FRACTURE TOUGHNESS OF NARROW-GAP WELDED JOINTS IN THE NUCLEAR PRESSURE VESSEL STEEL 22 NiMoCr 3 7

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SUMMARY

The mechanical testing of Narrow-Gap welded joints in 100 and 200 mm thick sections of the steel 22 NiMoCr 3 7 has revealed that the weld metal, and not the HAZ or the weld metal–parent metal boundary, is the critical region. This modified gas shielded welding process operates with a very low heat input in the order of 6.500 J/cm/pass and the combination of small diameter welding wires and high welding speeds contributes to the excellent joint properties in the as-welded conditions.

To investigate the effect of preheating and post-welding heat treatment on the mechanical properties of Narrow-Gap welds, tensile, notch impact, flat bend and fracture toughness test specimens were extracted from joints welded with the following conditions:

1. no preheating; no post-weld heat treatment;
2. no preheating; soaking at 300°C;
3. no preheating; stress-relief h.t. at 600°C;
4. preheating 200-250°C; no post-weld heat treatment;
5. preheating 200-250°C; soaking at 300°C;
6. preheating 200-250°C; stress relief h.t. at 600°C.

Tensile testing at room temperature and at 250°C of round specimens oriented across the seam, revealed the ultimate fracture to be always located in the base material, remote from the welded zone. Although pores or slag inclusions had an influence on bend-test results of specimens in the as-welded condition, the results generally show failure free bends to 180° with no evidence of cracking in the HAZ or at the fusion boundary.

Using sharp-notched impact bend specimens with the notch located in the centre of the seam as well as in and across the HAZ, absorbed energy-test temperature curves have been determined for each welding condition. In comparison to the base material impact toughness, the weld metal exhibits superior toughness in the temperature range −60° to 0°C, but yielded lower values at room temperature. After stress relieving at 600°C, the impact toughness of the weld metal reduced significantly, apparently due to precipitations occurring in the weld-metal microstructure. Test results from welded specimens with the notch in the HAZ show this region to have superior notch impact toughness to the base material.

Crack opening displacement (COD) specimens 45×90×380 mm with the fatigue crack located in the weld metal and in the HAZ were tested at 0° and 20°C using both the recommendation in BS DD 19: 1972 as well as acoustic emission measurements for the determination of COD values. For this method of fracture toughness testing it has been shown that the occurrence of a critical event must be clearly defined as corresponding to stable crack growth or alternatively to unstable crack propagation.

1. Introduction

The application of Narrow-Gap welding to the joining of low alloyed fine grained structural steels in heavy sections is ultimately aimed at reducing or eliminating the problem of reheat cracking in the heat affected base material while providing a fully mechanized welding process which can be applied in all welding positions. The combination of high welding speeds and small diameter welding wires with this modified and automated gas shielded welding process results in small weld seams, very narrow heat affected zones and good joint properties in the as-welded condition. Welding of the reactor construction steel 22 NiMoCr 3 7 in thick sections using joining processes characterized by high welding heat input, has been associated with intercrystalline cracking in the coarse grained region of the HAZ during stress relief heat treatment at 600 °C /¯1,2,3_7. The Narrow-Gap welding process operates with a very low energy input in the order of 6500 Joule/cm/pass and the mechanical properties of the deposited weld metal are enhanced by the multi-pass welding technique.

The first investigations of the Narrow-Gap welding of 50, 100 and 200 mm thicknesses of the steel 22 NiMoCr 3 7 have not only been concerned with the production of acceptable welded joints with a range of welding consumables, but also with the determination of the influence of preheating and post-welding heat treatment processing on the mechanical properties of the joints. These properties were determined by testing of tensile,notch impact, flat bend and fracture toughness test specimens. With respect to the fracture mechanics investigations, the testing of base material and Narrow-Gap welded specimens was done according to the procedures recommended in BS. DD 19 /¯4_7. During these tests, acoustic emission measurements were used to determine the start of stable crack growth or unstable crack propagation and thereby to facilitate the calculation of critical COD-values.

2. Welding process

The Narrow-Gap welding machine in IFAM permits linear-unidirectional one-sided welding of section thicknesses up to 300 mm in the horizontal, horizontal-vertical and overhead positions. The welding head is mounted on a track and carriage system which allows welding over a length of 3 meters, Fig. 1. Test pieces from 200 mm forged sections of the steel 22 NiMoCr 3 7 are shown prepared with end pieces and held in a special holding fixture which was constructed as an integral part of the work table.

The welding head comprises two seperate wire and gas feeding systems and position control units, with the distance between the front and rear torch being fixed at 345 mm. The water cooled torches, the gas feed tubes and the control sensors are designed to pass into the 0,6...0,9 mm gap. The initial setting of the position of each torch with respect to the weldments is done manually with all other functions, e.g. gas feed, wire feed, weld start and stop sequences, being automatically controlled. The operation principle of this process is related to the wire feeding process, whereby as a result of a bending operation, the wire electrode is caused to exit the contact tube at right angles to the welding direction and to develop a circular arc of approximately 100 mm radius. The wire electrode in the front torch is directed towards the left hand wall in the gap while that in the rear torch is inclined to the other wall, such that, for each pass of the welding head effectively two overlapping fillet welds are deposited. In this way, adequate side wall fusion is ensured.

Preheating to a temperature of 200...250 °C and maintenance of interpass temperatures is done with a propane gas burner which has been incorporated into the work table. To simulate the restraint conditions applied to thick section weldments in practice, a clamping system is used to control the gap geometry and to hinder the distortion as a result of shrinkage stresses. In this way, a near parallel gap of 8 mm width can be maintained during welding. End pieces are used to facilitate welding over the entire length of the weldments. Degreasing of circular saw cut surfaces has proven adequate edge preparation but in this case a steel backing strip must be used for starting the weld.

3. Base material

The steel 22 NiMoCr 3 7 in rolled and forged sections is characterized by high tensile strength at service temperatures up to 400 °C [5]. In the quenched and tempered condition, this fine grained low alloyed steel exhibits ultimate tensile strengths of 630...690 N/mm^2 and 575...640 N/mm^2 at room temperature and 250 °C respectively. Minimum yield strengths of 475 and 430 N/mm^2 have been measured at the respective temperatures [6]. With respect to tensile strength, similar test values were obtained for specimens orientated parallel to and across the rolling direction. Relatively large variations in mechanical strength result from different heats of the steel. Testing of specimens from this steel quality but with a Ni-content of 1,14 % instead of 0,88 % showed minimum yield strengths of 560 and 520 N/mm^2 at room temperature and 200 °C respectively [7]. The notch impact toughness of this material is specified to be 65 J/cm^2 (DVM-transverse) or a minimum of 42 J/cm^2 (Charpy-V) at 20 °C [5]. Testing of specimens with a machined and pressed notch (Schnadt-A_o) yielded the transition curve shown as the broken-line in Fig. 4. This line corresponds to the minimum measured value during testing of base material specimens (longitudinal and transverse orientation) at the respective temperatures. By very thick sections, the impact toughness of this steel has been shown to vary considerably across the section [8].Tests on specimens from a 100 mm thick section revealed no dependence on the extraction of specimens [9].

Fracture toughness testing of pressure vessel steels in the unirradiated and irradiated conditions has been previously done using linear-elastic methods, usually in the temperature range of -20...-200 °C /‾10_7. To investigate the fracture behaviour of this steel at higher temperatures, the first tests on 100 mm single-edge cracked, three- point bend specimens were conducted at +20 °C and a Crack-Opening-Displacement according to an elastic-plastic analysis calculated /‾4_7. As a result of the extremely large values for δ_m, calculated for a displacement V_m corresponding to the attainment of maximum load, further tests were conducted on 45 mm bend specimens in the temperature range of +20 °C...-50 °C. Two heats of the steel were tested, corresponding to the 100 and 50 mm thicknesses /‾6_7. The test results are summarized in Table I and are graphically displayed for the 100 mm thick steel in Fig.2. Although at -20 °C critical COD-values were obtained, the fracture surface clearly shows that stable crack growth preceeded the abrupt fracture. This occurrence is even more pronounced at -10 °C and 0 °C. For this reason, during testing of specimens from the 50 mm steel, acoustic emission analysis was used to monitor the start of stable crack growth and thereby to permit the determination of critical COD-values. As a result of the vastly different fracture behaviour of the 50 mm thick steel, as well as problems with temperature influences on the measuring equipment, these tests must be repeated before an interpretation of the results is possible.

The steel 22 NiMoCr 3 7 exhibits good weldability, but experience has shown that when welded with high energy input processes such as summerged-arc and electro-slag welding, the base material adjacent to the fusion boundary is prone to stress relief cracking during post-welding heat treatment at 600 °C /‾11_7. The combination of the formation of secondary carbides in the overheated HAZ and adverse thermal and residual stress conditions have been shown to lead to the occurrence of intercrystalline crack formation /‾12_7. In this respect, the application of the Narrow-Gap process to the welding of this steel is of particular interest.

4. Welding investigations

Although gas shielded welding processes are used in heavy construction welding, MIG- and MAG-welding of thick section steels has until now not been widely investigated. For this reason a preliminary investigation of a range of 8 solid wires and 4 flux-cored wires was conducted to determine the most suitable consumables for Narrow-Gap welding. Three solid wires were selected for the welding test on 100 mm sections /‾9_7. A total of 18 welds comprising 6 welds with each of the selected consumables were produced with the following welding conditions:

1. no preheating; no post-welding heat treatment
2. no preheating; soaking at 300 °C
3. no preheating; stress relieving at 600 °C

4. preheating at 200 - 250 °C; no post welding heat treatment
5. preheating at 200 - 250 °C; soaking at 300 °C
6. preheating at 200 - 250 °C; stress relieving at 600 °C

Non-destructive testing using ultrasonics and X-ray methods revealed a minimum of porosity and inclusions which was not considered significant to effect the extraction of test specimens. Macro-examination of cross-sections, Fig. 3, confirmed a low level of defects. The micrograph of the heat affected zone reveals the HAZ to be only 1,2 mm wide with the zone of large grain growth being only 250 μm wide. Preheating reduces the hardness of the weld deposit but the hardness peaks in the HAZ persist with preheating.

5. Mechanical testing of welded joints

5.1 General properties

Tensile testing of specimens oriented across the weld seam and tested at room temperature and 250 °C revealed the fracture to always occur in the base material remote from the welded zone. In all tests no evidence of a lack of side-wall fusion was detected.

To further test the quality of the weld metal-parent metal boundary, flat bend specimens from each joint were tested. Although no cracking occurred at the fusion line or in the heat affected zone in any of the specimens, the testing of several specimens in the as-welded condition was terminated as a result of failures initiating from small pores in the weld metal.

The test results of notch-impact bend testing of Narrow-Gap welded specimens with a sharp notch in the centre of the weld seam are given in Fig. 4 . The broken line represents the lower limit of notch impact toughness from tests on base material specimens. Although at 20 °C the average tenacity of the weld deposits is lower than the minimum value measured for the base material, at temperatures below 0 °C, the weld metal exhibits relatively higher toughness. Preheating at 200 °C improves the weld metal toughness significantly, whereas stress relieving heat treatment at 600 °C causes a downward shift of the curve. This embrittlement following heat treatment processing has only been detected with one of the welding wires and is apparently due to precipitations occurring in the weld microstructure.

5.2 Fracture toughness

To investigate the fracture characteristics of the weld deposits and to compare the fracture behaviour of the weld metal and of the weld affected and unaffected base material, single-edge notched bend specimens (45x90x380) with a Chevron notch and subsequent fatigue crack located in the centre of the weld seam as well as in the HAZ, were tested at room temperature. Acoustic emission measurements /‾13_7 were used to monitor crack growth and using a change in slope of the emission-displacement diagram as a criterion for the ocurrence of a critical event, the corresponding critical displacement V_c^* and δ_c values were determined, Fig. 5. The emission activity for three welded specimens in various heat treated conditions is displayed against the force-displacement characteristics. Emissions arising from plastic deformation at the crack tip were suppressed by using a high discriminator level, so that the recorded emission resulted principally from crack extension and to a lesser extent from friction at the specimen supports. Lubricant was used to minimise emission developing during initial separation of the fatigue crack under increasing applied load. The fractographs in Fig. 5 reveal that in each case the initial crack advancement in the centre of the seam was followed by the crack movement out of the weld seam and into the base material.

Table II lists the results of the fracture toughness testing of Narrow-Gap welded specimens. For 7 specimens with the fatigue crack in the centre of the weld seam (COD-values calculated according to the recommendations in BS. DD 19 as well as using AEA to determine critical values) the influence of preheating, soaking and stress relief heat treatment is evident. Without preheating and in the as-welded condition the calculated δ_c- and δ_c^*-values of 90 and 62 μm are not to be compared with the minimum fracture toughness of 277 μm for the 50 mm thick plate and even more so with the δ_m-value of 1100 μm obtained for the 100 mm thick section. However, welded specimens produced with preheating at 200 °C all yielded acceptable fracture toughness in comparison to the base material. The measured values give the assurance that at room temperature the weld metal does not exhibit a brittle fracture behaviour. For 3 specimens with the fatigue crack located in the HAZ adjacent to the fusion boundary and tested at 20 °C, extremely high δ_m-values ranging from 1,90...2,34 mm were calculated. To determine the reason for this apparent increase in fracture toughness of the heat affected base material, the fractured specimens were sectioned and the crack extension from the tip of the fatigue crack investigated, Fig. 6. When the fatigue crack was located in the centre of the weld seam (1) a step-wise crack advancement alternatively in the dendritic structure and the recrystallized microstructure resulted. However in the other cases and even with the tip of the fatigue crack at the weld metal - parent metal boundary (4), the crack growth occurred as a result of the static crack moving at right angles to the fatigue crack, through the HAZ and then propagating in the base material remote from the welded zone. As a result of this "crack arrest effect" the high fracture toughness values were obtained. This effect has also been observed during testing of notch-impact bend specimens with a sharp notch located in the HAZ adjacent to the fusion boundary.

6. Concluding remarks

The production of acceptable welded joints in 50, 100 and 200 mm sections of the steel 22 NiMoCr 3 7 has been achieved using the Narrow-Gap welding process. The parallel weld seams are characterized by a low volume of weld metal with narrow heat affected zones and minimal coarse grain growth. Weld defects such as porosity and slag inclusions can be kept to a low and tolerable level and the problem of a lack of side-wall fusion has not arisen. Metallographic investigations of the HAZ have revealed no intercrystalline cracking following stress relief h.t. at 600 °C, which has previously proven to be an inherent problem with welding of this reactor construction steel.

In general, the mechanical properties of the weld deposits with the Narrow-Gap process compare favourably with the properties of the base material. The fracture toughness of the base material and welded joints was investigated using a method of crack opening displacement testing. The fracture toughness of the weld deposits was shown to be strongly influenced by preheating and post-welding heat treatments, but from the available test results, the welds exhibit acceptable toughness at room temperature. During these tests, acoustic emission measurements were used to determine the start of stable crack growth and the first indications are that this monitoring method could be useful for determining critical values during fracture toughness testing.

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Table I: Fracture toughness test results from base material 22 NiMoCr 3 7 specimens.
Specimen size: 45 x 90 x 380

Crack-Opening Displacement /_um_7 as influenced by temperature

Test temp. °C	Calculated COD-value to BS.DD.19 100 mm section	Calculated COD-value to BS.DD.19 50 mm section
-50	-	304
-50	-	298 +
-30	281 +	285
-30	405 +	290
-20	914 +	-
-20	946 +	-
-10	1000 +	-
-10	1238	-
0	1130	289
0	1190	283
20	1190 *	277
20	1102 *	315

* Specimen size: 100 x 200 x 830

+ Critical value

Table II: Fracture toughness test results from Narrow-Gap welded specimens tested at 20 °C.
Specimen size: 45 x 90 x 380

Crack-Opening-Displacement /_um_7 as influenced by welding conditions

Test No.	Welding conditions a	b	c	d	e	Fatigue crack-location	Calculated COD-value to BS.DD.19	Calculated COD-value using AEA
1	X		X			Weld metal	90 +	62 +
2	X			X		Weld metal	132 +	120 +
3	X			X		Weld metal	159 +	104 +
4	X				X	Weld metal	861	103 +
5		X	X			Weld metal	264	187 +
6		X		X		Weld metal	426	274 +
7		X			X	Weld metal	894	-
8	X	X				HAZ	1900	-
9	X				X	HAZ	1820	-
10		X			X	HAZ	2340	-

a = no preheating
b = preheating at 200 °C
c = no post-weld h.t.
d = soaking at 300 °C
e = stress relief h.t. at 600 °C
+ Critical value

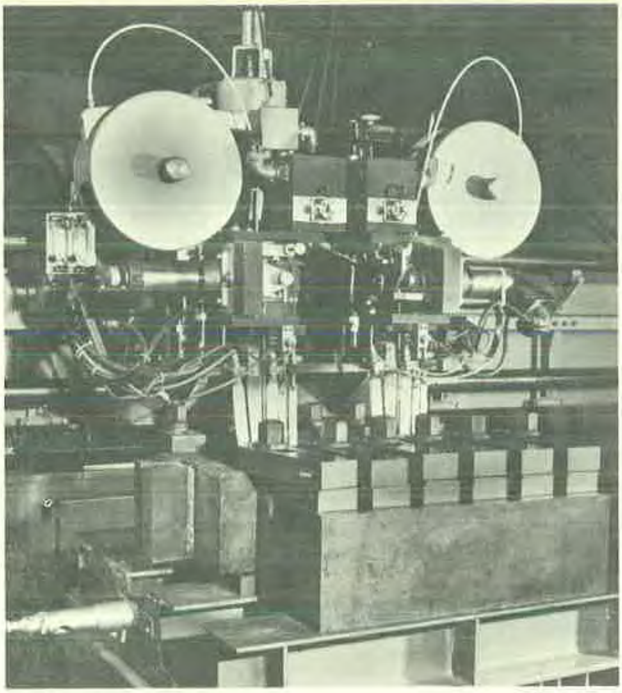


Fig. 1 Narrow-Gap welding head arranged for welding of 200 mm thick forged sections of the steel 22 NiMoCr 3 7

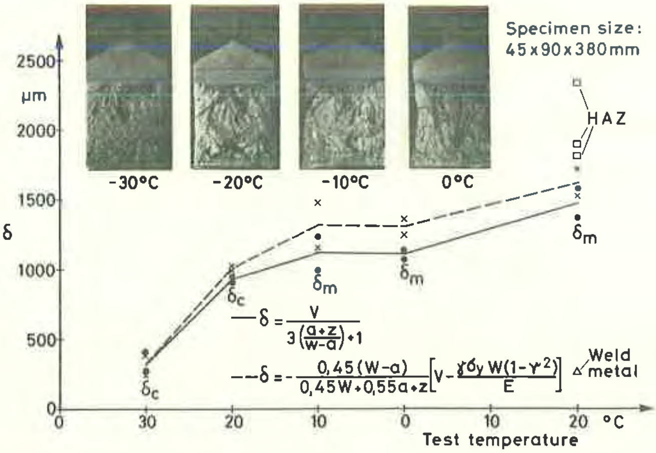


Fig. 2 Crack-Opening-Displacement as a function of temperature for base material specimens from a 100 mm thick section of the steel 22 NiMoCr 3 7

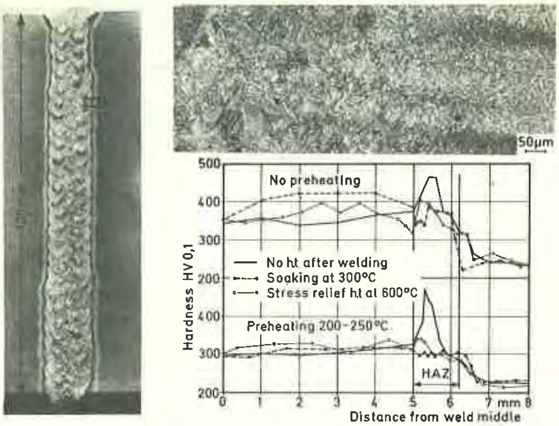


Fig. 3 Microstructure and hardness of Narrow-Gap weld seams in various heat-treated conditions

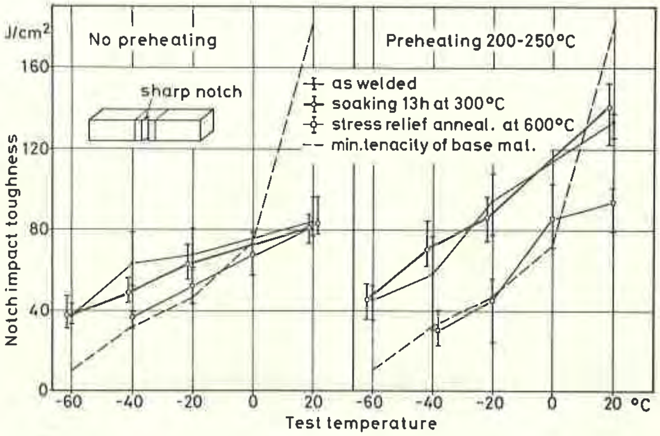


Fig. 4 Notch impact toughness of base material and Narrow-Gap welded joints as a function of temperature

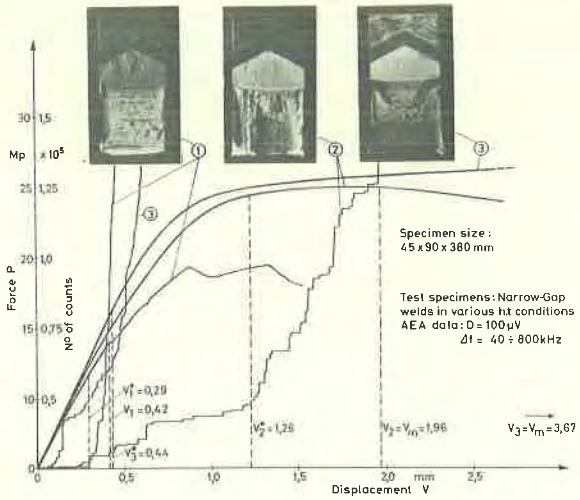
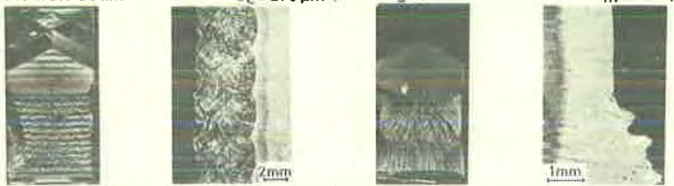


Fig. 5 Force-displacement and acoustic emission-displacement diagrams recorded during COD-testing of Narrow-Gap welded specimens

1. Fatigue crack in the centre of the weld seam $\delta_c = 270\,\mu m$ | 2. Fatigue crack in the HAZ $\delta_m = 1900\,\mu m$



No preheating but stress relief h.t. at 600°C | As-welded condition with no preheating

3. Fatigue crack in the HAZ $\delta_m = 1820\,\mu m$ | 4. Fatigue crack in the HAZ $\delta_m = 2340\,\mu m$

No preheating but stress relief h.t. at 600°C | Preheating at 200°C + stress relief h.t. 600°C

Fig. 6 Fracture surfaces from Narrow-Gap welded COD-specimens and sections showing the zone of the first crack advancement