Weld Metals for P91 – Tough Enough?

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1. Introduction

The major challenge facing the power generation industry into the 21st century will be to achieve the targets of increased efficiencies brought about by stringent environmental regulations, whilst ensuring that reliability, availability and maintainability are not compromised. Figure 1 [1] presents the projected increases in efficiencies of various power plant to the year 2020. By the year 2002 it is expected that efficiency figures approaching 50% will have been achieved for at least one ultrasupercritical unit, Avedøre Unit 2, currently being built in Denmark [2].

For coal, which is expected to remain a major source of fuel for power generation throughout the world, the challenge is to develop new, and evolve existing technologies to achieve significant improvements in costs, reliability and thermal efficiency.

A key factor in any power station is the choice of materials designed to operate at the highest possible steam temperature consistent with reasonable component weights and thicknesses. Over the last 15 years new generation materials, particularly in the form of modified 9Cr-1Mo (P/T91), have been widely used for replacement equipment and for new construction.

It is inevitable that material technology will move on and that steels with improved creep performance capable of operating at higher temperatures, will be developed and used [3]. Examples of some of these "new generation" steels are given in Table 1. These steels are essentially developments of P91 with some modifications to the alloying content designed for service temperatures up to about 620°C (1148°F) (Figure 2) and one of the concerns being addressed by the industry is to establish safe mechanical property levels for welded joints.

This paper is concerned with P91 weldment toughness and the possible risks of fast fracture during construction and/or operation since the implications of large scale fractures can be catastrophic in terms of both human life and economic losses.

2. Background

It can be argued that weld metal toughness is an irrelevant consideration in fabrications which are designed to operate at temperatures in the range 500-600°C (900-1100°F); far above the range at which any possible risk of fast brittle fracture would be expected. However, there are situations where components might be pressurised or loaded at ambient temperatures during testing or construction phases.

One such example would be hydrotesting, which, depending on code requirements, may be undertaken at any temperature between 0-30°C (32 – 86°F), although most will be above 20°C (68°F). ASME guidelines recommend that the minimum temperature for hydrotesting is 20°C (68°F).

To cater for these situations, it is considered by some authorities that the weld metal should have a minimum toughness at +20°C (68°F). The AWS specification does not specify impact requirements, but the non-mandatory appendix to A5.5-96 proposes that a suitable test criterion can be agreed by the purchaser and supplier if required. On the other hand, the recently introduced European specification BS EN 1599: 1997 requires a minimum average of 47J (35ft-lbs) and a minimum individual value of 38J (28 ft-lbs) at +20°C (68°F). These values, shown in Table 2, are in line with those authorities who have decided to impose their own toughness requirements and specified values of 35-50J (26-37ft-lbs) at +20°C (68°F) (after a prescribed PWHT) are typical. However, it is difficult to justify the need for significantly higher toughness than that specified for X20 (12CrMoV), a well-established weld metal with a minimum requirement of 34J (25ft-lbs) average and 22J (16ft-lbs) single value at +20°C (68°F).

In general terms, those elements which are beneficial in improving creep performance are detrimental in terms of toughness, i.e. Nb, V and, to a lesser extent, N and Si. A composition balanced to restrict the retention of delta (δ) ferrite and to give a fully martensitic microstructure helps to contribute to both optimum toughness and creep performance. Of course, those steels which are more highly alloyed (Table 1) will tend to have higher strength, with corresponding lower weldment toughness values when essentially matching composition weldments are used.

It is therefore important that sound criteria, based upon Fitness for Purpose, are established for P91 weldments and that these are then used in the future for setting acceptance levels for the newer high strength steels. Failure to do this will result in arbitrary levels being written into standards and specifications, many of which may be unachievable with some process/consumable combinations.

It should be noted that the flux based processes, in particular submerged arc and flux cored arc welding which offer major productivity benefits, and therefore construction efficiencies are also those which have relatively high oxygen contents and correspondingly low toughness [4] (see Figure 3).

This paper will review weldment toughness from a range of consumables, welding processes, heat treatments, etc. It will also present some fracture toughness data and, from an analysis of this data and an assessment of "detectable" defects draw conclusions as to how tough P91 and similar weldments need to be.

3. P91 weld metal toughness

In fabrications of P91 steel, gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW) and submerged arc welding (SAW) are currently the most commonly used welding processes. After appropriate post-weld heat treatment, satisfactory weldment mechanical and creep properties have been consistently achieved under both workshop and on-site conditions.

Recently, in response to the continuously increasing pressure to improve productivity/efficiency and lower fabrication/maintenance costs, the flux cored arc welding (FCAW) process, using both metal cored wire (MCW) and flux cored wire (FCW), has also been considered. Flux cored arc welding can offer not only significant productivity benefits and welder-friendly operability but also can be used for all-positional welding, particularly for ASME 5G/6G fixed pipework where the application of SAW becomes impracticable.

Consequently, the development of consumables for FCAW process has become an active area and special attention is being paid to the development of small diameter (∅1.2mm/0.045”) flux cored wires. However, due to their relatively short history, both mechanical and creep test data for FCW and MCW weldments are still limited.

In the last decade, efforts have concentrated on achieving deposit compositions and hence microstructures that provide an optimum balance of mechanical properties, primarily toughness and creep resistance. It has been widely recognised that weld metal toughness of P91 steel is influenced by many factors, but the most important ones are welding process, weld metal chemical composition, post-weld heat treatment (PWHT) procedure and weld bead sequence.

3.1. Welding process and toughness

Welding process and the consumables used can dramatically influence the toughness properties of P91 weldments because of the effects of fluxes and shielding gases. Table 3 summarises the typical range of all-weld metal impact toughness of various welding processes, and Table 4 lists the typical impact properties achieved from current generation consumables.

3.1.1. GTAW and SMAW

From Table 4, it can be seen that the GTAW process using pure argon shielding produces the highest weld metal toughness at +20°C(68°F) and impact energy values of >100J (74ft-lbs) are consistently achieved. This is because of the high purity microstructure with extra low levels of oxygen (typically <100ppm). In addition this process also produces small and therefore well refined deposit beads. Processes that rely on fluxes (e.g. SMAW, SAW and FCW) and other shielding gases (e.g. FCW, MCW), on the other hand, represent rather more complex situations. In the cases of flux related processes, deoxidation potential and degree of the flux basicity play an important role in dictating the toughness of weld metal. Data in Table 4 indicate that the SMAW process is capable of achieving 50-95J (37-70ft-lbs) average at +20°C after an adequate PWHT, and therefore can comfortably meet the requirement of 47J(35ft-lbs) average (38J min) in the BS EN 1599 specification (Table 2).

3.1.2. SAW

For welding positions and components where mechanised welding is appropriate, SAW is undoubtedly the preferred and most productive process. To date, predominantly 2.4mm diameter 9CrMoV-N solid wire has been used for SAW in construction. Although trials have also been carried out with MCW, the preferred option for SAW has tended to be solid wire. After a typical economical and practical PWHT of 755°C(1391°F)x3hrs, the toughness of SAW weld metal generally achieved so far is scattered within a range of 35-70J(26-52ft-lbs) at +20°C(68°F) and may sometimes fall short of the requirement of 47J(35ft-lbs). Nevertheless, a slightly enhanced PWHT (longer soaking time and/or higher temperature) will usually enable satisfactory toughness to be achieved.

3.1.3. FCAW

At present, there are no national specifications covering flux cored wires for P/T 91 steel. In the design of the alloying of FCWs, efforts have been made to ensure the deposit compositions are as close as possible to the requirements of the corresponding SMAW weld metal (e.g. AWS E9015-B9). However, it should be noted that there are some features that are specially associated with FCW consumables. In order to achieve the capability of all-positional welding, a rutile-based flux is essential and this contributes to a substantially higher recovery level of titanium in the deposit. In addition, slightly higher silicon content, typically 0.3%, is required for sufficient deoxidation and optimum operability. As a result of these, the weld metal hardness of FCW is normally higher than that of SMAW deposits, typically 20HV higher in hardness after a similar PWHT. In view of this, slightly higher temperatures, e.g. 760°C (1400°F), have been used for PWHT to ensure adequate tempering of the weld metal. The FCAW deposits also have higher oxygen content than the SMAW welds; using the shielding gas of Ar-CO_2 mixture (Ar-20-25%CO_2), the oxygen content of the deposit is typically in a range of 600-1000ppm, compared with 300-700ppm for SMAW deposits.

The weld metal impact toughness of FCW varies between different manufacturers. The best toughness currently achieved is typically 25-35J(18-26ft-lbs) at 20°C(68°F). In the recent tests carried out using a shielding mixture of Ar-CO_2 (80/20), ~30J(22ft-lbs) average at 20°C(68°F) has been consistently achieved after a PWHT at 760°C(1400°F) for 4 or 5 hours.

With FCAW process, shielding gas composition can influence weld metal toughness. Generally, a less oxidizing gas mixture (e.g. lower CO_2 level) will produce lower oxygen content and higher toughness. This effect was discussed with MCW in an earlier paper [4] and has been found to equally apply to FCW. A recent evaluation showed that using a gas mixture of Ar-CO_2 (95/5) reduced the oxygen content in the weld deposit by some 100ppm and improved impact toughness by about 10% compared with 80/20 gas.

4. Fracture toughness assessment

The toughness data already presented, and those from extensive studies carried out by other manufacturers and research organisations have been almost exclusively based on Charpy impact tests. It has been shown that this test may not be sufficiently sensitive to the effect of compositional and other variables, and may give misleading results when compared with fracture toughness (CTOD) data. It has also been found that the fracture toughness is more strongly influenced by the PWHT schedule employed than is the Charpy test. Panton-Kent [5] found that Charpy impact data for P91 weld metals was not affected by changes in Nb content in the range 0.02-0.09% or by an increased holding time (2-8hrs) at the PWHT temperature of 750°C (1382°F). Whereas CTOD testing revealed a detrimental effect of increased Nb at extended PWHT times.

A summary of comparable Charpy and CTOD data are given in Table 5 [6, 7, 8]. The chemical compositions of the deposits tested are given in Table 6. The electrodes used for the toughness evaluation were both commercial products and experimental electrodes designed to give controlled compositional variations. It should however, be noted that the commercial consumables were, in the main, first generation SMAW electrodes rather than the current generation consumables reviewed earlier in the paper.

The CTOD testing employed B×B single edge notched bend specimens (with a nominal 23×23mm cross-section) notched on the weld centreline. After fatigue pre-cracking to give a/w=0.5 (where a: is crack depth and w: specimen width) specimens were tested in displacement control over a range of temperature to generate a transition curve. All specimen machining and testing were performed in accordance with BS7448. The temperature for a CTOD of 0.1mm was determined from the transition data on the basis of a “by-eye” lower bound curve. Figure 4(a, b and c) show the toughness transition behaviour of the weld metals, deposited with commercial consumables detailed in Table 6, with regard to Charpy impact energy and CTOD values. From the toughness data, certain trends are apparent; for example, the Charpy impact toughness recorded for the weld root was consistently lower than the weld cap. This is presumed to arise, at least in part, from dilution effects, and the higher strain in the weld root. The fracture toughness data also suggest a beneficial effect of the addition of ~1%Ni, an adverse effect of increased Nb (up to 0.09%) and a beneficial effect of increased Mn (~1.5%). A lowering of Si content has also been found to have a favourable effect on impact toughness, although, as mentioned earlier, it is important to ensure that sufficient Si is present to achieve adequate deoxidation and weldability. Fracture toughness data have also revealed a detrimental effect of high nitrogen (~640ppm) and reduced Mn content (~0.7%). It should be noted that these trends are based the welding, heat treatment and compositional ranges studied.

5. Discussion

5.1. Chemical composition, oxygen content and toughness

Alloying elements have a significant influence on the properties of weld metal. The effects of the major alloying elements in P91 steel, such as niobium, vanadium, nitrogen and silicon, have been reviewed by many reports [4, 6-9]. It is essential that the effect of compositional variables on toughness is not considered in isolation; the effect on creep performance must also be considered in order to achieve an optimum balance of properties. This has been reflected in the changes to weld metal composition that have occurred over the last ten years or so, as the importance of attaining a certain minimum toughness has been recognised. There has been a general reduction in Nb content (from ~0.08/0.09% to ~0.05/0.06%; and in the case of FCW, even down to as low as ~0.03%) and the addition of up to ~0.8%Ni, and these latter values are typical of the current generation consumables considered in this paper.

Many these elements are beneficial in achieving optimum creep strength, but can be detrimental in terms of toughness. An optimum compositional balance that can offer a good combination of creep and toughness properties is always desirable for a P91 weld metal. Although not widely reported, it is also believed that some residual elements, such as titanium and aluminium, can also significantly lower toughness. In the case of FCW, to compensate for the high titanium content, the additions of other toughness lowering elements (niobium in particular) are normally controlled to the minimum specified levels.

The composition of P91 material is at the threshold of δ-ferrite retention, and it is generally believed that the presence of δ-ferrite has a detrimental influence on both creep resistance and toughness. It is therefore important to achieve a balanced composition that can minimise the possibilities of residual ferrite and ensure a fully martensitic microstructure. A measure of the propensity for δ-ferrite retention is provided by the chromium equivalent (Cr_{eq}) [10] and ferrite factor (FF) [11] compositional parameters. For the modified 9Cr1Mo deposits investigated, FF appeared to provide the best correlation with δ-ferrite content, and in general no significant δ-ferrite is retained for a composition with a FF<6. Consideration of the tempering response of the deposit microstructure is another important aspect. The alloying additions to P91 welding consumables should be controlled to ensure that the Ac1 transition temperature of the weld metal is sufficiently low for optimum tempering, but high enough to avoid reaustenisation during PWHT. For this reason, elements that lower Ac1, e.g. Mn, Ni, are generally controlled to avoid any fresh martensite formation after PWHT.

Weld metal toughness is strongly influenced by the oxygen content. Figure 3 illustrates the effect of deposit oxygen content with welding processes using wire form P91 consumables, e.g. GTAW, SAW and FCAW (FCW and MCW). It can be seen that a low oxygen content is always beneficial to a satisfactory toughness. It is therefore very important that weld metal is adequately deoxidised.

5.2. PWHT procedure and toughness

Effective tempering of the martensitic microstructure is essential to achieve a reasonable level of toughness. In practice this involves selecting both an appropriate temperature and time. The general trend of the effect of PWHT on P91 weld metal has been summarised [4]. Recent experience with FCW deposits showed a good agreement. However, because of their 'harder' microstructures, slightly higher temperature (i.e. 760°C) and longer soaking times (~4h) were found to be beneficial in improving impact toughness.

5.3. Bead arrangement, refinement and toughness

Microstructural refinement/auto-tempering, which are controlled by heat input, interpass temperature, bead size and deposition sequence, can also influence weld metal toughness, as is generally the case for weld metals which undergo austenite transformations during cooling and reheating in multipass welding. It has been reported that thin weld beads result in superior weld metal refinement and hence produce better impact properties [12]. For SMAW deposit, this was reported as resulting in improvement for up to 50% in absorbed impact energy at +20°C(68°F).

In a recent investigation carried out using Metrode Chromet 9-B9 (AWS A5.5 E9015-B9) SMAW electrodes, two welds with fully weaved beads were tested. The nominal bead thickness were 2mm and 4mm respectively (as shown in Figure 5). The impact results, however, did not show any distinct improvement and appeared to be unaffected by weld layer thickness. A parallel test was also carried out using a weld of three beads/layer but notching from both the weld centre and the side (as illustrated by Figure 6). The results showed that the specimens notched from the weld centre had a lower toughness than the specimens notched from the side where the weld beads were fully over-lapped and no doubt experienced multi-thermal cycle refining.

5.4. Test temperature and toughness

Although +20°C(68°F) is the test temperature normally specified for impact testing, minor variations in this test temperature can result in significant changes in impact results. This arises because the ductile-brittle transition temperature for P91 SMAW weld metals occurs at about 20°C(68°F). Figure 7 shows a typical transition curve of Chromet 9MV-N weld metal and it can be seen that the transition of this weld metal takes place in the temperature range of 0-40°C(32-104°F).

5.5. Productivity and toughness

In order to reduce costs and downtime, particularly for site repairs, there is much interest in the use of high productivity welding processes, particularly flux cored arc welding. Unfortunately, as has been previously explained, these fluxed processes with higher oxygen contents combined with larger weld beads, tend to give somewhat lower toughness than the well established SMAW process. Nevertheless, the productivity benefits, up to 50% reduction in welding time, are such that FCW consumables are being seriously considered for current applications, provided reasonable toughness values can be achieved. It is probably unreasonable to expect the toughness of FCW weld metal to match that of SMAW deposits and future specifications should reflect these limitations, particularly in the light of the fitness for purpose calculations described in the following section.

5.6. What does this toughness data really mean?

Looking at the available toughness data it would be appear that in the main the deposits investigated gave minimum ambient temperature impact values in the range 35-50J (26-37 ft-lbs). However, these values, if used as specification limits are somewhat arbitrary and it would seem prudent to consider the available fracture toughness (CTOD) data and see what these really translate to in terms of a tolerable flaw size.

If, for example, we look at the commercial consumable deposits detailed in Table 6, and consider an example of a header of 450mm outside diameter and 50mm wall thickness, and with design conditions of 580°C(1076°F) and 176 bar. If we consider commercial SMAW consumable W3, which gave the poorest toughness of the commercial consumable deposits, this gave a CTOD value of $\delta c = 0.021$mm at +20°C.

Calculation using TWI's Crackwise software [13], which automates the engineering critical assessment procedures set out in BS7910, for a hydrotest condition assuming pressurisation to 1.25 times design at ambient temperature, indicates that the maximum tolerable surface breaking flaw size for a longitudinal seam weld is 135.6mm in length and 13.6mm in depth, i.e. greater than ¼ wall thickness (Figure 8); the corresponding failure assessment diagram is given in Figure 9. This suggests that despite the apparently poor ambient temperature fracture toughness, the defect tolerance is generally good, by virtue of the application of PWHT, and in the example cited, the relatively low membrane stress. Defects considerably smaller (shorter and shallower) should be readily detected by current NDT technology. The graph presented at Figure 10 shows the change in the maximum tolerable flaw size with increased toughness; once the toughness in the present example exceeds a level of CTOD ≈ 0.08mm, little further benefit is gained and plastic collapse becomes dominant. This analysis was based on the first generation SMAW consumables and even more conservative values should be achieved with the improved toughness available from current generation consumables. This analysis may therefore provide confidence in the use of the higher productivity processes such as FCAW and SAW where the combination of higher oxygen contents and larger, less well refined weld beads inevitably result in reduced toughness (Table 3), although the CTOD behaviour of these deposits needs to be determined.

5.7. Implications for next generation materials

The continued drive towards improved thermal efficiency will inevitably result in the following:

a) Greater use of more advanced materials (Table 1);
b) Use at greater thicknesses for a wider ranges of components;
c) A demand for "matching" welding consumables with a good combination of creep properties and toughness;
d) Increased use of higher productivity welding processes to improve manufacturing efficiency.

It is also reasonable to assume that alloy designs aimed primarily at improved high temperature creep properties will inevitably lead to lower inherent toughness. However, it has been shown in work on E911 steel that if the modern generation consumable designs are used in conjunction with the correct heat input and weld bead sequence plus the use of an optimum heat treatment then weld metal impact values comparable with those for P91 weldments can be achieved [14]. Once initial searching of candidate consumables has been carried out, it would be prudent to carry out fracture toughness testing (CTOD) and tolerable defect calculations to ensure fitness for purpose.

6. Conclusions

This paper has attempted to answer the question: "Are modern generation weld metals for P91 steel tough enough and fit for purpose?"

In trying to answer this question, toughness data from first generation and current generation welding consumables have been reviewed. The influence of welding processes, particularly those needed for improved productivity, and the effect of welding variables have been assessed. Fracture toughness data from CTOD has been analysed and using accepted engineering critical assessment procedures, maximum tolerable flaw sizes have been calculated.

It is concluded that the toughness of weld metals deposited using the commonly employed SMAW process is adequate. Tolerable flaw sizes, assuming hydrotest conditions at +20°C (68°F) are large and should be readily detected with current NDT technology. It is therefore our view that current generation SMAW weld metals are tough enough! The analysis performed should provide confidence in the use of higher productivity processes, but fracture toughness testing of FCAW and SAW deposits is required.

It should be noted that more onerous properties may be required for the next generation consumables for more advanced creep resistant steels (e.g. E911, P92) and similar fitness for purpose analyses should be carried out.

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8. References

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Table 1. Chemical composition of 9-12%Cr steels used in power plant tubing and piping

	P91	P92	P122	E 911
C	0.08 – 0.12	0.07 – 0.13	0.07 – 0.13	0.09 – 0.13
Si	0.20 – 0.50	max. 0.50	max. 0.50	0.10 – 0.50
Mn	0.30 – 0.60	0.30 – 0.60	max. 0.70	0.30 – 0.60
P	Max. 0.020	max. 0.020	max. 0.020	max. 0.020
S	Max. 0.010	max. 0.010	max. 0.010	max. 0.010
Ni	Max. 0.40	max. 0.40	max. 0.50	0.10 – 0.40
Cu	-	-	0.30 – 1.70	-
Cr	8.00 – 9.50	8.50 – 9.50	10.0 – 12.5	8.50 – 9.50
Mo	0.85 – 1.05	0.30 – 0.60	0.25 – 0.60	0.90 – 1.10
W	-	1.50 – 2.00	1.50 – 2.50	0.90 – 1.10
V	0.18 – 0.25	0.15 – 0.25	0.15 – 0.30	0.18 – 0.25
Nb	0.06 – 0.10	0.04 – 0.09	0.04 – 0.10	0.06 – 0.10
Al	Max. 0.040	max. 0.040	max. 0.040	max. 0.040
N	0.030 – 0.070	0.030 – 0.070	0.040 – 0.100	0.050 – 0.090
B	-	0.001 – 0.006	max. 0.005	0.0005 – 0.005

Table 2: Mechanical property requirements for weld metals of various specifications for type 91 material

Type	Specifications	Shielding Gas	Tensile strength MPa	Yield strength at 0.2% offset, MPa	Elongation %	Toughness requirement @20°C Avg/min, J	Preheat and interpass temperature, °C	Postweld condition	PWHT procedure
Parent Steel	Type 91		585-850	415	20	(>41)			730 to 780^{O}C
Covered Electrode	BS EN 1599:1997; ECrMo91B		585	415	17	47/38 [a]	200 to 300	PWHT	750 to 770^{O}C 2 to 3hrs
Solid Wire	pr EN 12070:1996; CrMo91		585	415	17	47/38 [a]	250 to 350	PWHT	750 to 760^{O}C 3hrs
Covered electrode and solid wire	GEC-Alsthom 30/658		No mechanical property specified, but expected to exceed the parent steel properties					PWHT	
Covered electrode	AWS A5.5-96 E90XX-B9		620	530	17	Not specified [b]	232 to 288	PWHT	730 to 760^{O}C 1hr
Solid wire	AWS A5.28-96 ER90S-B9	Argon/5%O_2 [c]	620	410	16	Not specified [b]	150 to 260	PWHT	730 to 760^{O}C 1hr

a: Minimum average from three test specimens and only one single value lower than minimum average is permitted.

b: AWS does not specify impact requirements for E90XX-B9 or ER90S-B9, but the non-mandatory appendices to A5.5-96 and A5.28-96 propose that a test criterion should be agreed by the purchaser and supplier.

c Other gas mixtures can be used as agreed between the purchaser and supplier.

Table 3. Weld metal impact toughness properties and hardness of various welding processes*

Process	Consumable type	Size, mm	Typical impact energy at ambient temperature, J	Typical lateral expansion at ambient temp. mm	Typical hardness, HV (10kg)
GTAW	Solid wire	2.4	100-240	2.0-2.5	240-260
	MCW	1.2	100-150	1.8-2.1	240-260
SMAW	Covered electrode	2.5, 3.2, 4.0, 5.0	30-90	0.7-2	230-250
SAW	Solid wire	2.4	30-70	0.5-1.0	240-260
	MCW	1.6	25-70	0.4-0.8	240-260
GMAW	FCW	1.2	10-40	0.15-0.6	230-270
	MCW	1.2, 1.6	30-40	0.4-0.5	240-260

*: PWHT: 755-760°C x 2-5 hours followed by furnace cool.

Table 4. Average all-weld metal toughness current generation P91 consumables

Process	Metrode Product/form	Gas/Flux*	PWHT , °C / h	Average CVN J @ +20°C (68°F)
SMAW	**Chromet 9MV**	NA	755 / 3	50
	Chromet 9MV-N	NA	755 / 3	65
			755 / 8	95
	Chromet 9-B9	NA	746 / 1	20
			755 / 1	35
			755 / 2-3 or 760 / 1	60
			774 / 2	85
GTAW	**9CrMoV-N (solid wire)**	Argon	755 / 3	220
	Cormet M91(MCW)	Argon	755 / 3	150
SAW	**9CrMoV-N (solid wire)**	LA491	755 / 3	40
	Cormet M91 (MCW)	LA491	755 / 3	40
FCAW	**Cormet M91 (MCW)**	Ar-He-CO_2*	755 / 3	35
		97.5/2.5	755 / 3	30
		80/20	755 / 3	25
		80/20	755 / 6	30
	Supercore F91 (FCW)	80/20	755/3	20
		80/20	760 / 5	30
		95/5	760 / 4	33

*: Mixture ratio = Ar-38%He-2%CO_2

Table 5. Summary of Charpy and CTOD data for SMAW Grade 91 weld metal following PWHT of 2 hours at 760°C.

Weld	Composition	FF	Cr_{eq}	Temperature for Absorbed Energy of 40J (°C)		Temperature for a CTOD of 0.1mm (°C)
				Cap	Root	
Commercial W1	Low Ni, Med Nb	10.0	7.7	3	21	32
Commercial W2	Low Ni, High Nb	11.7	8.8	15	22	27
Commercial W3	~1%Ni, Med Nb	7.1	4.6	10	12	56
Commercial W5	~1%Ni, Low S, Low N, High O	7.0	4.7	-9	14	8
Experimental W2	High N	8.9	6.2	-3	-3	21
Experimental W3	Low Mn	10.1	7.5	-14	0	11
Experimental W4	High Mn	9.0	6.3	-9	-2	-8
Experimental W8	~1%Ni, ~0.09%Nb	7.8	4.8	8	40	~120
Experimental W11	~1%Ni, ~0Nb	7.1	4.2	-26	24	57

Table 6. Chemical composition of weld deposits used for impact and CTOD toughness testing

Weld	Composition	Element, wt%													
		C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	Cu	Co	O	N
Commercial W1	Low Ni, med Nb	0.09	0.97	0.41	0.006	0.012	8.7	0.08	0.99	0.06	0.17	0.02	0.01	0.049	0.045
Commercial W2	Low Ni, high Nb	0.08	1.02	0.42	0.003	0.009	9.3	0.03	0.98	0.09	0.21	0.01	<0.01	0.046	0.048
Commercial W3	~1%Ni, med Nb	0.10	1.07	0.39	0.005	0.009	8.9	0.68	0.99	0.05	0.18	<0.01	<0.01	0.034	0.047
Commercial W5	~1%Ni, low Si, low N, high O	0.08	1.12	0.19	0.004	0.010	8.9	0.70	0.91	0.03	0.19	0.01	0.01	0.060	0.021
Experimental W2	High N	0.07	0.95	0.14	0.005	0.012	8.9	0.06	0.96	0.04	0.18	0.03	<0.01	0.062	0.064
Experimental W3	Low Mn	0.08	0.69	0.17	0.004	0.010	9.0	0.05	0.98	0.04	0.19	0.01	<0.01	0.060	0.045
Experimental W4	High Mn	0.08	1.47	0.18	0.004	0.010	9.3	0.04	0.97	0.05	0.20	0.01	<0.01	0.052	0.046
Experimental W8	~1%Ni, ~0.09%Nb	0.10	0.96	0.39	0.003	0.009	8.6	0.72	0.96	0.09	0.23	0.02	<0.01	0.043	0.039
Experimental W11	~1%Ni, ~0%Nb	0.10	0.90	0.35	0.004	0.009	8.4	0.69	0.96	<0.01	0.23	0.02	<0.01	0.050	0.040

Ca, B all <0.0005
Ti, Al, Sn, As, Pb, Zr, all <0.01

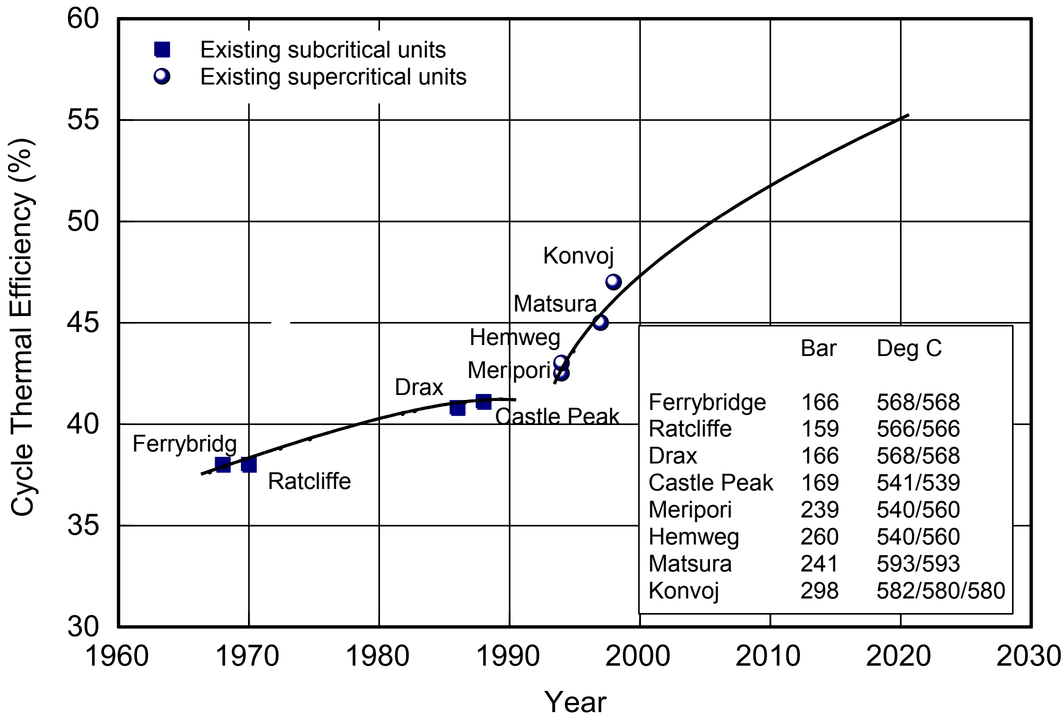


Figure 1: Developments in Thermal Efficiency (Mitsui Babcock Technology Centre) [1]

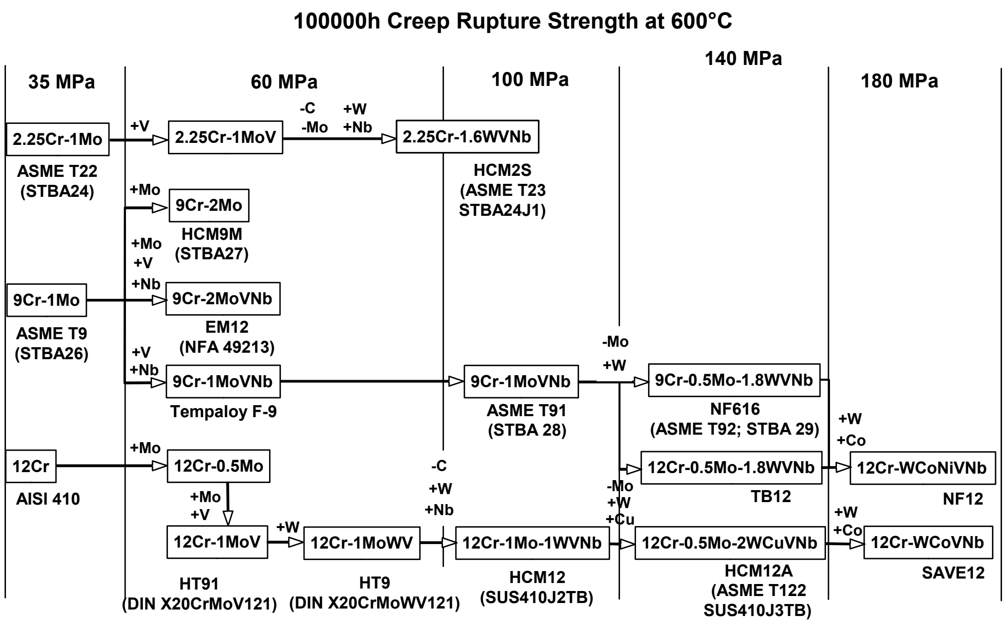
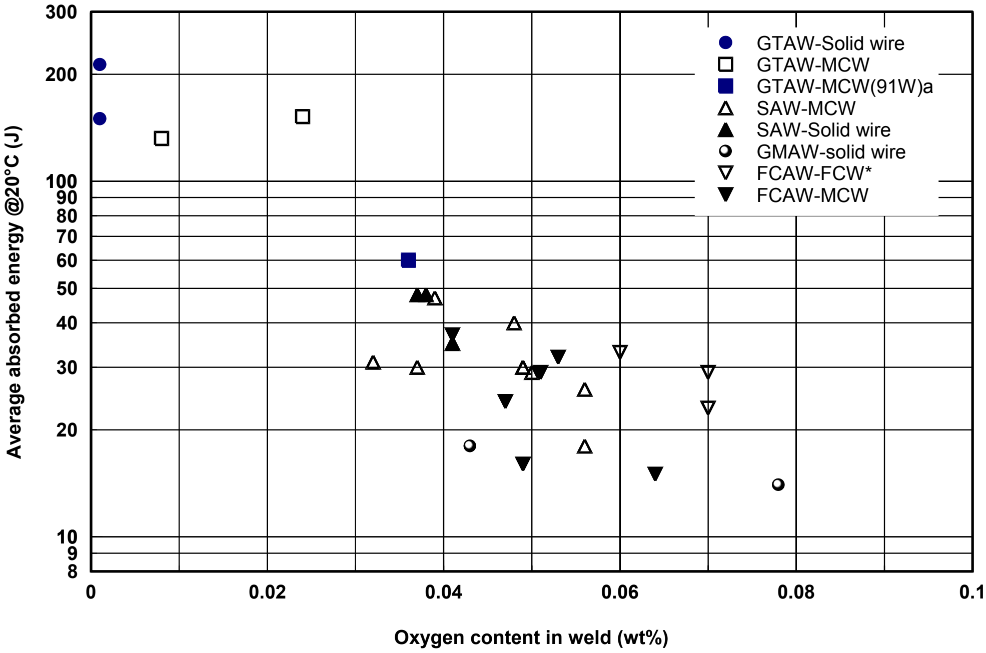
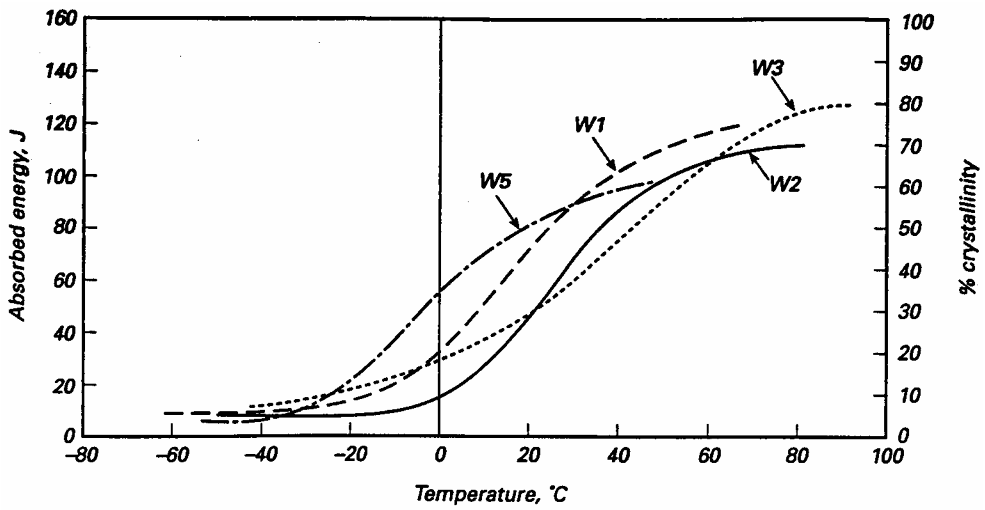


Figure 2: Development Progress of Ferritic Steels for Boilers [3]

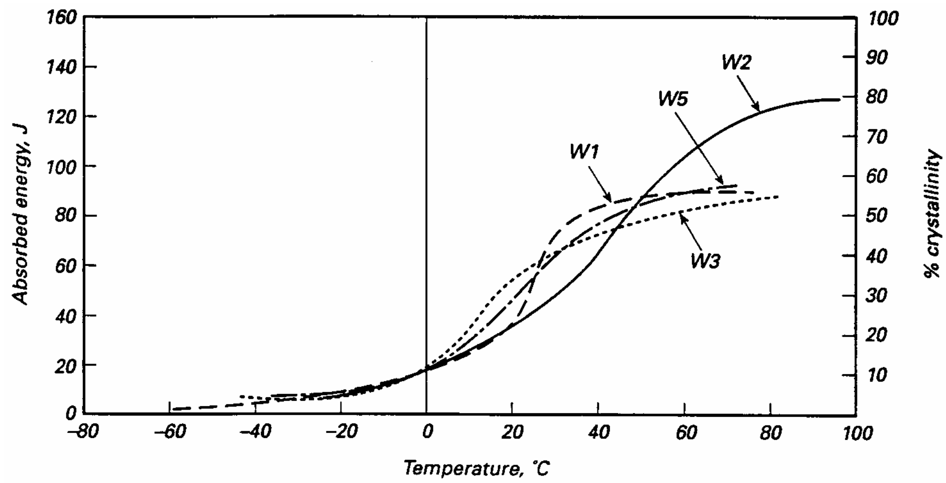


*: PWHT procedures for the FCW weld metals were 760°C/4-5h+FC

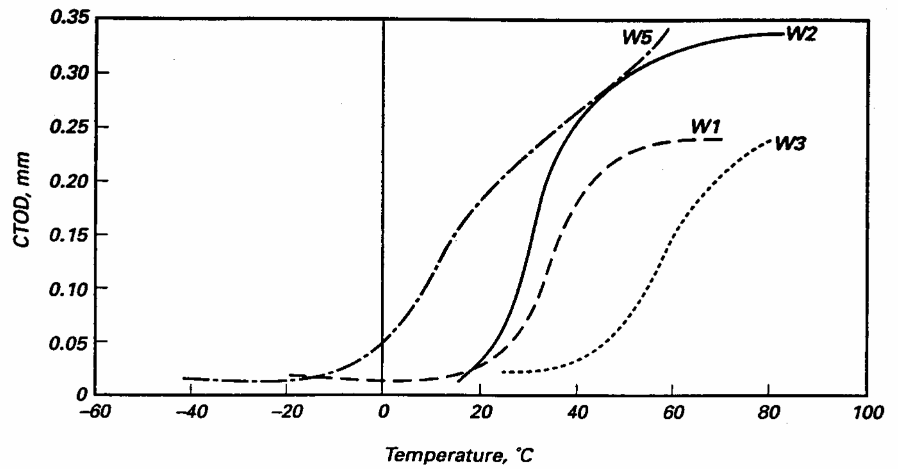
Figure 3. Effect of oxygen content on impact toughness of P91 steel weld metals from wire related welding processes.



a. Charpy transition data for the cap sub-surface location of the commercial consumable deposits notched at weld centreline.

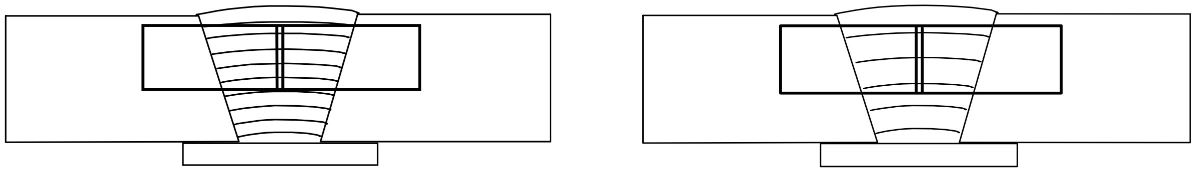


b. Charpy transition data for the root sub-surface location of the commercial consumable deposits notched at the weld centreline.



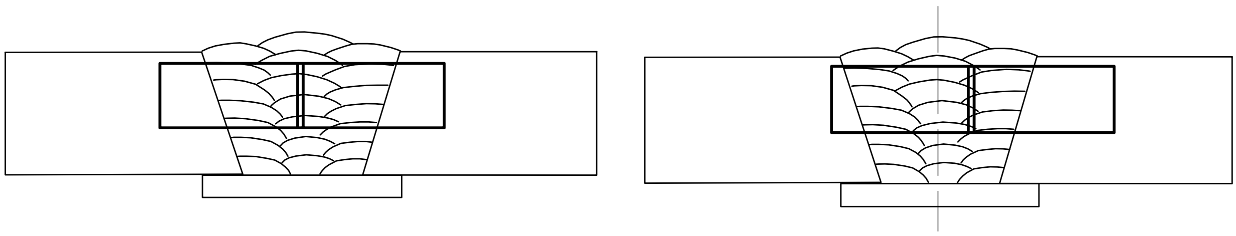
c. CTOD transition curves for the commercial consumable deposits notched at at the weld centreline

Figure 4. Charpy impact and CTOD toughness transition curves of P91 weld metals from the first generation consumables



(a) Thin beads (~2mm) (b) Thick beads (~4mm)

Figure 5. Illustration of the bead build-up of the fully weaved weld joints



(a) Centre (b) Side

Figure 6. Illustration of the notching positions for the impact test

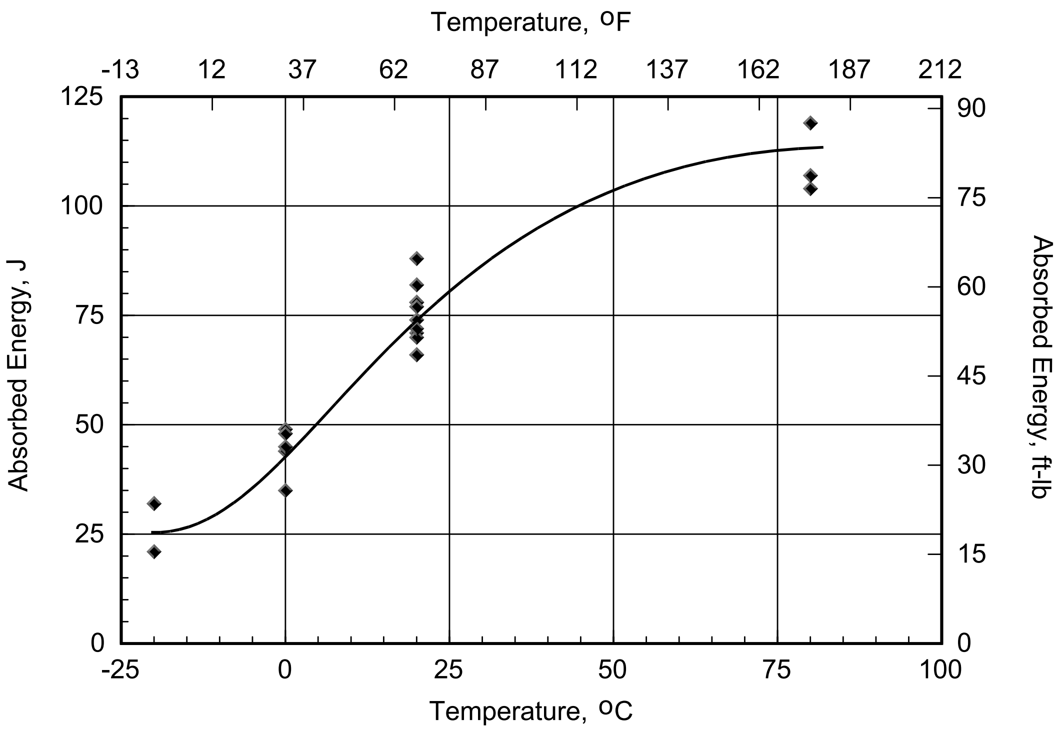


Figure 7. Impact transition curve of Chromet 9MV-N weld after a PWHT of 755°C/3h

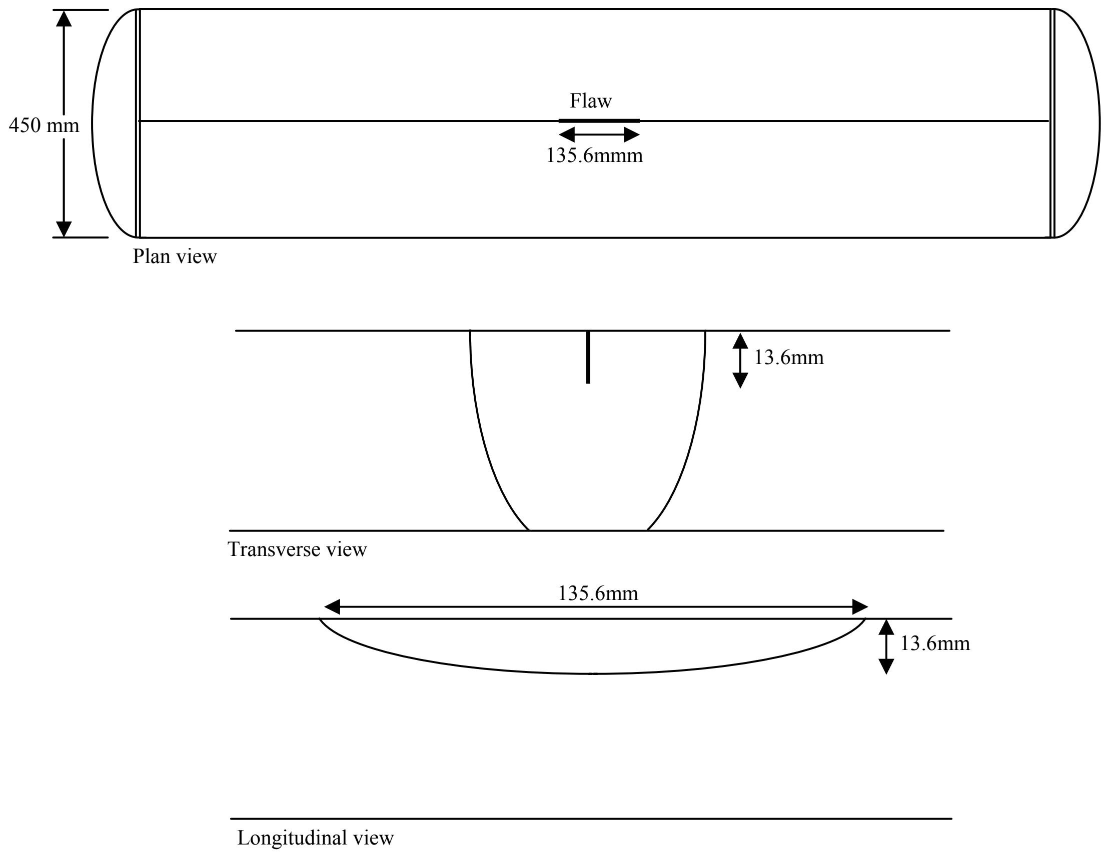


Figure 8. Schematic showing header with maximum tolerable surface breaking flaw in longitudinal seam weld

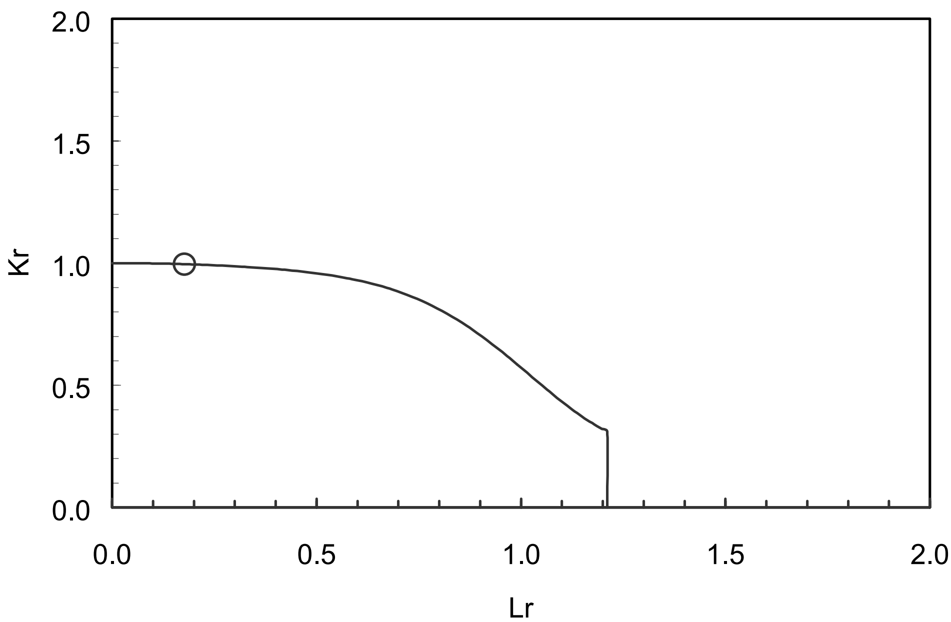


Figure 9. Failure assessment diagram for weld W3 (CTOD = 0.021mm)

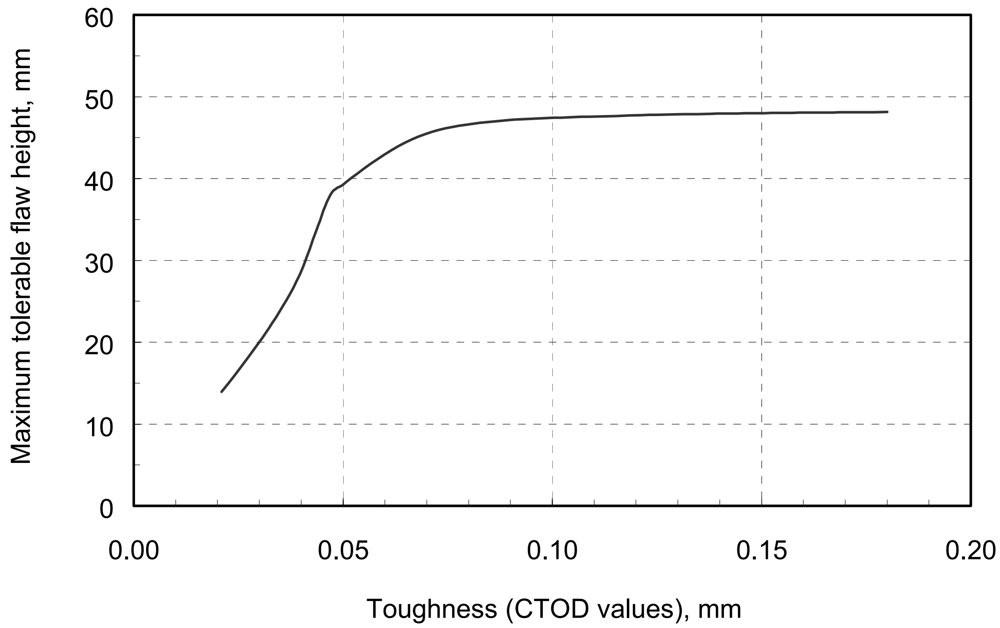


Figure 10. The change of maximum tolerable flaw size with increased toughness (flaw aspect ratio = 10:1)