation in case of the tensile strengths exists but the toughness could not be readily described. The significant influence of a PWHT, however, can

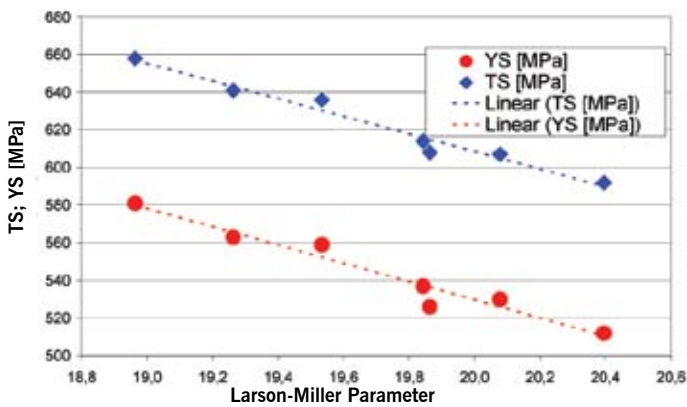


Figure 8: Relationship between the LM-parameter and the yield and tensile strength depending on PWHT-conditions for the rutile flux cored all weld metal from Böhler DCMS Ti-FD (E81T1-B2M) wire.

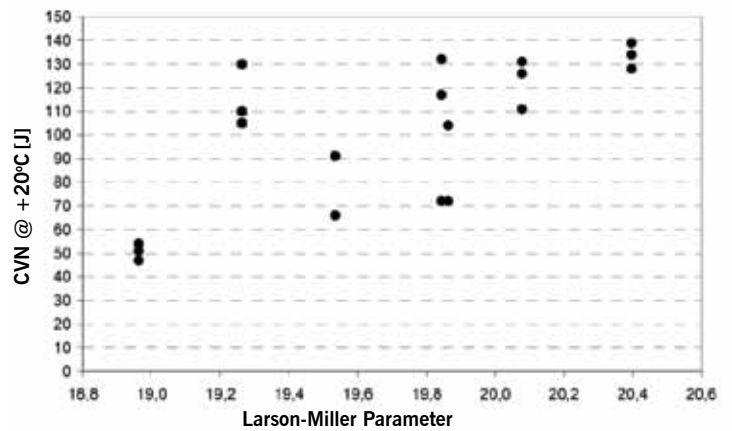


Figure 9: Relationship between the LM-parameter and toughness at room temperature depending on PWHT for the rutile flux cored all weld metal from Böhler DCMS Ti-FD (E81T1-B2M) wire.

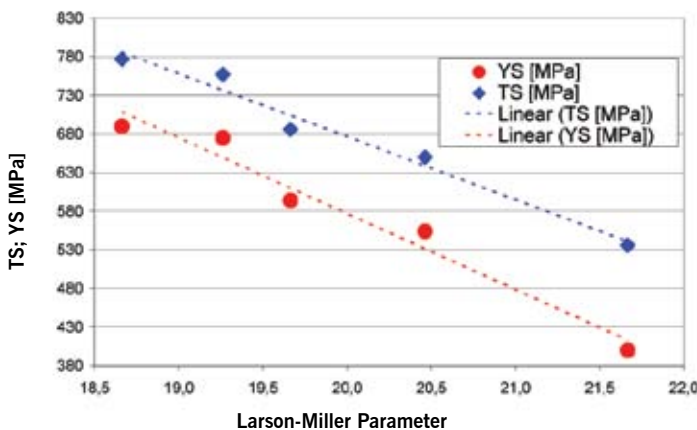


Figure 10: Relation between LM and yield and tensile strength depending on PWHT-conditions for the rutile flux cored all weld metal from Böhler CM 2 Ti-FD (E 91T1-B3M) wire.

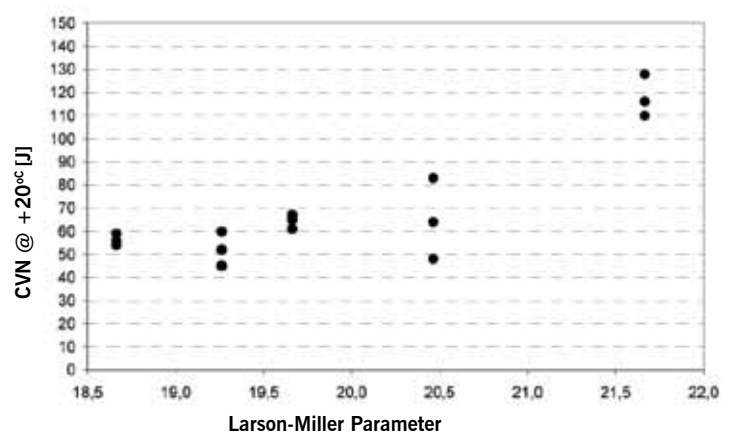


Figure 11: Relation between LM and toughness at room temperature depending on PWHT for the rutile flux cored all weld metal from Böhler CM 2 Ti-FD (E 91T1-B3M) wire.

be seen in this graph. The higher the annealing time and the longer the holding time, the higher the toughness and the lower the strength of the weld metal.

The J-factor of Böhler DCMS Ti-FD (E 81T1-B2M) weld metal is usually in the range of 120-160, while the X-factor is about 15 ± 2 . The 54J transition temperature concept can not be applied due to the rutile slag.

2,25% Cr 1% Mo

A similar interpretation can also be drawn for the 2,25% Cr 1% Mo types. In Figure 8 the relation between Larson-Miller parameter and tensile and yield strength depending on the PWHT and in Figure 9 the relation between Larson-Miller parameter and toughness depending on the PWHT of the all weld metal of a rutile flux cored wire Böhler CM 2 Ti-FD [E 91T1-B3M / T ZCrMo2 P M 1] are shown.

The J-factor and the X-factor of Böhler CM 2 Ti-FD (E 91T1-B3M) weld metal are in the same range as that mentioned with the previous types.

9% Cr 1% Mo 0,2% V 0,08% Nb

The investigation of the corresponding P91-flux cored weld metal pointed out a similar behaviour as already mentioned with the previous types (Figure 12, 13).

Beside these short term properties, the long term behaviour of the weld metal is of great interest. Therefore a long-term creep testing programme with all weld metal was initiated, based on the results of an ongoing creep rupture pre-study at 600°C, in which the specimens were running for about 22 000 hours. All specimens tested in this pre-study are considerably above the lower scatter band of the base metal and slightly above the values for SMAW weld metal [4].

9% Cr 1,8% W 0,5% Mo 0,2% V 0,08% Nb

Böhler P92 Ti-FD is the latest development of creep resistant flux cored wires. As shown in Figure 14, one of the main criteria, toughness, is also on a very high level for this type of steel, while tensile strengths also remain within the limits.

This flux cored weld metal is also incorporated in the long term creep testing programme.

Conclusions

Rutile flux cored wires have benefits which make them very attractive for welders and welding engineers. The application

References

- [1] Specification for seamless ferritic alloy-steel pipe for high temperature service SA-335/SA-335M: 2007 Section II, Part A, P. 561-574.
- [2] R Fuchs: Chrome-Moly and the Embrittlement Factors; Internal Report 1995.
- [3] R Bruscatto: Temper Embrittlement and Creep Embrittlement of 2¼ Cr-1Mo Shielded Metal Arc Weld deposits; Welding Research Supplement; April 1970.
- [4] H Heuser, R Fuchs and B Hahn: Properties of matching filler metals for T91/P9; In Conference Proceedings; EPRI-RRAC Fifth International Conference on Welding and Repair Technology for Power Plants; 2002; 4-1.

of FCAW for the welding of creep resistant steels is a huge metallurgical challenge but it can be shown that flux cored wires meet the technical requirements. The rutile flux cored concept has limits only in the case of toughness requirements at below room temperature. Furthermore, rutile flux cored weld metals have to cope with slightly higher levels of impurity as compared to solid wire and basic stick electrode welds, but in the acceptable range.

These investigations have shown that most of the common specifications can be met with flux cored wires and the benefits of flux cored arc welding can be transferred to most of the creep resistant welding tasks.

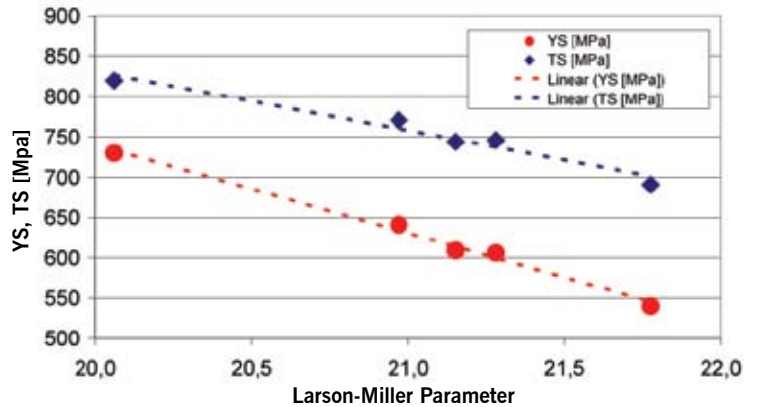


Figure 12: Relationship between the LM-parameter and yield and tensile strength depending on PWHT-conditions for the rutile flux cored all weld metal Böhler C9MV Ti-FD (E 91T1-B9M) wire.

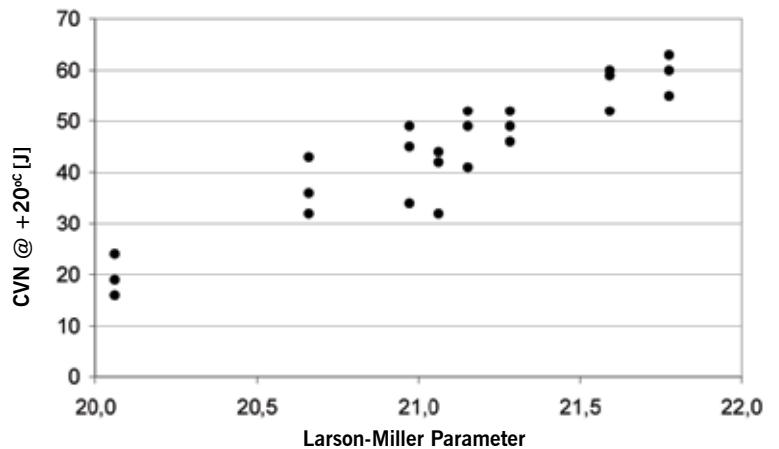


Figure 13: Relationship between the LM-parameter and toughness at room temperature depending on PWHT for the rutile flux cored all weld metal Böhler C9MV Ti-FD (E 91T1-B9M) wire.

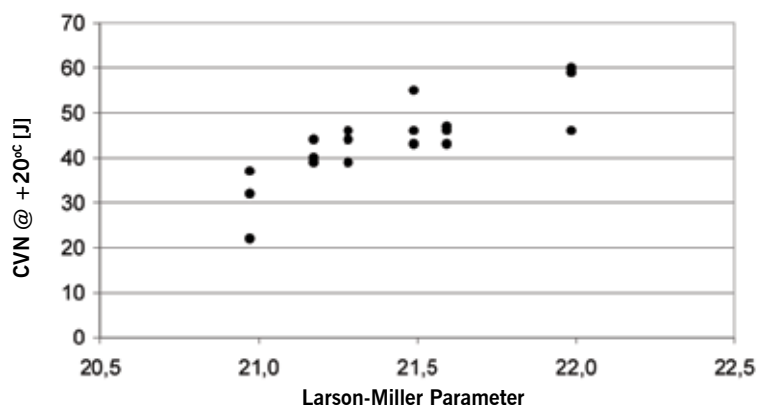


Figure 14: Relationship between the LM-parameter and toughness at room temperature depending on PWHT-conditions for the rutile flux cored all weld metal Böhler P92 Ti-FD (E 91T1-GM) wire.