RECENT DEVELOPMENTS IN WELDING CONSUMABLES FOR P(T)-91 CREEP RESISTING STEELS

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Synopsis

Weld metals for type 91 steels are now readily available and consumables/process combinations can be utilised to give compositions and hence microstructures which are optimised for long term creep performance. This paper reviews the compositional requirements for type 91 consumables in the light of requirements for long term performance, ambient temperature toughness and currently available specifications. In particular, it describes the latest development and performance of a range of welding consumables designed for the SMAW, GMAW, GTAW and SAW processes, and provides some insight into the welding consumables for the next generation of steels for high temperature service.

1. INTRODUCTION

The major challenge facing the power generation industry into the 21st Century will be to achieve the targets for increased efficiencies demanded by both mature economies and developing nations. Environmental regulations requiring reduced CO_2 emissions coupled with inevitable pressures on reliability, availability and maintainability will all be major driving forces. Materials developments, and in particular advanced creep resisting steels for high temperature pressure components, will continue to play a significant role in improvements for existing plants and will increasingly do so in new projects. Modified 9CrMo steels (P/T91) are already well established and variants such as P92 and P911 are likely to take a share of the market in the next few years.

The advantages of such steels are clearly illustrated by Fig. 1 which shows a comparison of the required designed wall thicknesses for a given set of service conditions for P91, P22 and X20 CrMo steels. These benefits can be exploited by reductions in wall thickness and weight for a given operating condition or by increasing design/operating temperature with consequent improvements in thermal efficiency. Of course such advantages can only be fully exploited provided these steels can be welded with appropriate welding consumables to give weldments which will not compromise the integrity and operating lifetime of the completed structure.

This paper describes the development of a range of modified 9Cr1Mo welding consumables designed for the SMAW, GMAW, GTAW and SAW processes and provides some insight to the consumables for the next generation of high temperature ferritic steels.

2. WELD METAL COMPOSITION

2.1 General considerations

The weld deposit composition is designed to be as close as possible to the parent steel type 91 [1] (Table 1) consistent with achieving optimum properties and weldability. Early design specifications adopted by the UK power generating utility, CEGB, in the mid 1980's matched the composition of the parent alloy very closely but the toughness of the weld metal proved to be rather low after tempering at a typically economic time and temperature cycle (usually 2/3h at 750-760°C). It is therefore necessary to explain why weld metal compositions, particularly for the flux-related SMAW and SAW processes, differ from parent material specifications.

Early work in the USA [2] showed that reducing weld metal niobium content to a level as low as 0.02% gave significantly tougher weld metal than the parent level (0.06-0.10%). The advantage of this modification has been confirmed in the present work. However, many authorities consider that a lower limit of 0.04%Nb is essential for satisfactory creep resistance. The niobium range for current designs is therefore usually controlled to 0.04-0.07%.

It is widely recognized that nickel can be useful in improving weld metal toughness. The addition of a controlled level of nickel is beneficial for two reasons. It lowers the Ac_1 temperature bringing this closer to the postweld heat treatment (PWHT) temperature and this improves the response to tempering. It also reduces the tendency for residual delta (δ) ferrite being present which is believed to be undesirable. However, excessive levels of nickel (>1%) are also detrimental. The Ac_1 may be so low that PWHT at the top end of the temperature range could cause some austenite to form which in turn transforms to fresh untempered martensite on cooling. Excessive nickel also contributes to degradation of creep properties by changing the optimum long-term evolution of carbide precipitation during service. Nickel is therefore usually controlled in the range of 0.4-1.0%.

Variations in vanadium, carbon and nitrogen have been found to have smaller influences on toughness. Manganese is preferably controlled at a higher level than the parent material to aid deoxidation and ensure a sound deposit. However, some authorities limit Mn+Ni to 1.5% maximum as a safeguard against austenite reformation at the highest PWHT temperatures. Variants of the standard consumables are manufactured within this constraint, but to allow sufficient manganese for effective deoxidation, the nickel level is reduced towards 0.5% and the average toughness may be somewhat reduced. Toughness is inevitably compromised further when users specify both manganese and nickel within parent metal limits.

Silicon is an essential deoxidant. In conjunction with chromium, it may also contribute to a minor degree to the alloy’s oxidation resistance. Although some specifications have effectively the same range as type 91 parent material, a low level of silicon benefits weld toughness [2]. In this respect, the AWS specification limit of 0.30% is lower than the parent material and is somewhat restrictive for certain consumable types.

The composition of modified 9CrMo material is at the threshold of δ ferrite retention. Although the effect of δ ferrite on the weld metal performance is not fully understood, it is generally believed that it has a detrimental influence on both creep resistance and some other mechanical properties [3-7]. It is therefore considered important to achieve an overall balanced weld composition which can minimise the possibilities of residual δ ferrite. There are a number of compositional parameters (e.g. the chromium equivalent (Cr_{eq}) [8] and the Kaltenhauser ferrite factor (FF) [9]) which provide an indication of the tendencies for δ ferrite retention. Some recent studies have suggested that a Cr_{eq} value ≤8 (or FF≤6) is desirable for a fully martensitic microstructure [10].

2.2 Specification ranges

The specification composition ranges from a number of sources are given in Table 1 together with mechanical property requirements after PWHT in Table 2. The European and USA weld metal specifications are similar to the parent material specifications. The manganese and silicon levels, particularly in the European EN specifications have been broadened to accommodate a number of different manufacturers' design philosophies. The nickel limits recognise the beneficial effects on toughness with a maximum of 0.8 or up to 1.0% in all specifications and minimum of 0.4% in the EN specifications. The minimum levels for the strengthening elements niobium, vanadium and in some cases nitrogen are lowered compared with the parent specification and this also recognises the beneficial effects on toughness and the fact that high levels are not required to provide suitably overmatching strength. The mechanical property requirements of the weld metals are all generally in line with the parent steel except that slightly lower minimum elongations are permitted and minimum toughness values are mandatory in the EN specifications whereas values are by agreement in AWS.

There is some divergence where preheat and interpass temperature are specified for test coupons to determine mechanical properties. The lower range of 205±55°C in AWS A5.28 for filler wire, compared with 260±14°C in AWS A5.5 for covered electrodes, can be justified with respect to the process-dependent levels of potential hydrogen. However, this logic has been reversed in the EN specifications for no apparent reason. Fabrication welds typically employ a range of 200-300°C. PWHT requirements vary with respect to time at temperature, the AWS limit of 1h being too short in practice, as will be noted later.

3. MECHANICAL PROPERTIES

A high resistance to softening by PWHT (temper-resistance) is an intrinsic feature of modified 9CrMo weld metals and is also noticeable in the high temperature (supercritical) HAZ of weldments. Therefore weld metal tensile strength will always overmatch the parent material and cross-weld tests typically fail in parent material beyond the hardened HAZ. High temper-resistance also increases the difficulty of obtaining high toughness in directly matching SMAW deposits within realistically short PWHT regimes. The composition modifications primarily gain toughness by promoting a more rapid tempering response.

3.1 Creep properties - parent material

Type 91 alloy was originally developed in the mid 1970's by ORNL under a US government sponsored project. The final optimised version of the alloy, based on over 100 experimental heats, was aimed at achieving a 10^5h rupture stress of 100MPa at 600°C. However, the 10^5h values were originally derived by numerical or parametric extrapolation and have subsequently been adjusted to around 93MPa. The long-term performance characterised by long-term tests and service experience is greatly superior than that of materials of both lower and higher alloy content for service in the temperature range 500-600°C such as P22 and X20 (Fig. 1).

3.2 Creep properties - weldments

Numerous tests have shown that creep failure of welded joints in type 91 steel welded with matching or near-matching weld metals occurs in the HAZ of the parent material. The consequent reduction in transverse creep strength of weldments is about 20% at 600°C [11].

Fig. 2 shows a plot of stress-rupture properties for type 91 base material with some representative weldment data for comparison. From the figure, a number of observations can be made: i) with the possible exception of very short duration tests, all the weldments lie below the average claimed by ORNL for type 91 steel; ii) in longer duration tests, weldment properties show increasing divergence from the parent material average; iii) all the weldments, made with a range of consumables, show similar behaviour.

The failure location in cross-weld tests is at the outer boundary of the HAZ. This region is partially re-austenitised by re-heating within the intercritical temperature range during the welding thermal cycle and most of the carbon and nitrogen are precipitated from solution. Further recrystallisation of the transformed microstructure during PWHT produces a relatively soft martensite which lacks the carbo-nitride grain strengthening essential for creep resistance. This weakened zone where “type IV” creep failure occurs is characteristic of all creep resisting CrMo steels. Fig. 3 shows a typical hardness survey with a hardness almost 40HV below the base material average, in the critical region [12].

Since type IV failure is typical for cross-weld creep tests (except possibly for very high stress/short duration tests), the role of the weld metal creep performance could be considered as having little practical significance, except that it should perform at least as well as the outer HAZ region - the type IV zone. Some authorities accept this view. However, there are two other contrasting opinions concerning the influence of weld metal creep properties on the overall behaviour of weldments, in particular that weld metal might be optimised to delay the onset of type IV failure. Both of these views arise from considering that weld metal creep strength will influence how creep strains are partitioned competitively across a weldment. One proposal is that the weld metal should actually be weaker than the parent material and comparable with the type IV zone creep strength [13]. The alternative proposition is that the relatively wide weld fusion zone should have a strength comparable to the base material so that less strain will be transferred to the narrow type IV zone and failure will therefore be delayed [10].

There is general agreement that the failure mode of weldments is ultimately controlled by HAZ behaviour, but currently there is no consensus as to whether the choice of weld metal might delay such failure and so prolong component life.

3.3 Effects of weld metal composition

The weld metal compositions of four different commercial SMAW electrodes [10] are given in Table 3 together with cross-weld creep properties after PWHT 760°C/2h in Table 4. Three electrodes A, B and C were compared with batch D. Consumable D gave the longest rupture times and only composition C failed in the weld rather than the type IV zone. This electrode had the lowest level of those elements considered critical for creep resistance, especially Nb and C+N.

Similarly the other compositions A and B can be interpreted (along with differences in hardness after PWHT) as intermediate in creep strength between compositions C and D. These results lend some support to the view that it is preferable for weld metal to match the parent metal and to overmatch the type IV zone and that this optimum condition was achieved with the electrode D.

The performance of weldments in actual service is likely to be significantly better than that obtained in cross-weld creep tests, except for unusual situations where material thickness and loading conditions are directly simulated by uniaxial creep tests. In most actual weldments, this is not the case and the weld metal and narrow type IV zone are constrained by surrounding material, especially in radially loaded pressure tubing where this constraint increases with thickness [11,14].

3.4 Weld metal toughness

It can be argued that weld metal toughness is an irrelevant consideration in fabrications which are designed to operate at temperatures of 500-600°C - far above the range at which any possible risk of fast brittle fracture could occur. However, there are situations where components might be pressurised or loaded structurally at ambient temperatures during testing or construction phases. To cater for these situations, it is considered by some authorities that the weld metal should satisfy a minimum toughness value at +20°C. The AWS specification does not specify impact requirements, but the non-mandatory appendix to A5.5-96 proposes that a suitable test criterion should be agreed by the purchaser and supplier. On the other hand, the recently introduced European specification EN 1599: 1997 requires a minimum average of 47J and a minimum single value of 38J at 20°C. These values appear to be roughly in line with those authorities who have decided to impose their own toughness requirements and values in the range 35-50J at 20°C after a prescribed PWHT are typical. However, it is difficult to justify the need for toughness >41J specified for parent material, or indeed higher than that specified for X20, a well-established weld metal with minimum of 34J average and 22J single values.

There are four factors which have a major influence on weld metal toughness:

1. Composition: In general terms, those elements which are beneficial in improving creep performance are detrimental in terms of toughness, i.e. niobium, vanadium and to a lesser extent nitrogen and silicon. A composition balanced to restrict δ ferrite and to give a fully martensitic microstructure [10] helps to contribute both optimum toughness and creep performance.
2. PWHT: Effective tempering of the martensitic microstructure is essential to obtain a reasonable level of toughness. In practice this involves selecting both an appropriate temperature and time. The AWS specification requires PWHT of 730-760°C for 1h. This is considered insufficient for normal fabrication procedures and a minimum of 2-3h at temperature range 750-760°C is usual, or longer for thicker sections [11]. This temperature-time aspect is recognised by EN 1599 which specifies a PWHT requirement of 750-770°C for 2-3h. As was mentioned, it is important not to set PWHT at too high a temperature because of the risks of austenite reformation and the transformation to fresh untempered martensite, particularly in nickel bearing welds. The effects of PWHT temperature and time (expressed as a tempering parameter, $P = °K(\log t + 20) \times 10^{-3}$) on weld metal toughness are summarised in Fig. 4. In practice, for the welds described here, a PWHT regime of 755°C for 2-3h (or P=~21) gives satisfactory results although longer times will generally give enhanced toughness. This parameter value equals to 8h at 730°C, the lowest specified tempering temperature.
3. Welding process: The choice of welding process can have a dramatic influence on weld metal toughness because of the effects of fluxes and shielding gases. The highest toughness at +20°C after PWHT are achieved with solid wire and metal cored wire (MCW) using GTAW with pure argon. These give low oxygen contents typically less than 100-200ppm whereas the fluxed processes (SMAW, SAW) give values of 400-800ppm with significant reductions in toughness. The situation with GMAW, particularly with active gas mixtures, is more complex because of the variable recovery of key elements such as manganese, silicon and niobium.

4. Although not reviewed here, microstructural refinement which is influenced by heat input or bead size and sequence can also vary the toughness, as is the case generally for weld metals which undergo transformations during cooling and reheating in multipass welding.

4. SOLID AND METAL CORED WIRES FOR P(T)-91 MATERIAL

Apart from SMAW electrodes, there is also a strong need for consumables for other welding processes, namely GTAW, GMAW and SAW. In the present paper, discussion is concentrated mainly on the development and investigation work carried out by Metrode recently on one newly developed MCW and some commercial solid wires. For the toughness examinations, the welds were prepared using the conditions shown in Table 6 and were subject to a PWHT at 755°C for 3h prior to the testing at +20°C.

4.1. GMAW welding

As a process of potentially high productivity, interest in GMAW for welding type 91 material is increasing. Of the wires available for GMAW process, because of its flexibility in alloying and lower cost, MCW is attracting more attention and is now being used in real applications.

Table 5 shows the deposit compositions of the MCW and one solid wire using different shielding gases. Data in the table indicate that the levels of the more reactive elements, such as silicon, manganese and niobium, are significantly influenced by the shielding gas. The general trend is that the recovery rate of these elements decreases as the oxidizing potential of the shielding gas increases. The oxygen content in the deposits, on the other hand, increases significantly as the gas oxidizing potential increases. The other alloying elements, however, demonstrated a very stable transfer irrespective of the oxidizing potential of the gas used. The MCW deposit composition generally meets the AWS requirement, the exception being the silicon content. In order to optimize the operability, particularly when using a less active gas, some additional silicon was required and this resulted in a level of ~0.35-0.38%Si in the deposit. However, this level is still in conformance with the European specification.

It should be pointed out that MCW has the advantage of enabling the formulation to be adjusted to give the required deposit analysis for a given wire/gas combination. In contrast, solid wire specifications are based on wire composition, not weld deposit. The effect of shielding gas activity on deoxidant burnout should be noted, especially as solid wire used here had a more favorable silicon level (0.41%Si) than the AWS specification (0.15-0.30%Si). The latter range may prove to be satisfactory only for GTAW and auto-GTAW processes.

The operability of the GMAW process using a MCW is strongly influenced by the type of the shielding gas. In general, a suitably high content of CO_2 in the gas is beneficial. However, higher CO_2 contents will inevitably increase the weld metal oxygen level. Of the various commercial gases tested, a mixture of Ar+2.5%CO_2 was found suitable for both the MCW and the solid wire, and capable of providing the best balance of operability and weld metal toughness. For even better operating performance, a higher CO_2 content could be used in the case where weld appearance and soundness is considered to be a high priority while maximum toughness is not required. Chemical composition, particularly deoxidation tendency of the wire, also has a significant effect on the operability. As mentioned earlier, a silicon level of =0.35% appeared to be necessary for satisfactory operating behaviour of the MCW.

Table 7 shows the weld metal toughness for different shielding gases. With a gas of Ar+2.5%CO_2, the MCW weld consistently achieved average toughness of ~30J. Higher toughness (~37J) was obtained by using less oxidizing gas mixture (G1), but with a considerable degradation in operability. The solid wire demonstrated rather poor toughness, although its welding operability was reasonable. The results indicate that the weld metal toughness is strongly influenced by the oxygen content, as illustrated by Fig. 5. The trend shown in the figure suggests that, for the MCW weld metal to achieve a toughness >47J, an oxygen level of =0.04% would be an important target for the GMAW process. This oxygen level would have to be achieved in combination with good operability if the productivity benefits of the GMAW process are to be realised in practice*.

4.2 GTAW welding

There is a need for consumables for the GTAW process for various applications in welding type 91 material where other processes are neither practicable nor economic. Solid wires with or without nickel addition are available but relatively expensive and offer little flexibility in alloying content for some of the newer more highly alloyed steels. Metal cored wire, on the other hand, offers a viable alternative particularly where continuous consumables are required for auto-GTAW or for spool-on-gun manual GTAW.

Typical weld metal(/wire) compositions for two solid and the MCW's are shown in Table 8. The compositions are similar, the MCW having a somewhat higher manganese level to balance up the slightly lower nickel content for optimum toughness and thermal stability.

The GTAW weld deposits give very low oxygen content and comparatively high impact values as shown in Table 9. The highest toughness is achieved with the solid wires with nickel and impact values in excess of 200J at +20°C are routinely achieved. The solid wire deposits without nickel also give excellent toughness, as do the MCW weldments, with values in the range 130-150J for auto and manual GTAW.

During the studies, two practical aspects have been noted about the use of MCW for GTAW:

1. The filler metal tends to 'spit' and 'sparkle' as it is fed into the weld pool, and this may be slightly disconcerting to welders who are used to the smoother melting of a solid wire. The feed speed also has to be increased for a given deposition rate to compensate for the lower density of the MCW compared with that of a solid wire. The reason for the 'spitting' is believed to be reactions in the high temperature plasma between the surface oxide film on the metal powders and deoxidants such as silicon and manganese.
2. MCW deposits show a greater sensitivity to porosity and/or slag inclusions. This is not considered to be a serious problem because most of the GTAW welds are root runs or relatively small multi-run deposits and the mechanical properties, particularly toughness, are very good. However, this aspect is the subject of further investigation.

4.3 Submerged arc welding (SAW)

For applications where mechanized welding is practically convenient, SAW is undoubtedly preferred and more productive than SMAW. Welding type 91 material with the MCW using SAW was investigated. Five fluxes of different levels of basicity were employed.

The deposition characteristics of the various MCW/flux combinations were similar, but the slag release and bead profiles of the deposits varied with the different fluxes. Of the fluxes tested, F02, F03 and F04 showed satisfactory slag release and good cosmetic bead appearance.

Table 10 lists the typical composition of the deposits. The alloying contents were generally within the expected range, although the recovery of some elements, particularly manganese and silicon, varied with the flux. The oxygen level of the deposits varied with

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* The latest tests showed, by controlling the oxygen content to 0.038-0.40% and lowering the levels of residual elements, the GMAW welds of CORMET M91 MCW have achieved average 70J at 20°C after PWHT using gas mixture of Ar+2.5%CO_2, and 58J with G1 gas.

flux but were within a range of 440-560ppm.

Charpy tests were carried out on two welds containing intermediate and high oxygen contents and the results are listed in Table 11. The weld metal with lower oxygen content, 490ppm, achieved an average toughness of 30J, while the one with higher oxygen level, 560ppm, demonstrated much lower toughness. This agrees with the trends exhibited in GTAW and GMAW (Fig.5). It is noted again that in order to achieve the EN specified toughness, oxygen levels <0.04% will probably have to be achieved, although there may be some scope to improve toughness by increasing the nickel content and modifying the welding procedure.

Since the composition control with the solid and MCW's is within the limits for other processes which have been subject to high temperature creep testing, it is assumed at this stage that creep performance will be similar. Practical experience to date with the consumable supports this view.

5. FURTHER DEVELOPMENTS

The commercial application of type 91 is now well established, but the development of this alloy system has continued with further improvements in performance. In the new generation of modified steels, creep strength is increased by adding tungsten to raise the Mo-equivalent (Mo+0.5W) from 1% to about 1.5% in a matrix composition essentially similar to type 91.

Two new steels of this type are now commercially available. The first originated in Japan as Nippon Steel NF616 and following an EPRI project became the basis for ASME type P92, with 0.5%Mo-1.8%W [15]. The second alloy, E911 (anticipated ASME type P911) has 1%Mo-1%W and was developed within the European COST 501 co-operative action [16]. Welding procedures for these materials are essentially similar to those applied to type 91. Welding consumables are close to matching base material but generally require a small addition of nickel to optimise toughness [15, 17]. As with type 91, the creep performance of welded joints is controlled by type IV failure in the HAZ, but with an overall enhancement in rupture stress.

Further active developments are aimed at increasing the applicable service temperature of tungsten-modified steels by raising chromium to ~11% to improve hot corrosion resistance. The prototype for this class of steel is the well-established German type X20 (12%CrMoWV with 0.2%C). Like the modified 9%Cr steels, the new 11%Cr steels have improved weldability with around 0.1%C, supported by a controlled addition of N and V+Nb to optimise creep strength. An example of this type is Sumitomo HCM12A which is the basis for ASME type P122.

An intrinsic problem with tungsten bearing 0.1%C-11%Cr steels is the tendency for δ ferrite retention and in type P122 this is suppressed with the addition of about 1%Cu. In other respects the composition is similar to type P92 and creep performance is claimed to be equivalent [18]. Additions of up to 3%Co are used to suppress ferrite in other modified 11%Cr alloys which may offer considerably higher creep resistance than the advanced 9%Cr types [19].

As with the application of type 91, the driving force for these developments is not only the advantage of higher strength to allow thinner sections with improved heat transfer and thermal fatigue performance, but also the environmental imperative which requires new and improved materials for advanced power plants operating at higher temperatures with the maximum thermal efficiency and reduced emissions.

6. SUMMARY AND CONCLUSIONS

The commercial application of type 91 creep resisting steels is now well established and work is continuing to extract further improvements in thermal efficiency from more advanced alloys. Weld metals for type 91 steels are readily available and consumable/process combinations can be utilised to give compositions and hence microstructures which are optimised for long term creep performance.

The present work has shown that within these compositional constraints, now well established in a number of internationally recognised standards, there are limits as to the levels of toughness which can be achieved. Whether or not the toughness requirements specified in the European standards can be justified in terms of fitness for purpose is open to debate, but the fact is that with certain consumable/process options, the specified values appear to be difficult to achieve. This is the case with the higher productivity processes (GMAW and SAW) and particularly so when MCW's are used as an alternative to solid wires. This is unfortunate, because MCW's offer a rapid, economic and flexible route to the production of consumables not only for the type 91 alloys, but also future generations of improved alloys with higher chromium content and addition of tungsten. These modifications give further improvements in creep strength, but will have an additional deleterious effect upon weld metal toughness and some re-examination of the required limits will almost certainly be necessary.

The present work to date has:

1. Reviewed the compositional requirements of type 91 steel weld metal in light of requirements for long term performance, ambient temperature toughness and currently available specifications.
2. Summarised the development of a type 91 metal cored wire, which with slight modifications can be used for the GMAW, GTAW and SAW processes.
3. Indicated that toughness levels achieved with the low nickel GMAW and SAW wires examined do not meet requirements of European standards although they may well be fit for purpose. Further work is required.
4. Shown a clear relationship between toughness measured in terms of absorbed energy at +20°C and weld metal oxygen content. From this it is predicted that in order to achieve impact values of greater than 40J at +20°C, oxygen content lower than 0.04% will be necessary, particularly when nickel is restricted within the parent material limit of 0.4%.

7. ACKNOWLEDGMENTS

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Table 3. Weld metal composition evaluated in creep tests

Ref.	A	B	C	CHROMET 9MVN (D)
C	0.09	0.08	0.08	0.10
Mn	1.0	1.0	1.1	1.1
Si	0.4	0.4	0.2	0.4
Cr	8.7	9.3	8.9	8.9
Ni	<0.1	<0.1	0.7	0.7
Mo	1.0	1.0	0.9	1.0
V	0.17	0.21	0.19	0.18
Nb	0.06	0.09	0.03	0.05
N	0.05	0.05	0.02	0.05
HV[a]	225	235	225	253

a: after PWHT

Table 4. Cross-weld creep properties (PWHT 760°C/2h)

Ref	**A**		**B**		**C**		**CHROMET 9MVN (D)**		
temp. °C	600		600		600	650	600		650
stress, MPa	110	130	110	130	130	110	110	130	110
rupture time, h	1780	515	2271	607	367	29	3429	1730	51
elongation, %	3.8	5.2	3.9	8.0	8.7	11.7	3.0	5.3	7.7
red. of area, %	41	58	39	57	57	76	31	37	70
failure zone	HAZ: type IV				weld		HAZ: type IV		

Table 5. Chemical composition of the GMAW weld metals

Wire/type	Gas	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	N	O
	G1[a]	0.074	1.16	0.40	0.011	0.008	8.4	0.34	1.0	0.04	0.21	0.044	0.041
CORMET M91	G2	0.083	1.10	0.38	0.011	0.008	8.7	0.36	1.1	0.04	0.20	0.041	0.051
MCW	G4	0.079	0.90	0.25	0.010	0.008	8.7	0.35	1.1	0.03	0.21	0.053	0.100
	G1	0.098	0.33	0.30	0.003	0.007	8.6	0.06	1.0	0.07	0.20	0.045	0.042
9CrMoV	G2	0.108	0.30	0.30	0.004	0.007	8.6	0.06	1.0	0.07	0.20	0.033	0.043
Solid wire	G3	0.119	0.25	0.22	0.003	0.007	8.4	0.07	1.0	0.06	0.19	0.053	0.072
	G4	0.12	0.22	0.19	0.003	0.007	8.2	0.06	1.0	0.05	0.18	0.037	0.078

a: Shielding gas: G1=60%Ar+38%He+2%CO_2, G2=97.5%Ar+2.5%CO_2, G3=80%Ar+20%CO_2, G4=78%Ar+20%CO_2+2%O_2.

Table 6. Welding conditions used for the preparation of the test plates

Wire/type	Size	Process	Pre-heat/Interpass temperature, °C	Voltage, V	Current, A	Nominal heat-input, kJ/mm
	∅1.6mm	GMAW	100/200-250	29	330	1.5
CORMET M91 MCW	∅1.6mm	Man.-GTAW	100/200-250	12	130	1.1
	∅1.2mm	Auto-GTAW		10	195	2.1
	∅1.6mm	SAW	100/200-250	30	300	1.6
9CrMoV-N Solid wire	∅2.4mm	GTAW	100/200-250	13	170	1.2
9CrMoV Solid wire	∅1.6mm	GMAW	100/200-250	30	250	2.1
	∅1.6mm	GTAW	100/200-250	12	130	1.2

Table 7. Impact toughness of the GMAW weld metals

Wire/size	Type	Shielding gas	PWHT	Average impact absorbed energy @20°C, J	Average lateral expansion, mm
CORMET M91 ∅1.6mm	MCW	G1	755°C/3h+FC	37	0.45
		G2	755°C/3h+FC	32	0.53
9CrMoV ∅1.6mm	Solid wire	G2	755°C/3h+FC	18	0.33

Table 8. Chemical composition of the GTAW consumables

Wire/type	Type	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	N	O
9CrMoV	Wire[a]	0.10	0.37	0.41	0.005	0.008	8.8	0.07	1.0	0.07	0.22	0.021	0.003
Solid wire	Deposit	0.09	0.39	0.41	0.004	0.007	8.6	0.01	0.9	0.08	0.21	0.024	0.001
9CrMoV-N Solid wire	Wire[b]	0.09	0.50	0.34	0.001	0.006	8.7	0.72	1.0	0.06	0.22	0.040	0.004
CORMET M91	Deposit	0.09	1.10	0.40	0.011	0.011	8.8	0.35	1.0	0.07	0.20	0.039	0.008[c] 0.024[d]

a, b: Wire composition (mill certificate); c: Auto-GTAW; d: Manual-GTAW

Table 9. Impact toughness of the GTAW weld metals

Wire	Type/size	PWHT	Average impact absorbed energy @20°C, J	Average lateral expansion, mm
9CrMoV	Solid wire ∅1.6mm	755°C/3h+FC	145	2.21
9CrMoV-N	Solid wire ∅2.4mm	755°C/3h+FC	213	2.26
		755°C/3h+AC	233	2.35
CORMET M91	MCW			
Auto-GTAW	∅1.2mm	755°C/3h+FC	132	1.77
Man-GTAW	∅1.6mm	755°C/3h+FC	152	2.09
		755°C/3h+AC	138	1.96

Table 10. Chemical composition of the SAW weld metals

Wire/size	Flux /basicity index	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	N	O
CORMET	F01/1.7	0.07	0.80	0.31	0.013	0.015	8.8	0.34	0.96	0.04	0.20	0.039	0.048
M91	F02/2.3	0.08	0.81	0.37	0.010	0.016	8.5	0.35	1.03	0.04	0.19	0.034	0.044
∅1.6mm	F03/2.7	0.09	1.11	0.31	0.008	0.015	8.9	0.34	0.99	0.04	0.20	0.037	0.049
	F04/3.0	0.08	1.10	0.29	0.007	0.018	8.8	0.36	0.97	0.03	0.20	0.038	0.046
	F05/3.0	0.08	1.10	0.40	0.009	0.017	9.0	0.36	1.02	0.03	0.20	0.039	0.056

Table 11. Impact toughness of the SAW weld metals

Wire/size	Flux	PWHT	Average impact absorbed energy @20°C, J	Average lateral expansion, mm
CORMET M91 ∅1.6mm	F03	755°C/3h+FC	30	0.46
CORMET M91 ∅1.6mm	F05	755°C/3h+FC	18	0.21

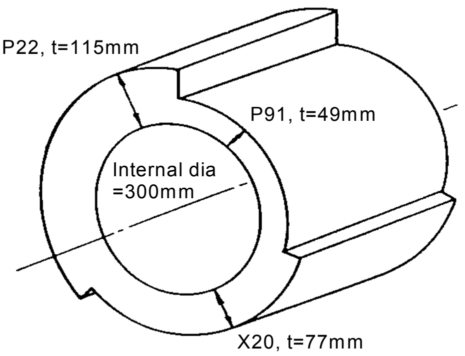


Figure 1. Comparison of required wall thicknesses for equivalent service. (Temperature 600°C, pressure 30MPa, 100,000h life)

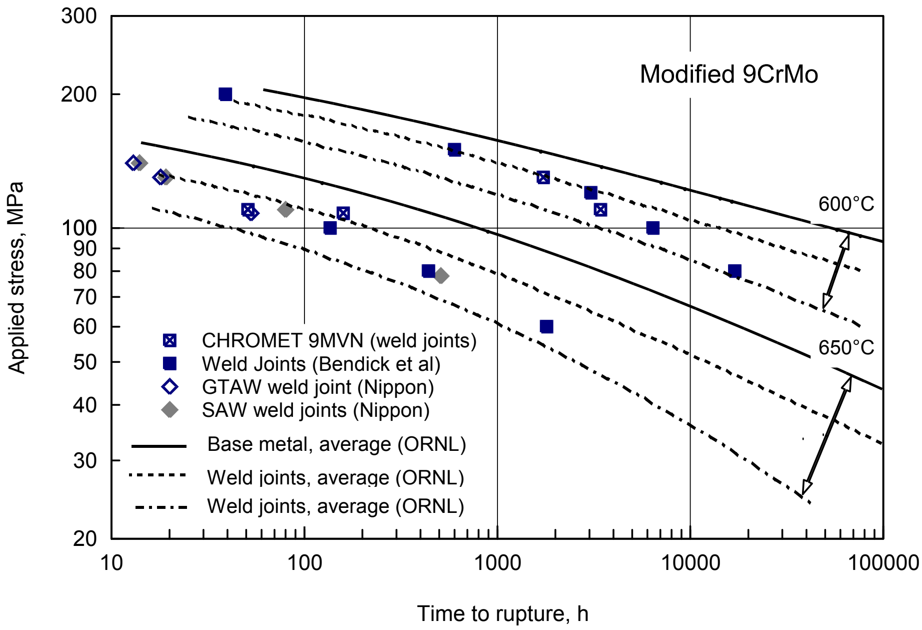


Figure 2. Creep properties of modified 9CrMo material weldments

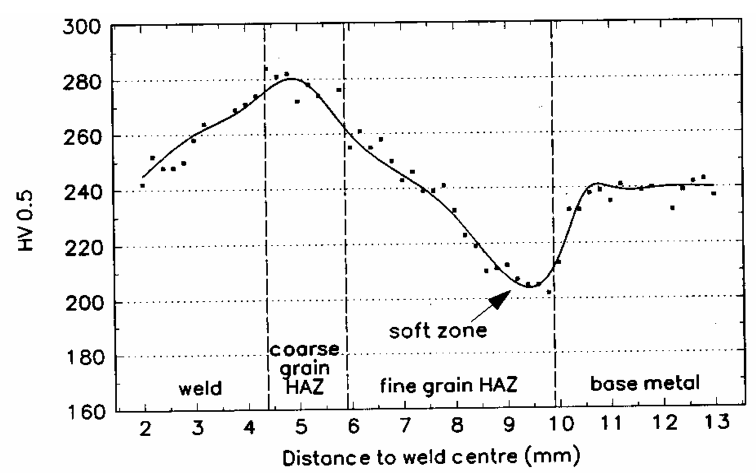


Figure 3. Microhardness across a T91 weldment [12]

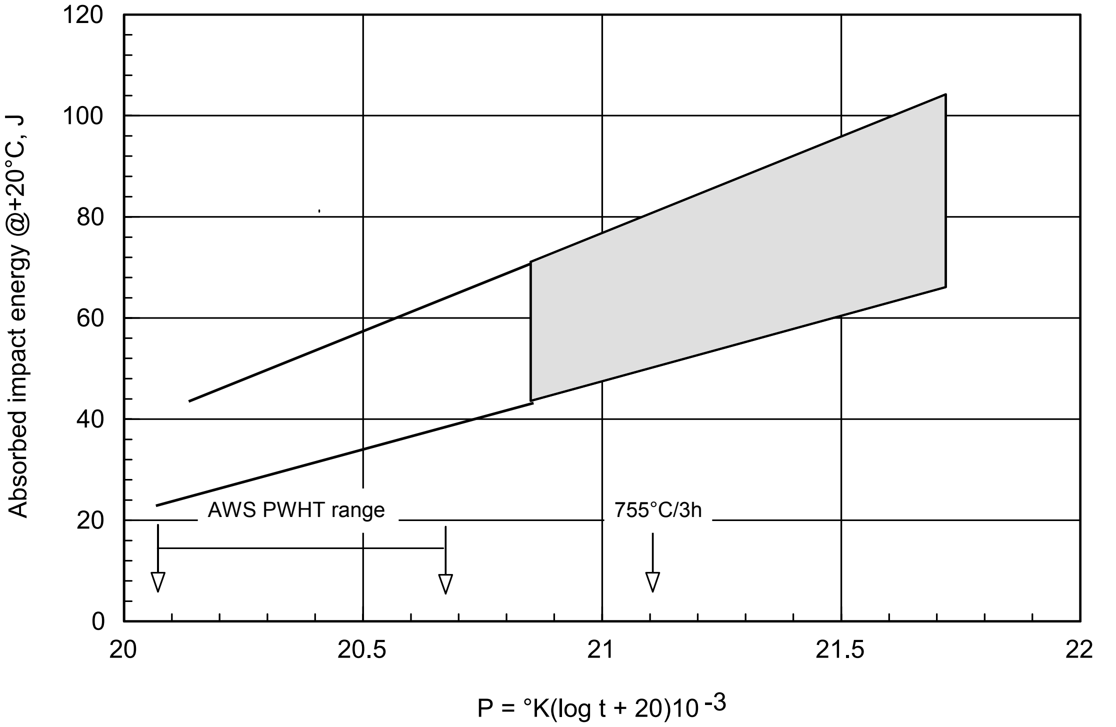
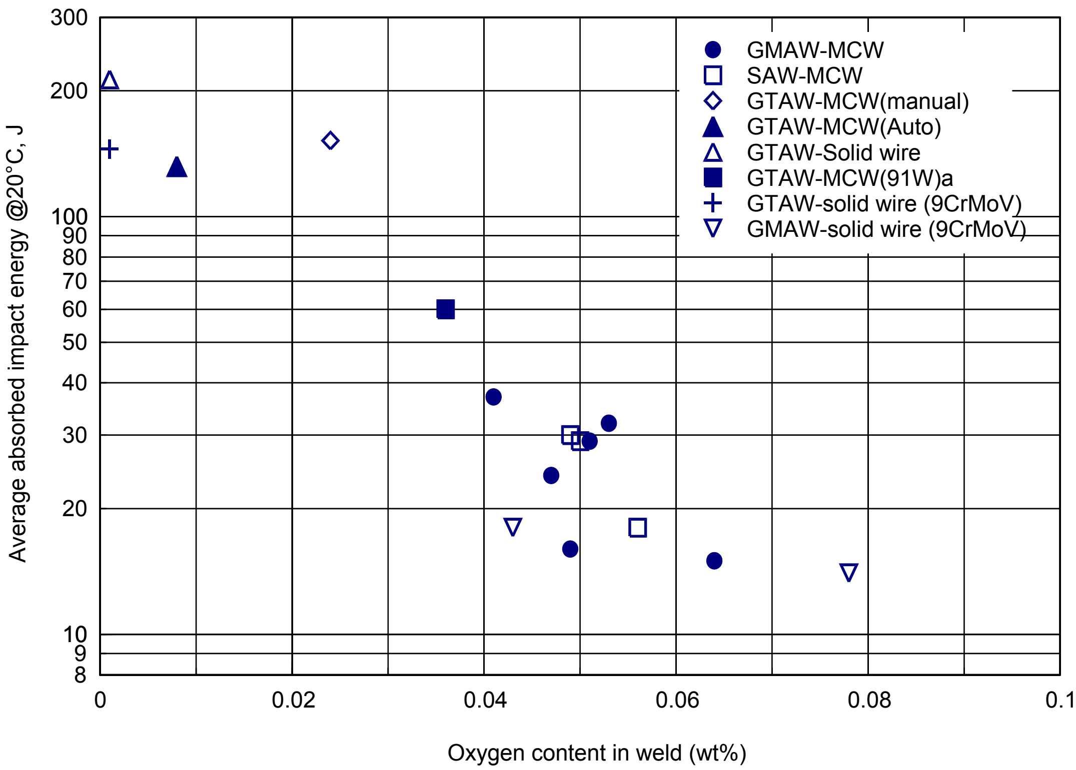


Figure 4. The effect of PWHT temperature and time on weld metal toughness



a: 91W is a type of metal cored wire with tungsten addition

Figure 5. Effect of oxygen content on impact toughness of some type 91 weld metals