# EFFECT OF VARIOUS FACTORS ON TOUGHNESS IN P92 SAW WELD METAL

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## ABSTRACT

In order to increase efficiency in thermal power plants, new grades of 9 %Cr steels have been developed and are now being used. Even though these steels are used at high temperature, where toughness is not a matter of concern, it is important that the welded joints show a good toughness at room temperature, for fabrication and construction steps and for start up / shut down considerations. As a consequence the best toughness / creep compromise has to be obtained to guarantee all the requirements. The present work aims at evaluating the effect of various chemical elements on weld metal toughness in P92 steels. All-weld metal characterizations using submerged arc process were done. Chemical elements which were varied are carbon, chromium, nitrogen and tungsten. Variations of W, C and Cr within the base material range did not significantly affect toughness of the weld metal. However nitrogen content has a great influence on toughness level, decreasing N content resulting in a toughness improvement. The detrimental effect of B and Ti on toughness of weld metal for P92 steels has also been confirmed. An optimised chemical composition has been defined on the basis of this work. This solution features a promising toughness / creep compromise, as very good toughness at room temperature and satisfactory creep behaviour have been obtained.

***IIW-Thesaurus keywords:*** *Arc welding; Creep resisting materials; Creep strength; Filler materials; High alloy Cr Mo steels; High alloy steels; Impact toughness; Mechanical properties; Power stations; Steels; Strength; Submerged arc welding; Toughness.*

## 1 INTRODUCTION

To increase thermal efficiency and decrease emissions of carbon dioxide, thermal power plant designers wish to raise the operating temperature and pressure of boilers. This drives the development of new creep resisting steels. Table 1 shows the various grades that are now being used in thermal power plant. 9 %Cr martensitic creep resisting steels are of particular interest because they show a better oxidation resistance than 2¼ Cr steels and a superior creep resistance. For these two main reasons, 9 %Cr steels allow to increase steam parameters up to supercritical values (300 bar, 600 °C), thus leading to increased efficiency and equivalent reduction of $CO_2$ emissions of 30 % [1]. The use of P92 steels rather than P91 allows increasing admissible stress by 30 %. The further benefit is a significant weight reduction and therefore reduced fabrication costs.

In order to take full advantage of the properties of these steels, it is necessary to have welding consumables leading to similar creep resistance in the weld metal than in the base metal. Even though these steels are used at high temperature, where toughness is not a matter of concern, it is important that the welded joints show a good toughness at room temperature, for fabrication and construction steps and for start up / shut down considerations. The present work aims at evaluating the effect of various chemical elements on weld metal toughness in P92 steels.

In 9 %Cr steels, the creep resistance is due to Cr, Mo, V and Nb which act as precipitation strengtheners. Fine carbides and nitrides precipitates form

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**Table 1 – Chemical composition of creep resisting grades, as per ASTM A335**

| Grades | C<br>% | Mn<br>% | P<br>% | S<br>% | Si<br>% | Cr<br>% | Mo<br>% | V<br>% | Nb<br>% | W<br>% | Ni<br>% | B<br>ppm | N<br>ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P22 | 0.05<br>0.15 | 0.30<br>0.60 | -<br>0.025 | -<br>0.025 | -<br>0.50 | 1.90<br>2.60 | 0.87<br>1.13 | | | | | | |
| P23 | 0.04<br>0.10 | 0.10<br>0.60 | -<br>0.030 | -<br>0.010 | -<br>0.50 | 1.90<br>2.60 | 0.05<br>0.30 | 0.20<br>0.30 | 0.02<br>0.08 | 1.45<br>1.75 | | 5<br>60 | -<br>300 |
| P91 | 0.08<br>0.12 | 0.30<br>0.60 | -<br>0.020 | -<br>0.010 | 0.20<br>0.50 | 8.00<br>9.50 | 0.85<br>1.05 | 0.18<br>0.25 | 0.06<br>0.10 | | -<br>0.40 | | 300<br>700 |
| P92 | 0.07<br>0.13 | 0.30<br>0.60 | -<br>0.20 | -<br>0.10 | -<br>0.50 | 8.50<br>9.50 | 0.30<br>0.60 | 0.15<br>0.25 | 0.04<br>0.09 | 1.50<br>2.00 | -<br>0.40 | 10<br>60 | 300<br>700 |

during tempering and give to the material its creep resistance [1]. In T/P 92, the addition of W further improves creep resistance by strengthening the material, mainly through Laves phase precipitation during creep. Addition of a small amount of B also improves creep resistance [2]. These elements which increase creep resistance are known to be detrimental for toughness in weld metal. The challenge is then to achieve the best toughness/creep compromise.

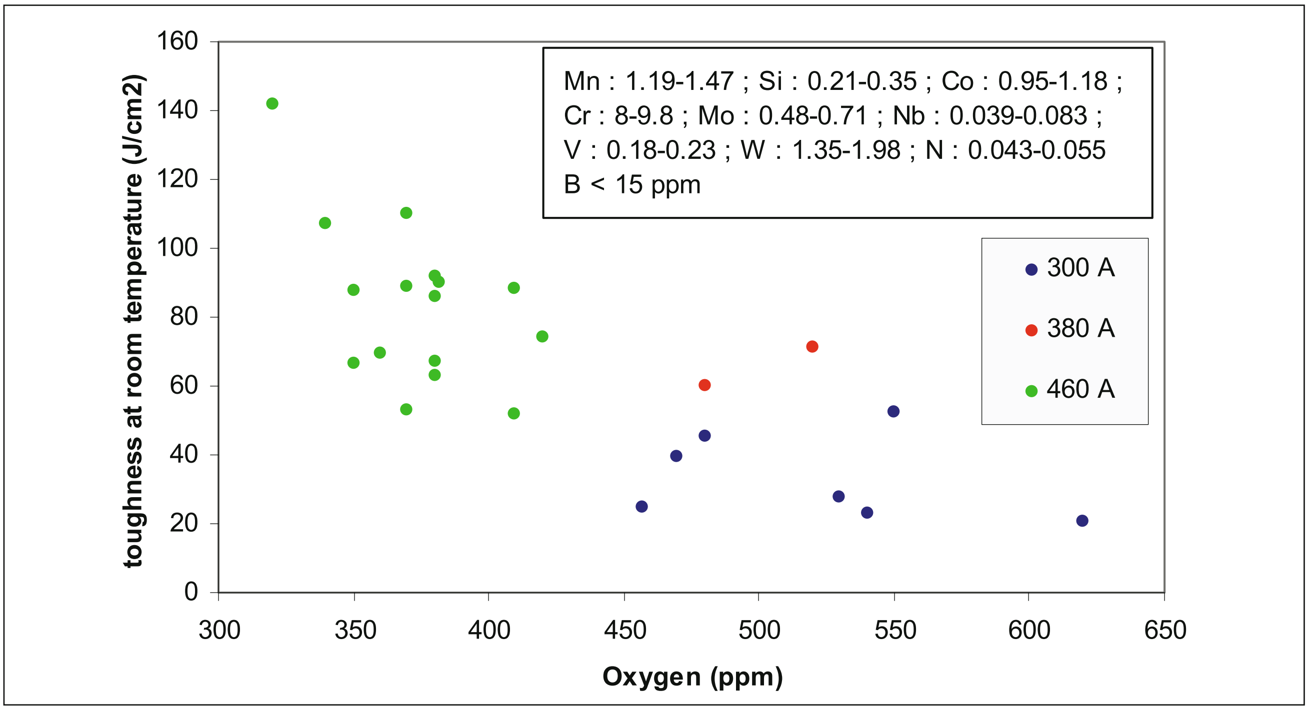
The effect of Ti and Al which can be considered as impurities coming from raw material of flux cored wire has been studied [3]. The authors showed that Ti and Al have a detrimental effect on toughness, whereas Ti can intentionally be added to slightly improve creep resistance.

## 2 PREVIOUS WORK

During a previous work [4], which dealt with the development of welding consumables for P92 steels, we already investigated the effect of some chemical elements in the weld metal.

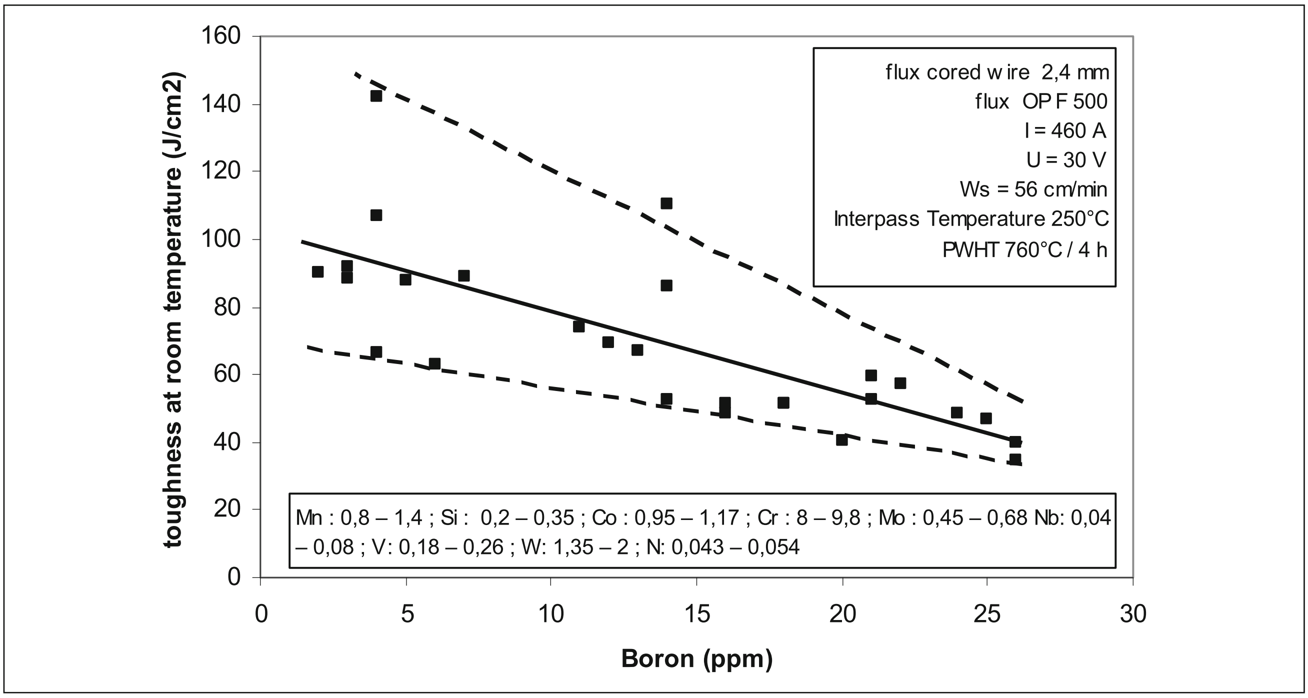
– As can be seen in Table 1, P92 steel is alloyed with a small amount of Ni. In our first trials, the welding consumables were designed to give 0.5 %Ni in the weld metal. Isostress (85 MPa) creep rupture tests on various chemical composition showed that replacing 0.5 %Ni by 1 %Co was beneficial for creep resistance. A positive effect of Co alloying on toughness has also been reported [5]. Moreover Co does not significantly affect $AC_1$ temperature, unlike Ni. Consequently it gives greater safety for the PWHT, avoiding partial re-austenitisation if PWHT is performed at a too high temperature. This property can also be used to raise PWHT temperature to improve toughness, providing that the temperature range is narrow enough not to exceed $AC_1$ temperature. The Air Liquide Welding SAW combination is then alloyed with 1 %Co.

– This first study also highlighted the effect of O content on toughness in weld metal. Figure 1 a) confirms that weld metal toughness decreases as O content increases. It is then important to minimize the oxygen content in weld metal through the choice of flux and wire and also a control of welding current.

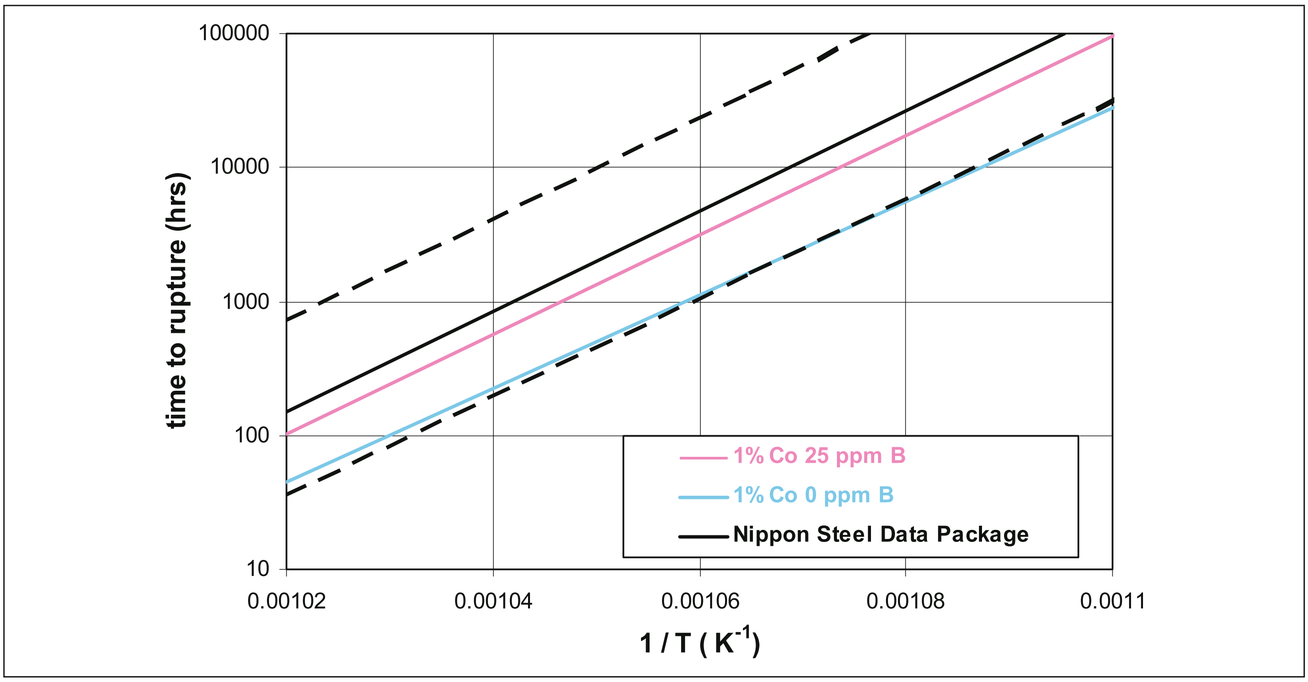


**a) Influence of oxygen content on weld metal toughness**

**Figure 1** *(continued)*



**b) Influence of boron content on weld metal toughness**



**c) Boron content on isostress (85 MPa) creep resistance in SAW P92**

**Figure 1**

– The influence of boron content was also studied, by varying the B content in SAW wire. Figure 1 b) illustrates the detrimental effect of boron on toughness. However, boron is essential for creep properties, its removal leading to a sharp decrease of creep properties [Figure 1 c)].

This study led to the development of a complete range of welding consumables for P92 steels. The creep properties of these consumables have been assessed by isostress (85 MPa) creep rupture tests. These consumables have then been used for assembling the main steam piping of the supercritical power plant in Avedore (Denmark). Long term creep rupture test (up to 35 000 hrs) at 550, 600 and 650 °C have been performed and are still on-going. The results are presented on Figure 2. The creep behaviour of these consumables is satisfactory, since the weld metal creep rupture points are at the same level as the base material. The base metal curve is taken form new ECCC P92 creep data sheet [6].

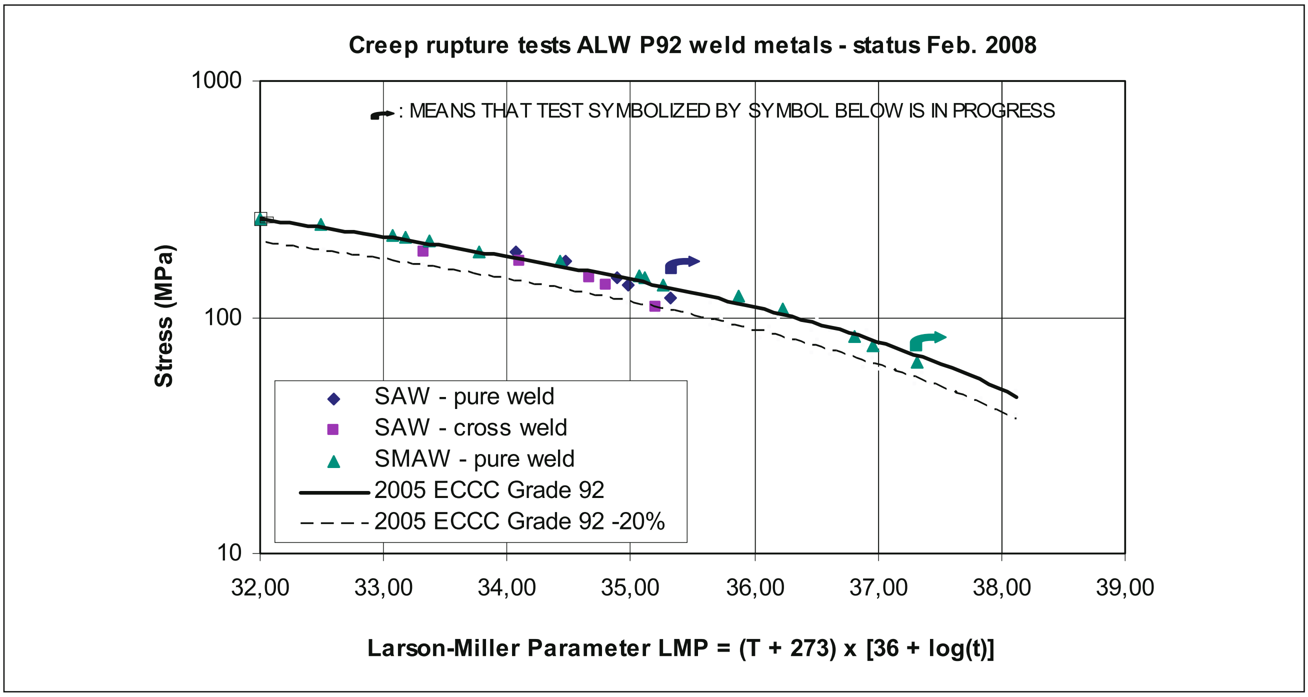


**Figure 2 – Creep rupture characterisation of P92 consumables used in Avedore power plant**

Although the weld metal toughness was conform to the minimum requirements of construction codes, we continued the development to further increase the toughness values.

## 3 EXPERIMENTAL PROCEDURE

All-weld metal characterizations using submerged arc process were done. A basic flux combined with a flux cored wire diameter 2.4 or 3.2 mm were welded to generate weld metal featuring different chemical analysis. Chemical elements which were varied are carbon, chromium, nitrogen and tungsten. Elements were varied in a range close to the base material range (Table 2). Indeed, development of the filler metal has been targeted within the chemical analysis of the base material, expected to result in the same properties of creep and oxidation resistance.

Two wire diameters were welded with such parameters to provide a similar heat input. 2.4 mm diameter wires were welded with 460 A, 30 V and 56 cm/min welding speed. 3.2 mm wire were welded with 530 A, 29 V and 60 cm/min welding speed. These two parameters sets result in a heat input of 14.8 kJ/cm and 15.4 kJ/cm respectively. Toughness notch is positioned in a reheated zone of the all-weld metal, that is to say a zone which is re-austenitized by the following runs. In that case, difference in run shape or size due to the wire diameter is not expected to have a noticeable influence. Interpass temperature was set to the range 230-250 °C. A lower interpass temperature is beneficial for toughness but not realistic from an industrial point of view [4]. A preheat temperature of 150 °C was used. The all-weld metal was not allowed to cool at room temperature, but kept at 250 °C during 3 hours to allow potential hydrogen to escape from the joint.

All samples were post weld heat treated at 760 °C during 4 hours, to improve toughness level and decrease hardness of the all-weld metal.

## 4 EFFECT OF CREEP ENHANCERS

### 4.1 Influence of boron

Although the effect of B has already been proved [4], we tried to precise its influence. A baseline wire containing 13 ppm boron was compared to a modified wire in which B has been removed from the formula. Figure 3 shows the two transition curves. The 50 J transition temperature is decreased by about 25 °C for the weld metal without boron. 50 J level was chosen to have a safety margin versus usual requirements (27 J at room temperature).

**Table 2 – Chemical range of the all-weld metals**

| | C<br>% | Mn<br>% | Si<br>% | Cr<br>% | Mo<br>% | Co<br>% | V<br>% | Nb<br>% | W<br>% | Ni<br>% | B<br>ppm | N<br>ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chemical range | 0.07<br>0.12 | 1.2<br>1.35 | 0.13<br>0.34 | 8.0<br>9.6 | 0.41<br>0.68 | 0.93<br>1.12 | 0.18<br>0.24 | 0.031<br>0.063 | 1.28<br>1.74 | 0.02<br>0.04 | 10<br>25 | 400<br>480 |

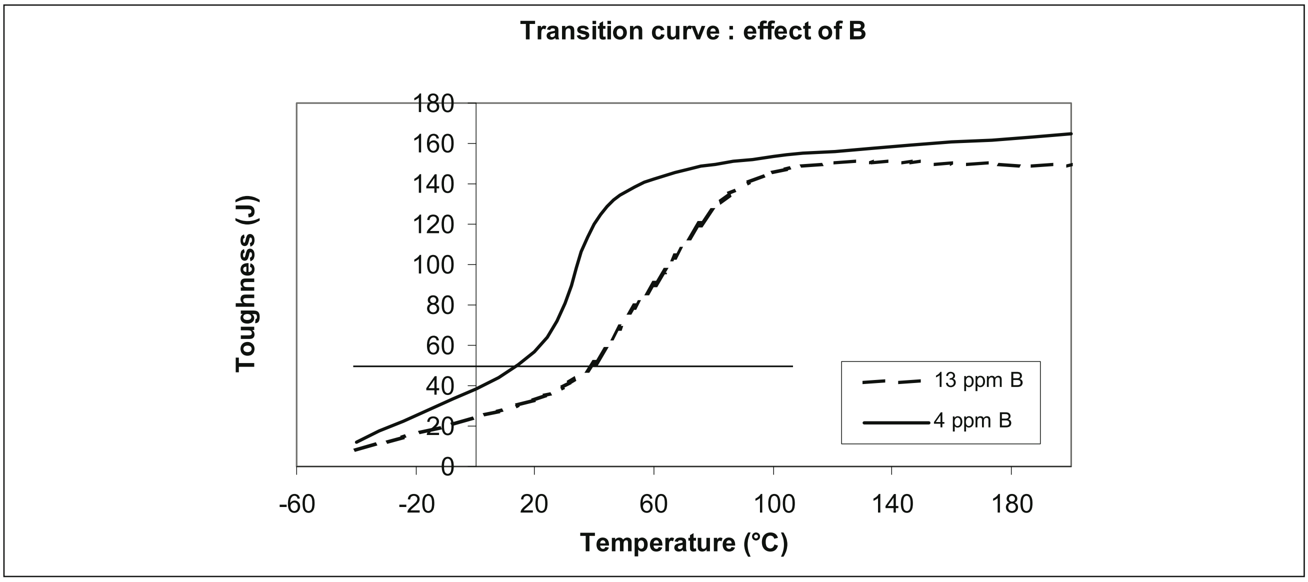


Figure 3 – Effect of B on Charpy transition curve

As B is added in the parent material for creep purpose, we considered that it cannot be removed from the formula, despite its detrimental influence on toughness. The B range of the weld metal has been chosen in the lower range of the base metal.

## 4.2 Influence of nitrogen

Due to its strong austenite former effect and its ability to form precipitates, nitrogen is highly susceptible to play a role on toughness. Effect of nitrogen amount in weld metal has thus been investigated as a potential way to improve toughness values at room temperature. Nitrogen has been kept comfortably over the minimum level of the base material to safely guarantee creep resistance. As can be seen on Figure 4, in a narrow range 400-500 ppm included in the base material range, nitrogen is rapidly deteriorating toughness values. The deterioration is particularly sensible above 450 ppm.

Nitrogen is prone to combine with B to form boron nitrides BN. At these levels of B and N, coarse BN are likely to form [7]. These boron nitrides may be the reason for deteriorated toughness values. On the other hand, very low N levels will certainly induce an increase of delta ferrite content. We thus considered that N level should be kept below 450 ppm but above 400 ppm.

## 4.3 Influence of tungsten

Tungsten is added in P92 steel to give improved creep resistance and high temperature strength. It has been shown that W-containing welds have a consistently worse toughness than W-free welds [5].

However, in the 1.2-1.8 % tungsten range, no clear effect of tungsten increase on room temperature toughness appears (Figure 5). Data have been split in two sets considering previous observations of nitrogen effect. Again, effect of nitrogen on toughness level is important, even if one must note that the range of tung-

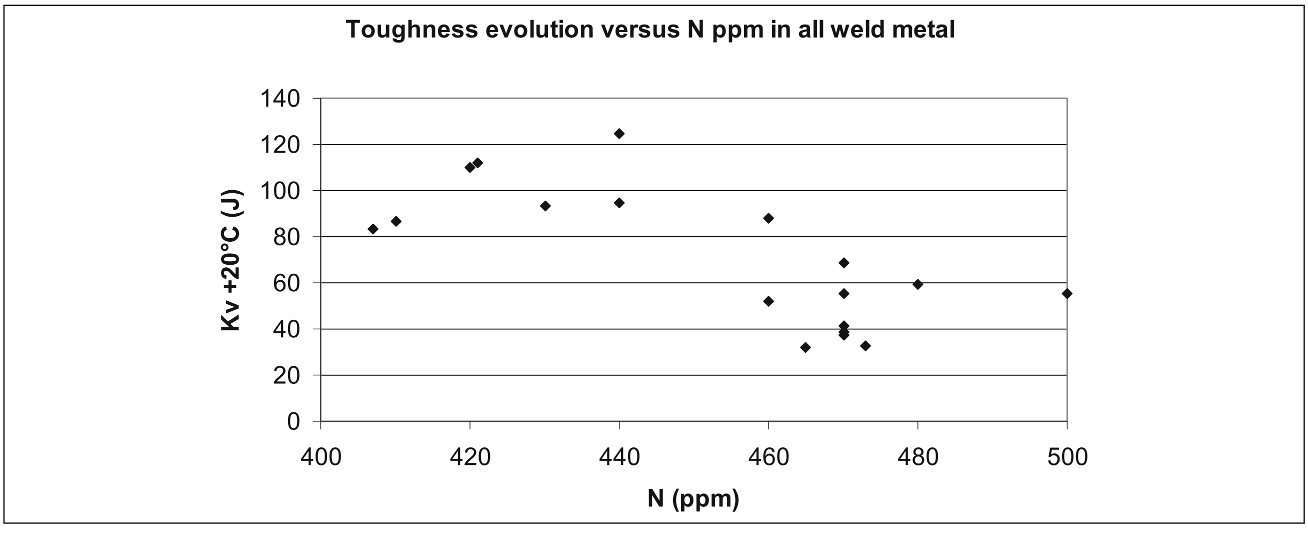


Figure 4 – Influence of nitrogen on toughness at room temperature

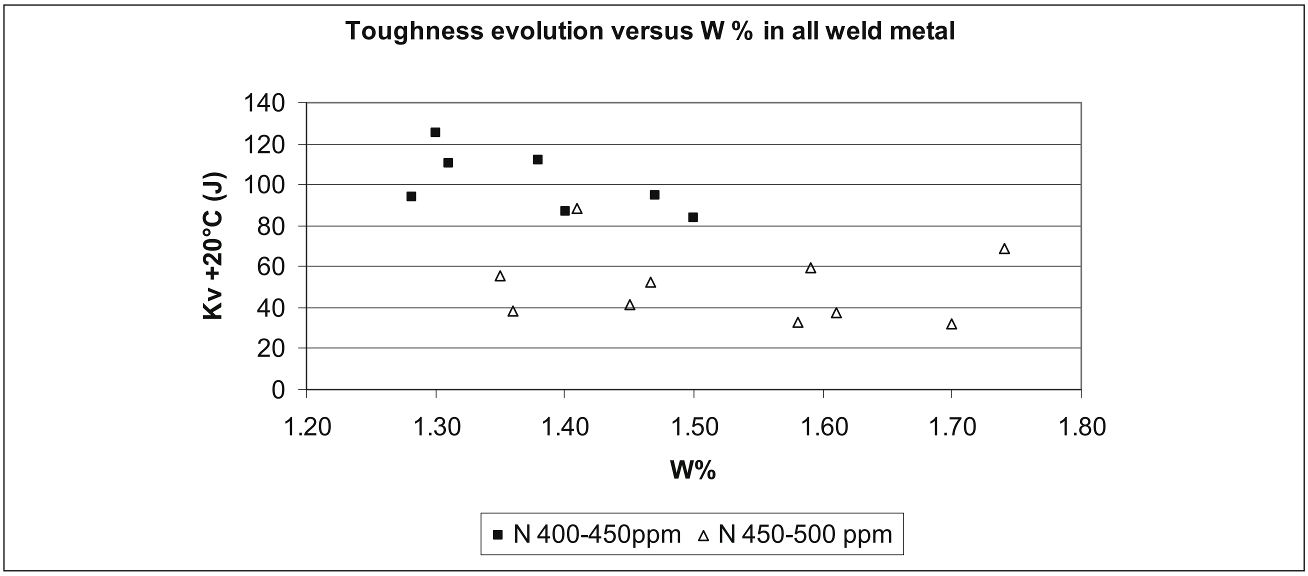


Figure 5 – Influence of %W on toughness at room temperature, for different N levels

sten in which two data sets are overlapping is quite small (1.35-1.5 %).

Tungsten being a ferrite stabilizer, it seems anyway judicious not to increase too much tungsten in the weld metal deposit even if up to 1.8 % no adverse effect is seen on toughness level.

### 4.4 Influence of titanium

Titanium addition to the weld metal deposit has proven to be a good creep enhancer but detrimental for toughness [3]. In order to assess this behaviour, a level of 160 ppm has been targeted in the weld metal, base level being 40 ppm.

Toughness level is deteriorated by this small addition of titanium (Figure 6). 50 J toughness level is obtained at -20 °C for the deposit bearing 40 ppm Ti and +35 °C for the deposit containing 160 ppm Ti.

Tensile properties are greatly increased by a 160 ppm Titanium addition, UTS from 730 MPa to 818 MPa, YS from 588 MPa to 699 MPa, elongation decreasing from 22.3 % to 16.3 %. This increase in tensile properties has obviously an adverse effect on toughness values. However the effect of titanium on microstructure has not been investigated during this study.

## 5 EFFECT OF CARBON AND CHROMIUM

C and Cr content were also varied, as they were expected to influence toughness level. Carbon varied from 0.07 % to 0.12 % and chromium from 8.0 % to 9.6 %. Figures 7 and 8 illustrate the effect of Cr and C respectively, for two nitrogen levels. It appears that variation of Cr through the range 8.0 – 9.6 % has no influence on toughness level. The main impact on toughness level in Figure 7 is nitrogen. Figure 8 in turn shows that nitrogen has a greater effect than carbon. However a slight decrease of toughness at room temperature can be observed as C content increases, for higher N contents.

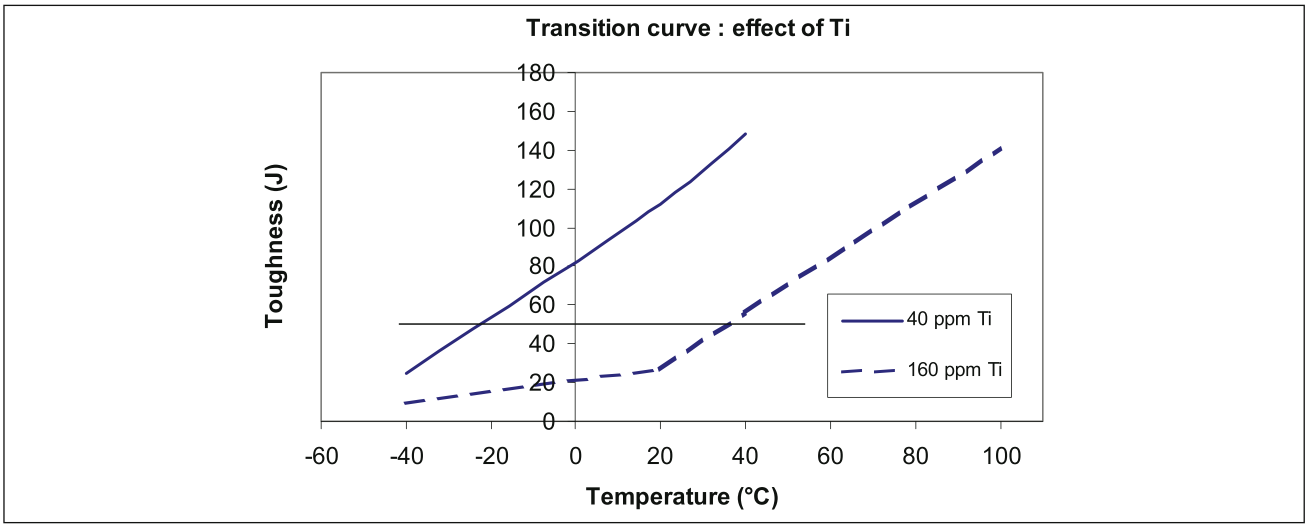


Figure 6 – Effect of Ti on Charpy transition curve

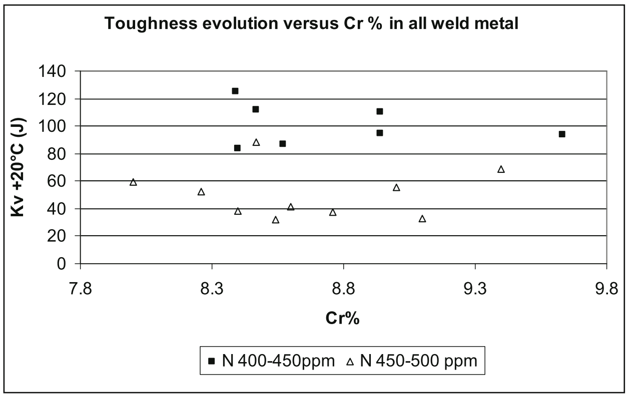


**Figure 7 – Influence of %Cr on toughness at room temperature, for different N levels**

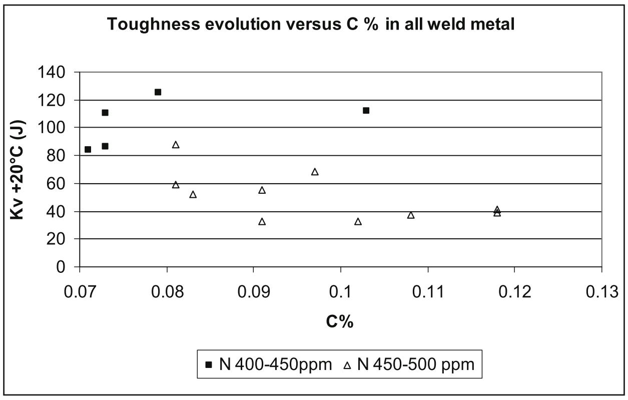


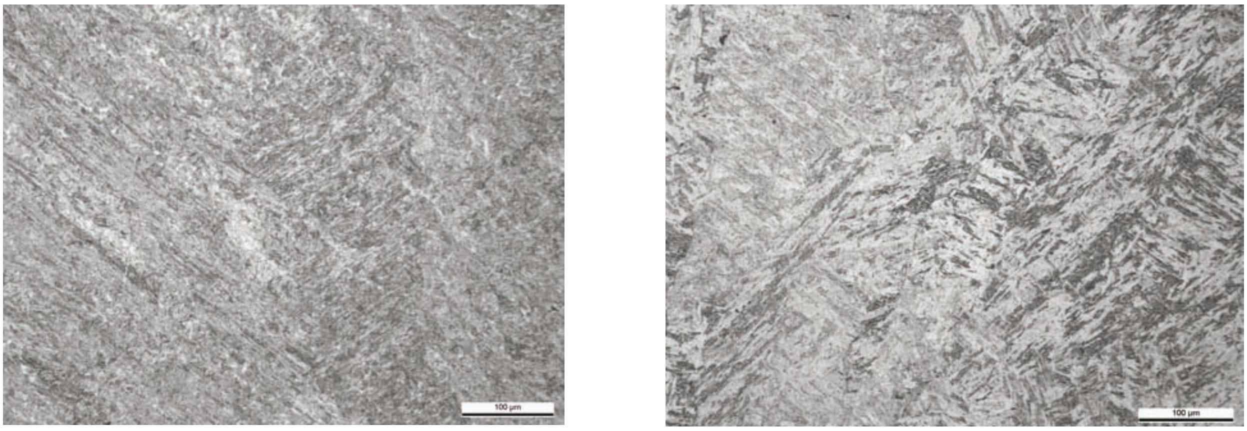
**Figure 8 – Influence of %C on toughness at room temperature, for different N levels**

## 6 MICROSTRUCTURAL EXAMINATION

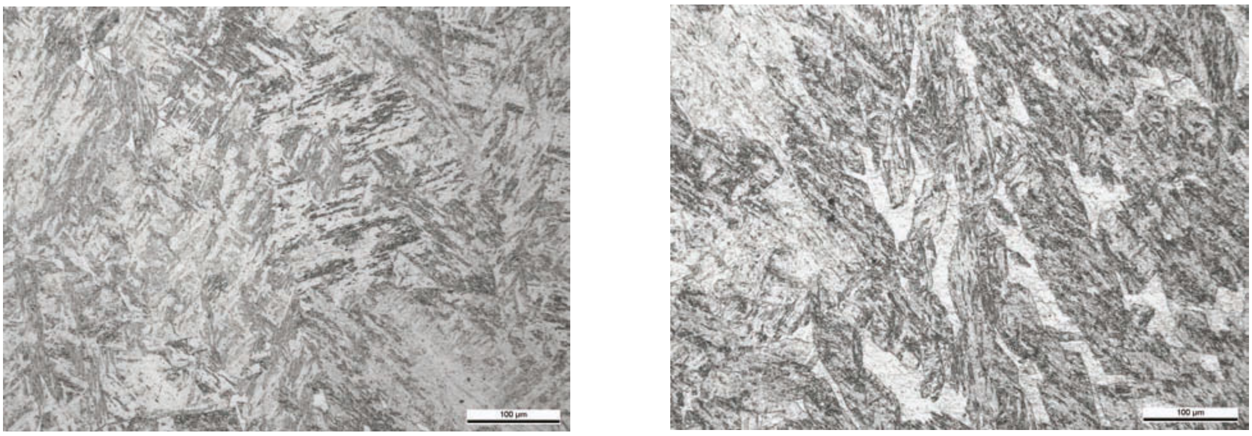
The variation of chemical elements as performed during this study is likely to have an effect on microstructure. In particular, Cr as a strong ferrite former will tend to increase delta ferrite. On the contrary N will act as austenite former and a decrease in N will increase delta ferrite. Chromium equivalent parameter $Cr_{eq}$ (Eq. 1) can be used as an indicator of the susceptibility of the chemical composition to form delta ferrite. Values of $Cr_{eq}$ were then determined for each deposit and microstructural examination were performed for different $Cr_{eq}$ values.

$$Cr_{eq}\,[8] = \%Cr + 6\,\%Si + 4\,\%Mo + 1.5\,\%W + 11\,\%V + 5\,\%Nb + 12\,\%Al + 8\,\%Ti - 40\,\%C - 2\,\%Mn - 4\,\%Ni - 2\,\%Co - 30\,\%N - \%Cu \quad (1)$$

Cross sections were cut in the all-weld metal deposits in as welded conditions and prepared by metallography. The samples were etched with Vilella's reagent and examined by optical microscopy. Microstructures in as-solidified zones are presented on Figure 9. All deposits show a predominantly martensitic struc-



**a) $Cr_{eq}$ 5.1** **b) $Cr_{eq}$ 6.2**

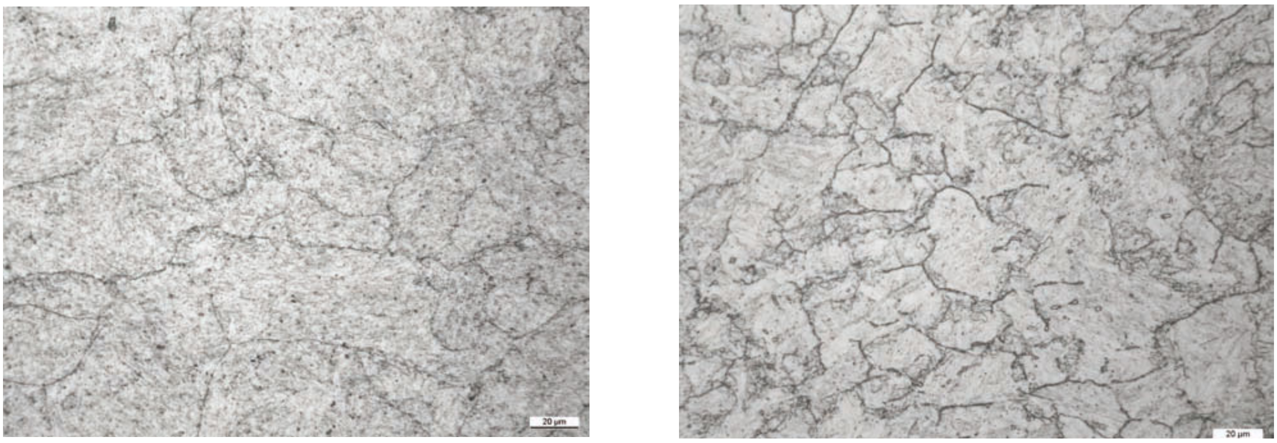


**c) $Cr_{eq}$ 7.7** **d) $Cr_{eq}$ 8.8**

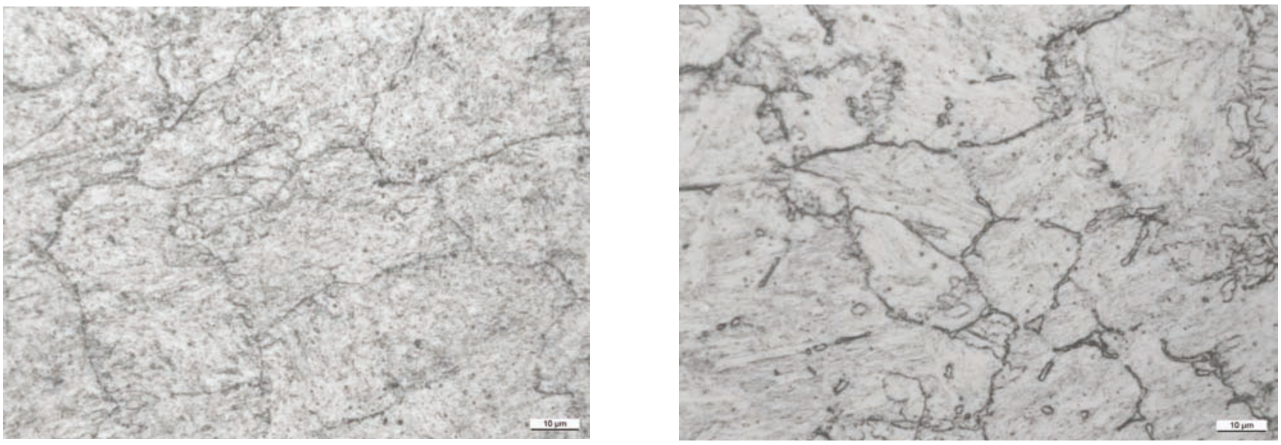
**Figure 9 – Examples of microstructures obtained in as-solidified zones in as welded conditions for weld metal showing various $Cr_{eq}$ level – Vilella's reagent**

ture. In the case of all-weld metal with $Cr_{eq}$ below 8, almost no delta ferrite can be observed. The deposit having a $Cr_{eq}$ of 8.8 shows a high quantity of blocky delta ferrite. These observations confirm that almost no delta ferrite develops for $Cr_{eq} < 8$.

In reheated zones (Figure 10), the microstructure is also martensitic, with carbides at prior austenite grain boundaries. In the case of high $Cr_{eq}$ deposit, narrow bands of delta ferrite can be observed at austenite grain boundaries and triple points.



**a) $Cr_{eq}$ 5.1** **b) $Cr_{eq}$ 8.8**



**c) $Cr_{eq}$ 5.1 (higher magnification)** **d) $Cr_{eq}$ 8.8 (higher magnification)**

**Figure 10 – Examples of microstructures obtained in reheated zones in as welded conditions for weld metal showing various $Cr_{eq}$ level – Vilella's reagent**

## 7 SELECTED CHEMICAL COMPOSITION

Supported by the previous study on chemical composition influence on toughness value, a seamless flux cored wire for submerged arc welding has been developed by Air Liquide Welding, combined with a basic submerged arc flux. The range of Nitrogen level is 400-450 ppm. The C content was set in the middle of the base metal range and B content close to the lower bound of base metal composition 10-20 ppm. No particular Ti addition was made.

The all-weld metal deposit was generated using a 3.2 mm diameter wire, with the following welding parameters: 530 A, 29 V, 60 cm/min. Preheating temperature was 250 °C, the sample was maintained at 250 °C during 3 hours after welding. Interpass temperature is 230-250 °C.

All samples were post weld heat treated at 760 °C during 4 hours.

Tables 3 and 4 gather chemical analysis and properties. The toughness level at room temperature is very good. $AC_1$ temperature has also been measured (with 100°C/h heating rate) and is high enough (802 °C) to avoid problem with the PWHT at 760 °C.

Short term creep test specimens have been generated in the all-weld metal deposit (Figure 11).

**Table 3 – All-weld metal deposit chemical analysis**

| C (%) | Si (%) | Mn (%) | Cr (%) | Mo (%) | Co (%) | Nb (%) | V (%) | W (%) | B (%) | N (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.10 | 0.21 | 1.20 | 8.5 | 0.42 | 1.03 | 0.045 | 0.21 | 1.38 | 0.0010 | 421 |

**Table 4 – All-weld metal deposit mechanical properties**

| Kv + 20 °C | $R_m$ (MPa) | $R_{p0.2}$ (MPa) | A (%) | Ac1 (°C) |
|---|---|---|---|---|
| 116-111-109 (112) | 730 | 588 | 22.3 | 802 |

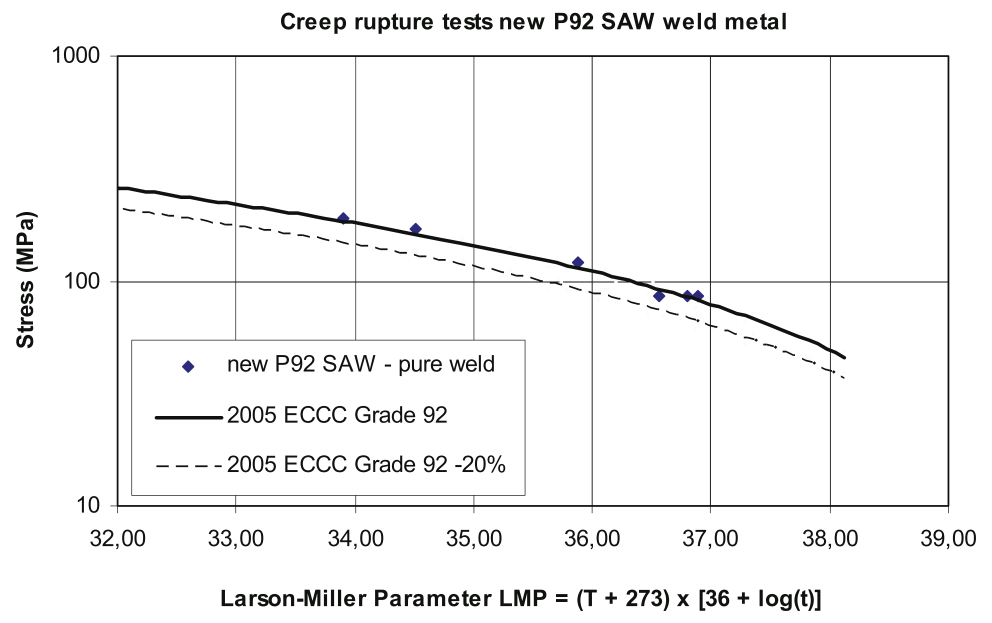


**Figure 11 – Creep rupture characterisation of new P92 SAW all-weld metal**

Weld metal creep strength reaches the level of the Grade 92 base material.

## 8 CONCLUSIONS

The effect of various chemical elements on toughness has been investigated. For this purpose all-weld metals were generated using a seamless flux cored wire with SAW, with different levels of C, Cr, W and N. Variations of W, C and Cr within the base material range did not significantly affect toughness of the weld metal. However Nitrogen content has a great influence on toughness level, decreasing N content resulting in a toughness improvement. Furthermore detrimental effect of B and Ti on toughness was also confirmed during this study. Despite adverse effect of nitrogen and boron on toughness, minimum values have been set in the weld metal in order to match creep properties of the base material.

As a result of this work, Air Liquide Welding developed an optimized seamless flux cored wire for SAW, combined with a basic flux. This solution features a promising toughness / creep compromise, as very good toughness at room temperature and satisfactory creep behaviour have been obtained. This study will now be pursued by a wider characterisation of this SAW solution. Mechanical properties and creep rupture tests will be performed on real joints.

In addition, Air Liquide Welding has also developed SMAW and GTAW to weld T/P92 steels to offer a full range of solutions to weld tubes and pipes.

## REFERENCES

[1] Hald J.: Microstructure and long-term creep properties of 9-12%Cr steels – ECCC Creep conference, 12-14 Sept. 2005, London.

[2] Vaillant J.C., Vandenbergue B., Hahn B., Heuser H., Jochum C.: T/P23, 24, 911 and 92 : new grades for advanced coal-fired power plants – Properties and experience – ECCC Creep conference, 12-14 Sept. 2005, London.

[3] Abson D.J.: The influence of Ti and Al on the toughness and creep rupture strength of grade 92 steel weld metal – TWI Confidential Members Report No. 833/2005.

[4] Vanderschaeghe A., Gabrel J., Bonnet C.: Mise au point des consommables et procédures de soudage pour l'acier grade 92 – ESOPE Conference, 23-25 Oct. 2001, Paris.

[5 Barnes A.M., Abson D.J.: The effect of composition on microstructural development and toughness of weld metals for advanced high temperature 9-13%Cr steels – 2nd International Conference Integrity of High Temperature Welds, 10-12 Nov. 2003, London.

[6] ECCC P92 data sheet, www.ommi.co.uk/etd/eccc/open.htm.

[7] Abe F.: Advanced ferritic steels for thick section boiler components in USC plants at 650°C – ECCC Creep conference, 12-14 Sept. 2005, London.

[8] Patriarca P.: US advanced materials development program for steam generators – Nuclear Tech, 1976, 28, 3, pp. 516-536.