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SUB-TASK 1.3: WELD STRENGTH MISMATCH EFFECTS - MULTIPASS WELD EVALUATION

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SUMMARY

WELD STRENGTH MISMATCH EFFECTS - MULTIPASS WELD EVALUATION

British Steel plc

An experimental programme has been undertaken as part of SINTAP Task 1 to quantify the mechanical and fracture toughness properties of multipass welded joints with weld strength mismatch. The programme used a conventional 25 mm thick Q & T steel which was heat treated to different strength levels and then welded under identical welding conditions to give nominally identical weld and HAZ structures in the different strength plates. Two types of welding were used to provide HAZs with different tensile properties adjacent to the weld. Testing was conducted at two crack depths in the parent materials, weld centreline and HAZ(FL) locations to provide Charpy, CTOD, and δ_5 data. Centre cracked tensile tests were also conducted in the same locations to assess the load - displacement, CMOD, δ_5 and local straining characteristics of the specimens.

Throughout the work, a consistent effect of notch depth on fracture toughness transition was observed for parent, weld metal and HAZ notch locations. CTOD transition temperatures (at 0.1 mm) were about 20 to 40°C lower for shallow notched specimens (a/w 0.15) compared to deep notched specimens (a/w 0.5). Beneficial effects of overmatching ($M = 2.15$) on HAZ(FL) CTOD and Charpy toughness values were observed for welds with a high strength HAZ. In both cases this was observed to be associated with crack deviation away from the high strength HAZ which occurred in the toughness transition region. The relationship between the direct measurement of CTOD using a δ_5 gauge and CTOD to BS 7448 appeared to differ with crack depth and weld strength mismatch level indicating that mismatch corrected CTOD procedures are required for assessing weld fracture toughness in shallow notched specimens.

Centre cracked tensile testing demonstrated that whilst the load bearing characteristics of overmatched welds usually equalled those of an equivalent unwelded plate, the load bearing characteristics of undermatched welds examined failed to match the parent plate. The CCT data also showed that higher values of CMOD or δ_5 and local strain in the notch region developed for a given test displacement in the undermatched welds compared to overmatched. These effects were present not only at the weld centreline, but also in the HAZ at the fusion line indicating that weld strength overmatching provides some strain limitation in the HAZ(FL) regions.

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WELD STRENGTH MISMATCH EFFECTS - MULTIPASS WELD EVALUATION

British Steel plc

1. INTRODUCTION

SINTAP Sub Task 1.3 was set up to investigate the effects of weld strength mismatch in multipass welded joints. The programme was designed to keep weld metal and HAZ microstructures constant whilst varying the parent material properties. This was achieved by heat treating plates of the same composition to different strength levels and then welding them under identical welding procedures. Since it was uncertain whether or not HAZ properties are significant in the question of weld strength mismatching the programme examined the effects of weld metal strength mismatch with HAZs at two strength levels. Welding was multipass using the Flux Cored Arc Welding (FCAW) process for low heat input welds and the Submerged Arc Welding (SAW) process for high heat input welding. The notch locations investigated were parent plate, HAZ at the fusion line and the weld metal centreline.

2. TEST PROGRAMME

The programme included conventional small scale tests (Charpy and tensile), fracture toughness tests (CTOD, δ_5) and centre cracked tensile (CCT) tests. The experimental procedure involved generation of load-displacement and CMOD-displacement curves in the CCT specimens and CTOD transition curves for the single edge notch bend (SENB) specimens. A range of different crack depths and orientations were investigated in the CTOD specimens as illustrated in Fig. 1. The test matrix for the programme is summarised in Table 1 and a diagram showing the approximate mismatch levels aimed for is given in Fig. 2.

Test Series 1 to 3 in Table 2 show the work undertaken on the parent materials which involved tensile testing (full stress strain curves), Charpy impact testing (full transition curves), CTOD and δ_5 testing (transition curves on surface notched and through thickness notched SENB specimens), and mini-wide plate testing (crack driving force curves on surface notched (SN) and through thickness notched (TTN) CCT specimens). The parent materials were in three strength conditions with approximate yield strengths of 675, 475 and 300 N/mm².

Test Series 4 to 6 in Table 1 summarises the work undertaken on the HAZ and weld metal of multipass FCAW welds with notches in the HAZ at the fusion line (FL) and weld metal (at centreline). Tensile properties of the weld metals were measured with waisted tensile specimens in the transverse orientation, giving full stress - strain data. HAZ tensile properties were measured by GKSS using micro-tensile specimens taken from the HAZ. Charpy tests were conducted at the fusion line and weld metal centreline. CTOD and CCT testing was also conducted at the FL and weld metal centreline locations using surface notched specimens with a/w of 0.15 and 0.5. Additional through thickness specimens were included for the overmatching and undermatching conditions. Notch locations were HAZ at FL and weld metal centreline.

Test Series 7 to 9 in Table 2 summarise the work undertaken on the HAZ of multipass SAW welds with notches in the HAZ (at FL). Tensile properties of the weld metal and HAZ were measured in the same way as in Series 4 to 6. Charpy, CTOD and CCT tests were conducted at the fusion line. The fracture mechanics tests were surface notched geometry with a/w of 0.15 and 0.5. Notch locations were HAZ at FL.

3. MATERIALS AND HEAT TREATMENTS

Details of the steel selected for the programme are given in Table 2. The steel was a 25 mm thick quenched and tempered grade made by the basic oxygen steelmaking process (BOS) and was continuously cast. Heat treatment consisted of reheating to 930°C for 50 min prior to water quenching and tempering at 580°C for 1 h.

Further heat treatments were conducted to produce nominal yield strengths of ~650, ~500 and ~350 N/mm² following a PWHT after welding. To achieve these strength levels in the welded panels, steel coupons were given the following treatments.

For the high strength condition, steel was welded in the as-received condition and then post weld heat treated at 560°C for 1 h. For the medium strength level, a high temperature tempering treatment at 675°C for 1 h was conducted prior to welding, whilst for the low strength level, a normalising heat treatment at 900°C for 1 h was used prior to welding. After welding all panels were given a PWHT using the conditions given above.

4. WELDING

Approximately 15 m of FCAW welds and 6 m of SAW welds were manufactured for the test programme. Details of the weld preps. and welding parameters used are given in Figs. 3 and 4. For both processes a single sided weld prep. with backing bar was used. One side of the weld prep. was perpendicular to the plate surface to allow HAZ notching of fracture toughness specimens. The other side had a bevel angle of 10° (FCAW procedure) and 15° (SAW procedure). Root gaps of 16 and 14 mm were used for the FCAW and SAW procedures respectively to try to ensure the weld widths were similar to those for which FE models already exist.

The FCAW welding consumables used were Fluxofil 35 / Argoshield 20 which is a 1.4Mn, 0.5Mo consumable. For the SAW procedure, Oerlikon SD3 1Ni $\frac{1}{4}$ Mo wire with OP121TT flux was used. Both consumables were selected to give weld metals of nominally ~500 N/mm² yield strength after PWHT.

Hardness traverses were conducted at 1 mm subsurface from the cap and root and at mid-thickness on most welds. Details of the welds produced and their weld metal hardness values are given in Table 3. Figure 5 shows a comparison of hardness traverses on the procedure test welds at mid-thickness. For both procedures, the weld metal hardness was similar indicating similar weld metal yield strength. For the HAZ, the FCAW procedure, with its faster cooling rate has produced a higher hardness close to the fusion line. Both procedures produce a HAZ soft zone which is significantly softer and wider for the high heat input SAW procedure.

5. TENSILE PROPERTIES

5.1 Parent Plates

The tensile properties of the parent materials were measured using 8 mm diameter tensile specimens located at mid-thickness. Since a large number of heat treatments were undertaken in the programme, multiple tests were conducted to produce information on the spread of tensile properties in the heat treated plates.

The mean yield and ultimate tensile strength (UTS) values with standard deviations are given in Table 4. For the normalised + PWHT condition an average yield strength of ~300 N/mm² (SD 9 N/mm²) and UTS of 510 N/mm² (SD 3 N/mm²) was obtained. For the tempered + PWHT condition an average yield strength of ~475 N/mm² (SD 42 N/mm²) and UTS of 610 N/mm² (SD 21 N/mm²) was observed and for the Q&T + PWHT an average yield strength of ~675 N/mm² (SD 34 N/mm²) and UTS of 753 N/mm² (SD 23 N/mm²) was observed.

Figure 6 shows the distribution of yield strength values obtained from the three strength conditions. The highest spread in tensile properties was for the tempered + PWHT condition and the least for the normalised + PWHT conditions. These results are in agreement with the data generated in the heat treatment trials which showed yield strength in the 675°C reheat regime to be very sensitive to reheating temperature, but quite insensitive in the 900°C regime⁽¹⁾.

The measured yield strength values of ~300, 475 and 675 N/mm² for the three strength conditions were within about 50 N/mm² of the original aim values and allow examination of a slightly wider range of mismatching levels than originally planned.

5.2 Weld Metals

Tensile properties of the weld metals were evaluated from longitudinal all weld metal tensile specimens (on the procedure test weld) and from transverse diametrical tensile specimens (on selected welds).

The weld metal yield strength results are given in Table 5 and Figs. 6 and 7. For the SAW procedure, similar strength values were recorded for the procedure test weld and the test programme welds, indicating that there was little influence of orientation or test specimen type on measured weld strength values. Average values of yield and UTS were 480 and 591 N/mm² respectively (Table 5) and these values were close to the aimed values for the project.

For the FCAW procedure, the procedure test weld gave yield and UTS values of 545 and 619 N/mm² which although slightly higher than the SAW values were within ~10% of the aim values for the project. Unfortunately, the results for the project test welds were significantly higher than the procedure test weld, with average yield and UTS values of 639 and 709 N/mm² respectively. The reasons for these differences were not established. However, investigations confirmed that the procedure test and project test weld metals were of the same chemical composition and welded to the same procedure.

5.3 Heat Affected Zones

An estimate of HAZ yield strength was established from a strength versus hardness correlation and direct measurements of tensile properties using micro-tensiles were performed at GKSS. The strength versus hardness relationship was developed using simulated HAZ strength and hardness data measured earlier in the project. Preliminary results suggested that the mean GHAZ strengths at the fusion line were ~510 N/mm² and 730 N/mm² for the SAW and FCAW procedures respectively. Detailed HAZ tensile results from micro-tensile specimens (Appendix 13) showed a range of HAZ strength levels indicating some expected weld to weld and location to location variation in strength levels. The peak GHAZ strength levels measured in the SAW welds were 560 and 580 N/mm².

Taking average hardness data from the hardness traverses for the FL to FL + 2.5 mm regions, the estimated HAZ strengths were ~430 N/mm² and 530 N/mm² for the SAW and FCAW procedures respectively. The maximum and minimum yield strength values measured in the SAW HAZ by micro-tensiles were 580 and 320 N/mm² respectively indicating a wide range of tensile properties in the SAW HAZ.

5.4 Average Mismatch Levels

The average strength mismatch levels achieved in the weld panels are summarised in Fig. 8. For the SAW welds average mismatch levels of 0.71, 1.01 and 1.62 were produced, which were similar to the original aim values of 0.77, 1.0 and 1.43. Unfortunately the aim of having the GHAZ yield strength less than the weld metal may not have been achieved. However, the average HAZ strength in the FL to FL + 2.5 mm region is lower than the weld metal strength and even lower strength levels are present in the outer parts of the SAW HAZ as shown in Fig. 5.

For the FCAW welds, due to the higher than expected weld metal strength, the mismatch levels were 0.95, 1.35 and 2.15. These were significantly higher than the aim values and resulted in a test matrix of approximately matching (M = 0.95), overmatching (M = 1.35) and higher overmatching (M = 2.15) weld strength compared to the planned matrix of undermatching, matching and overmatching. The aim of having GHAZ strength greater than the weld metal was achieved.

6. CHARPY PROPERTIES

6.1 Parent Plates

The Charpy impact toughness of the parent materials, some selected FCAW weld metals and their HAZs and selected SAW HAZs were measured over a range of temperatures to produce transition curves. In almost all cases, testing was done with triplicate specimens at 5 or 6 temperatures and a mean energy transition curve established from which the mean 27 J transition temperatures were defined. All Charpy tests were transverse to the rolling and welding directions and were taken 2 mm subsurface. For the weld metal and HAZ tests, the root side of the weld was notched.

The parent material Charpy curves for Q&T + PWHT, 675°C tempered + PWHT, and normalised + PWHT conditions, are shown compared in Fig. 9. The lowest 27 J temperature was obtained in the Q&T condition (-65°C) followed by the 675°C tempered condition (-50°C). The highest transition temperature was observed in the normalised condition (-15°C). Scatter in the triplicate tests was generally quite modest (usually <25 J) with the maximum difference in absorbed energy values being observed in the mid-transition region of the tempered steel (~50 J). The transition

curves for the Q&T and tempered conditions crossed over at ~ 50 J; the higher strength condition having the shallower transition curve below about 60 J.

6.2 Weld Metals

The Charpy transition curves for the three FCAW weld metals investigated (one in each mismatch condition) are compared in Fig. 10. The scatter in these tests was also low and generally similar or lower than that observed in the parent steels. For the undermatched condition (nominally $M = 0.95$) the 27 J temperature was -55°C , whereas for the other two conditions (nominally $M = 1.35$ and 2.15) the 27 J temperatures were -40 and -38°C respectively.

Examination of the Charpy notch locations to identify the weld metal microstructures sampled in each test series in terms of as-deposited and retransformed microstructures indicated little difference in the microstructures sampled. However, hardness data indicated that the weld metal with the slightly lower transition temperature also has the lowest hardness of the three welds and this is a likely explanation for its slightly lower 27 J temperature. Consequently the weld metal Charpy results suggest that there is probably no influence of weld strength mismatch on weld metal Charpy toughness in the welds under investigation and the small variation of $\sim 15^{\circ}\text{C}$ in transition is probably due to the slight intrinsic weld metal toughness variability expected in multipass welds.

6.3 Heat Affected Zones (Flux Cored Arc Welds)

The Charpy transition curves for the three FCAW HAZs investigated (one in each mismatch condition) are compared in Figs. 11 and 12 using mean and upper/lower bound curves to the data. The scatter in these tests was high which is typical for HAZ tests at the fusion line of multipass welds. For example, the range of absorbed energies for the triplicate tests at a fixed temperature was often > 75 J and in some instances was as high as 150 J. Consequently, definition of the transition temperature in these tests was subject to greater uncertainty than the previous results for parent plates and weld metals. As in previous figures, the transition curves in Fig. 11 were drawn through the mean energy values at each test temperature. For one of the data sets, the mean absorbed energy at -20°C was lower than at -40°C and for this data set the mean line curve has been drawn through the mean of the -20 and -40°C results at -30°C to avoid a region of negative slope in the transition curve.

The 27 J transition temperatures obtained from the mean transition curves were $\sim -75^{\circ}\text{C}$ ($M = 2.15$), $\sim -35^{\circ}\text{C}$ ($M = 1.35$) and $\sim -40^{\circ}\text{C}$ ($M = 0.95$). These results, which are illustrated in Fig. 11, suggest a complex effect of mismatching on HAZ Charpy toughness in multipass FCAW welds. At room temperature and $+40^{\circ}\text{C}$, overmatching seems to be beneficial to Charpy toughness, whereas at -20°C , the mean Charpy energies for the three conditions are very similar. At -40 to -60°C a beneficial effect of high levels of overmatching ($M = 2.15$) on HAZ (FL) Charpy toughness was apparent.

Macrographs illustrating the notch locations and fracture paths in specimens tested at -60°C in the highly overmatched and slightly overmatched conditions are given in Fig. 13. These photos show that whilst the notch locations in the HAZ at the fusion line were similar (Fig. 13(a)), the fracture paths differed (Fig. 13(b)) with the highly overmatched specimen deviating from the fusion line into lower strength plate. This fracture deviation may explain the observed beneficial effect of high overmatching on HAZ Charpy toughness.

6.4 Heat Affected Zones (Submerged Arc Welds)

The Charpy transition curves for the three SAW HAZs investigated are compared in Figs. 14 and 15. As observed in the FCAW HAZ tests, there was also considerable scatter in energy results from the SAW HAZ triplicate tests (up to ~ 150 J). Mean energy transition curves were plotted through average energy values at each temperature except where this would result in a negative slope in the transition curve.

The 27 J transition temperatures obtained were $+30^{\circ}\text{C}$ ($M = 1.62$), $+37^{\circ}\text{C}$ ($M = 1.01$) and $+20^{\circ}\text{C}$ ($M = 0.71$). Given the degree of scatter observed in the tests it seems unlikely that the small differences in 27 J temperature are significant and in fact Fig. 14 shows that the three mean curves are very close at the 50 J level. Consequently, there appears to be little influence of mismatch on HAZ Charpy toughness of the SAW welds ($M = 0.71$ to 1.62) for the lower part of the Charpy transition curves. However, for the upper part of the transition curve at $+80$ and $+100^{\circ}\text{C}$, the data indicates that overmatching is slightly beneficial to HAZ toughness.

7. CTOD AND δ_5 IN SENB SPECIMENS

7.1 Parent Plates

Fracture toughness levels in the parent plates were measured using 25 x 25 mm bend specimens with nominal crack sizes of a/w 0.5 and 0.15. The majority of tests were done with surface notched specimens (Y-Z orientation), but additional tests were done with through thickness notched specimens (Y-X orientation). Testing was conducted over a range of temperatures to define the CTOD transition behaviour and additional replicate tests were conducted at $\sim 18^\circ\text{C}$ below the Charpy 28 J temperature to allow further analyses using the master curve method, if required, at a later date. Double clip gauges were used on all specimens to enable load - CMOD traces to be generated and a δ_5 gauge was used to obtain a direct measurement of CTOD in tests conducted in the temperature range $+50$ to -50°C . Unfortunately, problems were encountered with the initial δ_5 testing on the parent plates and consequently δ_5 data for these tests has not been presented. However, subsequent δ_5 testing conducted on the weld metal and HAZ specimens with different δ_5 gauges and data logging arrangements proved more successful and these results are discussed in the relevant sections.

CTOD values calculated to BS 7448:Part 1⁽³⁾ are presented as CTOD transition curves in Appendix 5, Figs. A5.1 to A5.9. Comparison of the effects of notch geometry and orientation are given in Figs. 16 to 18 for plates in the Q & T, tempered and normalised conditions respectively. For the Q & T condition (followed by PWHT at 560°C for 1 h) three distinct transition curves were produced for the three notch geometry's investigated (Fig. 16). The 0.1 mm CTOD transition temperatures taken from lower bound curves were -50°C (SN a/w 0.15), -20°C (SN a/w 0.5) and $+10^\circ\text{C}$ (TTN a/w 0.5). The lower transition for the short cracked specimens was probably due to lower crack tip constraint whereas the higher transition temperature in the TTN specimens may be a result of different microstructural sampling effects. For example, the TTN geometry would have sampled all regions through the plate thickness and consequently any local microstructural inhomogeneity such as centre segregation from the continuous casting of the steel could have been sampled and may have influenced the CTOD values.

For the tempered condition (tempered at 675°C for 1 h followed by PWHT at 560°C for 1 h) the lowest transition temperature was again observed for the shallow notched specimens with a 0.1 mm CTOD temperature of -80°C (Fig. 17). In this heat treatment condition there was less difference in the transition curves for the deep notched specimens which may have been a consequence of effective tempering of the segregate regions resulting in a more homogeneous microstructure. The 0.1 mm CTOD temperature for the deep notched specimens was about -30°C to -40°C .

For the normalised condition (normalised at 900°C for 1 h followed by PWHT at 560°C for 1 h), with the exception of one lower result at $+20^\circ\text{C}$, the shallow notched geometry again gave the lowest transition temperature and the deep notched specimens gave similar transition curves, (Fig. 18). The 0.1 mm CTOD temperatures were about -40°C for shallow and about 0°C for the deep notched specimens.

A comparison of parent plate fracture toughness levels in terms of CTOD at different test temperatures has been made in Figs. 19 to 21 for TTN a/w 0.5, SN a/w 0.5 and SN a/w 0.15 geometry's respectively. In order to show the replicate test results obtained at the lower test temperatures, CTOD was plotted on a logarithmic scale. For all three notch types, the tempered condition tends to show the highest levels CTOD at each temperature, whereas the scatter in CTOD of the other two heat treatment conditions tends to overlap. For surface notched specimens, the lowest CTOD values at any given temperature tended to be for the normalised steel, although this was not universal (e.g. SN a/w 0.5 at $+20^\circ\text{C}$). The toughness ranking obtained from the CTOD tests was in broad agreement with the Charpy tests (Fig. 9) for the part of the Charpy curves above ~ 70 J. In this regime, the lowest transition temperature was for the tempered condition with the highest for the normalised condition. However, the ranking at the lower Charpy energy levels, which identified the Q & T condition as having the lowest transition temperature, was not the same as in the CTOD tests. This may have been a consequence of using a subsurface Charpy specimen in the toughness evaluation rather than one from mid-thickness.

7.2 Flux Cored Weld Metals

Fracture toughness levels in the FCAW weld metals were measured in a similar manner to the parent plates. Due to slight distortion during welding, the machined specimens were generally made to a common size of 23 x 23 mm compared to 25 x 25 for the parent plate specimens. Specimens with surface notched geometry's (a/w 0.5 and 0.15) were tested at all three mismatched conditions (M ~ 0.95 , 1.35, and 2.15) whilst the specimens with through thickness geometry (a/w 0.5) were tested for the undermatching and highly overmatching conditions only. All specimens were

notched at the weld centreline as shown in Fig. 22. For the surface notched tests, specimens were notched from the root side.

CTOD transition curves are presented in Figs. A6.1 to A6.8 of Appendix 6 and Fig. 23. The data for deep notched specimens exhibited less scatter than the shallow notched data. A similar effect of notch depth and orientation was seen in the weld metal tests to that observed in the parent plates with the lowest transition temperature and highest CTOD values being seen in the short surface notched specimens due to lower crack tip constraint.

Taking a CTOD transition temperature corresponding to 0.1 mm CTOD, the relative CTOD transition temperatures were $\sim 60^\circ\text{C}$ for the short surface notched specimens, -15°C for the deep SN specimens and -0°C for TTN a/w 0.5. The reason for the highest transition temperature in the TTN specimens may be the wider range of weld metal microstructures sampled by the fatigue precrack allowing fracture to initiate from the least tough region in the weld metal, although this has not been established in the present study.

The effect of weld strength mismatch on weld metal CTOD is shown in Figs. 24 to 26 for the TTN, deep SN and shallow SN specimens respectively. Unexpected results were obtained for the TTN and deep SN specimens at low temperature, because these tests indicated lower levels of toughness in the overmatched welds for most test temperatures. Since it is generally considered that for deep notched specimens (a/w 0.5) there is little effect of mismatch on CTOD to BS 7448, these differences may be due to some variation in the intrinsic fracture toughness of the weld deposits. This argument was proposed in an earlier progress report to explain the slightly higher Charpy toughness observed in undermatched weld metal⁽⁴⁾. Unlike the Charpy test weld panels, the differences in average weld metal hardness of the TTN CTOD weld panels was not large, although the cap regions of the overmatched weld were slightly harder. Other possible reasons for the slightly lower levels of toughness in the overmatched TTN specimens could be the slightly thicker specimen size (23 x 23 mm compared to 22 x 22 mm) and the presence of weld porosity which was present in one of the weld runs of the multipass weld in the overmatched condition.

For specimens with a/w = 0.15, where strength mismatch is expected to have an effect⁽⁵⁾, higher values of CTOD were measured in the highly overmatched ($M = 2.15$) weld metal but this effect was not seen for the lower level of strength overmatching ($M = 1.35$).

The relationship between δ_s and BS 7448 CTOD obtained from the weld metal tests is shown in Figs. 27 and 28 for the deep and shallow notched specimens respectively. For the deep notched specimens, δ_s values were similar to BS 7448 CTOD for low values of CTOD but tended to diverge from a 1:1 line at higher crack openings. The δ_s values were usually greater than BS 7448 CTOD for larger crack openings, but one possibly anomalous result was observed where a δ_s value smaller than the corresponding BS 7448 value was observed. For shallow notched specimens, the overall correlation between δ_s and BS 7448 CTOD was closer to the 1:1 line. This may be a reflection of the overestimation of CTOD by the BS 7448 method for short cracked specimens. The δ_s results for the short cracked specimens also showed an effect of weld metal strength mismatch, with smaller values of δ_s being observed in the highly overmatched weld metal for a given value of BS 7448 CTOD.

7.3 Heat Affected Zones (Flux Cored Arc Welding)

CTOD tests on the HAZ of the FCAW welds were conducted using the same matrix of mismatch conditions and crack geometry's as for the FCAW weld metals and CTOD was calculated to BS 7448:Part 2⁽²⁾. Through thickness test specimens were notched in the HAZ on the straight side of the weld preparation with the intention of sampling high proportions of grain coarsened HAZ close to the fusion boundary (e.g. typically >15%). The surface notched specimens (a/w = 0.5 and 0.15) were notched into the straight HAZ from the weld root side. No attempt was made to aim for specific regions of grain coarsened HAZ with the surface notched specimens. After testing, post test sectioning was conducted on all HAZ test specimens to verify the HAZ notch locations and identify the microstructures sampled by the fatigue crack tips using the procedures given in BS 7448 Part 2⁽²⁾. Macrographs illustrating the HAZ notch locations are presented in Fig. 29.

CTOD transition curves for the FCAW HAZ are presented in Figs. A7.1 to A7.8 of Appendix 7 and in Fig. 30. For the through thickness tests, smooth transition curves were obtained with little evidence of scatter and although the vast majority of specimens sampled >15% GCHAZ, there did not appear to be much effect of the amount of GCHAZ sampled on the test result. For the surface notched tests, some scatter in the test data was observed and the magnitude of the scatter increased for the shallow notched specimens. The microstructures in which fatigue precracks were located is given in Figs. A7.3 to A7.8 in an attempt to explain some of the scatter. However, although cracks accurately located in the GCHAZ or at the fusion line were often on the lower bound lines, this was not always

the case, indicating a wide range of toughness in the different microstructural regions in the multipass welds. For example, the toughness of GCHAZ regions increased with distance from the fusion line and was probably also influenced by the tempering effects of subsequent weld beads.

The effect of notch geometry on HAZ CTOD transition temperature is illustrated in Fig. 30 using test results from overmatched welds ($M \sim 2.15$). The same type of effect was seen in the HAZ as in the parent plates and weld metals, with the lowest transition temperatures and highest CTOD values in the shallow cracked specimens. Unlike the weld metals, however, there did not appear to be much difference between through thickness and surface notched specimens when the lower bound data was considered.

The effect of weld strength mismatch on HAZ CTOD is shown in Figs. 31 to 33 for the through thickness, deep surface notched and shallow surface notched specimens respectively. For most of the through thickness tests and the surface notched tests at the higher test temperatures, the overmatched welds exhibited higher HAZ CTOD values. These differences in CTOD values were reflected in clearly observable differences in HAZ fracture mode of the CTOD specimens as illustrated in Figs. 34 and 35. Figure 34 shows under and overmatched deep notched surface notched specimens tested at -40°C . The effect of overmatching was to prevent cleavage initiation in the GCHAZ, probably as a result of reduced triaxial stress at the crack tip which resulted from having a lower strength parent material adjacent to the HAZ region⁽⁶⁾. In terms of fracture appearance, this resulted in fracture in the IC/SCHAZ linked back to the crack tip by a shear step. A similar effect was observed in the shallow surface notched specimens as illustrated in Fig. 35 where the overmatched specimens often exhibited tearing away from the HAZ into the lower strength plate.

The observed effect of weld metal strength mismatch on HAZ CTOD is contrary to that recently reported by EWI/TWI⁽⁷⁾ where overmatching was shown to elevate HAZ transition temperature. This difference may be due to the different ways in which overmatching was achieved in the two programmes. In the present work overmatching was achieved by decreasing parent plate strength whereas in the TWI programme it was achieved by increasing weld metal strength. These differences suggest that there is probably a need to consider the local strength mismatch between both HAZ and weld metal and HAZ and parent plate as far as possible effects of mismatch constraint are concerned in the HAZ.

The relationships between δ_5 and BS 7448 CTOD obtained from the FCAW HAZ tests are shown in Figs. 36 and 37 for the deep and shallow notched specimens respectively. The results were similar to the weld metal results in so far as for the deep notched specimens, δ_5 was similar to, or greater than, BS 7448 CTOD. Also, for the shallow notched specimens, the results were distributed around the 1:1 line in a similar way to the weld metal tests. An effect of mismatch was observed for the shallow notched specimens (Fig. 37) such that all the undermatched condition δ_5 values were greater than the corresponding BS 7448 value whilst most of the overmatched δ_5 values (both $M \sim 1.35$ and 2.15) were less than BS 7448 CTOD.

7.4 Heat Affected Zones (Submerged Arc Welding)

Fracture toughness levels in the HAZ of the SAW welds were measured in the same way as the HAZ of the FCAW welds except that for these welds, no through thickness testing was undertaken. The results of the tests are presented in Figs. A8.1 to A8.6 of Appendix 8 as CTOD transition curves. Once again, the microstructures in which fatigue crack tips were located was identified and have been included in the figures. In general the lower bound to the transition curve data was made up of GCHAZ results for tests close to the fusion boundary. In the case of the matched condition with $a/w = 0.5$ (Fig. A8.2) tests conducted at $+60$, $+80$ and $+100^\circ\text{C}$ had cracks located in the weld metal and consequently the lower bound for the HAZ in this series of tests was not obtained.

The effect of weld strength mismatch on HAZ CTOD is illustrated in Figs. 38 and 39 for deep and shallow notched specimens respectively. Unfortunately due to variability in microstructural sampling, there were few temperatures at which clear comparisons of behaviour could be made. However, for the deep notched specimens where comparisons could be made there was a tendency for the overmatched specimens to have slightly higher CTOD values (e.g. GCHAZ at $+40$ and $+60^\circ\text{C}$). For the shallow notched specimens there were fewer opportunities to make meaningful comparisons of results for specimens sampling the same microstructures. However, on average, the room temperature tests sampling GCHAZ were higher in the overmatched condition compared to undermatching.

The δ_5 test results for the SAW HAZ are summarised in Figs. 42 and 43. Similar trends were observed to those for the FCAW HAZ except that in the shallow notched tests, Fig. 43, no obvious effect of mismatching was observed.

8. CENTRE CRACKED TENSILE TESTS

Centre cracked tensile specimens (nominally 25 mm thick x 100 mm wide) were tested for each of the conditions identified in the test matrix given in Table 1. For the parent materials, specimens with spark eroded through thickness cracks ($a/t = 1$), short semi-elliptical surface cracks ($a/t = 0.15$, $a/c = 0.3$) and deep semi-elliptical surface cracks ($a/t = 0.5$, $a/c = 0.5$) were used as shown in Fig. 42. For the FCAW welds, the same types of specimens were used for welds in the overmatched, nominally matched and undermatched conditions with notches located at the weld centreline and in the HAZ at the fusion line. All three notch types were used for the over and undermatched welds, but only the semi-elliptical surface notched specimens were used for the matched condition. For the SAW welds, semi-elliptical surface notched specimens were tested in the HAZ of all three mismatched conditions.

All specimens were instrumented with double clip gauges, twin LVDTs measuring over a gauge length of 150 mm, and strain gauges measuring surface strains remote from, and in the local vicinity of the notch as shown in Fig. 43. The latter strain gauges were post yield types due to the high local strains encountered.

In the case of the through thickness tests, a δ_5 gauge was employed to measure crack tip opening over a 5 mm gauge length at the crack tip (2.5 mm either side of the crack tip). All tests were conducted at room temperature.

8.1 Parent Plates

For each of the surface notched CCT tests, the test data has been summarised in the form of the following graphs:

- (a) Load v Displacement (Av. LVDT)
- (b) Load v CMOD
- (c) CMOD v Displacement
- (d) Surface Strains (strain gauges) v Displacement

For the through thickness notched tests, the same series of graphs were drawn except that δ_5 measurements at the crack tips were substituted for CMOD.

The results are presented in Figs. 44 to 47 for the short semi-elliptical notched tests and Appendix 9, Figs. A9.1 to A9.8 for the deep semi-elliptical notched tests and through thickness notched tests. As expected, in all cases the highest loads were sustained in the Q & T material, whilst the lowest were in the normalised material. Further analyses of the data in terms of stress (gross and net section) and strain are planned at a later date.

In general, the load - displacement graphs were as expected considering the different material strengths and defect sizes. The lower displacement in the Q & T steel illustrated in Fig. 44 was due to termination of the test at 10 mm total displacement compared to ~10 mm displacement on the 150 mm gauge length in the other two tests. The Luders plateau which was observed for the lowest strength condition with the smallest defect size (Fig. 44) was not present in tests with larger crack sizes, indicating that the presence of the Luders plateau was a function not only of the material condition, but also the level of constraint in the test piece caused by the defect geometry.

The shapes of the load - CMOD and load - δ_5 graphs were similar to the load - displacement graphs except that the proportion of displacement caused by crack opening was much lower in specimens with shallow cracks compared to deep cracks and through thickness cracks. In these latter specimens, all or most of the displacement was in the form of crack opening. The Luders plateau observed for the normalised steel with the shallow crack geometry was also observed on the load - CMOD graph, Fig. 45, showing ~0.3 mm of CMOD at the yield load prior to the onset of strain hardening.

Comparison of CMOD v displacement and δ_5 v displacement data for the specimens with short surface notches and through thickness cracks showed that above yield, less crack opening occurred for a given displacement in the normalised steel compared to the other two heat treatment conditions. However, this was not seen for the deep surface notched specimens where all displacement in all three heat treatment conditions was due to crack mouth opening (Fig. A9.3).

Strain gauge data for all tests showed that the strain gauges in the plane of the defects and about 5 mm from the crack tips (i.e. local gauges) recorded much higher strains than those located about 80 mm from the cracks (i.e.

remote gauges). In the case of the through thickness specimens, strains from the remote gauges remained elastic throughout the tests indicating that gross section yielding (GSY) was not reached in these tests (Fig. A9.8). A similar situation was observed for the deep surface notched tests, except for the normalised steel, where plastic strains were recorded on the remote gauges for displacements greater than about 1.5 mm. This effect coincided with a reduction in the slope of the strain - displacement output of the local gauge, indicating that GSY was occurring and plasticity was being transferred into the gross section due to strain hardening in the plane of the defect.

Two tests in the normalised steel (SN a/w 0.5 and TTN) terminated in brittle fracture whilst one test in the Q & T condition failed by ductile fracture after attainment of maximum load. All other tests were either terminated at ~10 mm displacement or were unloaded after maximum load.

8.2 Weld Metal

The results of the CCT tests conducted on specimens having notches at the centreline of FCAW weld metals are presented in Figs. 48 to 51 and Appendix 10 Figs. A10.1 to A10.8. For all three notch types examined, the highest loads were sustained in the welds made in the Q & T plates ($M = 0.95$), whilst the lowest were in the welds made in the normalised plates ($M = 2.15$).

For semi-elliptical notched geometry's, the load - displacement characteristics of the overmatched welds in the normalised plates ($M = 2.15$) were similar to the parent material without a weld, except that the Luders plateau previously observed in the weld free material was not present. For the through thickness notched specimen, the loads sustained by the overmatched weld was slightly higher than the equivalent weld free material.

For all notch geometry's, the load carrying capacity of the undermatched welds made in the Q & T material ($M = 0.95$) were less than the equivalent weld free Q & T material. Since there was some variation in the plate thickness in the weld regions due to removal of weld caps and backing plate, the exact extent to which the undermatched welds failed to reach the same stress levels as the weld free specimens has yet to be calculated.

Comparison of CMOD v displacement and δ_5 v displacement data for the mismatched welds showed that larger values of CMOD (Fig. 50) and δ_5 (Fig. A10.7) developed in the undermatched welds compared to the overmatched welds for a given level of displacement, particularly when the displacements were greater than ~0.5 to 1.0 mm.

In terms of local strains measured in the weld metals in the plane of the notch, there was also a clear and expected influence of strength mismatching, with the highest local strains being measured in the undermatched welds and the lowest local strains in the overmatched welds.

Two of the weld metal tests reached 10 mm displacement prior to unloading. These were the short surface notched specimens in tempered and normalised materials. All other weld tests failed after attainment of maximum load.

8.3 Heat Affected Zones (Flux Cored Arc Welds)

The results of CCT tests on specimens notched into the HAZ of the FCAW welds are given in Figs. 52 to 55 and Appendix 11, Figs. A11.1 to A11.8. The characteristics of the FCAW HAZ tests were in many ways similar to the weld metal tests, except that most of these tests ended in brittle fracture initiating from the grain coarsened HAZ. Post test sectioning of the specimens revealed that all three of the deep surface notched tests had notches located in the HAZ within 0.6 mm of the fusion line. For the shallow notched tests, two crack tips were located in the fine grained HAZ ~1 to 2 mm from the fusion line, and the third (Q & T material) had the crack tip in weld metal close to the fusion line.

In terms of load - displacement curves, none of the tests on the HAZ of the undermatched welds reached the maximum loads sustained in equivalent weld free plates, but the loads sustained by the overmatched welds were in general similar to those of the weld free plates. (Note that the slightly lower loads in the shallow notched test ($M = 2.15$) is probably due to reduced section thickness where the weld cap and backing were removed).

CMOD v displacement and δ_5 v displacement data showed similar characteristics to the weld centreline tests in so far as the highest CMOD (Fig. 54) or δ_5 (Fig. A11.7) for a given displacement generally occurred in undermatched welds and the lowest crack opening in the most highly overmatched welds. The exceptions to this were the tests with the deep semi - elliptical notches where the undermatched ($M = 0.95$) and nominally matched ($M = 1.35$) tests showed similar behaviour with all the displacement being due to crack opening (Fig. A11.3). For this notch geometry, the highly overmatched condition ($M = 2.15$) resulted in reduced CMOD for a given displacement level, once gross section yielding was reached.

Strain gauge data for the FCAW HAZ notched tests (Figs. 55, A11.4 and A11.8) showed that the levels of local strain in the plane of the notch were highest for the undermatched welds and lowest for the overmatched welds. The remote strain gauges indicated that GSY was reached in the normalised ($M = 2.15$) and tempered ($M = 1.35$) plates with shallow surface notches and the normalised plate with the deep surface notch. Gross section yielding was not reached in any of the undermatched welds.

8.4 Heat Affected Zones (Submerged Arc Welds)

The results of the CCT tests conducted on specimens having notches in the HAZ of the SAW welds are presented in Figs. 56 to 59 and Appendix 12, Figs. A12.1 to A12.4. Of the six tests conducted, five had notches located within 0.4 mm of the fusion line and all of these tests terminated in brittle fracture. The sixth test (shallow notched in the matched condition) had been accidentally notched at the weld metal centreline and was therefore not included in the summary figures. However, this test was unloaded without fracture at a displacement of ~10 mm on the 150 mm gauge length. Due to the brittle nature of the SAW HAZ at room temperature, three tests failed at CMOD values <1.0 mm (e.g. both shallow notched tests and the undermatched deep notched test).

In terms of load - displacement behaviour, the lowest levels of displacement were measured for the undermatched tests ($M \sim 0.65$), where displacements of ~1 mm were measured on the 150 mm gauge length of the LVDT (i.e. ~0.7% strain) as shown in Figs. 56 and A12.1. The overmatched tests ($M \sim 1.62$) on the other hand reached displacements of between 4.5 and 6 mm (i.e. ~3 to 4% strain). The matched condition test ($M \sim 1.01$) behaved in a similar way to the undermatched tests with a displacement of just more than 1 mm.

Comparison of the CMOD - displacement data showed that in the latter stages of the tests more crack opening occurred for a given displacement in the undermatched condition. However, this effect was not observed for the initial loading of the deeper notched tests where all the displacement was due to crack opening.

Strain gauge data was not recorded for the local strain gauge in the overmatched short cracked specimen. However, the remote gauge indicated that GSY occurred at an early stage in this test. Corresponding data for the undermatched test indicated that surface strains remote from the notch remained elastic indicating that GSY was not reached in this test. The strain gauge data for the deep notched tests (Appendix 12 Fig. A12.4) was a little confusing in so far as the lowest levels of surface strain recorded on the local gauges were for the matched condition ($M \sim 1.01$). For both the over and undermatched tests, the initial rise in strain measured by the local gauges versus displacement was very high (about 4 times that observed in the FCAW HAZs). This may have been due to the lower strength of the SAW HAZ compared to the FCAW HAZ (local undermatching compared to local overmatching). Remote strain gauges showed that surface strains remained elastic for the undermatched and matched tests ($M \sim 0.71$ and 1.01) whereas plasticity was transferred into the gross section for the overmatched test after ~1.3 mm of displacement indicating gross section yielding in the overmatched test.

9. CONCLUSIONS

1. For parent plates, weld metal centreline and HAZ (FL) tests a clear and consistent effect of notch depth on fracture toughness transition temperature was observed with short cracks a/w 0.15 having transitions about 20 to 40°C lower than corresponding deep notches specimens. Through thickness notched orientations tended to have the highest transition temperatures.
2. Studies undertaken on SENB fracture toughness test specimens with notches in a high strength HAZ (FCAW procedure) tended to show higher values of CTOD to BS 7448 in overmatched compared to undermatched welds. The effect was most marked in the transition region where comparison of test specimens revealed crack growth away from the HAZ towards the softer plate material in the overmatched specimens.
3. Similar studies on the lower strength HAZ (SAW procedure) were less conclusive due to experimental difficulties in obtaining over and undermatched specimens sampling identical microstructures. However, where valid comparisons could be made, the same type of effect was observed.
4. Studies conducted on SENB fracture toughness specimens with notches at the weld metal centreline (FCAW procedure) produced some contradictory results. For shallow cracks, higher values of CTOD to BS 7448 were measured in the highly overmatched weld metal, but for deep through thickness cracks, the results were contradictory, possibly as a result of weld to weld variations in fracture properties.

5. Delta five (δ_5) testing of deep notched SENB specimens with weld metal centreline and HAZ(FL) notch locations generally resulted in values similar or slightly greater than CTOD to BS 7448. Similar tests on shallow notched specimens resulted in δ_5 values either the same, greater or less than BS 7448 CTOD and this slight shift in correlation compared to the deep notched specimens may be due to overestimation of CTOD by BS 7448.
6. The relationship between δ_5 and BS 7448 CTOD also appeared to differ with weld strength mismatch for short notched specimens and consequently the effects of mismatch on BS 7448 CTOD observed in the present work may need to be re-examined after being corrected for mismatch by a suitable correction procedure.
7. Charpy specimens notched into the high strength HAZ (FCAW procedure) tended to exhibit higher energies in the highly overmatched weld compared to the under matched weld. This effect was shown to be associated with crack deviation towards lower strength regions of the HAZ.
8. Centre cracked tensile tests conducted on the parent materials exhibited continuous yielding for the Q & T and tempered steels, but a Luders plateau was observed for the normalised steel with a shallow crack. The appearance of the Luders plateau was in agreement with the guidance given in SINTAP Sub-Task 2.3. The absence of a Luders plateau in the deep notched specimens suggests that assumptions given in Sub-Task 2.3 for deep cracks in thin wall materials in tension may be conservative.
9. Centre cracked tensile tests conducted on mismatched FCAW welds, with notches at the weld centreline, demonstrated that the load bearing capacity of the undermatched welds were always less than those of weld free material. On the other hand, the load bearing capacity of the overmatched welds were always similar to those of weld free material. In terms of CMOD or δ_5 versus displacement, the overmatched condition consistently had a lower slope to the relationship.
10. Centre cracked tensile tests with notches located in the high strength HAZ (FCAW procedure) showed similar load - displacement characteristics to the weld metals. Higher applied CMOD or δ_5 in the HAZ was observed for a given displacement for undermatched welds.
11. Centre cracked tensile tests with notches located in the lower strength HAZ (SAW procedure) also showed similar characteristics to the FCAW welds, but due to their lower toughness and possibly also due to local undermatching, fracture occurred in all tests prior to attainment of maximum load. The lowest displacements were observed in the undermatched welds.

REFERENCES

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3. BS 7448:Part 1:1990.
4. Document No. SINTAP/BS/22, Task 1.3 Progress Report, April 1998.
5. H.G. Pisarski: 'The Effect of Weld Metal Mismatch on Structural Integrity Assessments - Experimental Studies', TWI Report No. 220010/12/94, August 1994.
6. GKSS Document No. SINTAP/GKSS/14, Task 1.2 Draft Report, July 1998.
7. H.G. Pisarski and A. Kinsey: 'Development of Fracture Assessment and Testing Procedures for HAZ Cracks - Testing of Surface Notched Specimens', TWI Report No. 5677/3/97, September 1997.

TABLE 1
TESTING MATRIX FOR MULTIPASS JOINTS

Test Series	Weld CR 800 - 500°C (s)	Aim PP Yield (MPa)	Aim WM Yield (MPa)	Aim HAZ Yield (MPa)	Aim MM Ratio (m)	Room Temperature Tensile Tests			CTOD and Centre Cracked Tensile Tests								
						WM	PP	HAZ	HAZ Notched			WM Notched			PP Notched		
									a/w 0.15	a/w 0.5	TTN	a/w 0.15	a/w 0.5	TTN	a/w 0.15	a/w 0.5	TTN
1	NA	650	NA	NA	NA	NA	X	NA	-	-	-	-	-	-	XO	XO	XO
2	NA	500	NA	NA	NA	NA	X	NA	-	-	-	-	-	-	XO	XO	XO
3	NA	350	NA	NA	NA	NA	X	NA	-	-	-	-	-	-	XO	XO	XO
4	10 s	650	500	>WM	0.77	-	-	XO	XO	XO	XO	X	XO	XO	-	-	-
5	10 s	500	500	>WM	1.00	-	-	O	XO	XO	-	X	XO	-	-	-	-
6	10 s	350	500	>WM	1.43	-	-	O	XO	XO	XO	X	XO	XO	-	-	-
7	125 s	350	500	<WM	0.77	-	-	XO	XO	XO	-	-	-	-	-	-	-
8	125 s	500	500	<WM	1.00	-	-	O	XO	XO	-	-	-	-	-	-	-
9	125 s	350	500	<WM	1.43	-	-	O	XO	XO	-	-	-	-	-	-	-

(X) HAZ tensiles on simulated/heat treated HAZ (British Steel) (O) Micro-tensiles on multipass welds (GKSS)

(X) Centre cracked tensiles to define crack tip driving force curves (British Steel)

(X) CTOD tests to define transition behaviour (British Steels) (O) R - curves and selected δ_5 measurements (GKSS)

TABLE 2
STEEL COMPOSITION AND PROCESSING

C	Si	Mn	P	S	Cr	Mb	Ni	Al	Cu	Nb	B	Ti	V	CE
0.13	0.41	1.42	0.015	0.002	0.023	0.003	0.022	0.042	0.012	0.034	0.0024	0.038	0.063	0.387

Steelmaking Process

- BOS

Casting

- Continuously Cast

Heat Treatment

Reheated

- 930°C for 50 min

Quenched and Tempered

- 580°C for 1 h

TABLE 3
SUMMARY OF TEST WELDS AND HARDNESS DATA

Test Specimens	Welding Process	Weld Code	Weld Metal Hardness	HAZ HV (FL)	Weld Code	Weld Metal Hardness	HAZ HV (FL)	Weld Code	Weld Metal Hardness	HAZ HV (FL)
		HIGH YIELD PLATE			MEDIUM YIELD PLATE			LOW YIELD PLATE		
WMCT SN a/w 0.15, 0.5, TTN	FCAW	Y6A19C			Y6A21C			Y6A20C		
WMCTOD SN a/w = 0.15	FCAW	Y6A19G			Y6A21D	220	262	Y6A20D	231	264
WMCTOD SN a/w = 0.5	FCAW	Y6A19H			Y6A18R	232	281	Y6A20E	221	248
WMCTOD TTN	FCAW	Y6A18M	236	283	NA			Y6A18P	237	284
WM CHARPY	FCAW	Y6A18D	229	284	Y6A18G	246	271	Y6A18J	236	281
HAZ CCT SN a/w 0.15, 0.5, TTN	FCAW	Y6A19F			Y6A21F			Y6A20F		
HAZ CTOD SN a/w = 0.15	FCAW	Y6A18N	233	257	Y6A21G	231	262	Y6A20G	223	290
HAZ CTOD SN a/w = 0.5	FCAW	Y6A19D			Y6A21H	223	287	Y6A20H	251	265
HAZ CTOD TTN	FCAW	Y6A18L	229	279	NA			Y6A18O	233	284
HAZ CHARPY	FCAW	Y6A18C	244	272	Y6A18F	239	277	Y6A18I	231	280
HAZ CCT SN a/w 0.15, 0.5	SAW	Y6A19I			Y6A21I			Y6A20I		
HAZ CTOD SN a/w = 0.15	SAW	Y6A19J	195	234	Y6A21J	187	224	Y6A20J	199	201
HAZ CTOD SN a/w = 0.5	SAW	Y6A19K	194	237	Y6A21K	184	225	Y6A20K	198	225
HAZ CHARPY	SAW	Y6A18E	196	220	Y6A18H	190	235	Y6A18K	196	232

TABLE 4
PARENT PLATE TENSILE PROPERTIES

Steel Condition	Average Yield Strength (N/mm ²)	Standard Deviation	Average Tensile Strength (N/mm ²)	Standard Deviation	Yield to Tensile Ratio	Strain Hardening Exponent n
Q&T + PWHT	675	34	753	23	0.9	0.088
675°C Temper + PWHT	475	42	610	21	0.78	0.117
900°C Normalise + PWHT	297	9	510	3	0.58	0.239

TABLE 5
WELD METAL TENSILE PROPERTIES

Weld Type	Average Yield Strength (N/mm ²)	Standard Deviation	Average Tensile Strength (N/mm ²)	Standard Deviation	Yield to Tensile Ratio	Strain Hardening Exponent n
FCAW	545 *	-	619	-	0.88	-
	639 +	15	709	13	0.90	0.111
SAW	489 *	-	594	-	0.82	-
	475 +	14	590	13	0.81	0.147
	480 †	13	591	10	0.81	

* All WM tests on procedure weld

+ Waisted transverse tensiles from test panels

† Mean of all tests

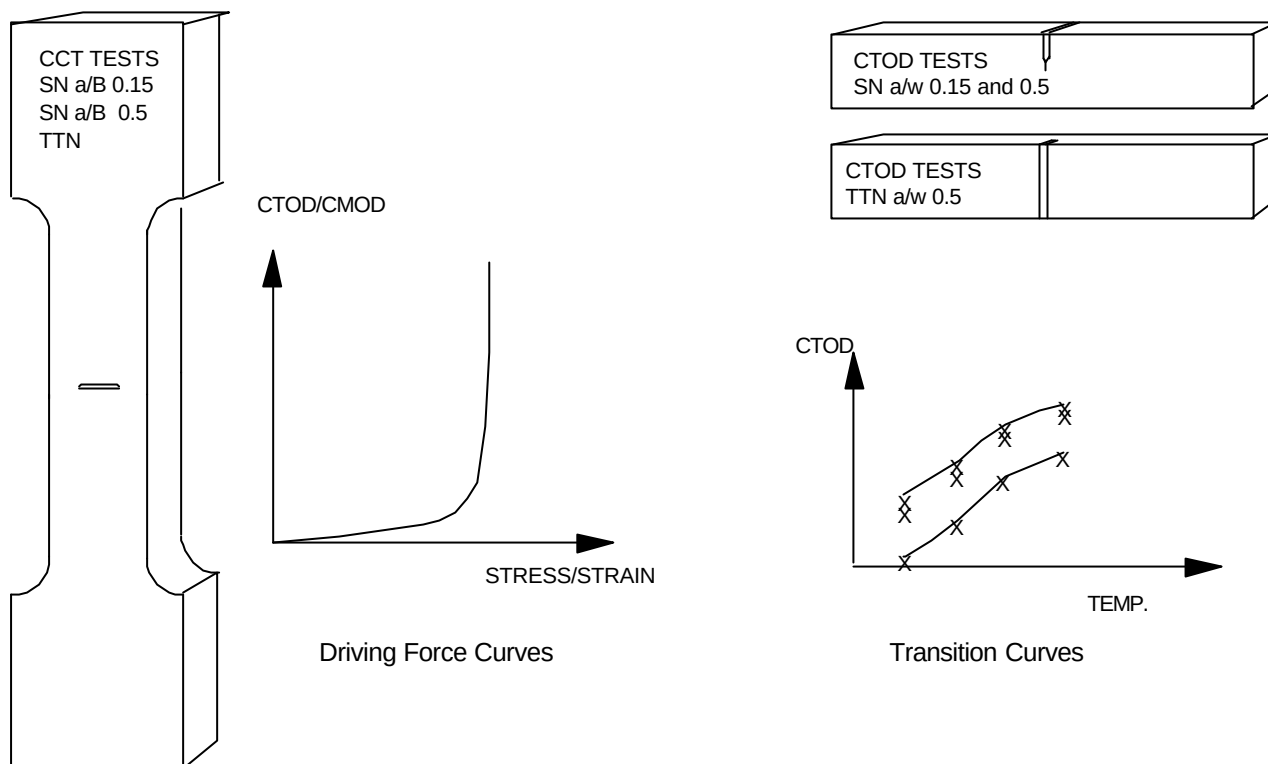
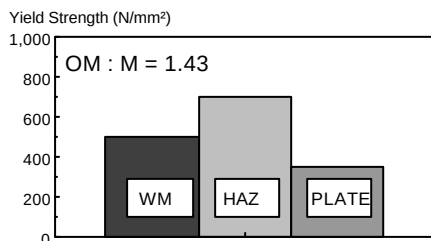
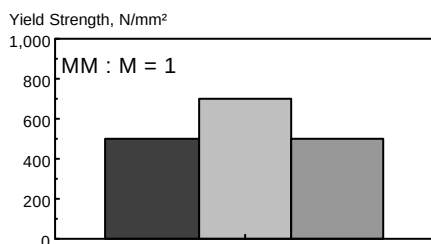
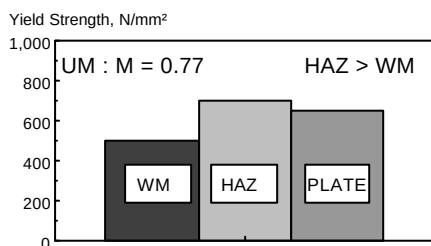


FIG.1

EXPERIMENTAL PROCEDURE

(D0697E06)

FCAW PROCEDURE



SAW PROCEDURE

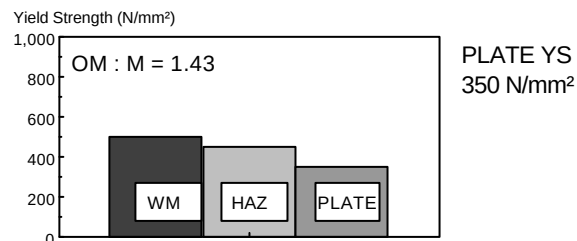
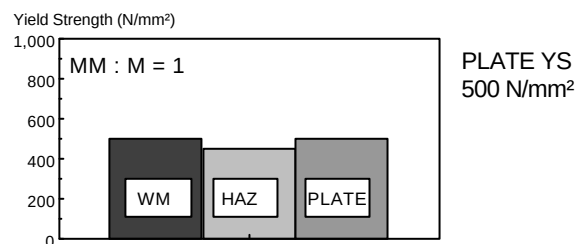
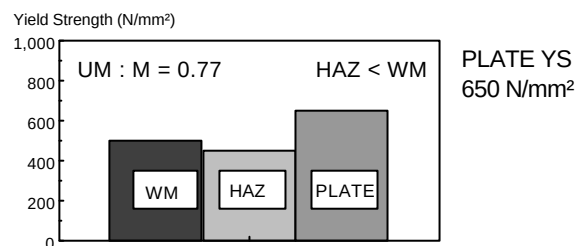
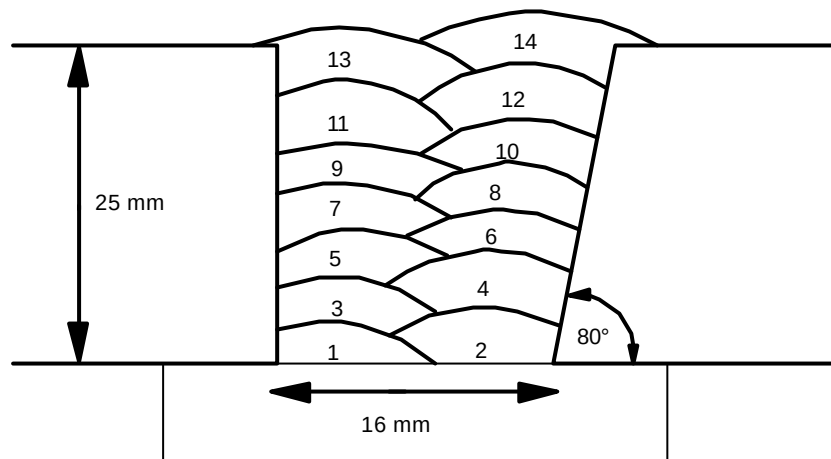


FIG.2

AN MISMATCH LEVELS WITH HEAT TREATED PLATES

(D0697E06)



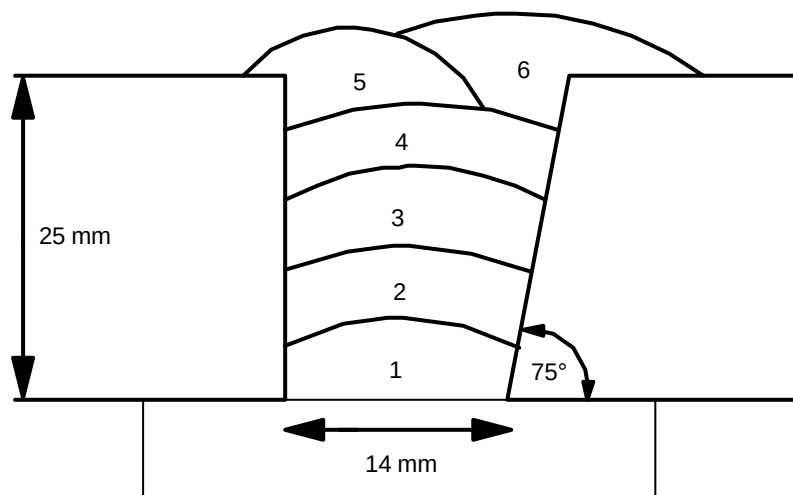
Welding Conditions

Current	250 A
Voltage	30 V
Travel speed	358 mm/min
Wire diameter	1.2 mm
Preheat	100°C
Intepass	150°C
Wire	Fluxofil 35
Gas	Argoshield 20
Arc energy	1.25 kJ/mm

FIG.3

MULTIPASS FLUX-CORED ARC WELDING PROCEDURE - 1 kJ/mm

(D0697E06)



Welding Conditions

Current	700 A
Voltage	30 V
Travel speed	250 mm/min
Wire diameter	3.25 mm
Preheat	200°C
Intepass	250°C
Wire	OESD3 1Ni $\frac{1}{4}$ Mo
Flux	OP121TT

FIG.4

MULTIPASS SUBMERGED ARC WELDING PROCEDURE - 5 kJ/mm

(D0697E06)

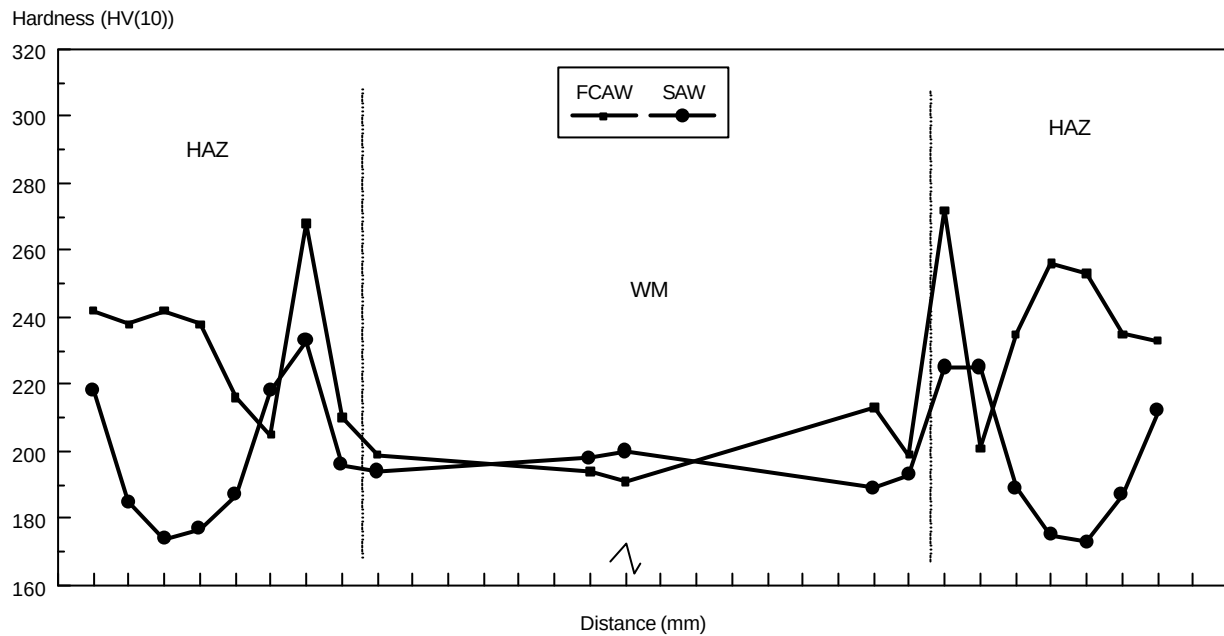


FIG. 5

**HARDNESS TRAVERSES AT MID-THICKNESS
FOR FCAW AND SAW PROCEDURES
(PROCEDURE TEST WELDS)**

(D0697E06)

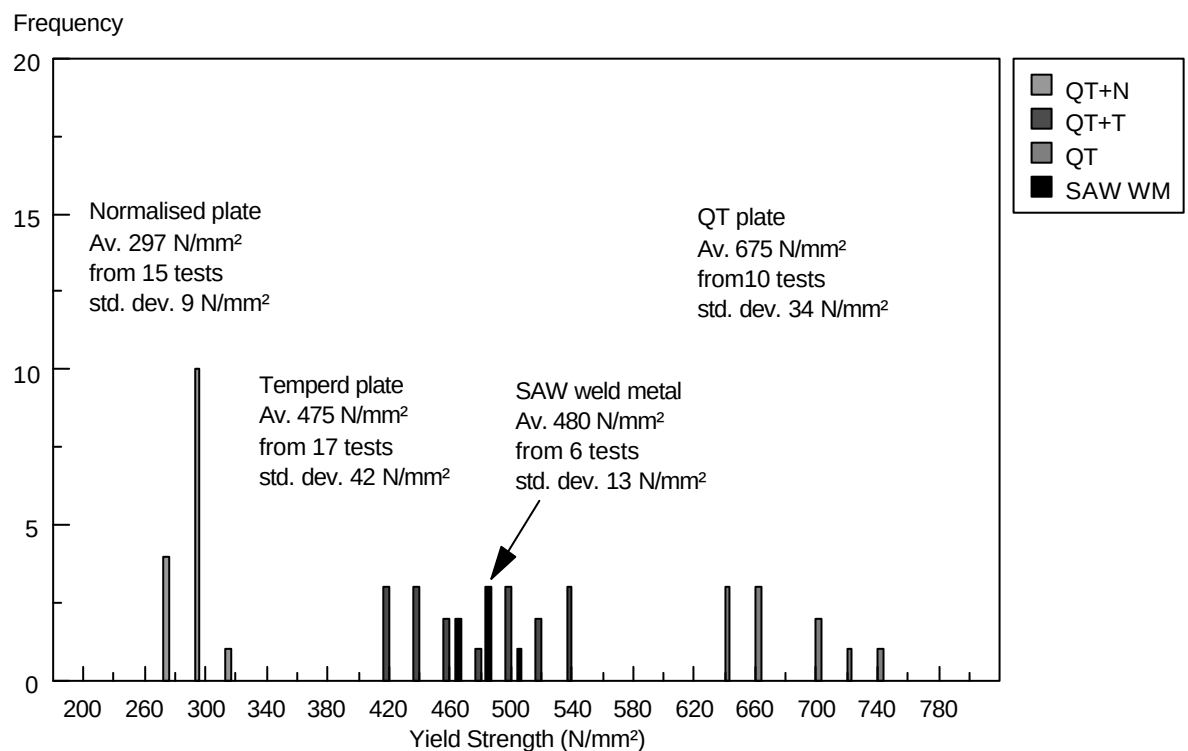


FIG. 6

**PARENT PLATE AND SAW WELD METAL
YIELD STRENGTH RESULTS**

(D0697E06)

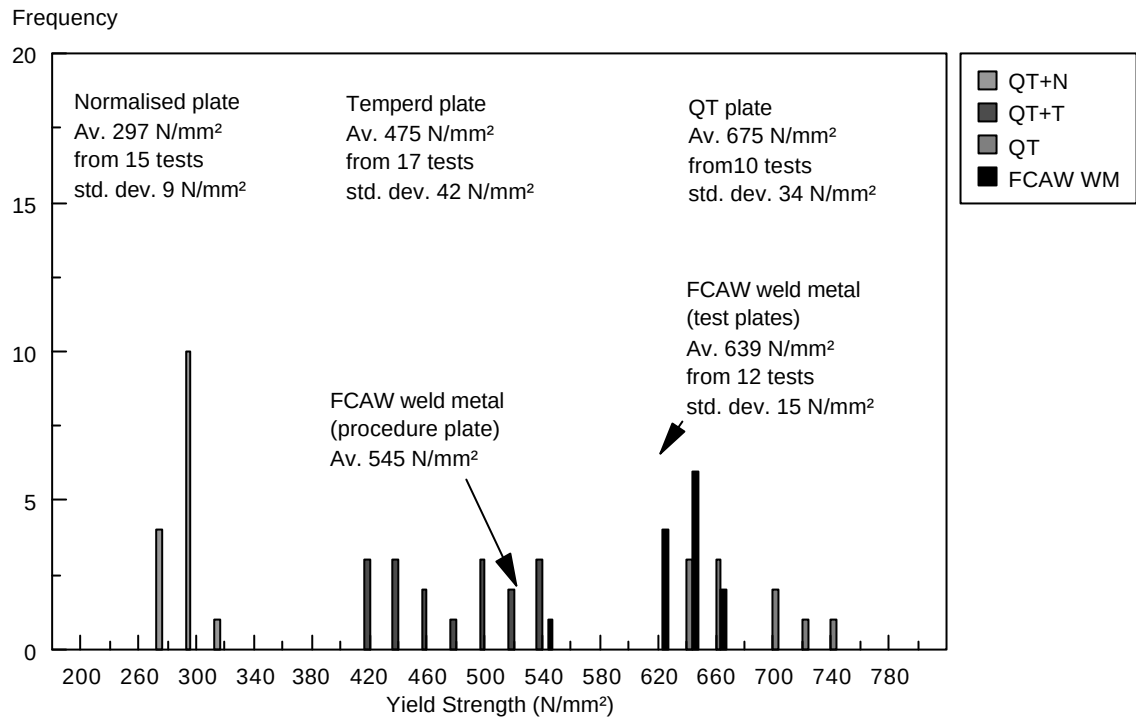


FIG. 7

PARENT PLATE AND FCAW WELD METAL
YIELD STRENGTH RESULTS

(D0697E06)

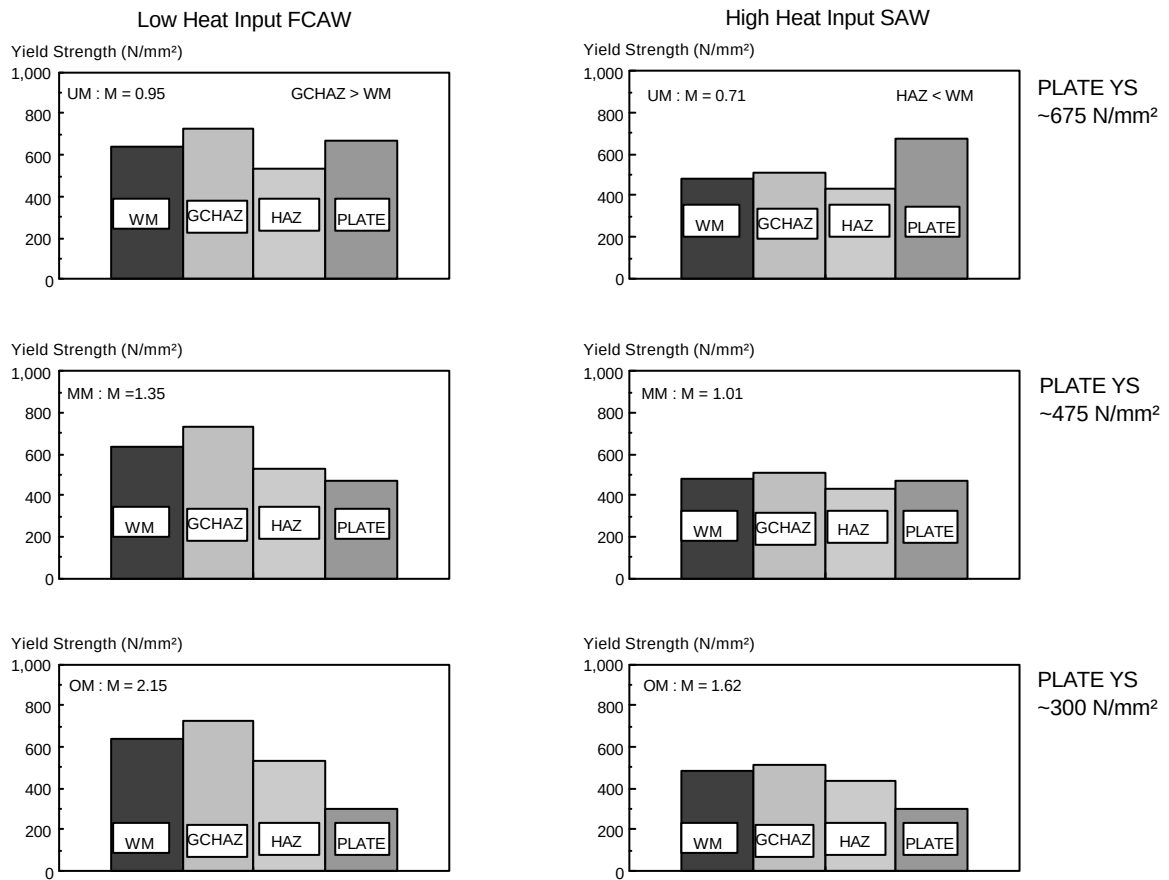


FIG. 8

ACHIEVED MISMATCH LEVELS WITH HEAT TREATED PLATES

(D0697E06)

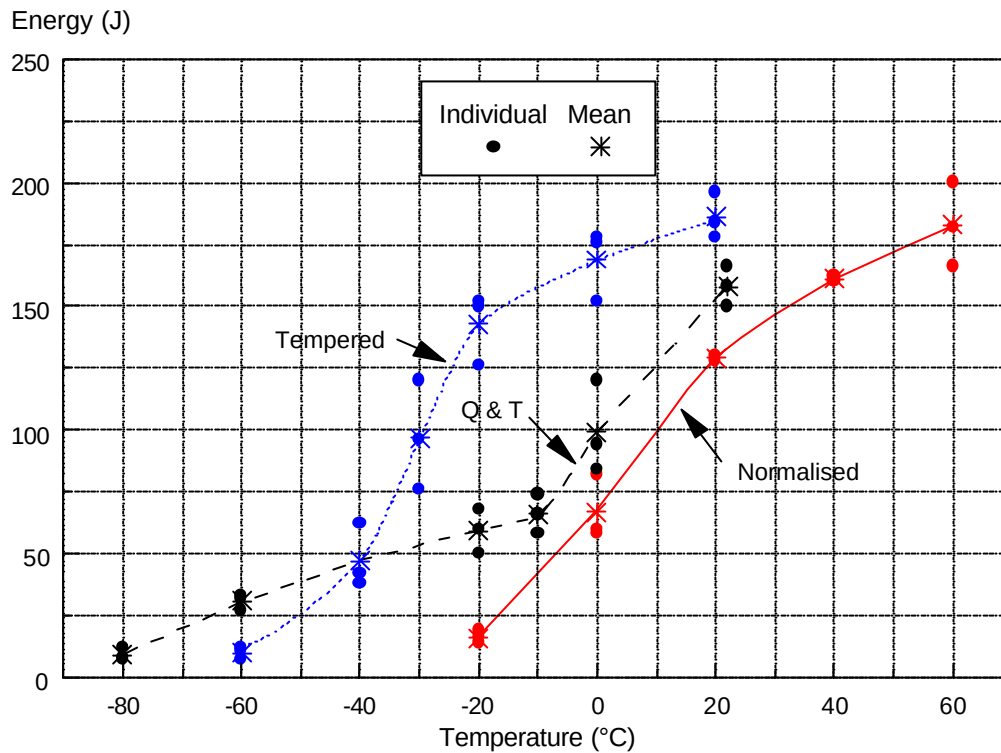


FIG. 9

CHARPY TRANSITION CURVES FOR PARENT
MATERIALS TRANSVERSE - SUBSURFACE

(D0697E06)

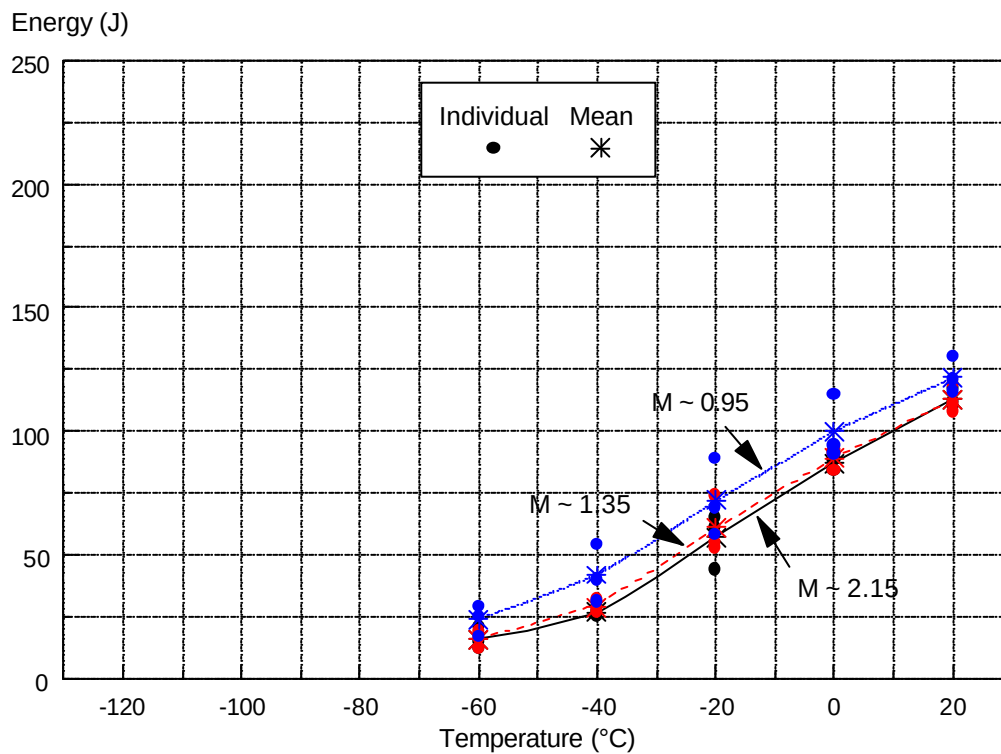


FIG. 10

CHARPY TRANSITION CURVES FOR FCAW WELD
METAL TRANSVERSE - SUBSURFACE (ROOT)

(D0697E06)

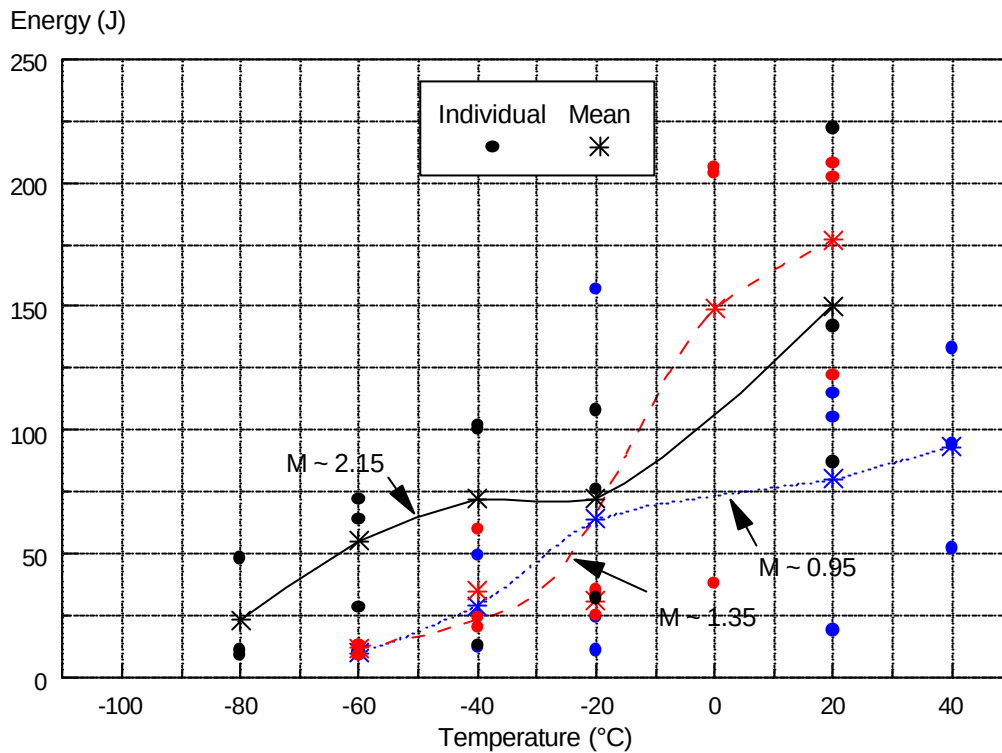


FIG. 11

CHARPY TRANSITION CURVES FOR FCAW HAZ (PWHT)
TRANSVERSE - SUBSURFACE (ROOT)

(D0697E07)

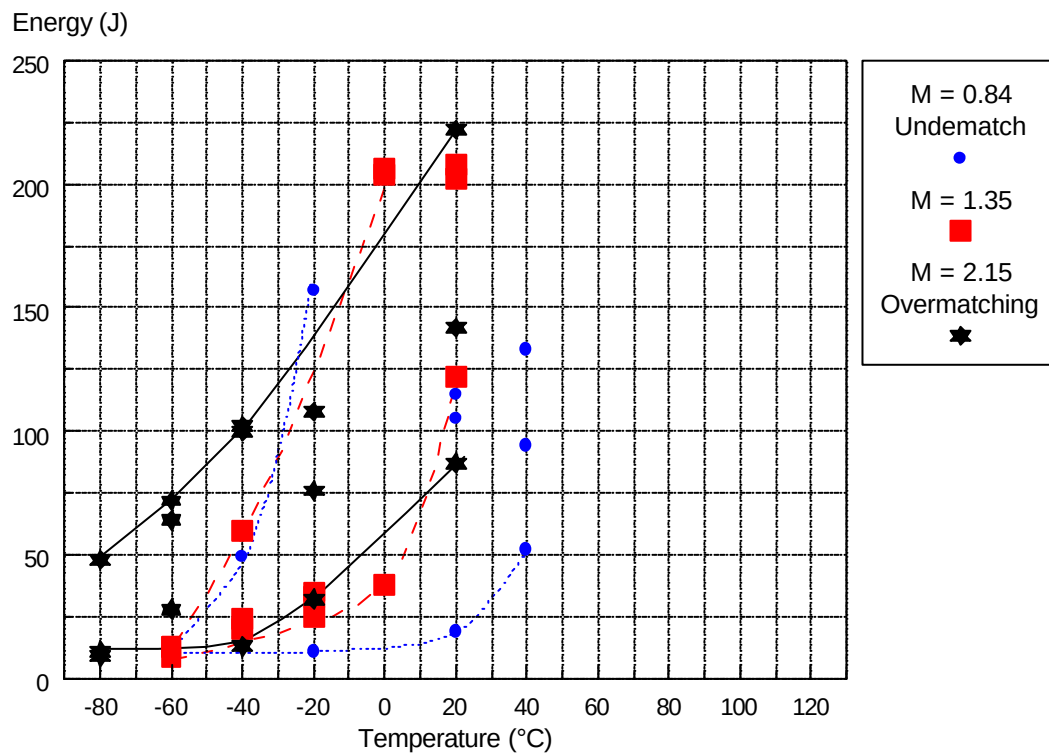
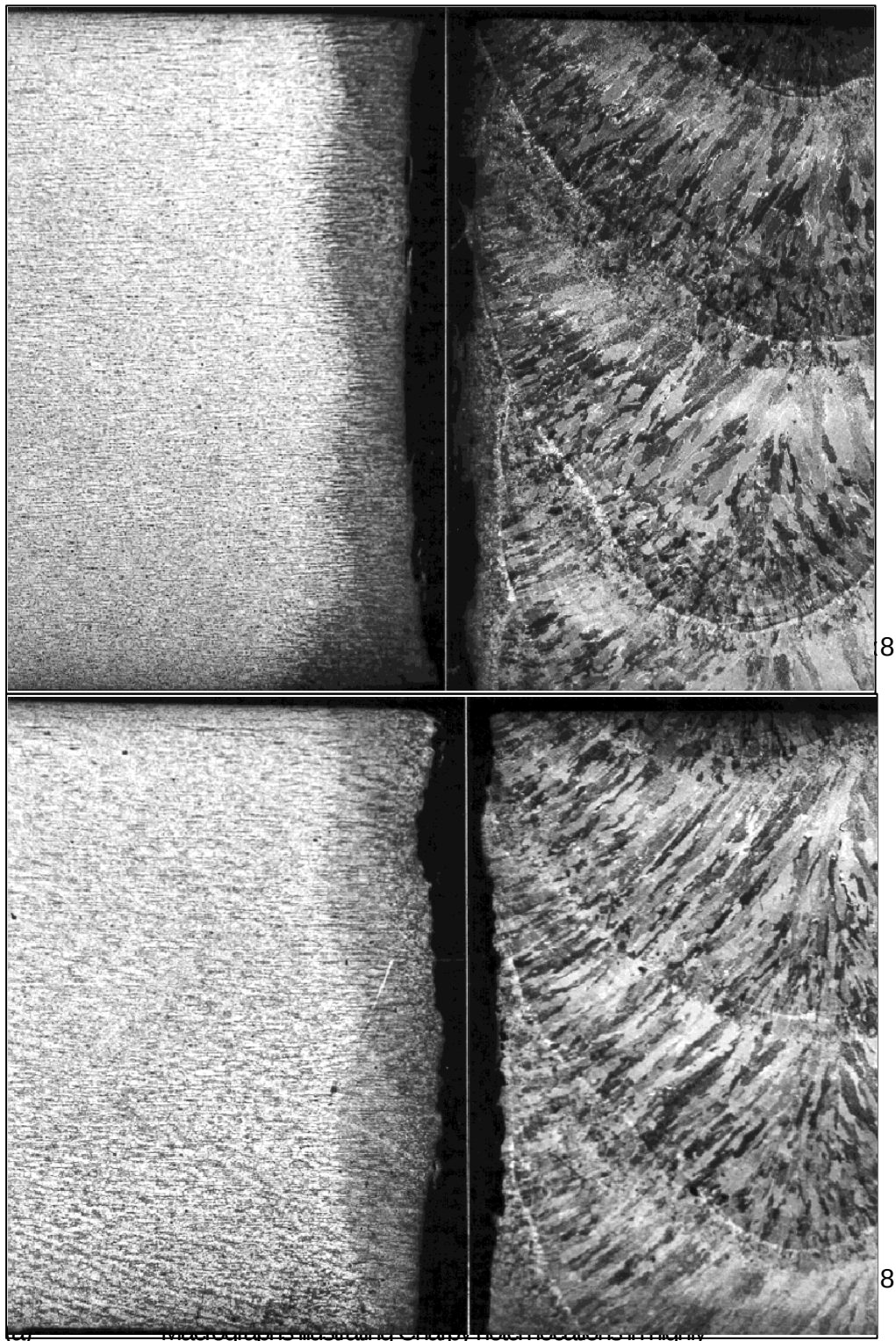


FIG. 12

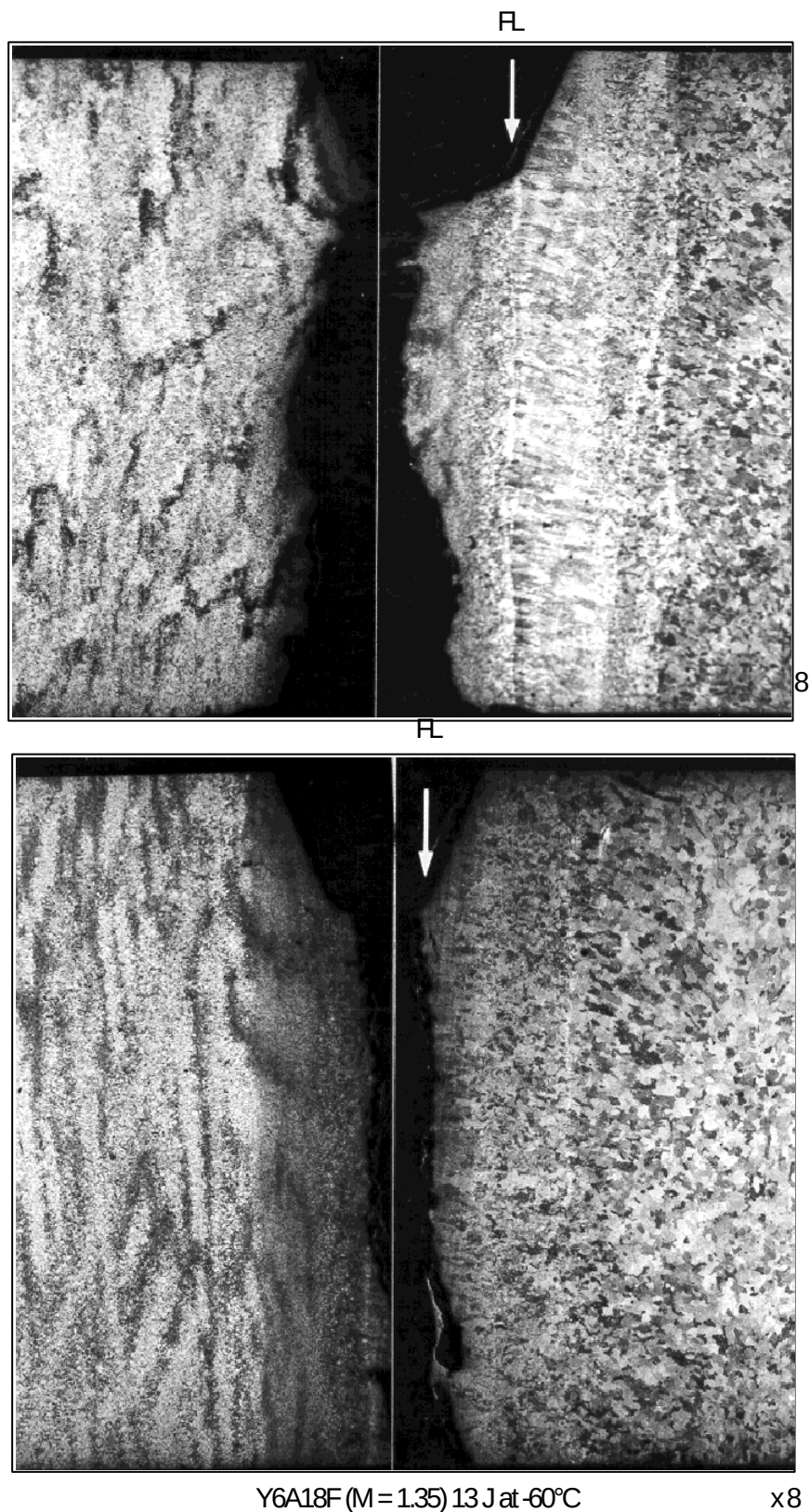
CHARPY RESULTS FOR FCAW HAZ (PWHT)
TRANSVERSE - SUBSURFACE (ROOT)

(D0697E07)



(a) Micrographs illustrating cleavage fracture in highly overmatched ($M = 2.15$) and overmatched ($M = 1.35$) specimens tested at -60°C

FIG. 13(a and b)
(Cont...)



- (b) Macrographs illustrating fracture paths in highly overmatched (M = 2.15) and slightly overmatched (M = 1.35) specimens tested at -60°C

FIG. 13(a and b)

(Continued)

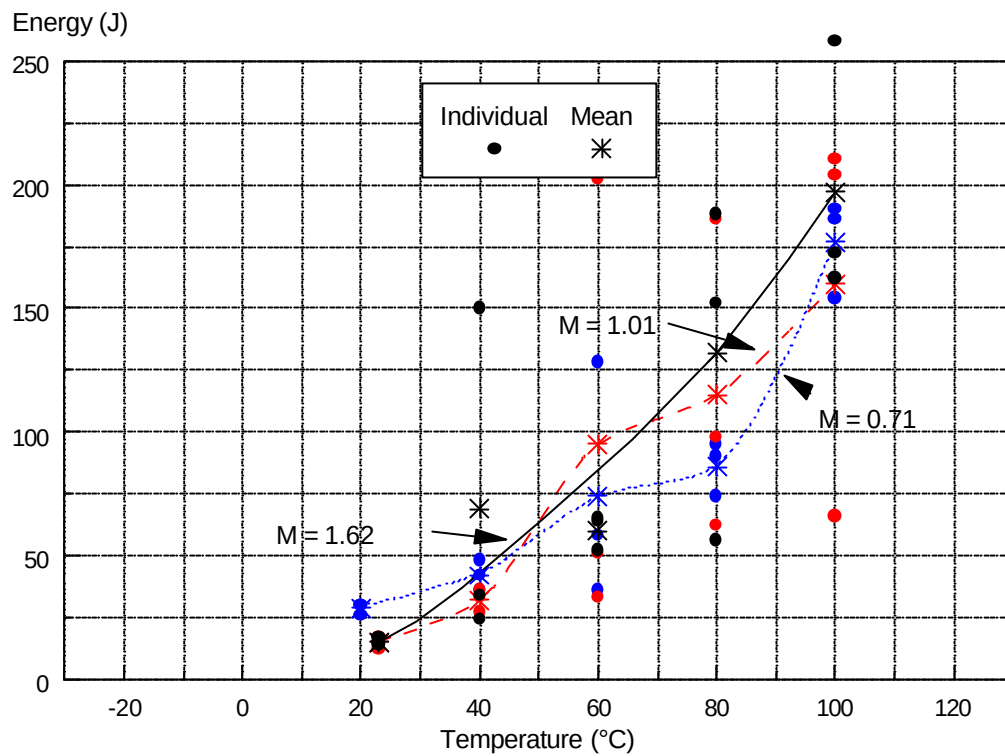


FIG. 14

CHARPY TRANSITION CURVES FOR SAW HAZ (PWHT)
TRANSVERSE - SUBSURFACE (ROOT)

(D0697E07)

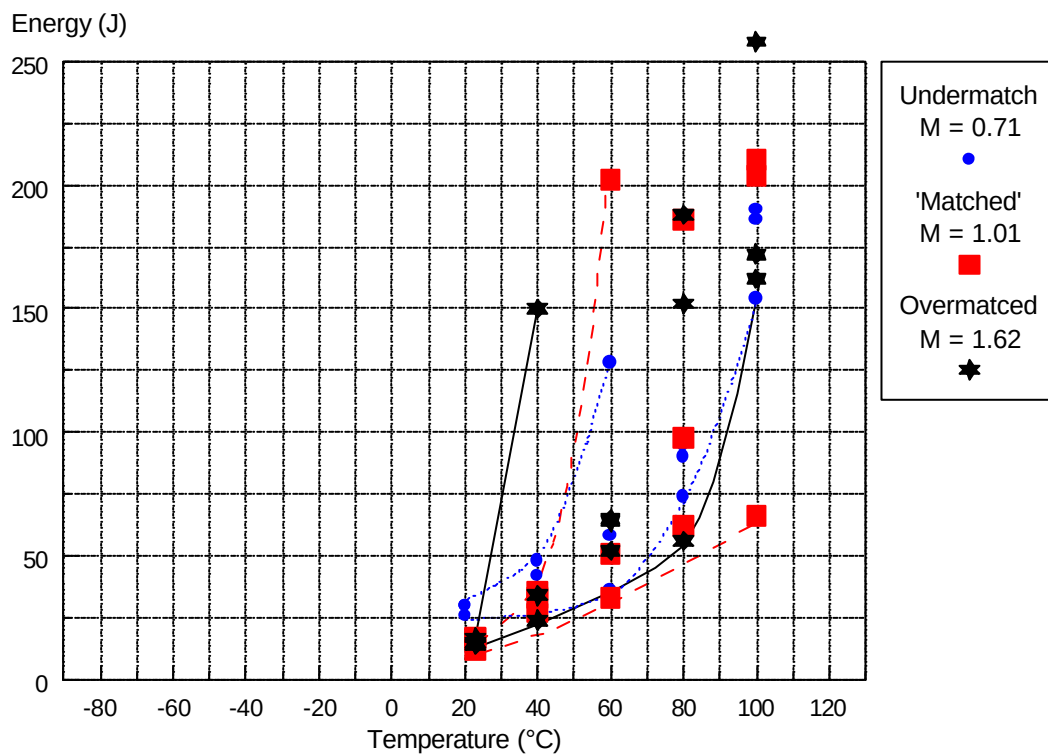


FIG. 15

CHARPY RESULTS FOR SAW HAZ (PWHT)
TRANSVERSE - SUBSURFACE (ROOT)

(D0697E07)

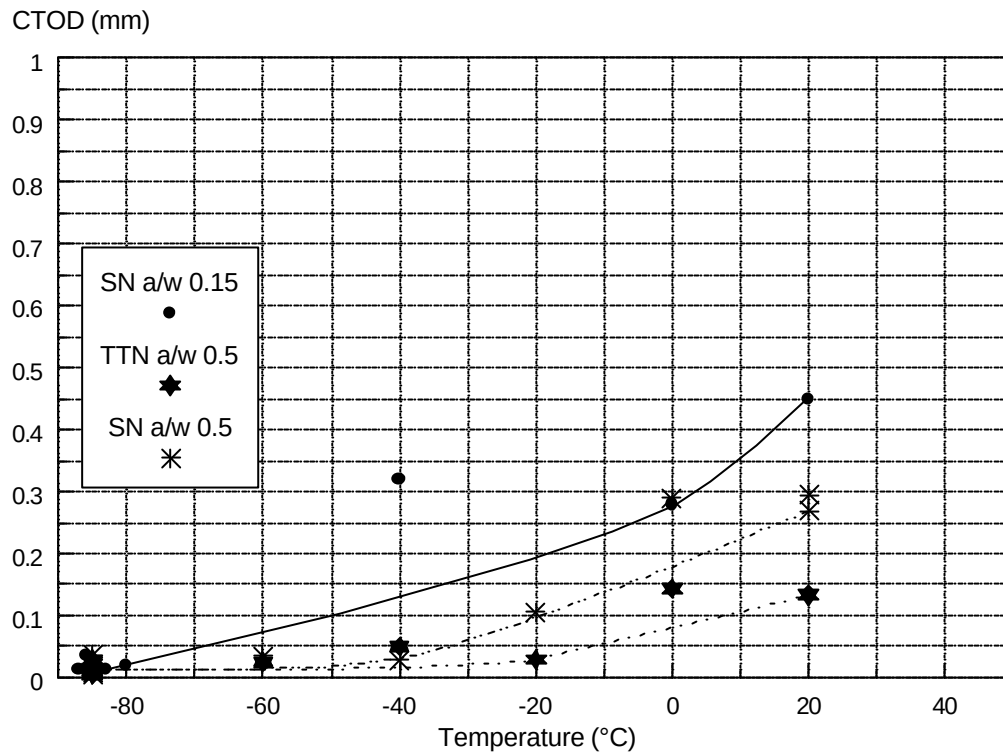


FIG. 16

CTOD TRANSITION DATA FOR RQT701
(PWHT) - TRANSVERSE

(D0697E07)

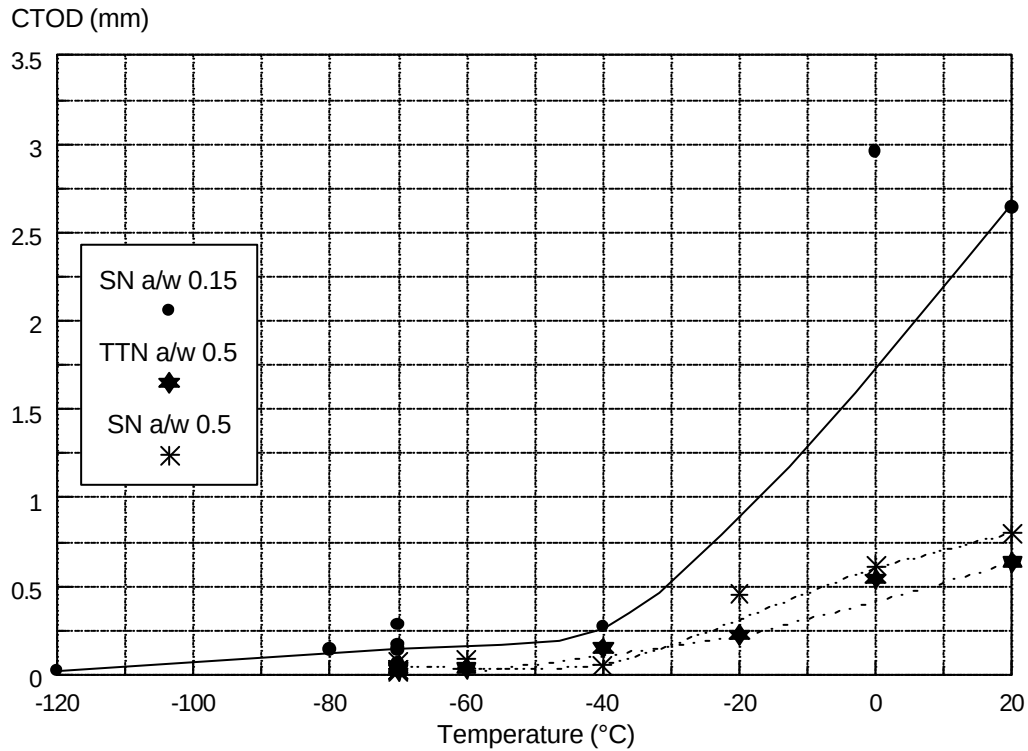


FIG. 17

CTOD TRANSITION DATA FOR TEMPERED
RQT701 (PWHT) - TRANSVERSE

(D0697E07)

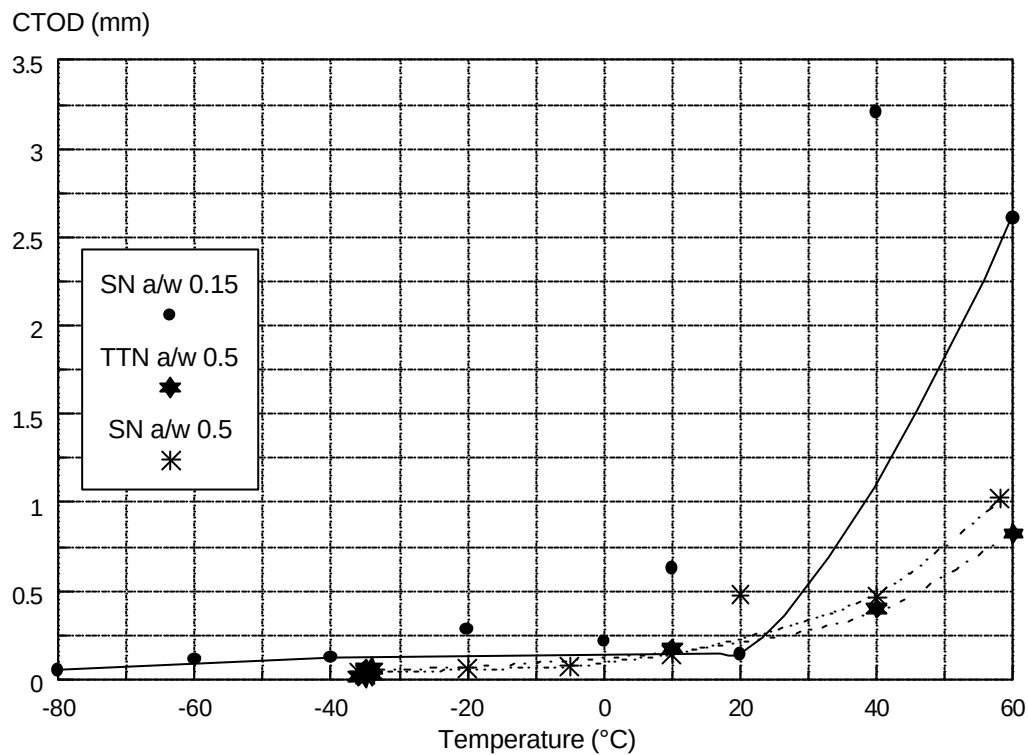


FIG. 18

CTOD TRANSITION DATA FOR NORMALISED
RQT701 (PWHT) - TRANSVERSE

(D0697E07)

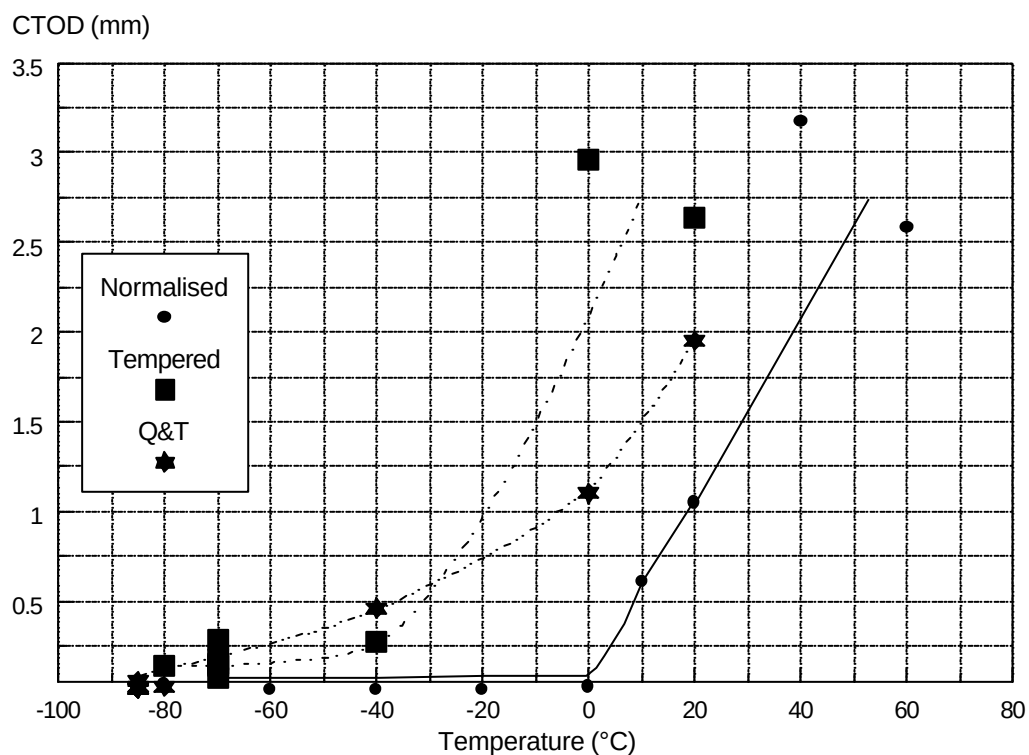


FIG. 19

COMPARISON OF CTOD TRANSITION DATA FOR PARENT
PLATES (PWHT) - TRANSVERSE - THROUGH
THICKNESS NOTCH a/w 0.5

(D0697E07)

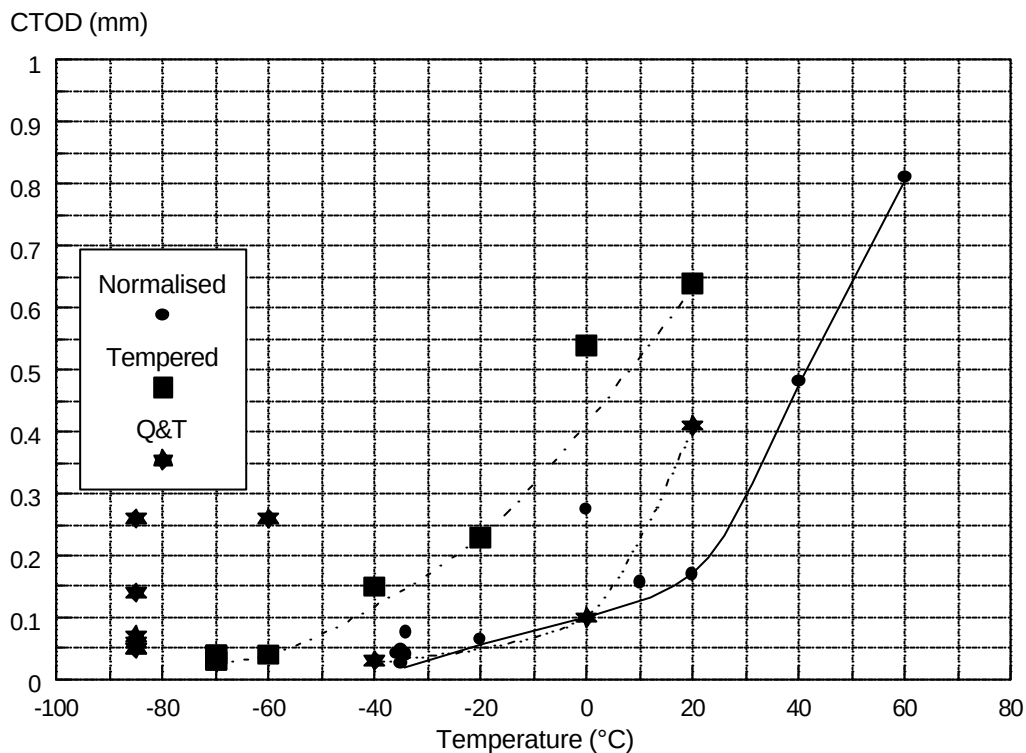


FIG. 20

COMPARISON OF CTOD TRANSITION DATA FOR PARENT
PLATES (PWHT) - TRANSVERSE - SURFACE NOTCH a/w 0.5

(D0697E07)

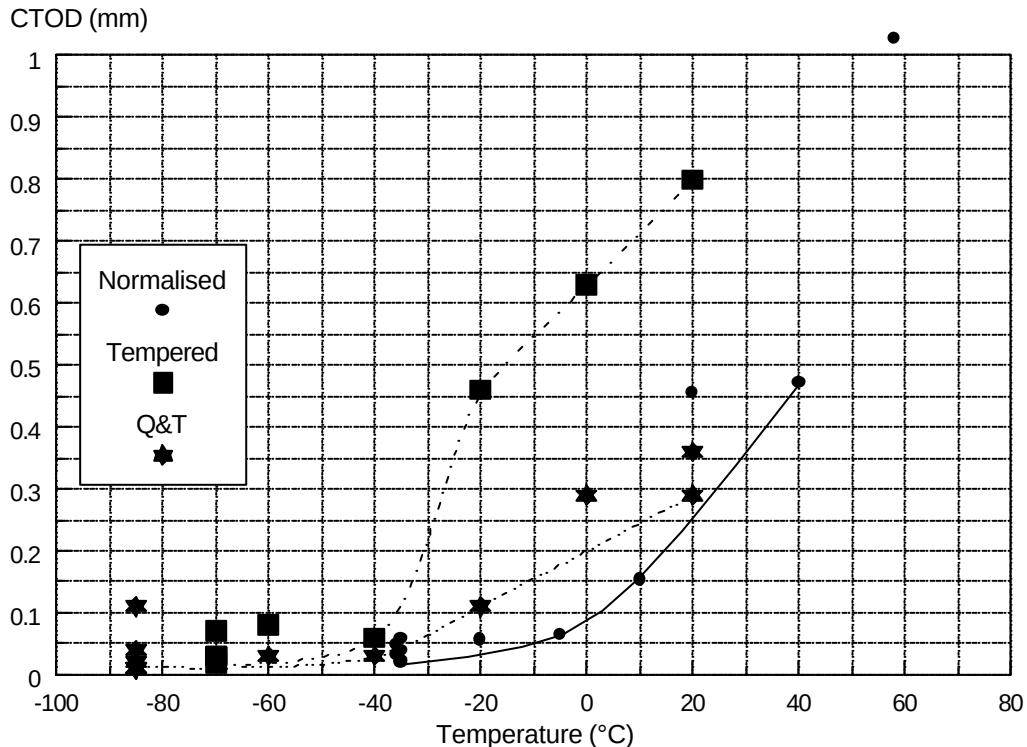


FIG. 21

COMPARISON OF CTOD TRANSITION DATA FOR PARENT
PLATES (PWHT) - TRANSVERSE - SURFACE NOTCH a/w 0.15

(D0697E07)

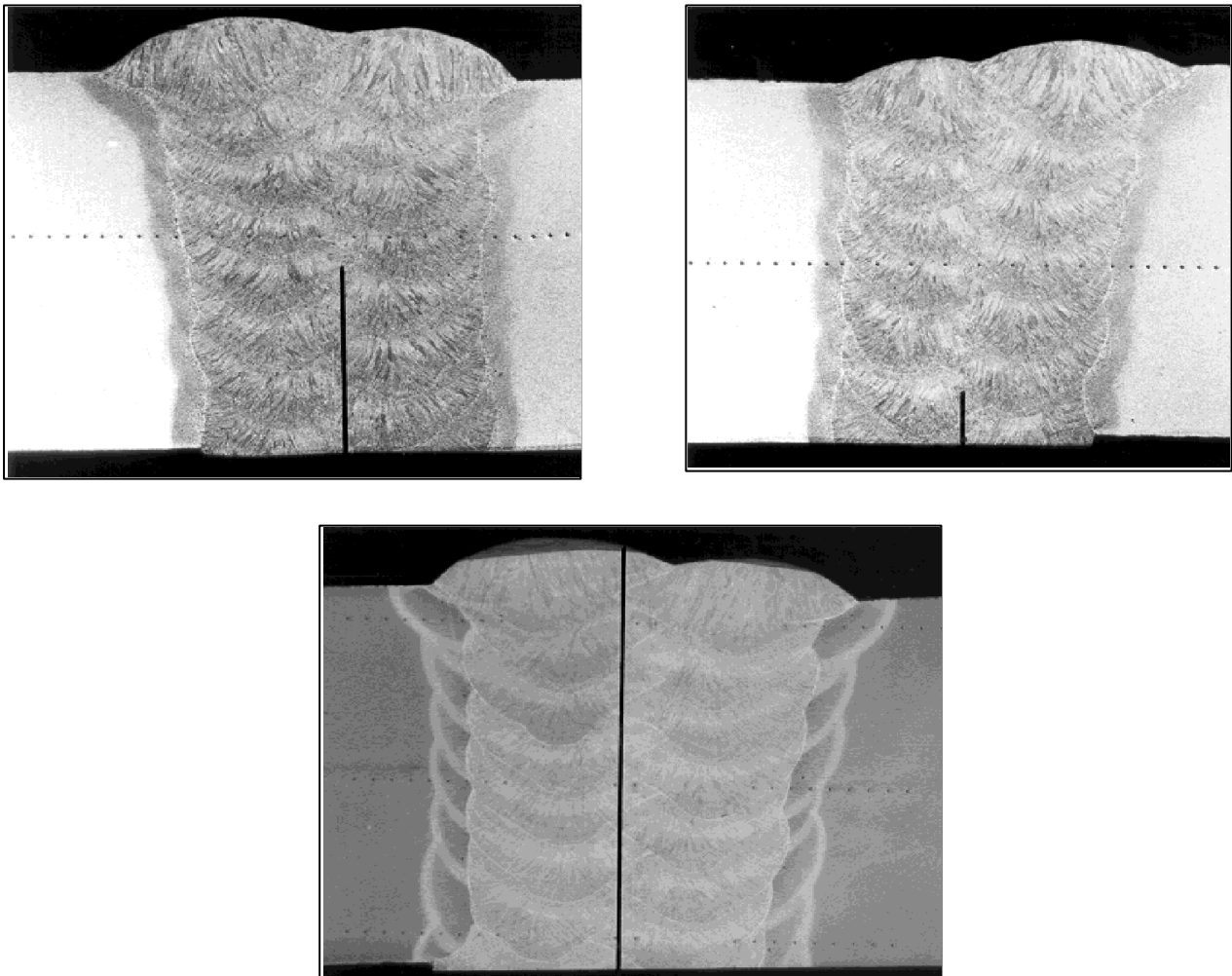


FIG. 22

MACROGRAPHS ILLUSTRATING NOTCH LOCATIONS
FOR FCAW WELD CENTRELINE TESTS

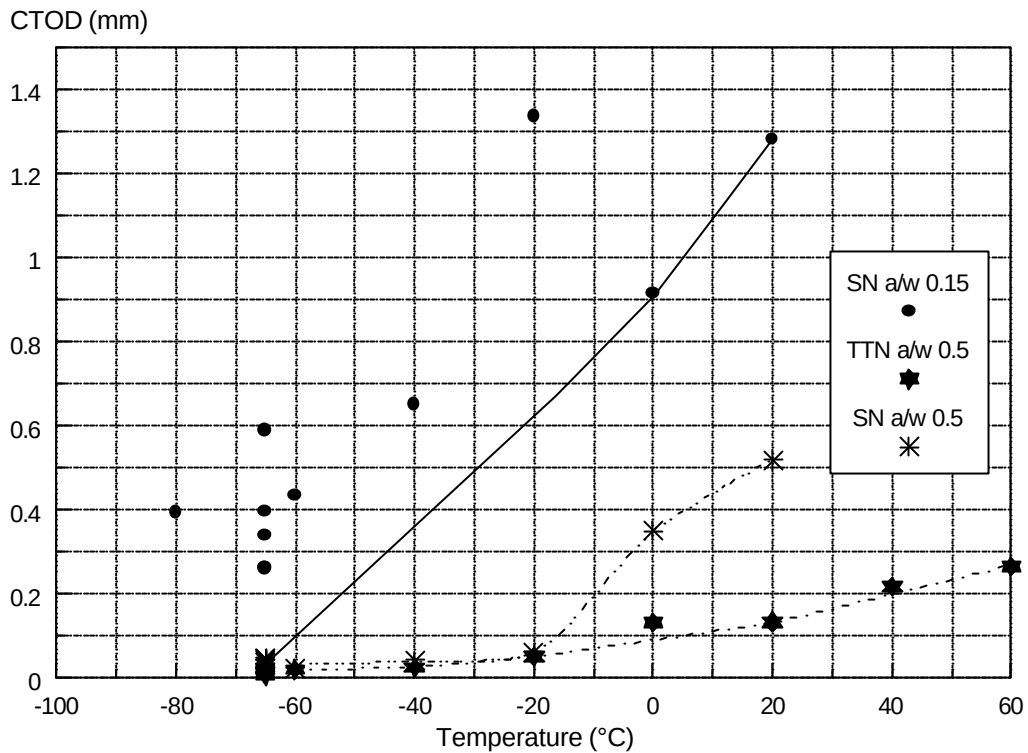


FIG. 23

BS 7448 CTOD TRANSITION DATA FOR FCAW WM (PWHT) -
TRANSVERSE - EFFECT OF NOTCH DEPTH AND
ORIENTATION (M = 215)

(D0697E08)

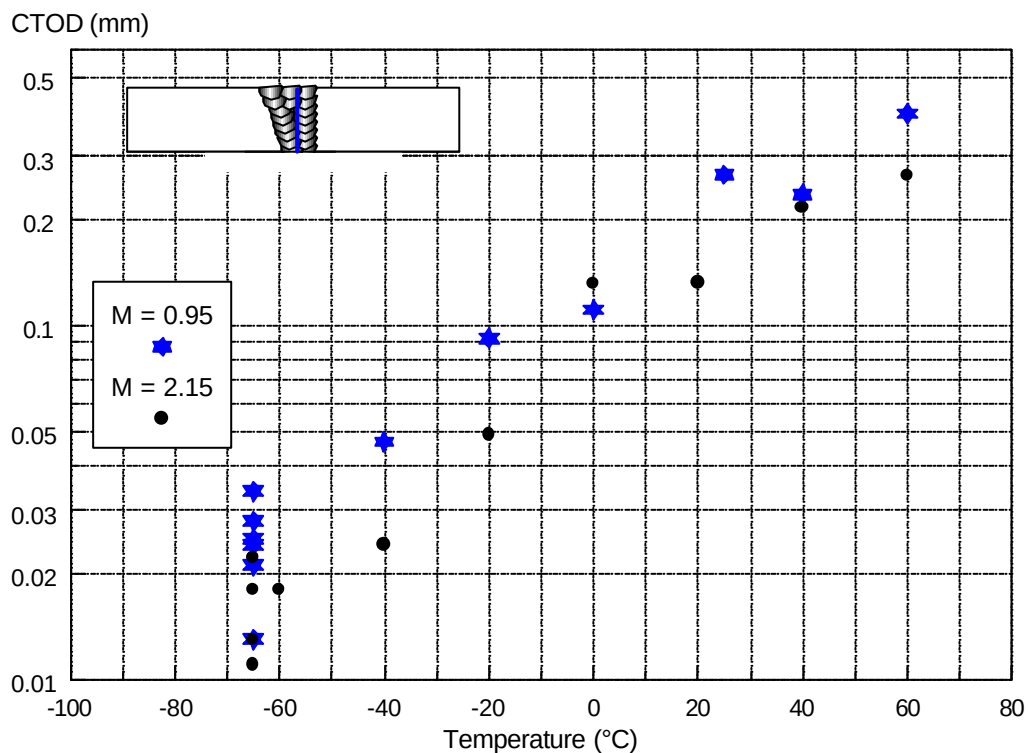


FIG. 24

COMPARISON OF CTOD TRANSITION DATA FOR FCAW WM
(PWHT) - TRANSVERSE - THROUGH THICKNESS NOTCH
a/w 0.5 - WELD CENTRELINE

(D0697E08)

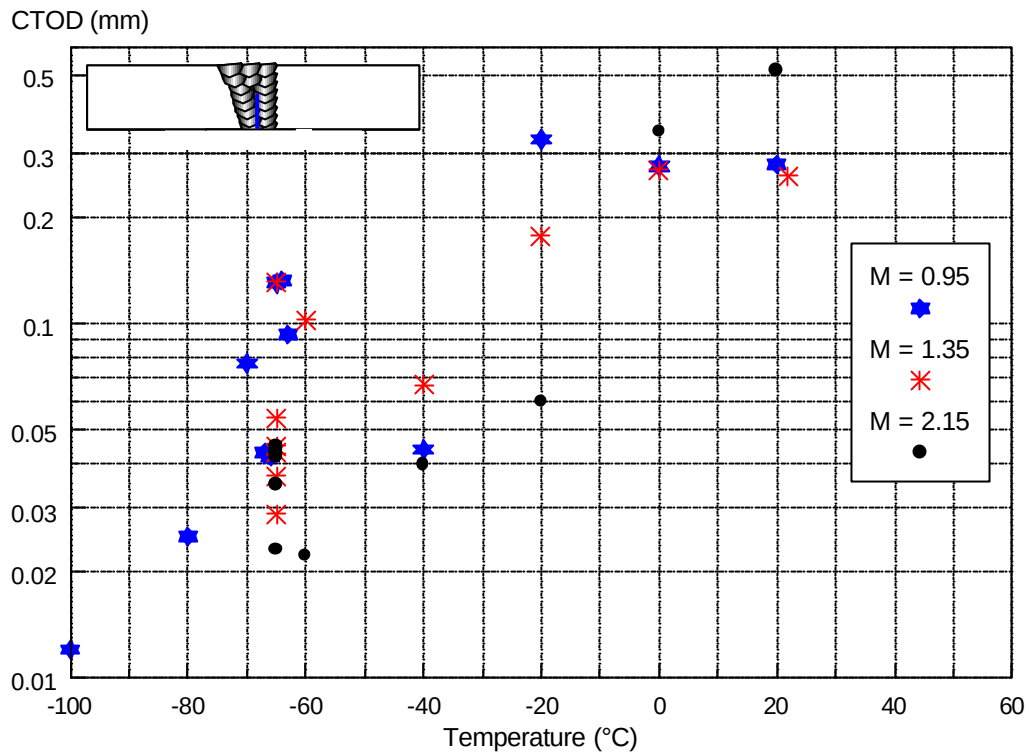


FIG. 25

COMPARISON OF CTOD TRANSITION DATA FOR FCAW WM
(PWHT) - TRANSVERSE - SURFACE NOTCH
at w 0.5 - WELD CENTRELINE

(D0697E08)

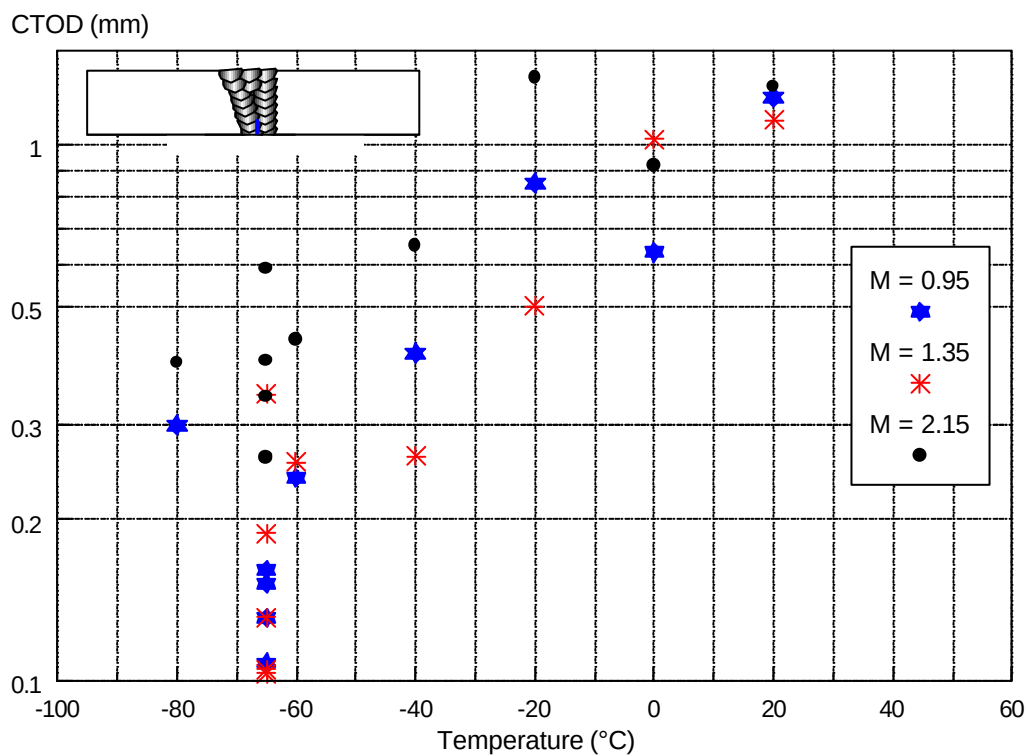
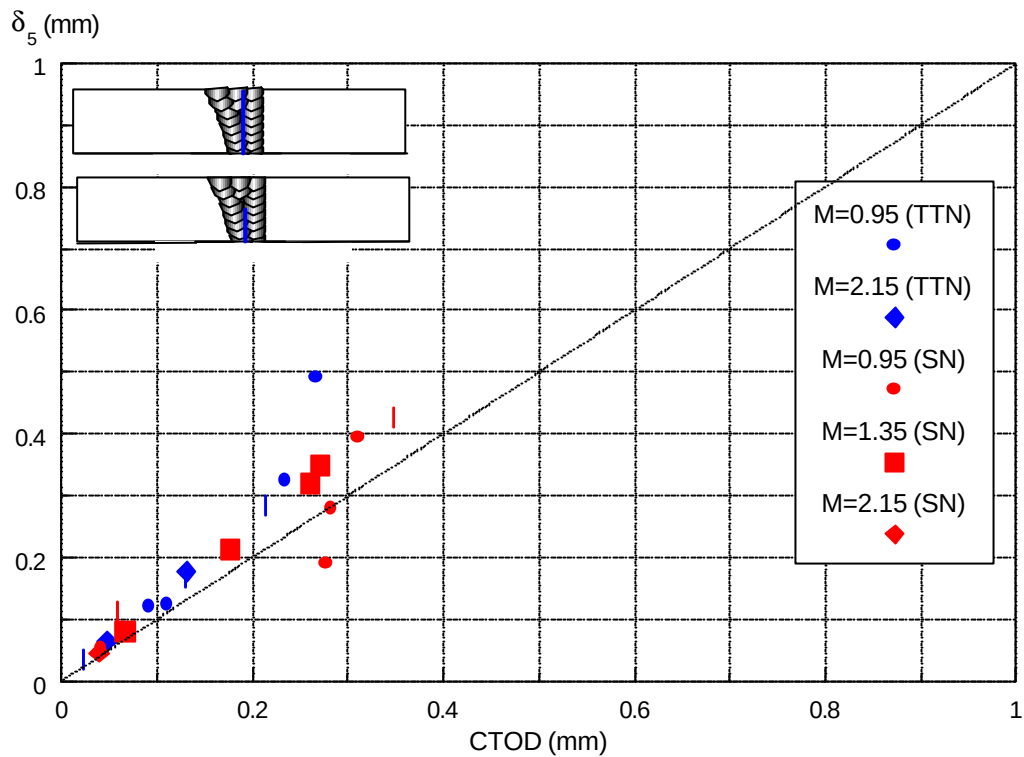


FIG. 26

COMPARISON OF CTOD TRANSITION DATA FOR FCAW WM
(PWHT) - TRANSVERSE - SURFACE NOTCH
at w 0.15 - WELD CENTRELINE

(D0697E08)



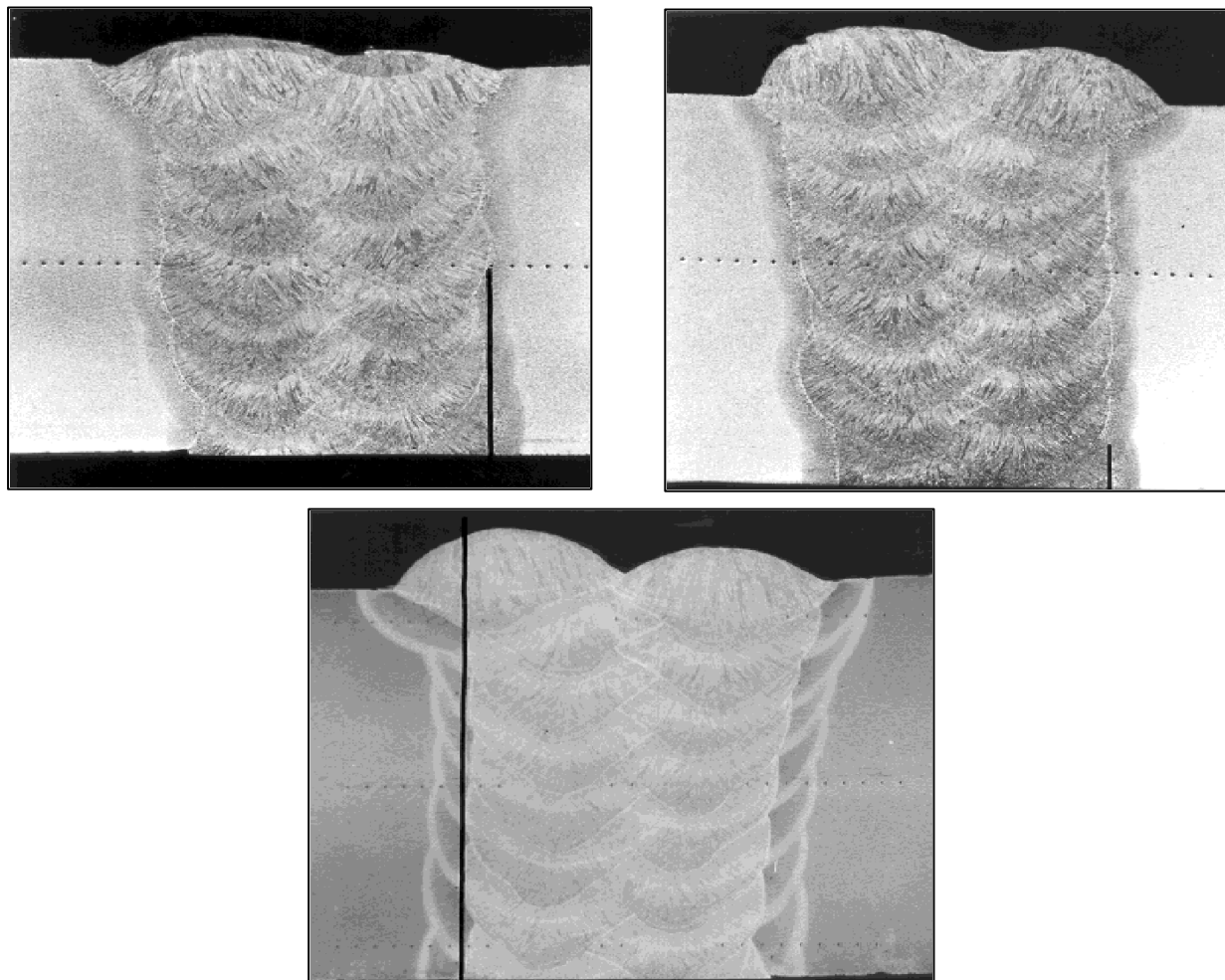


FIG. 29

MACROGRAPHS ILLUSTRATING NOTCH LOCATIONS
FOR FCAW HAZ NOTCHED TESTS

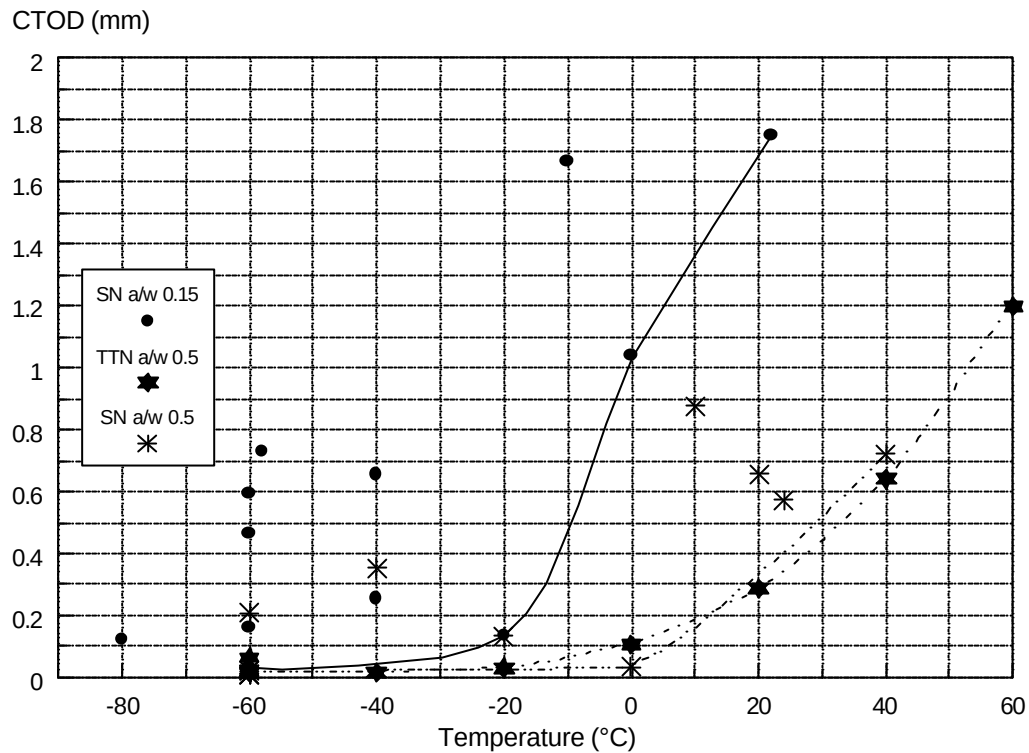


FIG. 30

BS 7448 CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - EFFECT OF NOTCH DEPTH AND
ORIENTATION (M = 2.15)

(D0697E08)

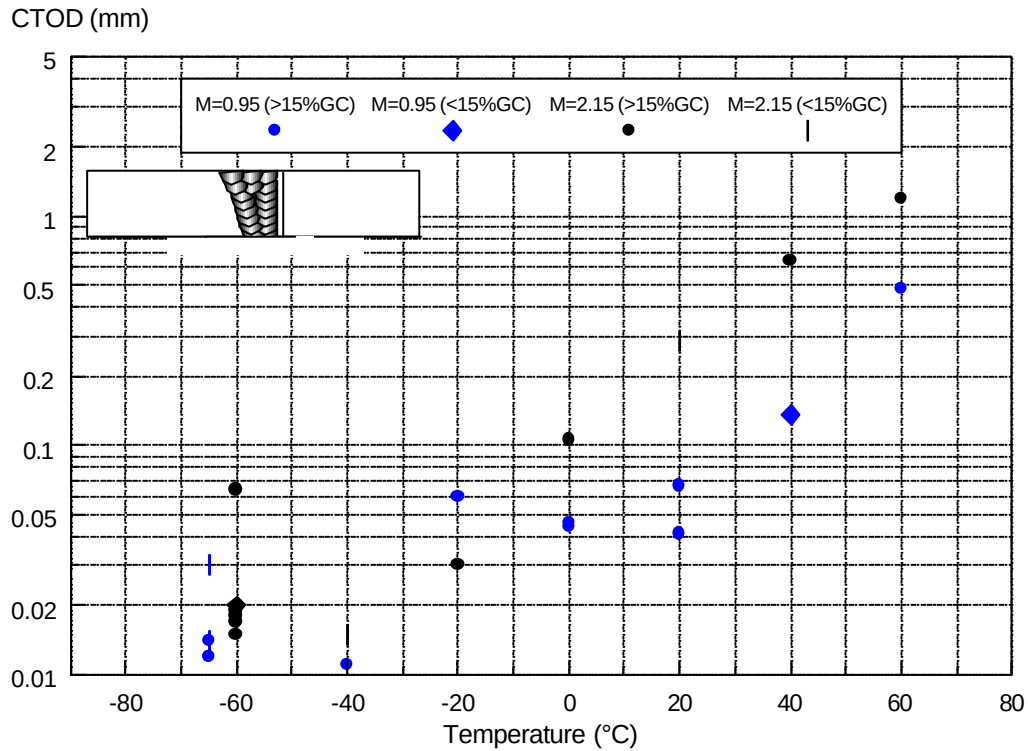


FIG. 31

COMPARISON OF CTOD TRANSITION DATA FOR FCAW HAZ
(PWHT) - TRANSVERSE - THROUGH THICKNESS
NOTCH a/w 0.5 - NOTCH IN HAZ

(D0697E08)

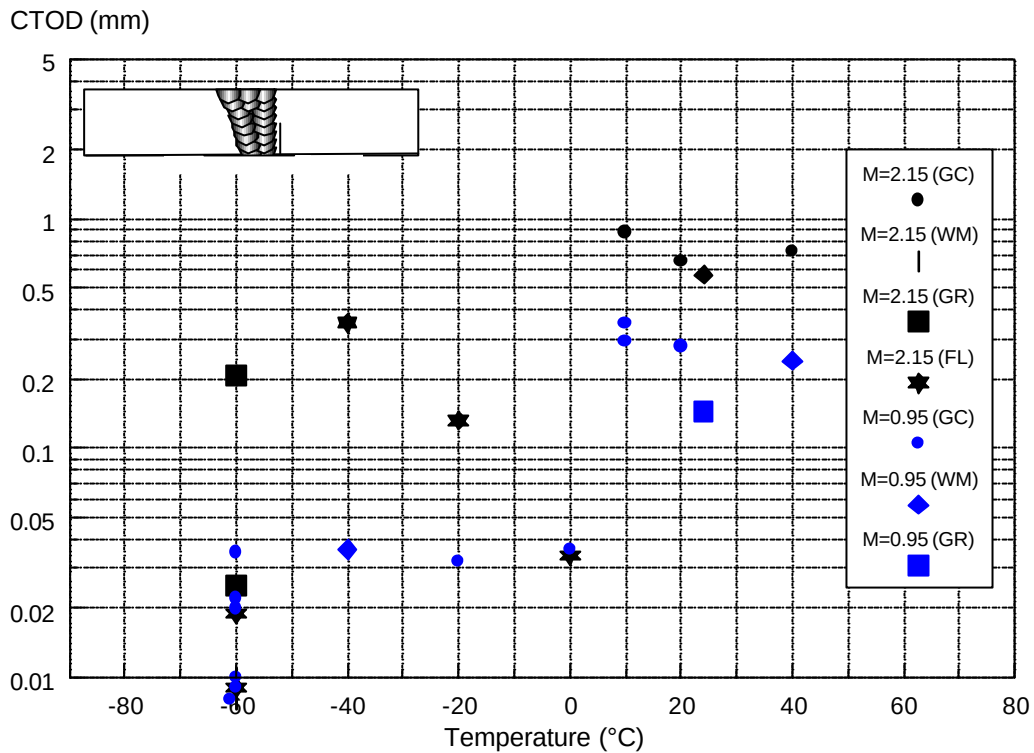


FIG. 32

COMPARISON OF CTOD TRANSITION DATA FOR FCAW
HAZ (PWHT) - TRANSVERSE - SURFACE NOTCH
a/w 0.5 - NOTCH IN HAZ

(D0697E09)

FIG. 33

COMPARISON OF CTOD TRANSITION DATA FOR FCAW
HAZ (PWHT) - TRANSVERSE - SURFACE NOTCH
a/w 0.15 - NOTCH IN HAZ

(D0697E09)

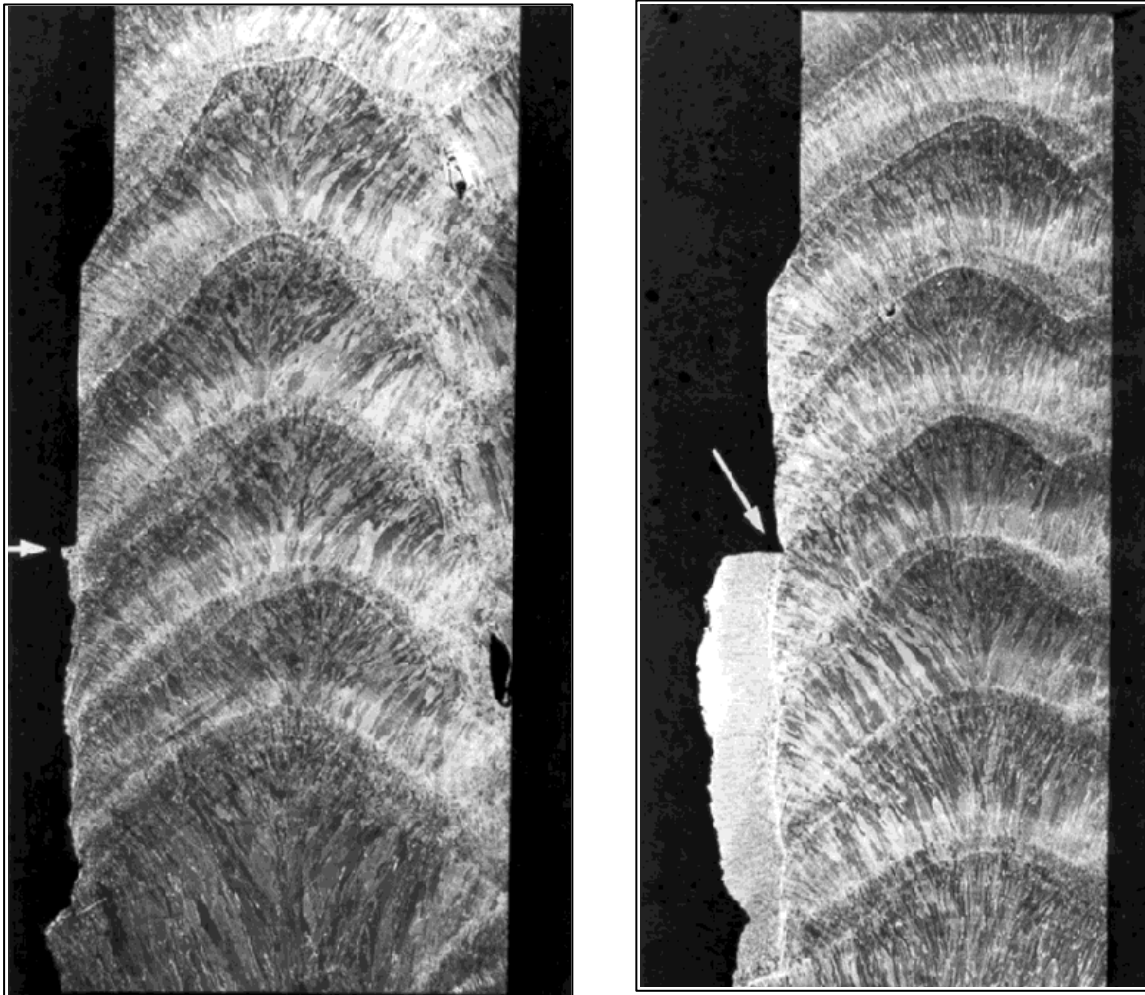
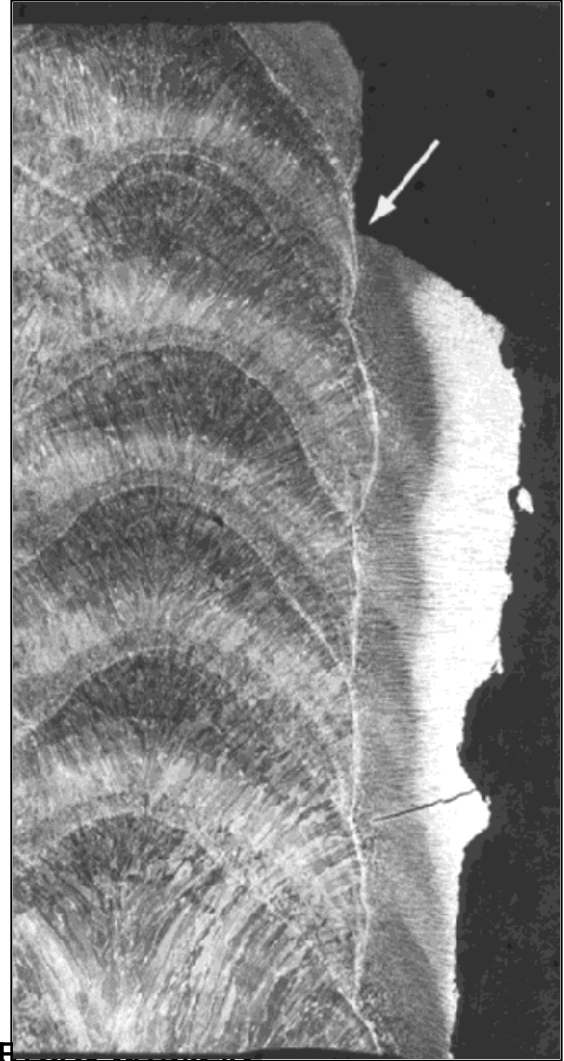
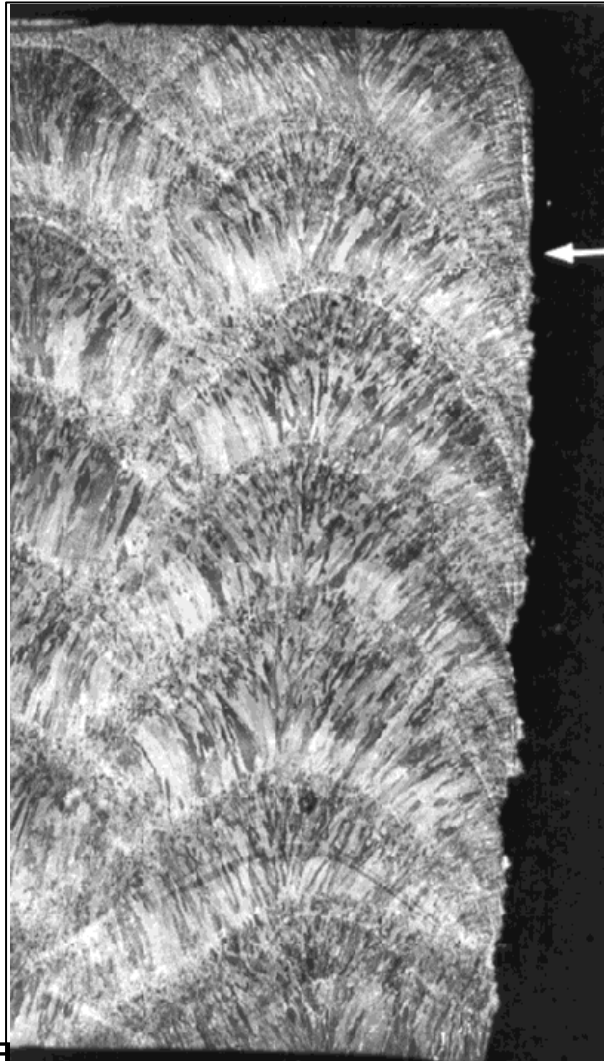


FIG. 34

MACROGRAPHS ILLUSTRATING THE EFFECT OF WELD METAL
STRENGTH MISMATCH ON FRACTURE OF FUSION LINE
NOTCHED CTOD SPECIMENS WITH DEEP NOTCHES
(ARROWS SHOW FATIGUE CRACK TIP LOCATIONS)



STRENGTH MISMATCH ON FRACTURE OF FUSION LINE
NOTCHED CTOD SPECIMENS WITH SHALLOW NOTCHES
(ARROWS SHOW FATIGUE CRACK TIP LOCATIONS)

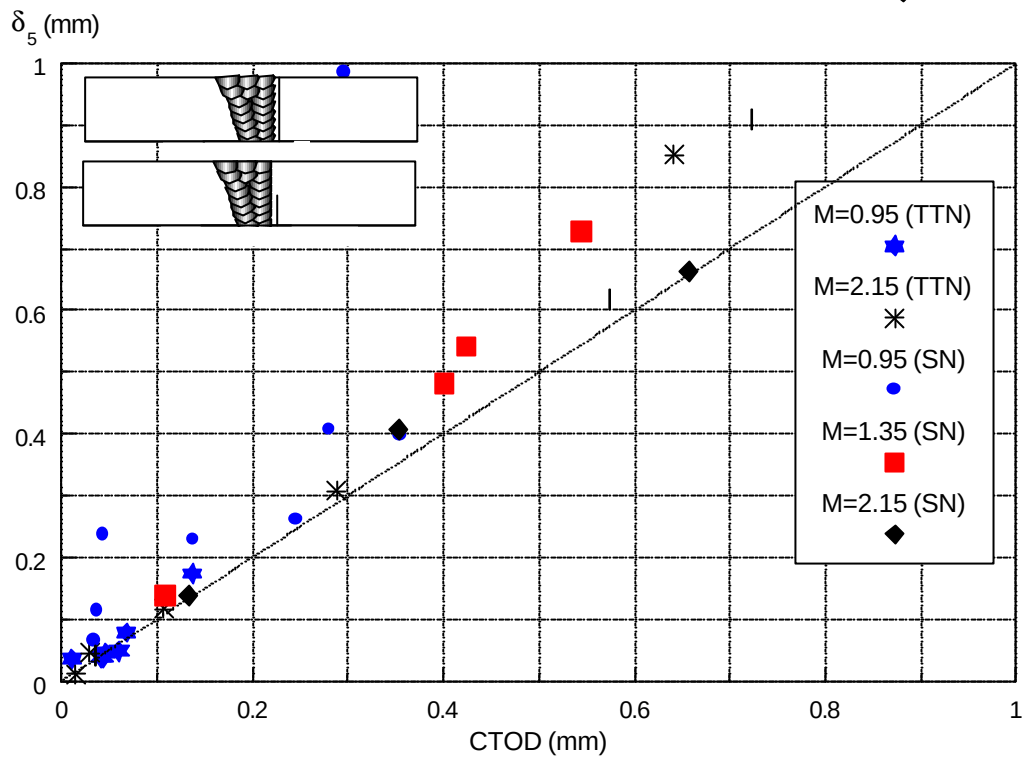


FIG. 36

d_5 v CTOD FOR FCAW HAZ (PWHT) - TRANSVERSE - THROUGH THICKNESS AND SURFACE NOTCH a/w 0.5

(D0697E09)

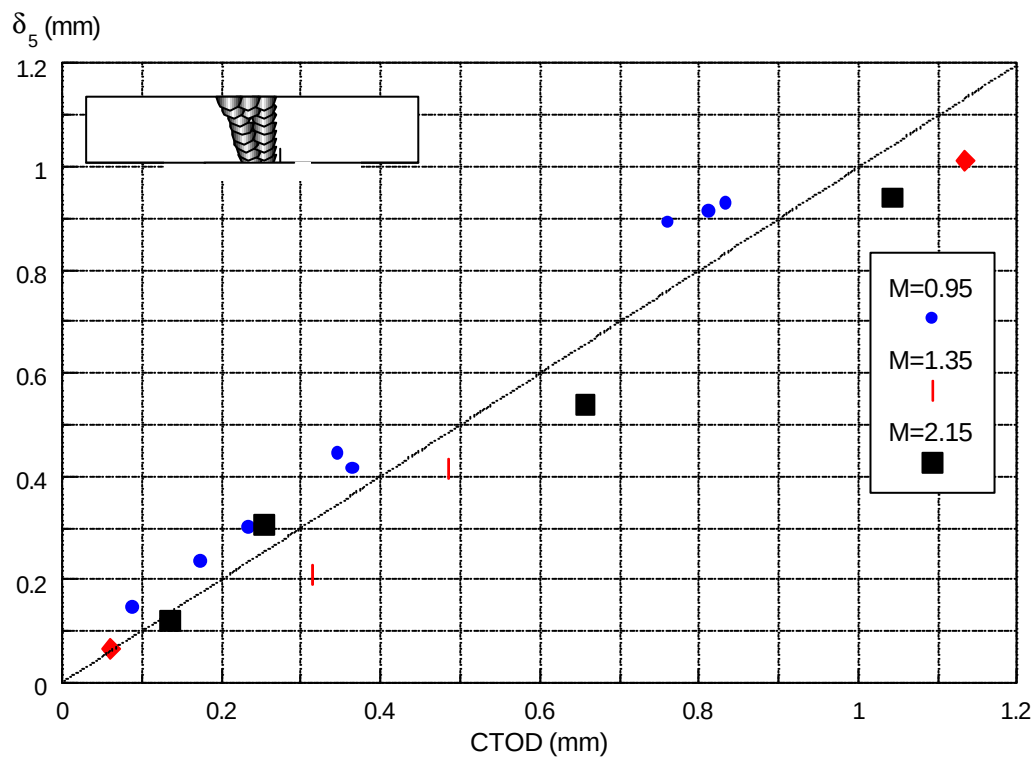


FIG. 37

d_5 v CTOD FOR FCAW HAZ (PWHT) - TRANSVERSE - SURFACE NOTCH a/w 0.15

(D0697E09)

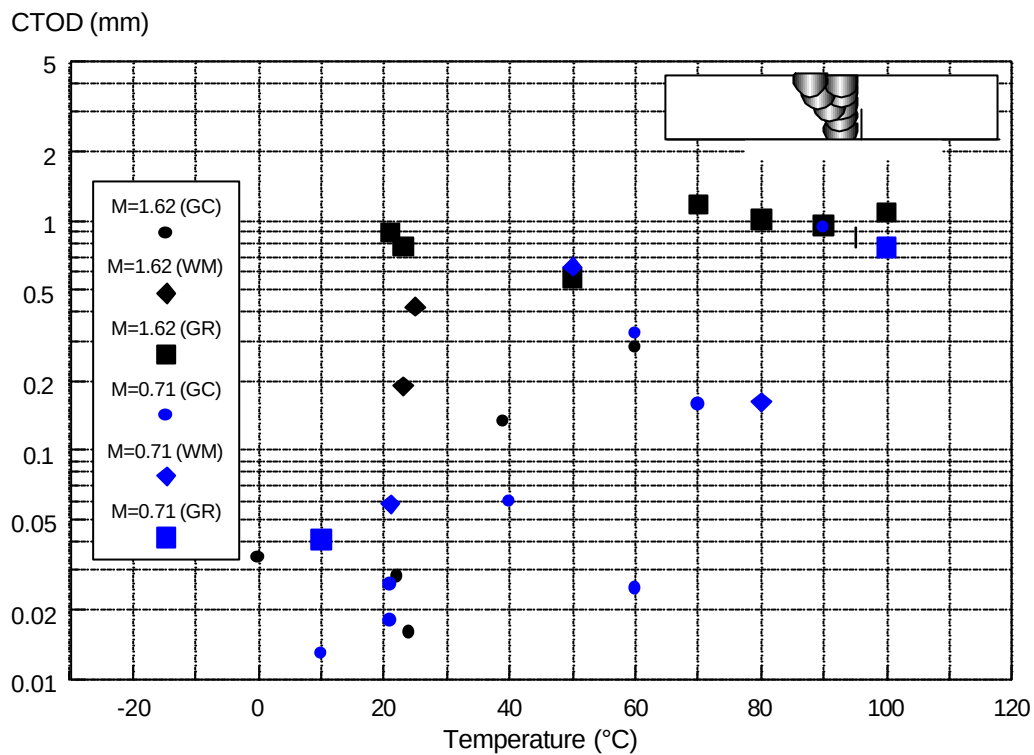


FIG. 38

COMPARISON OF CTOD TRANSITION DATA FOR SAW HAZ
(PWHT) - TRANSVERSE - SURFACE NOTCH
a/w 0.5 - NOTCH IN HAZ

(D0697E09)

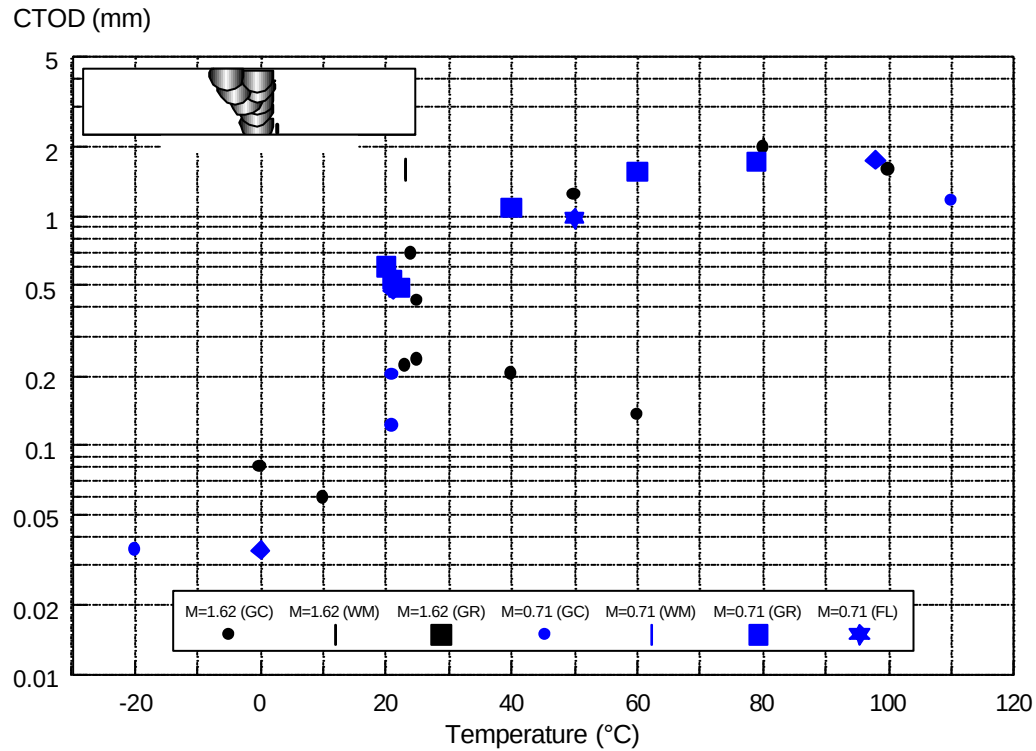


FIG. 39

COMPARISON OF CTOD TRANSITION DATA FOR SAW HAZ
(PWHT) - TRANSVERSE - SURFACE NOTCH
a/w 0.15 - NOTCH IN HAZ

(D0697E09)

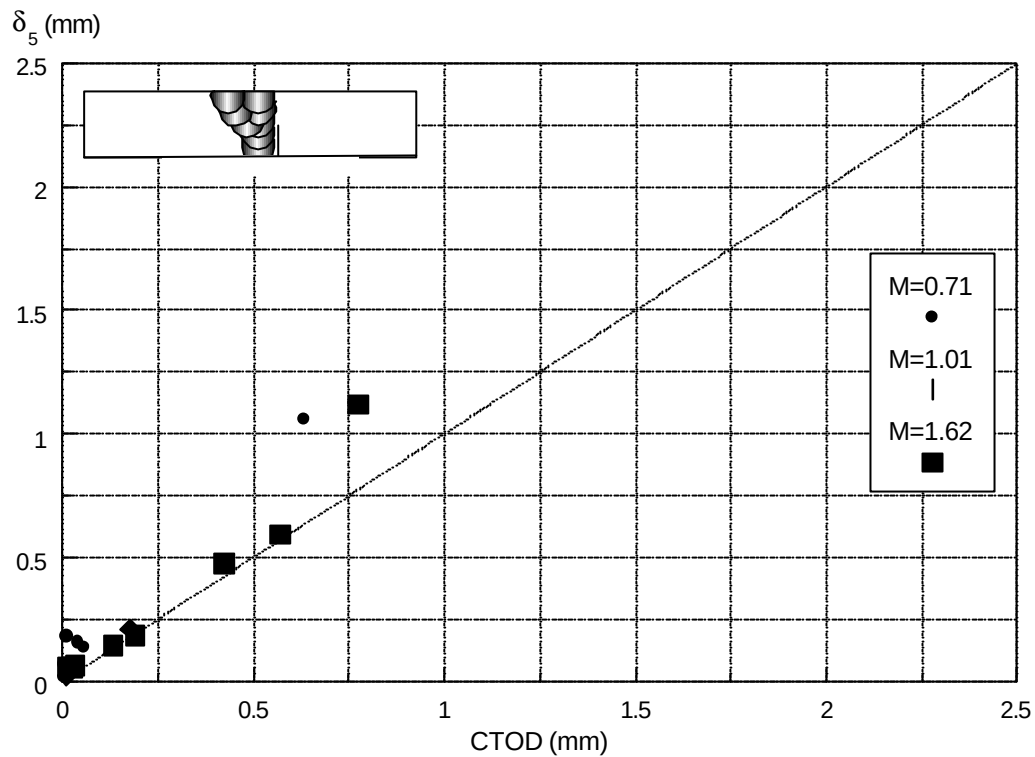


FIG. 40

δ_5 v CTOD FOR SAW HAZ (PWHT) - TRANSVERSE -
SURFACE NOTCH a/w 0.5

(D0697E09)

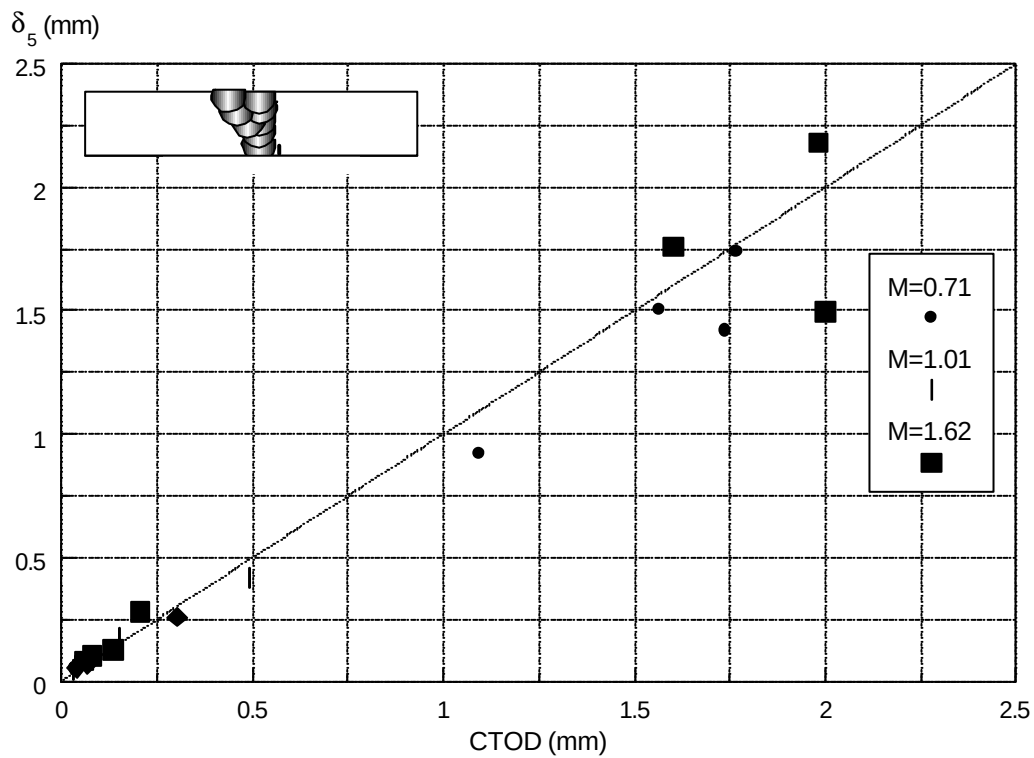


FIG. 41

δ_5 v CTOD FOR SAW HAZ (PWHT) - TRANSVERSE -
SURFACE NOTCH a/w 0.15

(D0697E09)

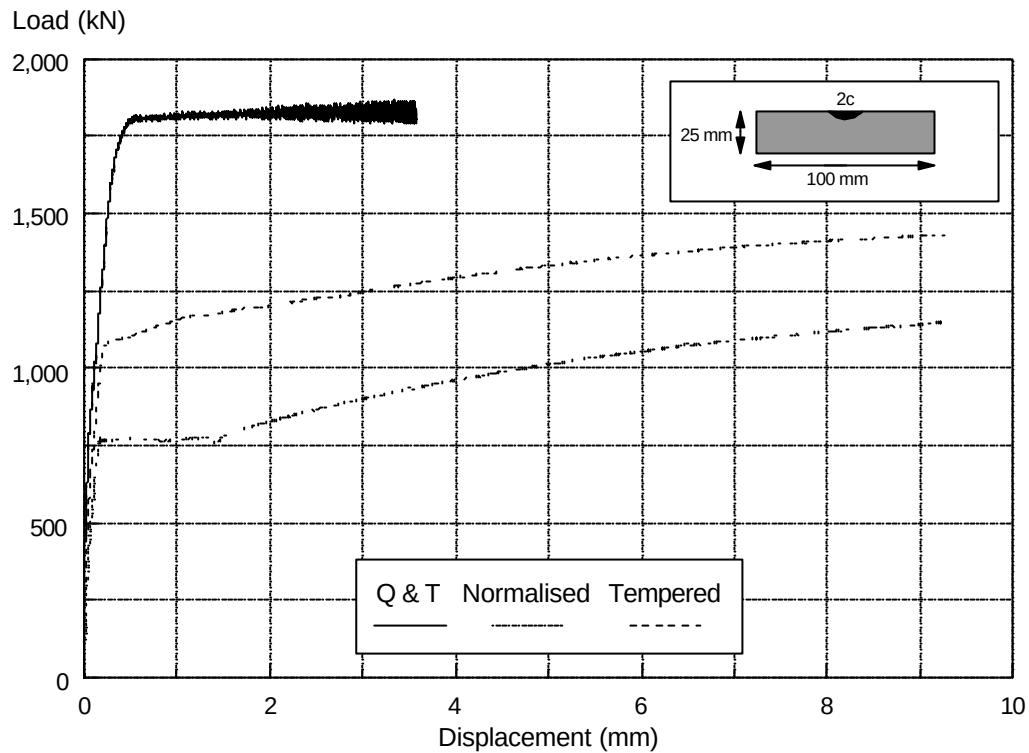


FIG. 44

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.15, ac 0.3

(D0697E10)

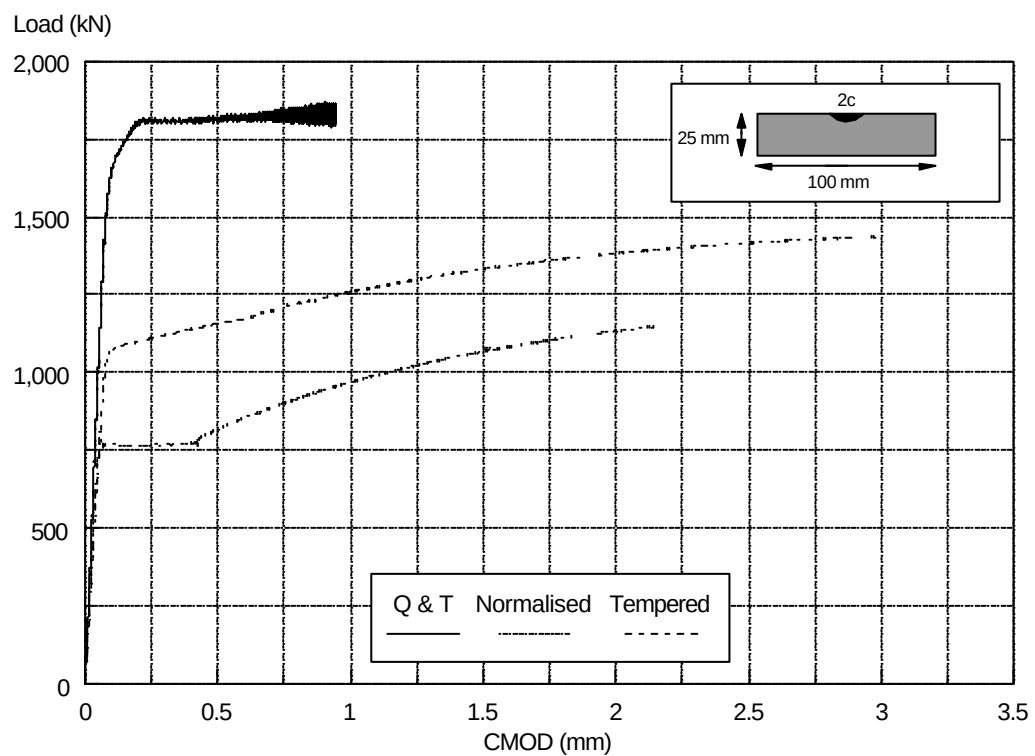


FIG. 45

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS -
TRANSVERSE - SURFACE NOTCH at 0.15, ac 0.3

(D0697E10)

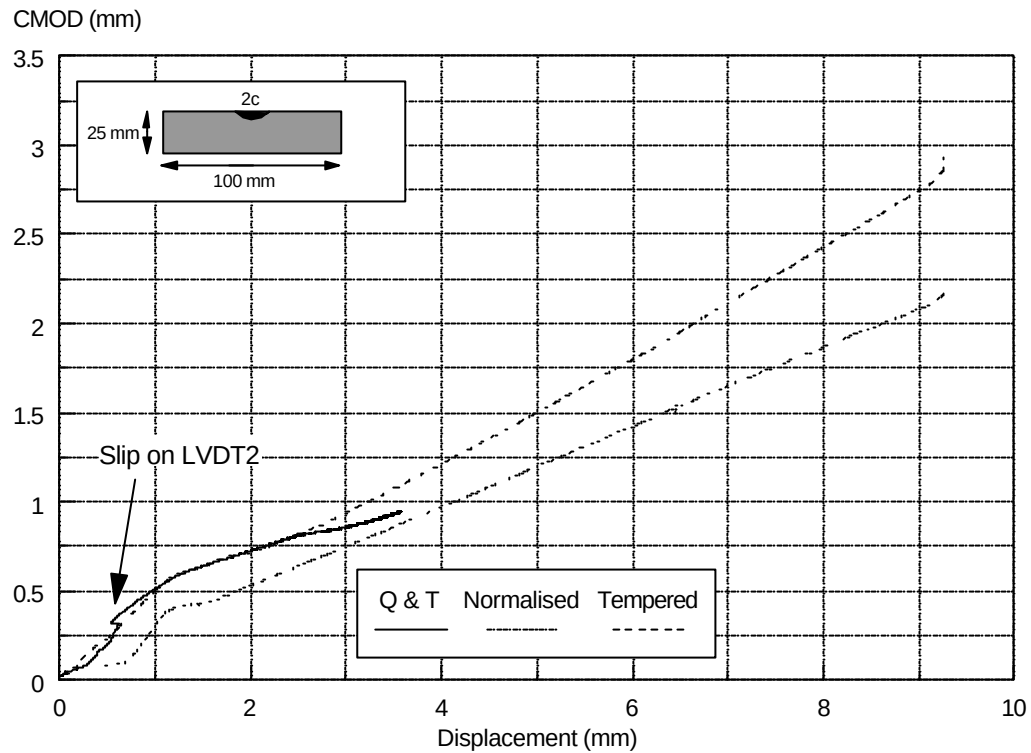


FIG. 46

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.15, at 0.3

(D0697E10)

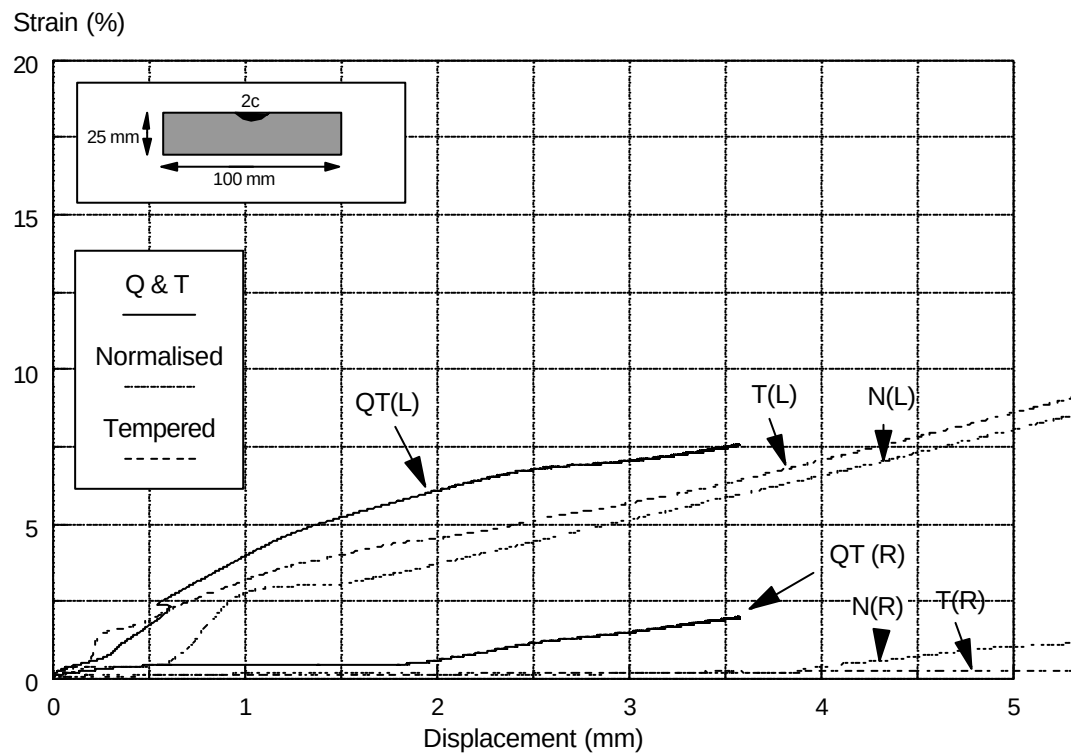


FIG. 47

OCT TEST STRAIN v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.15, at 0.3

(D0697E10)

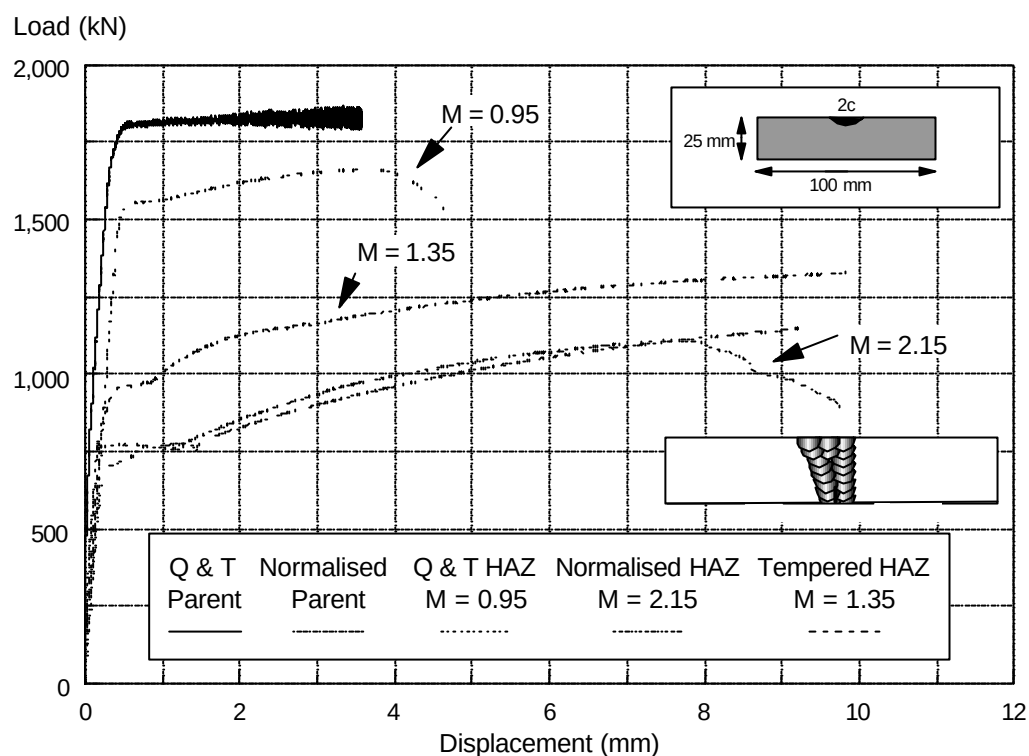


FIG. 48

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.15, at 0.3 - NOTCH AT WELD CENTRELINE

(D0697E10)

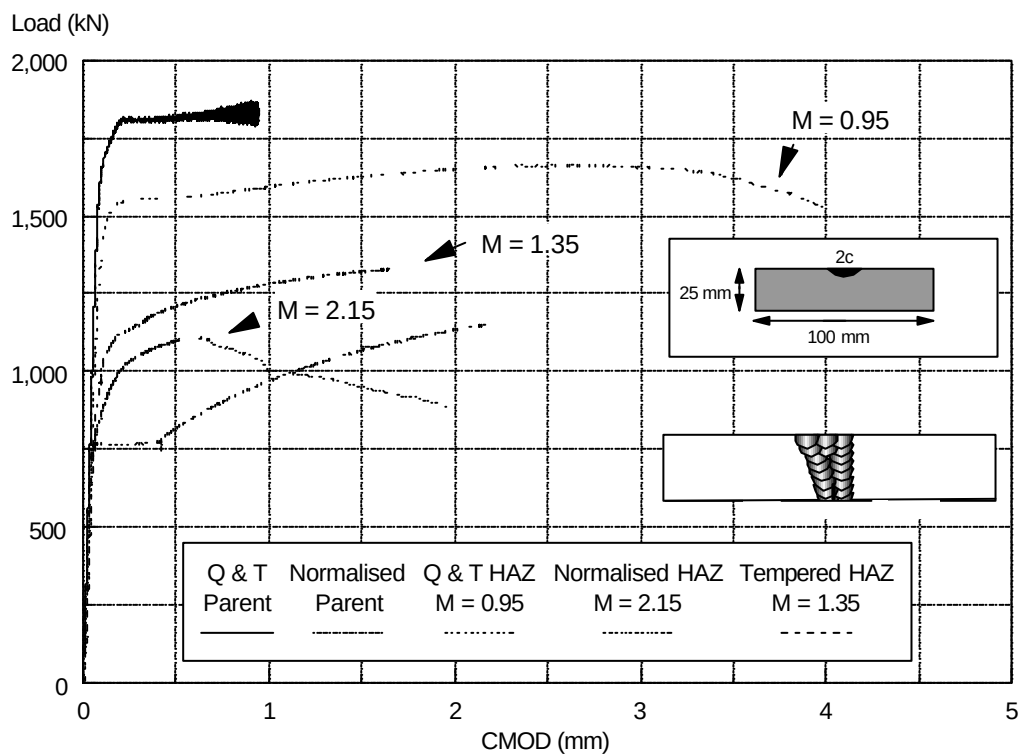


FIG. 49

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS
AND FCAW WELDS - TRANSVERSE - SURFACE NOTCH
at 0.15, at 0.3 - NOTCH AT WELD CENTRELINE

(D0697E10)

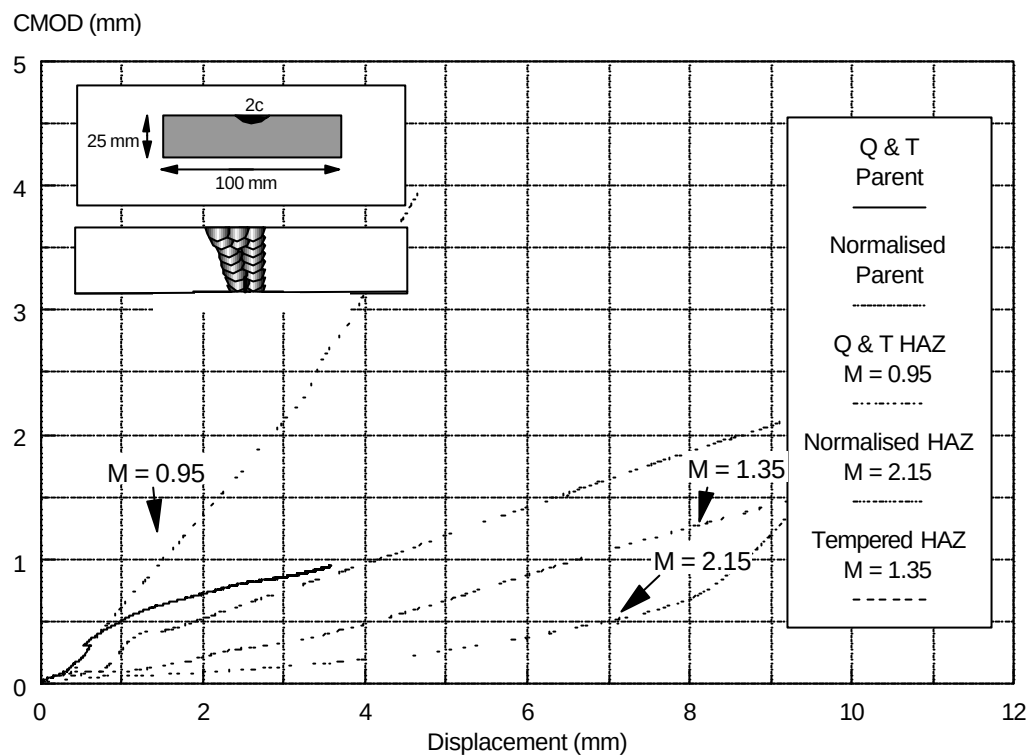


FIG. 50

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.15, at 0.3 - NOTCH AT WELD CENTRELINE

(D0697E10)

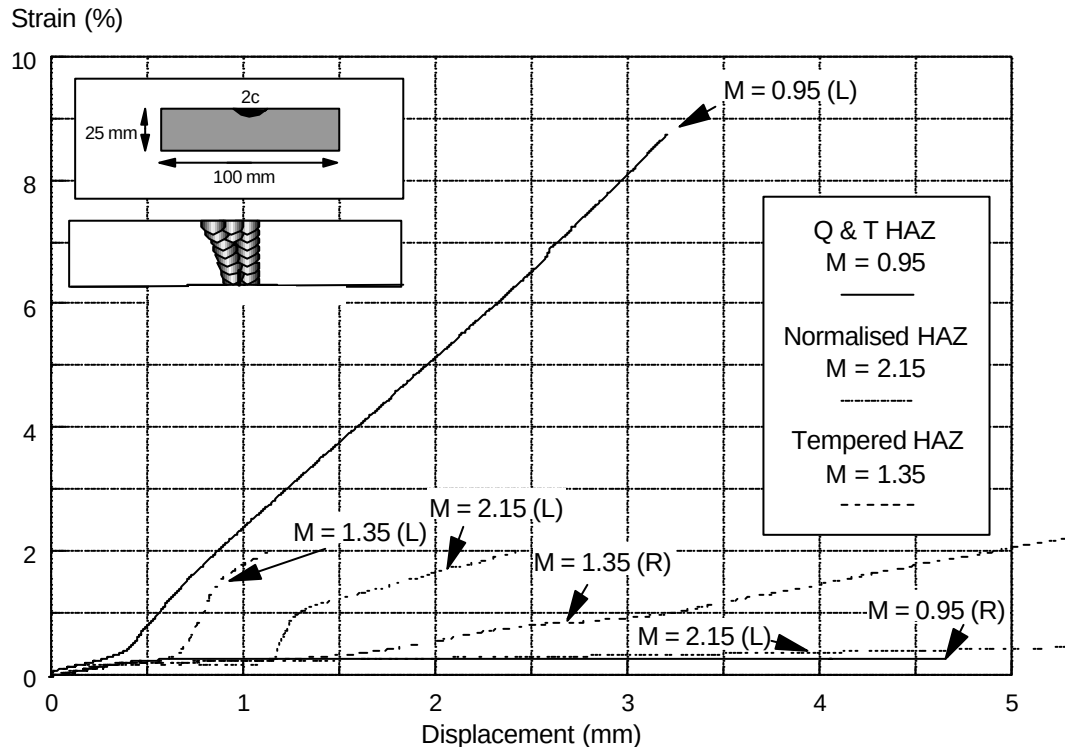


FIG. 51

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW WELDS -
TRANSVERSE - SURFACE NOTCH at 0.15, at 0.3 - NOTCH
AT WELD METAL CENTRELINE

(D0697E10)

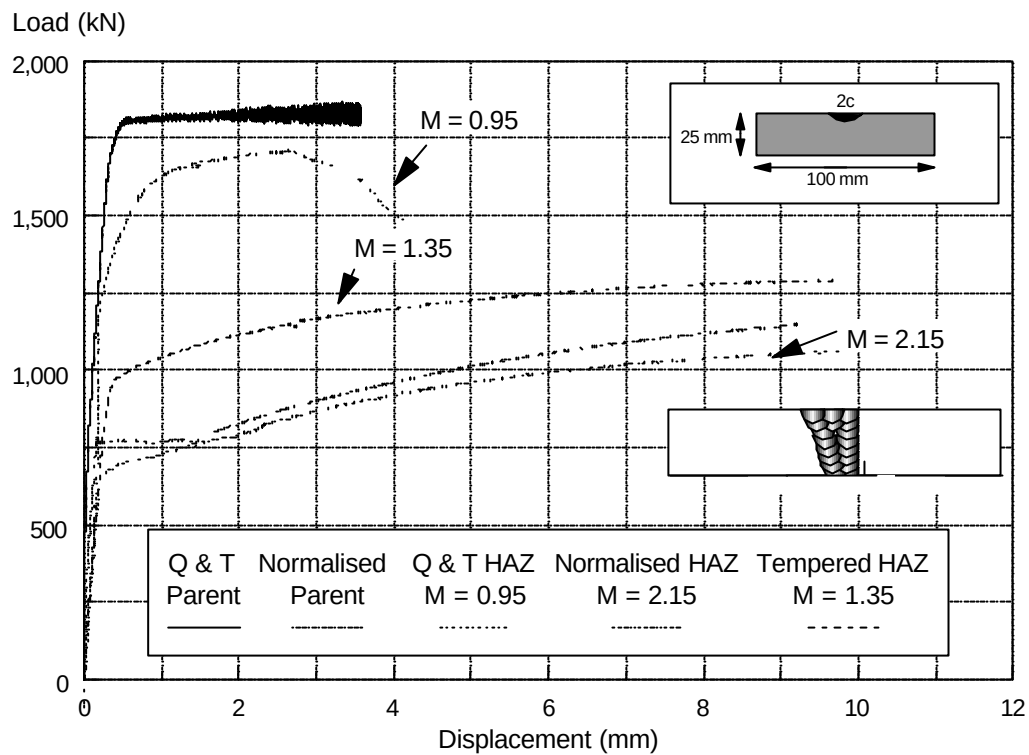


FIG. 52

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E10)

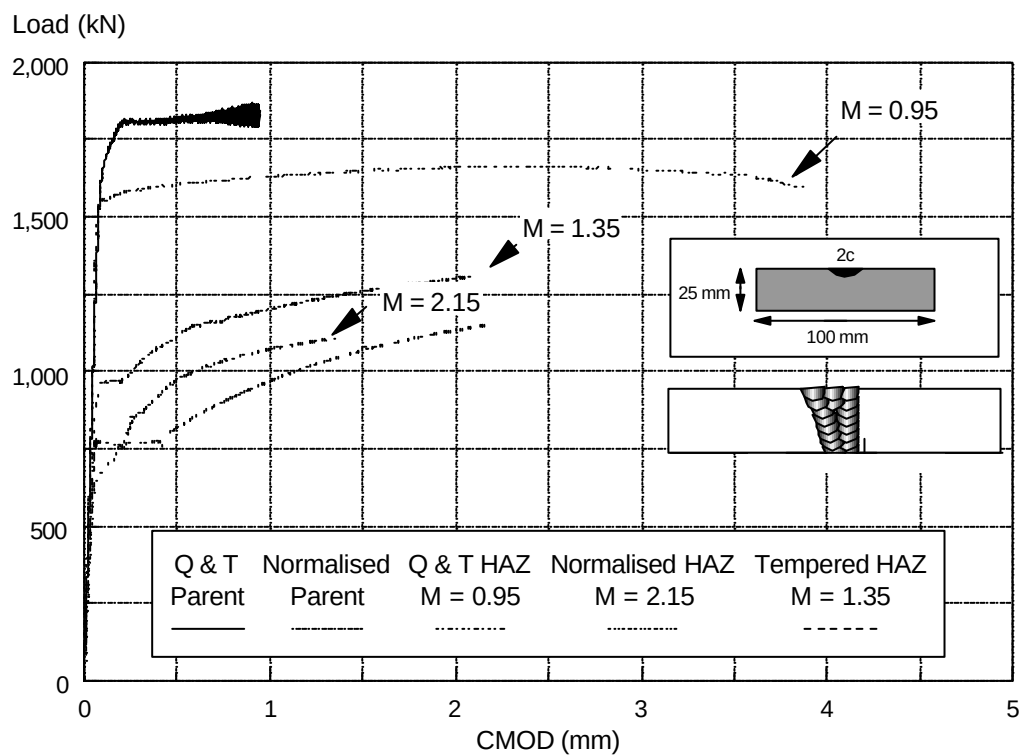


FIG. 53

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E10)

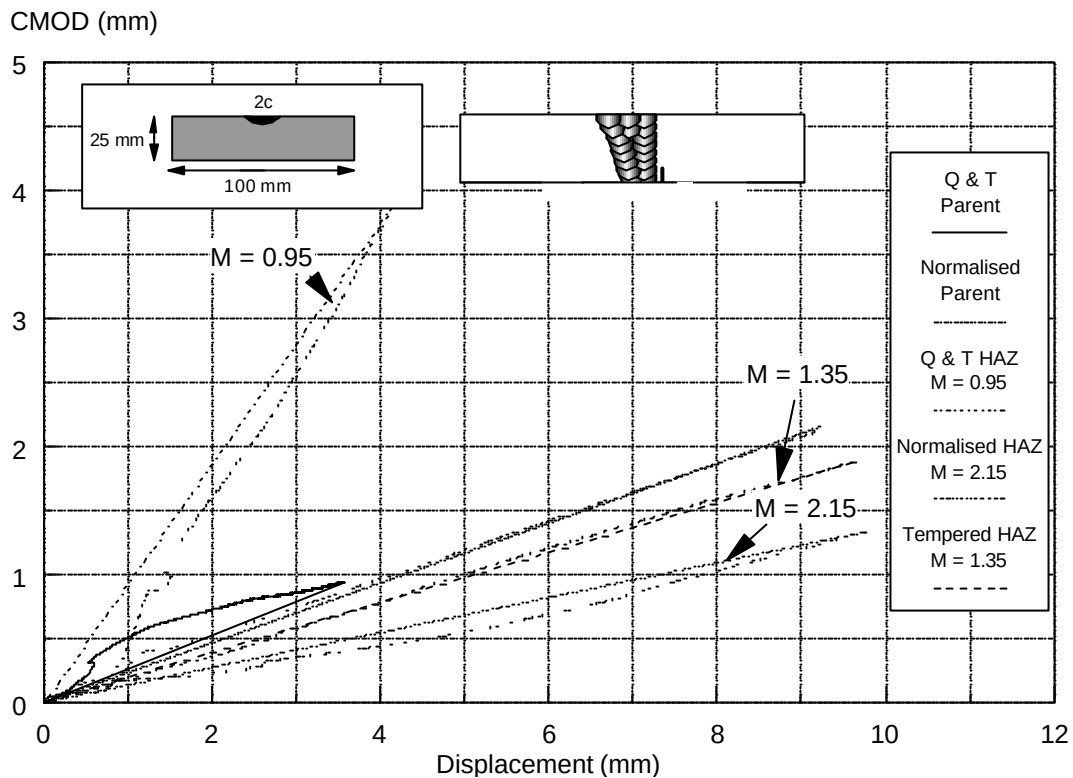


FIG. 54

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, ac 0.3 - NOTCH IN HAZ

(D0697E11)

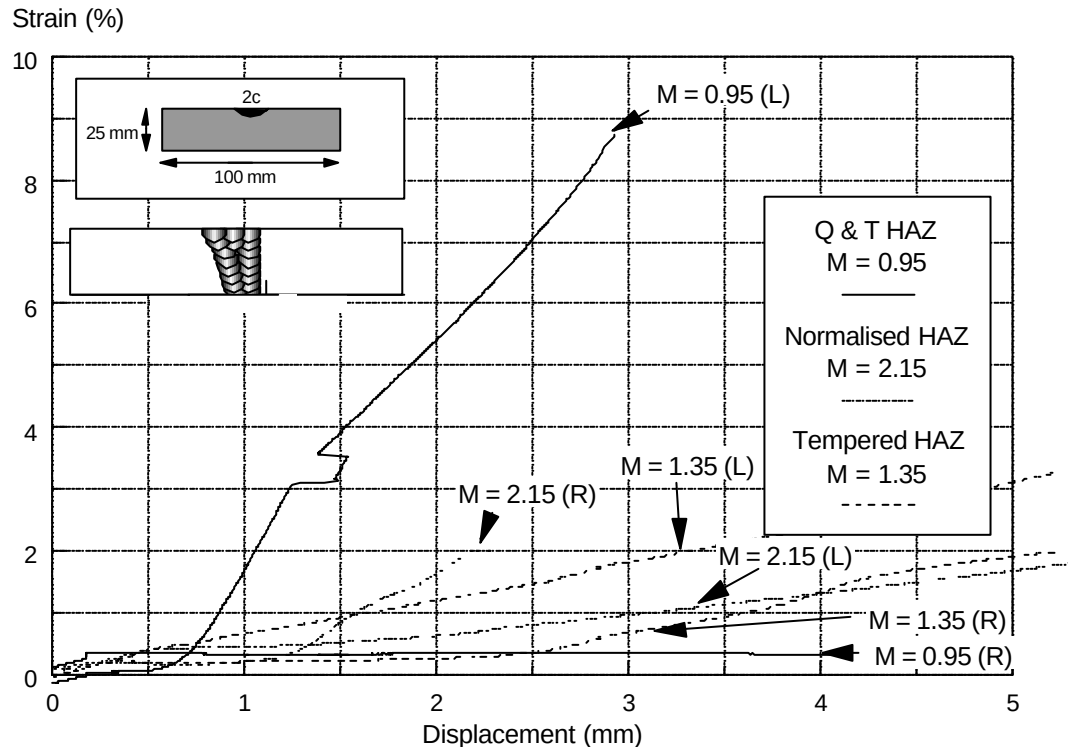


FIG. 55

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, ac 0.3 - NOTCH IN HAZ

(D0697E11)

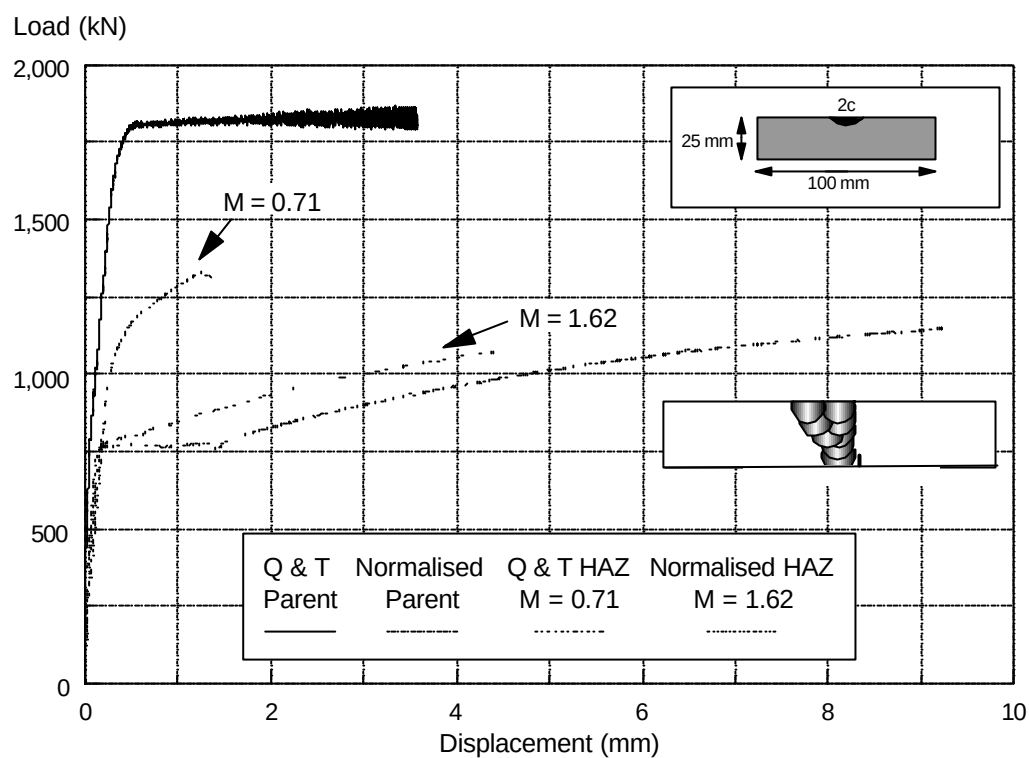


FIG. 56

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT MATERIALS AND SAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E11)

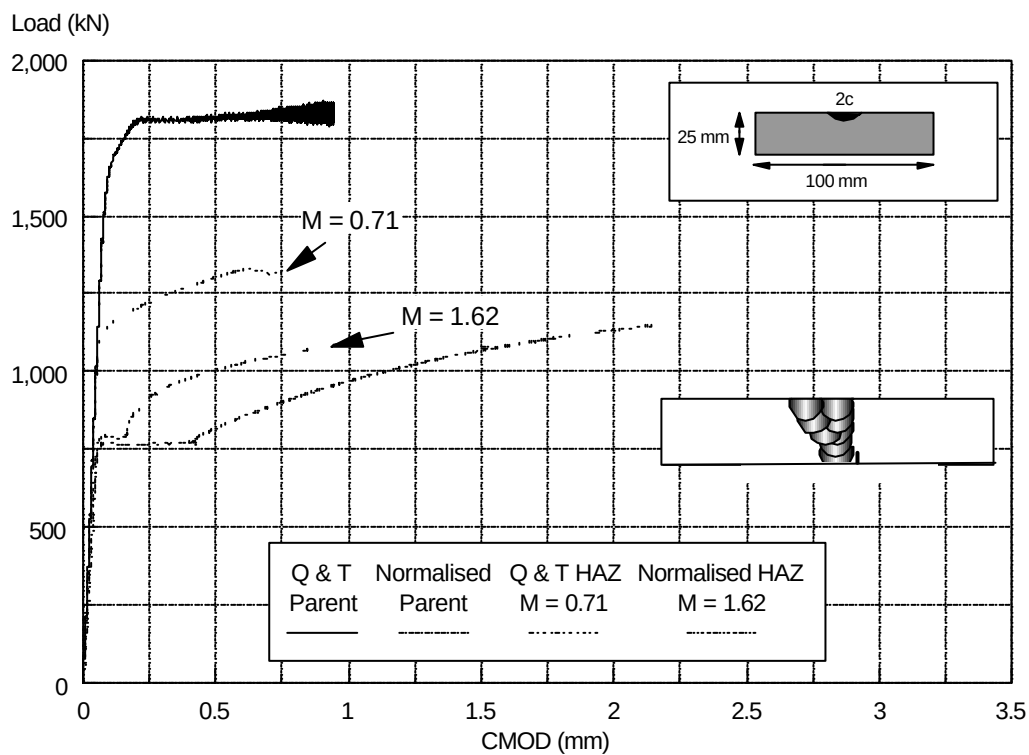


FIG. 57

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS AND SAW WELDS - TRANSVERSE - SURFACE NOTCH at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E11)

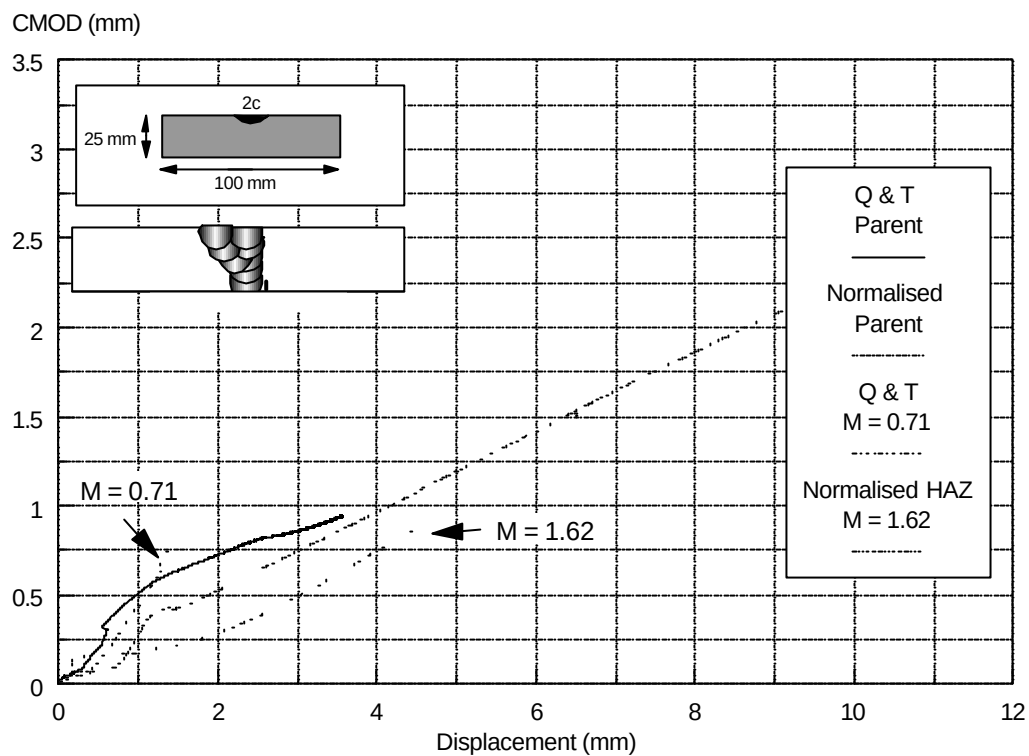


FIG. 58

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND SAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E11)

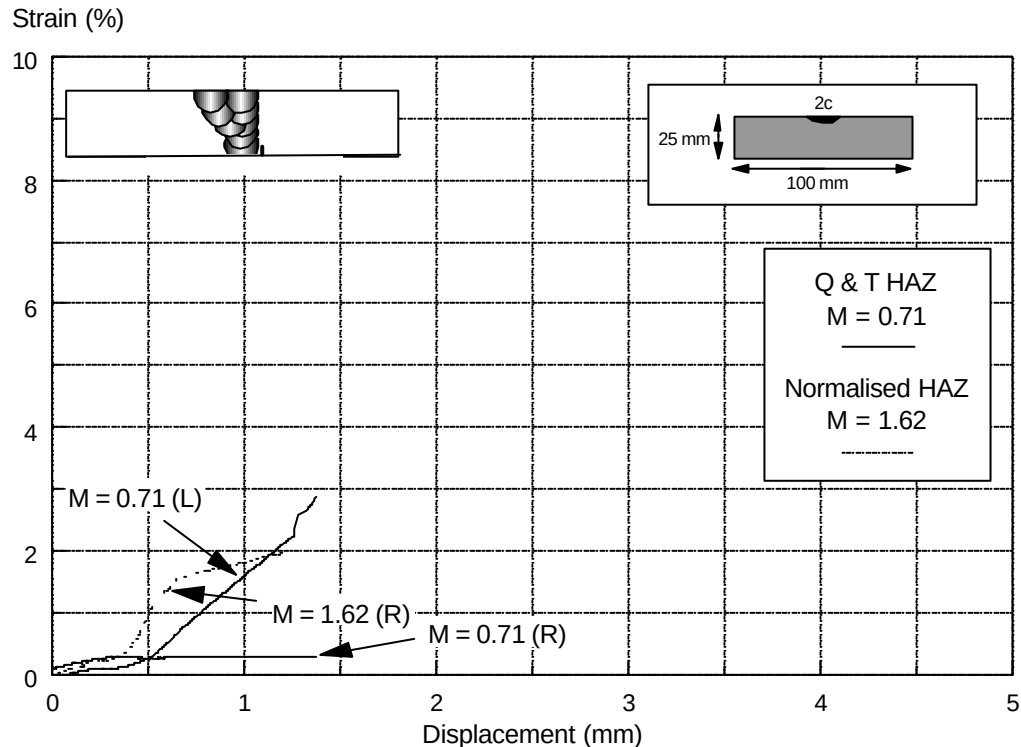


FIG. 59

OCT TEST STRAIN v DISPLACEMENT DATA FOR SAW
WELDS - TRANSVERSE - SURFACE NOTCH
at 0.15, a/c 0.3 - NOTCH IN HAZ

(D0697E11)

APPENDIX 1

CHARPY TRANSITION DATA FOR PARENT PLATES

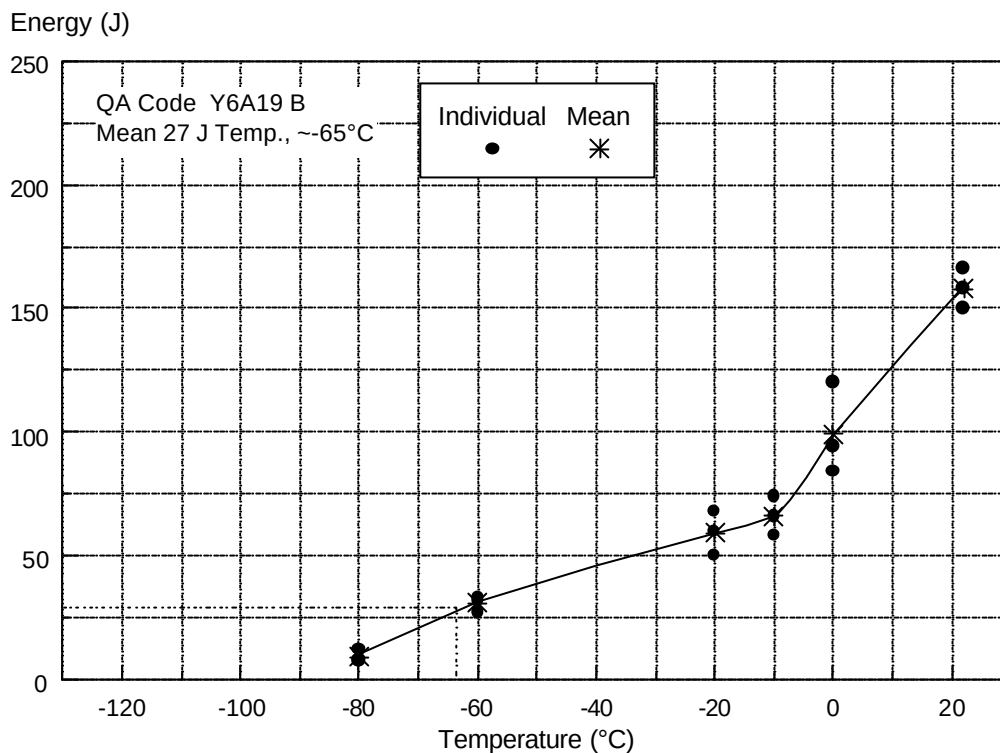


FIG. A11

CHARPY TRANSITION CURVE FOR RQT701 (PWHT) -
TRANSVERSE - SUBSURFACE

(D0697E13)

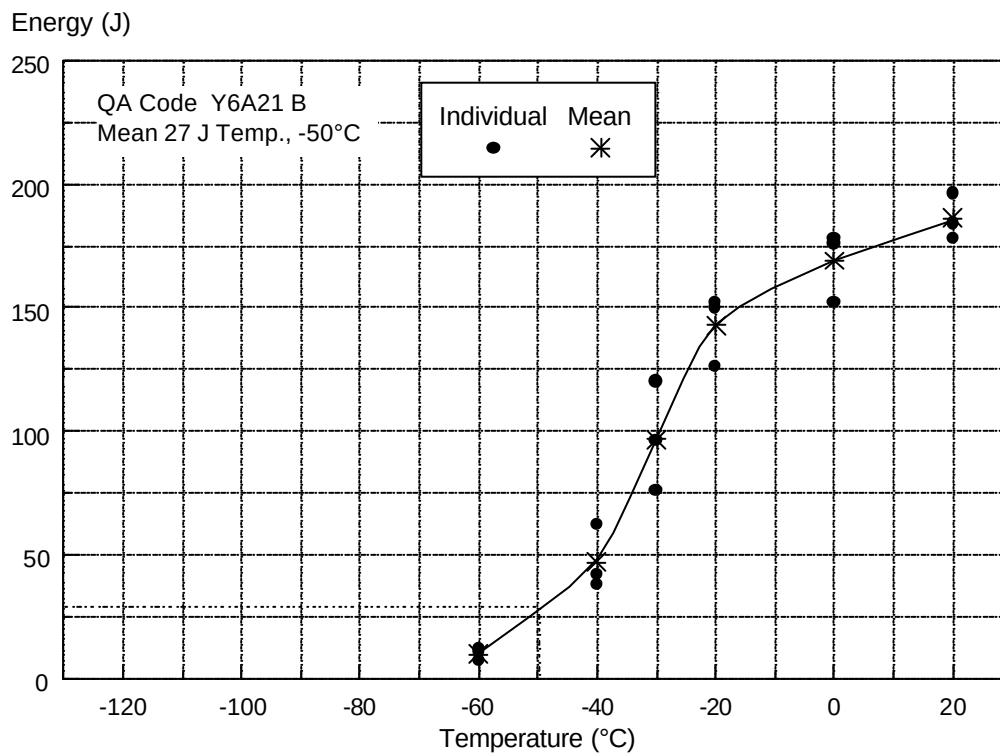


FIG. A12

CHARPY TRANSITION CURVE FOR RQT701 TEMPERED
AT 675°C (PWHT) - TRANSVERSE - SUBSURFACE

(D0697E13)

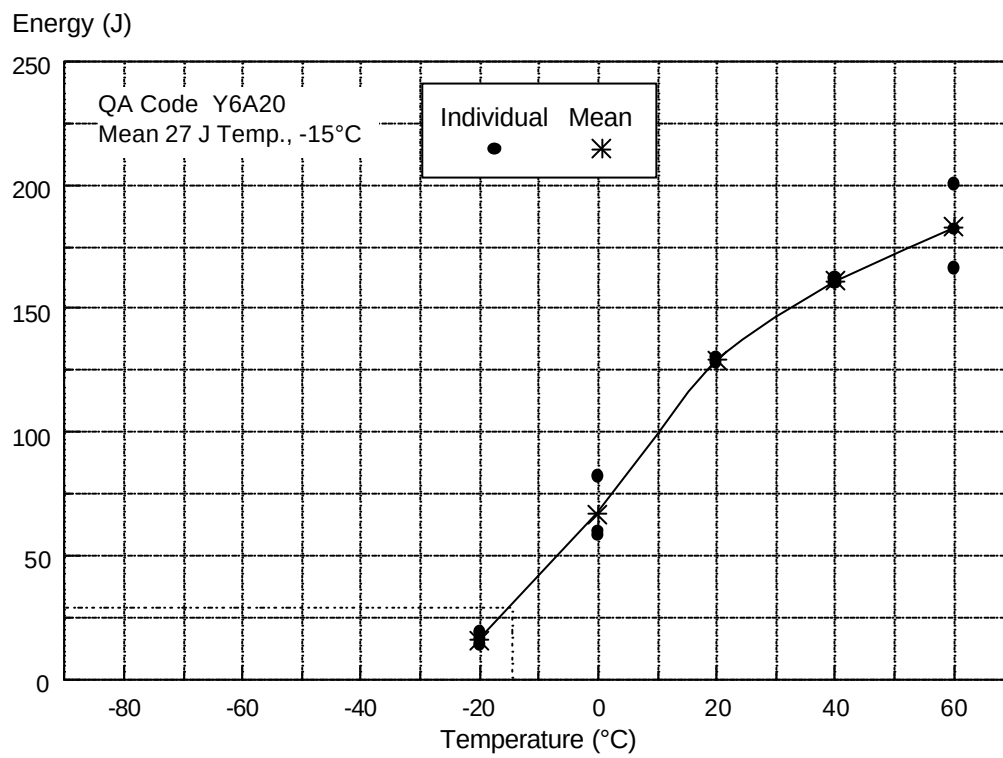


FIG. A13

CHARPY TRANSITION CURVE FOR RQT701 NORMALISED
AT 900°C (PWHT) - TRANSVERSE - SUBSURFACE

(D0697E13)

APPENDIX 2

CHARPY TRANSITION DATA FOR FCAW WELD METALS

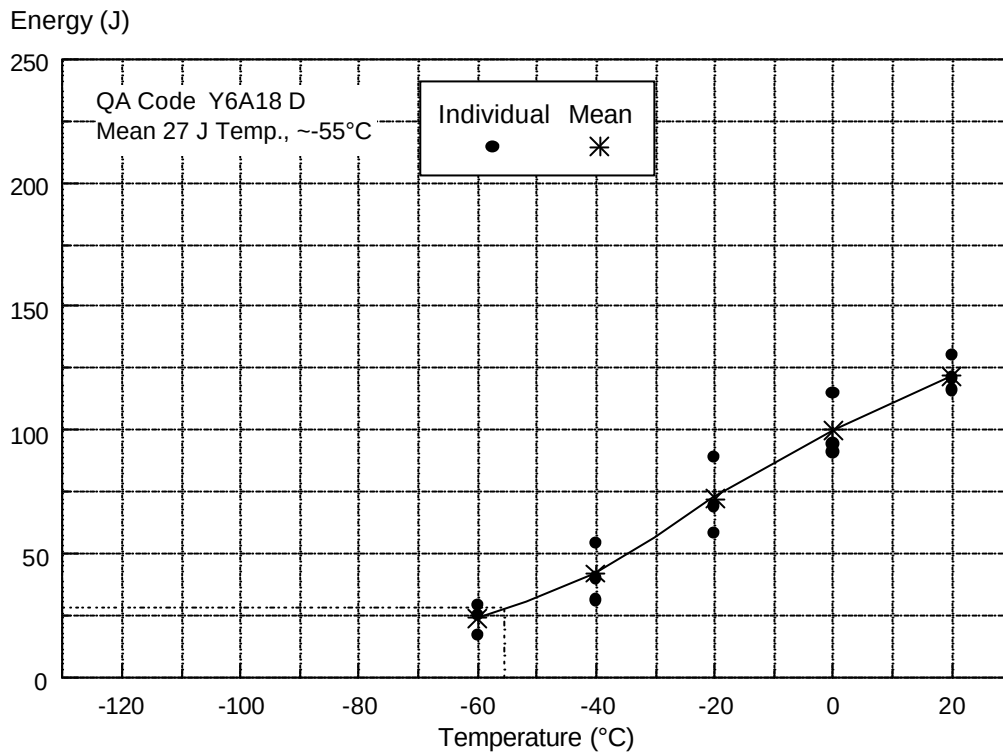


FIG. A21

CHARPY TRANSITION CURVE FOR FCAW WELD METAL
(PWHT) - TRANSVERSE - SUBSURFACE (ROOT) -
UNDERMATCHED WELD (M ~0.95)

(D0697E15)

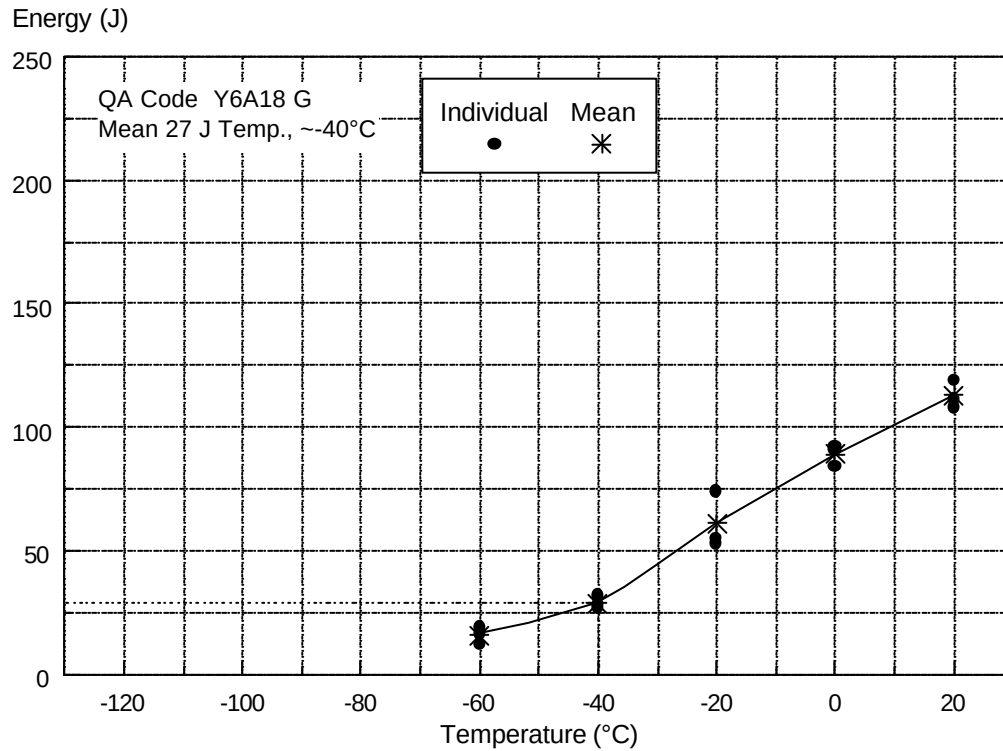


FIG. A22

CHARPY TRANSITION CURVE FOR FCAW WELD METAL
(PWHT) - TRANSVERSE - SUBSURFACE (ROOT) -
OVERMATCHED WELD (BUT M ~1.35)

(D0697E15)

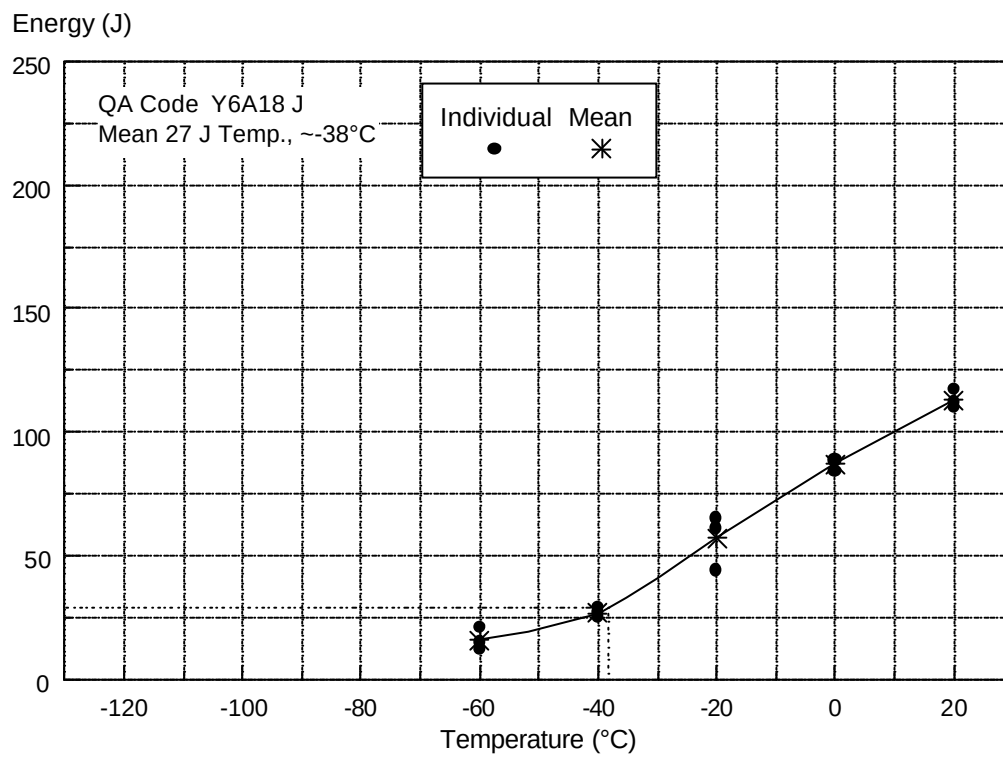


FIG. A23

CHARPY TRANSITION CURVE FOR FCAW WELD METAL
(PWHT) - TRANSVERSE - SUBSURFACE (ROOT) -
HIGHLY OVERMATCHED WELD (M-215)

(D0697E15)

APPENDIX 3

CHARPY TRANSITION DATA FOR FCAW HAZS

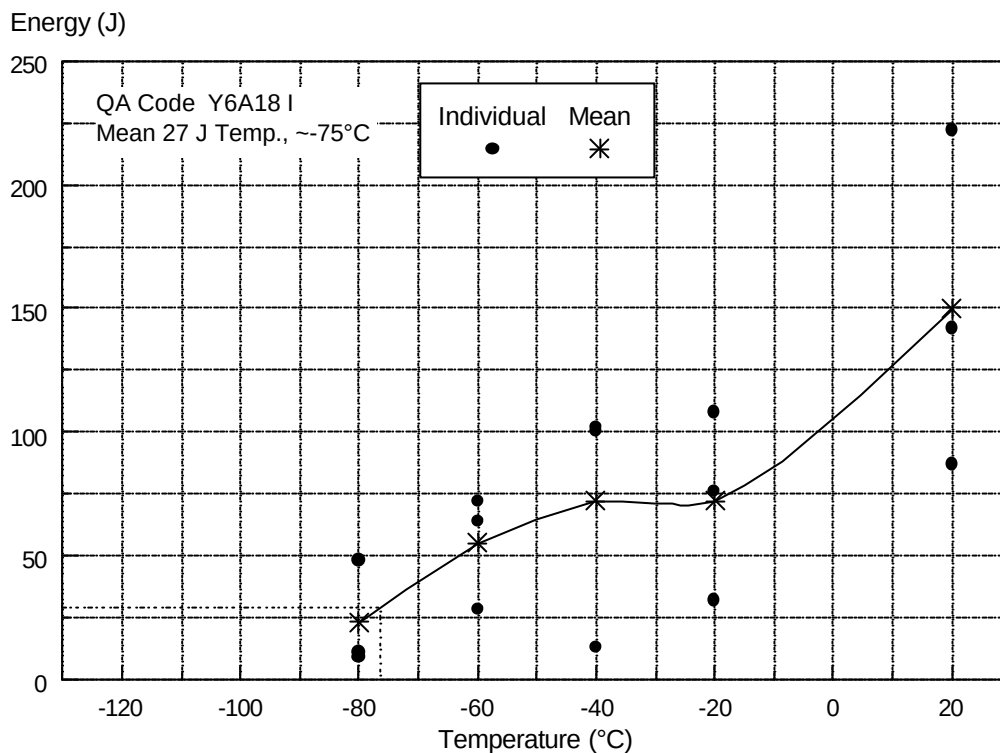


FIG. A31

CHARPY TRANSITION CURVE FOR FCAW HAZ (PWHT) -
TRANSVERSE - SUBSURFACE (ROOT) -
HIGHLY OVERMATCHED (M ~215)

(D0697E17)

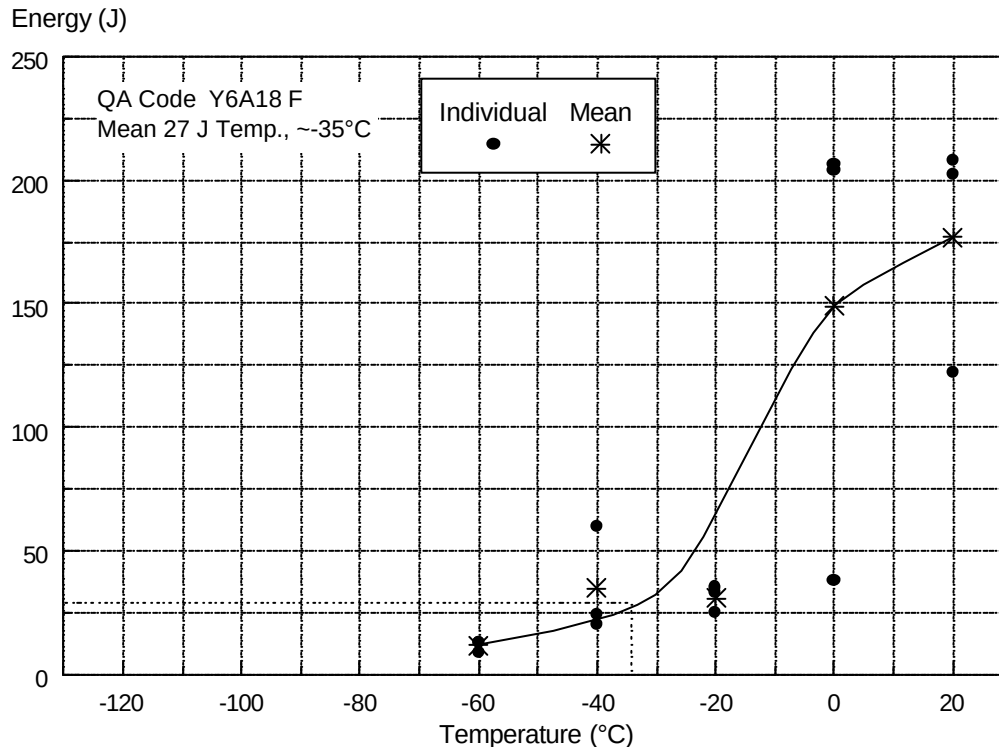


FIG. A32

CHARPY TRANSITION CURVE FOR FCAW HAZ (PWHT) -
TRANSVERSE - SUBSURFACE (ROOT) -
OVERMATCHED WELD (BUT M ~135)

(D0697E17)

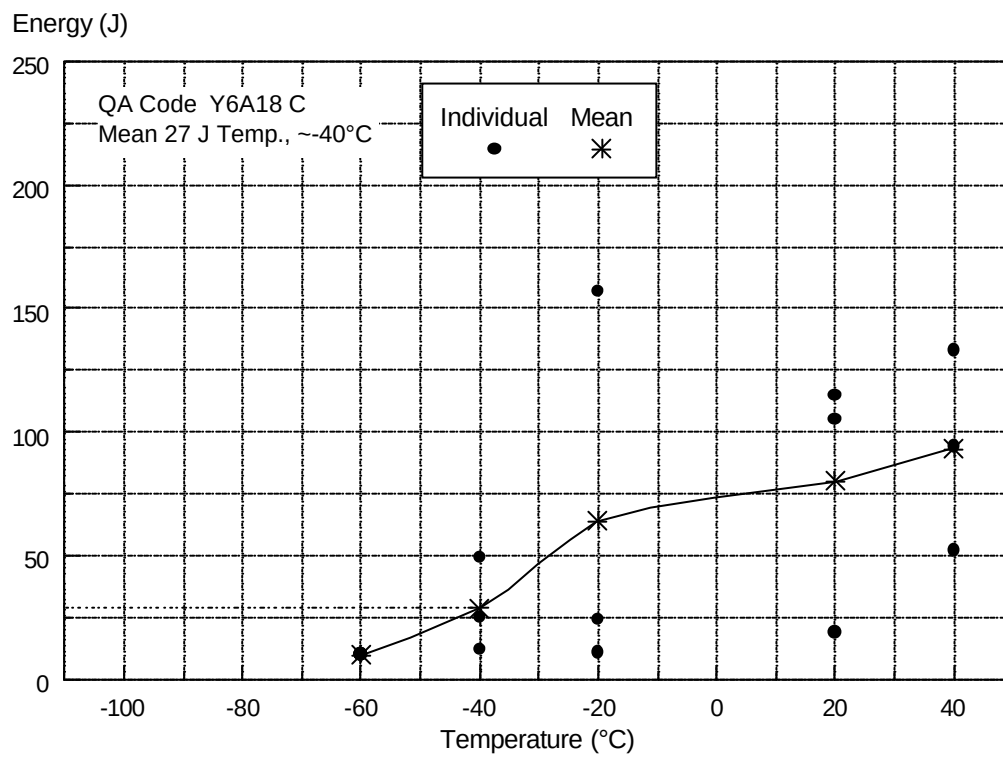


FIG. A3.3

CHARPY TRANSITION CURVE FOR FCAW HAZ (PWHT)-
TRANSVERSE - SUBSURFACE (ROOT)-
UNDERMATCHED (M ~0.95)

(D0697E17)

APPENDIX 4

CHARPY TRANSITION DATA FOR SAW HAZS

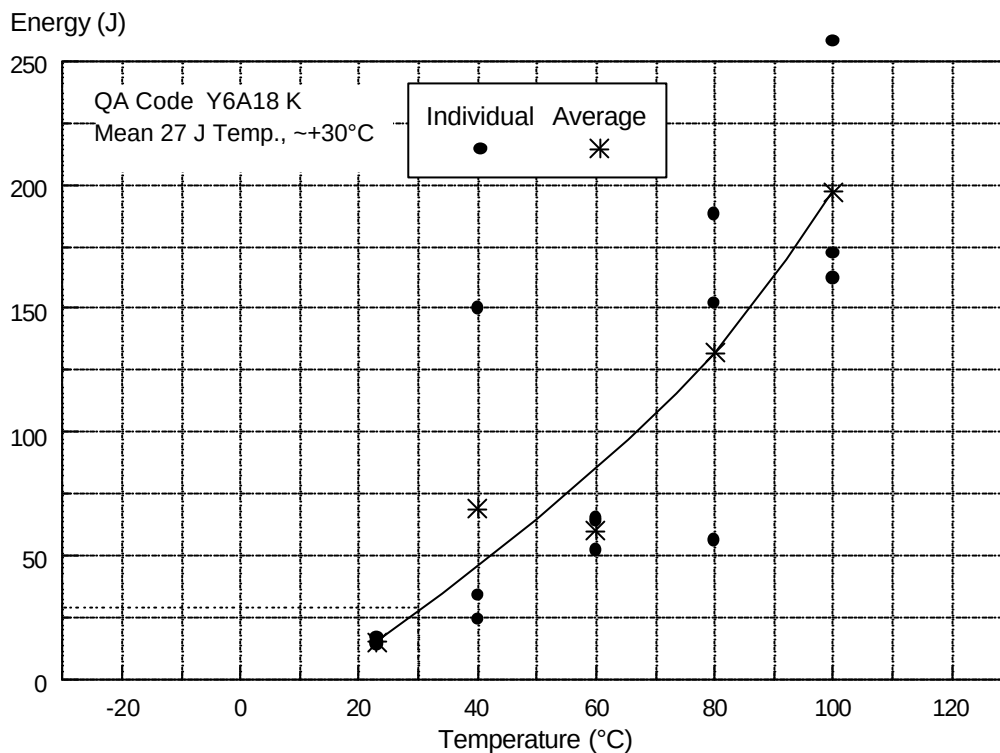


FIG. A41

CHARPY TRANSITION CURVE FOR SAW HAZ (PWHT) -
TRANSVERSE - SUBSURFACE (ROOT) -
OVERMATCHED (M ~1.62)

(D0697E19)

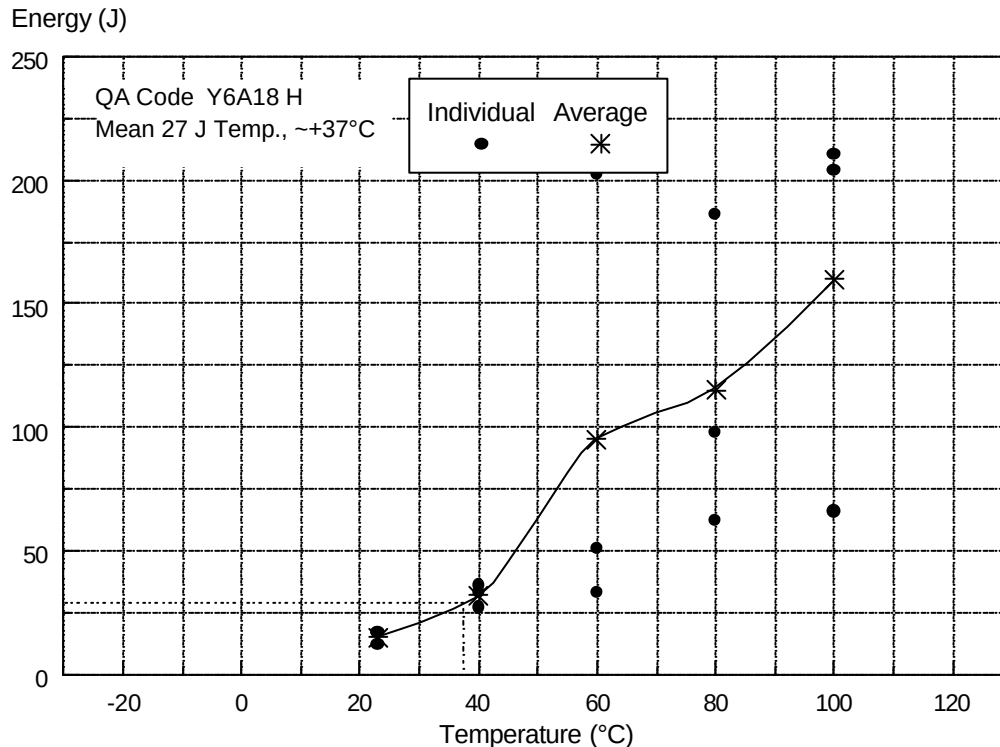


FIG. A42

CHARPY TRANSITION CURVE FOR SAW HAZ (PWHT) -
TRANSVERSE - SUBSURFACE (ROOT) -
MATCHED (M ~1.01)

(D0697E19)

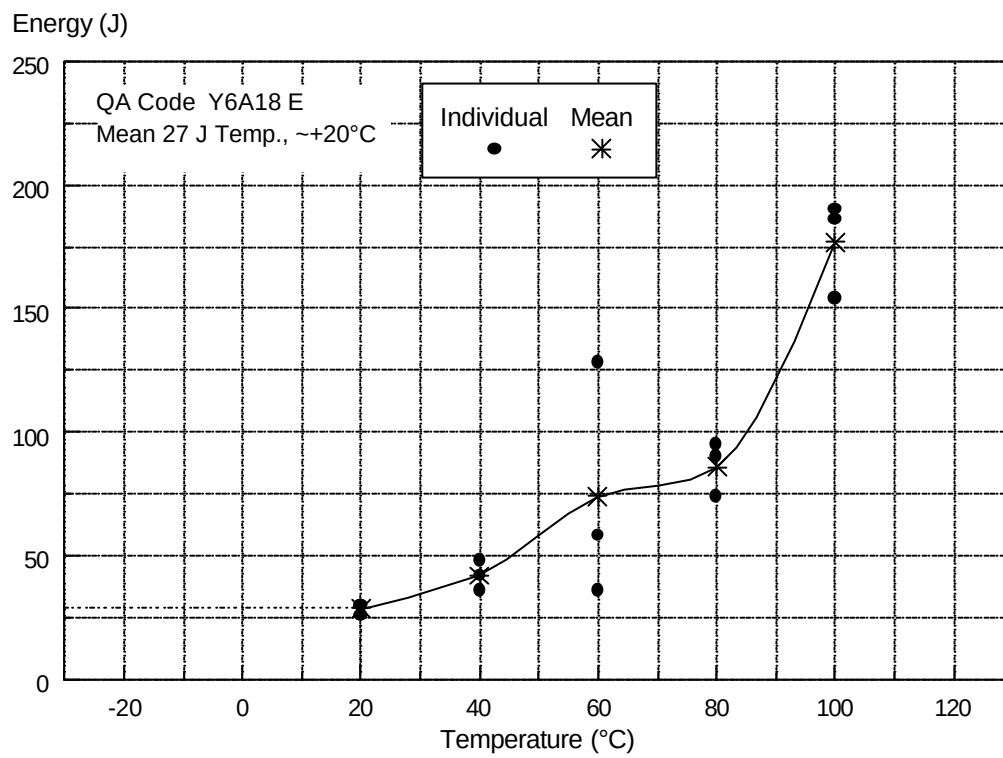


FIG. A43

CHARPY TRANSITION CURVE FOR SAW HAZ (PWHT)-
TRANSVERSE - SUBSURFACE (ROOT)-
UNDERMATCHED (M ~0.71)

(D0697E19)

APPENDIX 5

CTOD TRANSITION DATA FOR PARENT PLATES

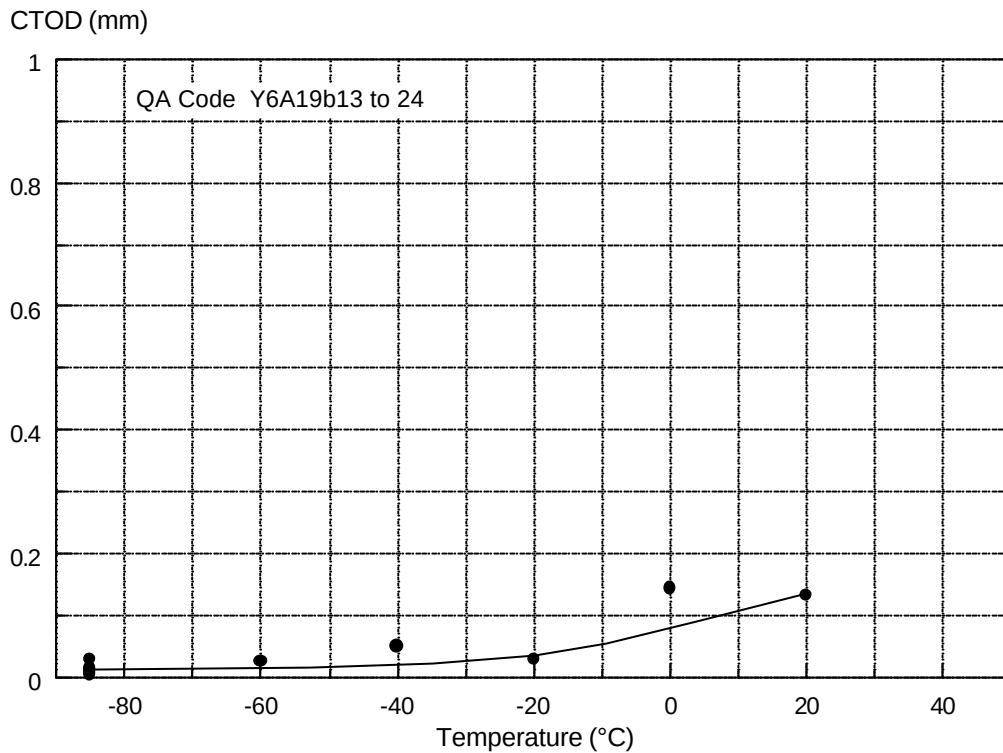


FIG. A51

CTOD TRANSITION DATA FOR RQT701 (PWHT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5

(D0697E21)

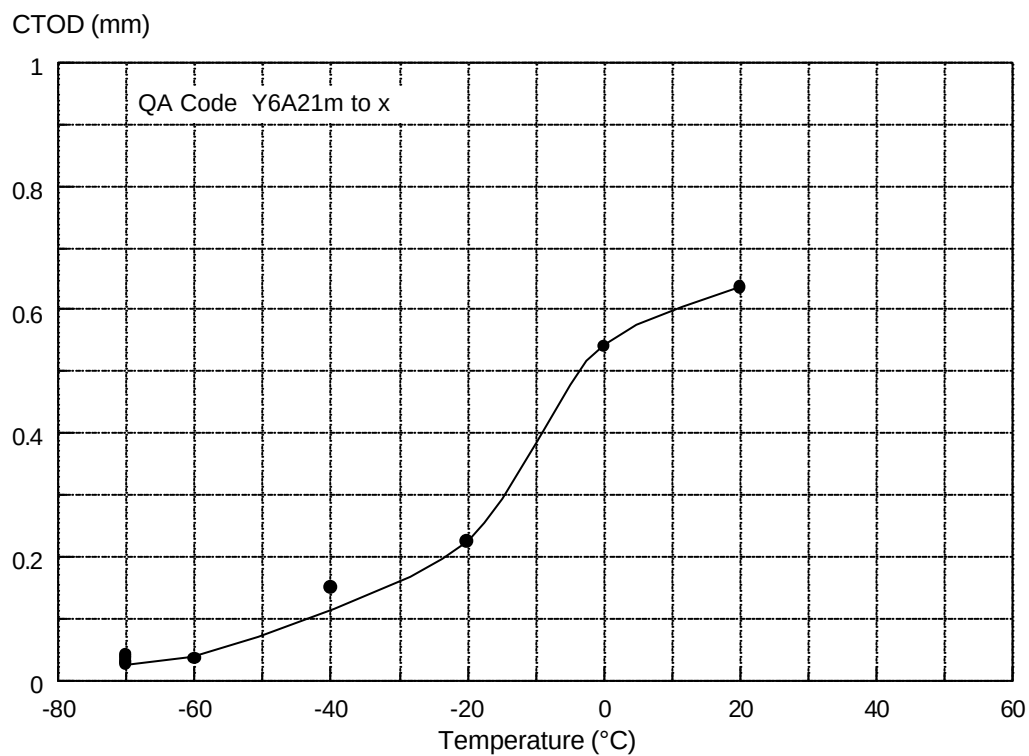


FIG. A52

CTOD TRANSITION DATA FOR TEMPERED RQT701 (PWHT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5

(D0697E21)

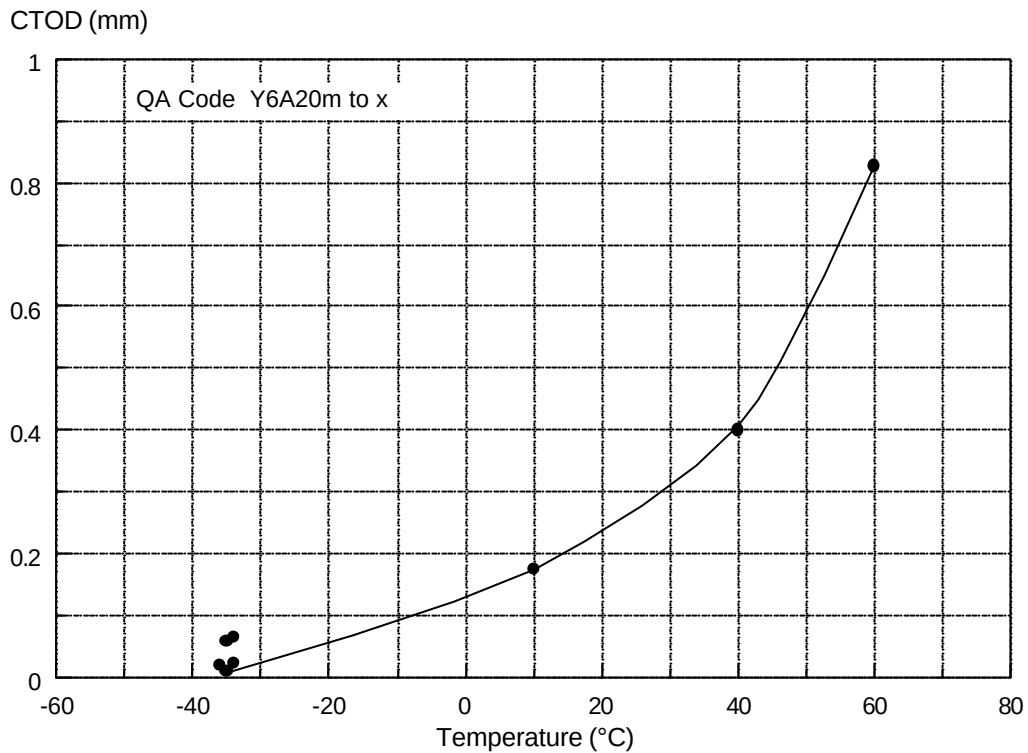


FIG. A53

CTOD TRANSITION DATA FOR NORMALISED RQT701 (PWHT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5

(D0697E21)

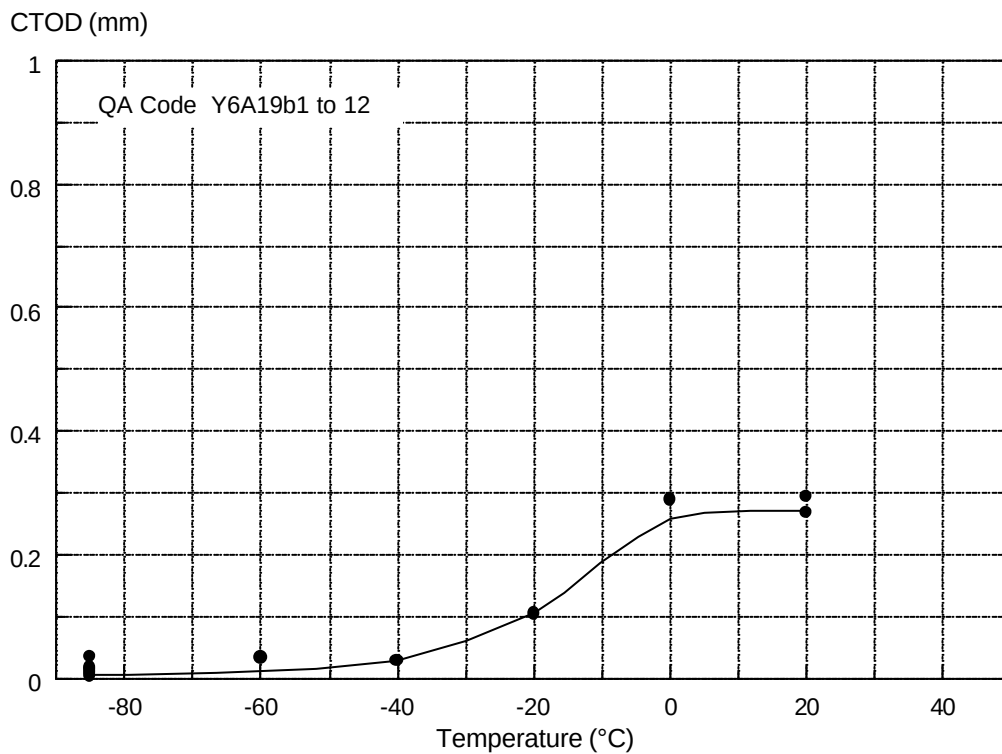


FIG. A54

CTOD TRANSITION DATA FOR RQT701 (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5

(D0697E21)

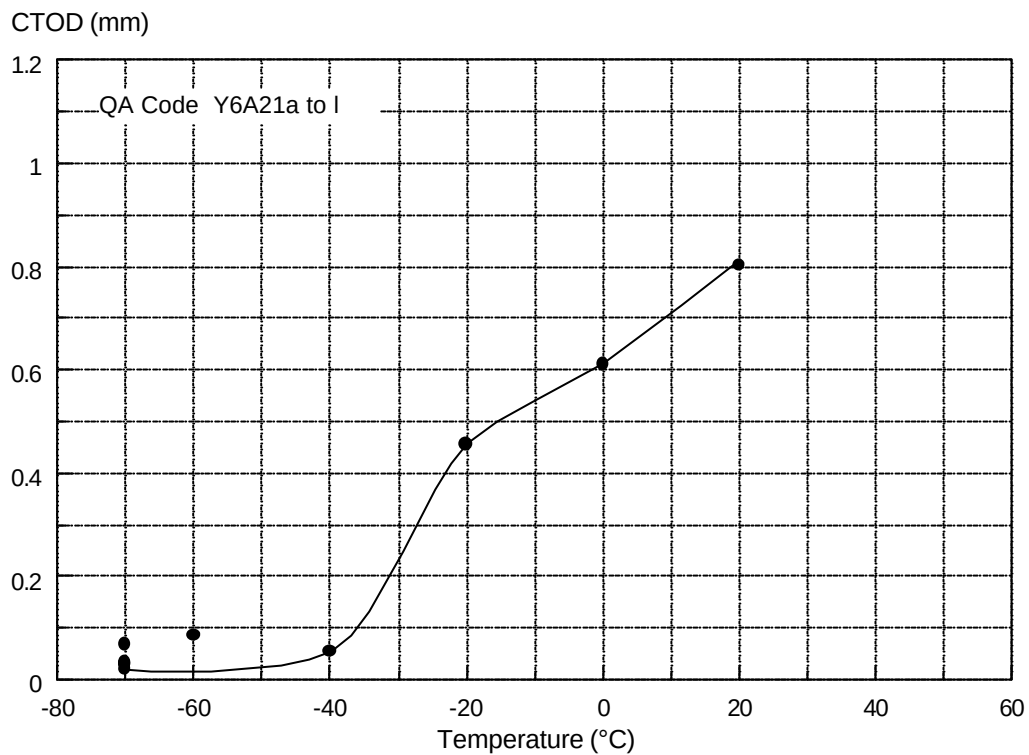


FIG. A55

CTOD TRANSITION DATA FOR TEMPERED RQT701 (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5

(D0697E21)

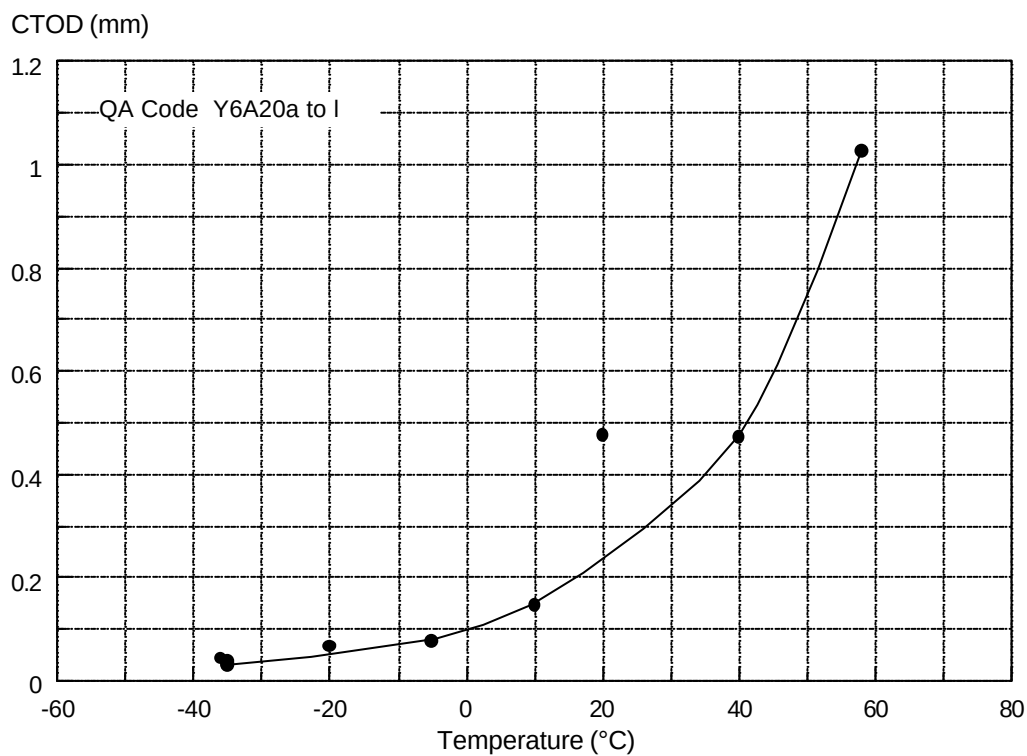


FIG. A56

CTOD TRANSITION DATA FOR NORMALISED RQT701 (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5

(D0697E21)

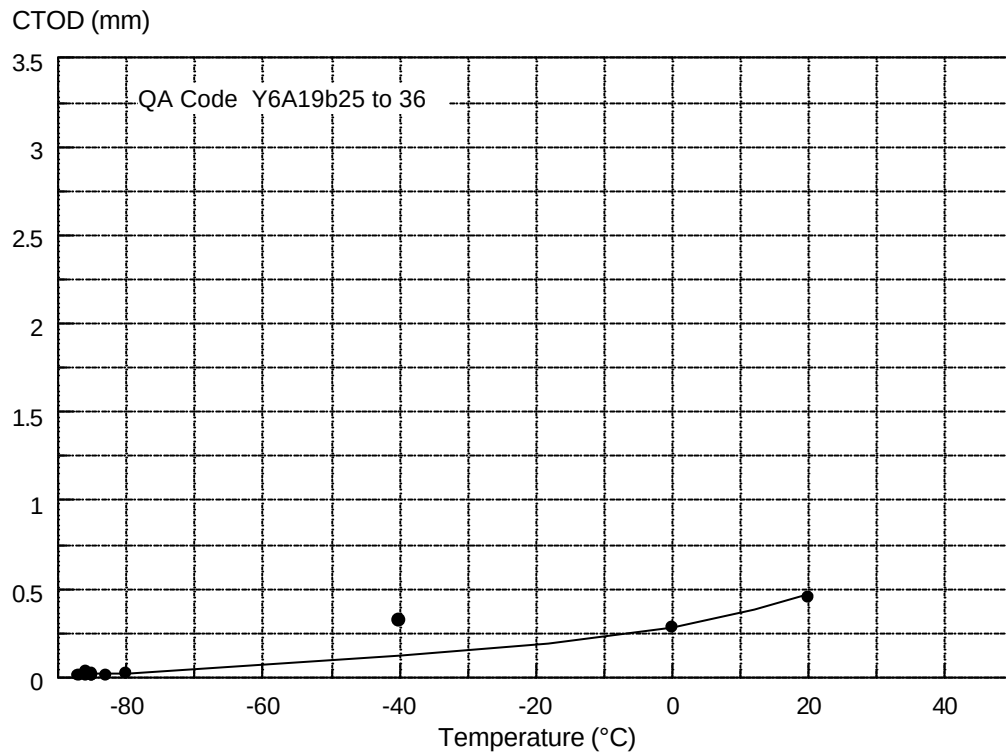


FIG. A5.7

CTOD TRANSITION DATA FOR RQT701 (FWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15

(D0697E21)

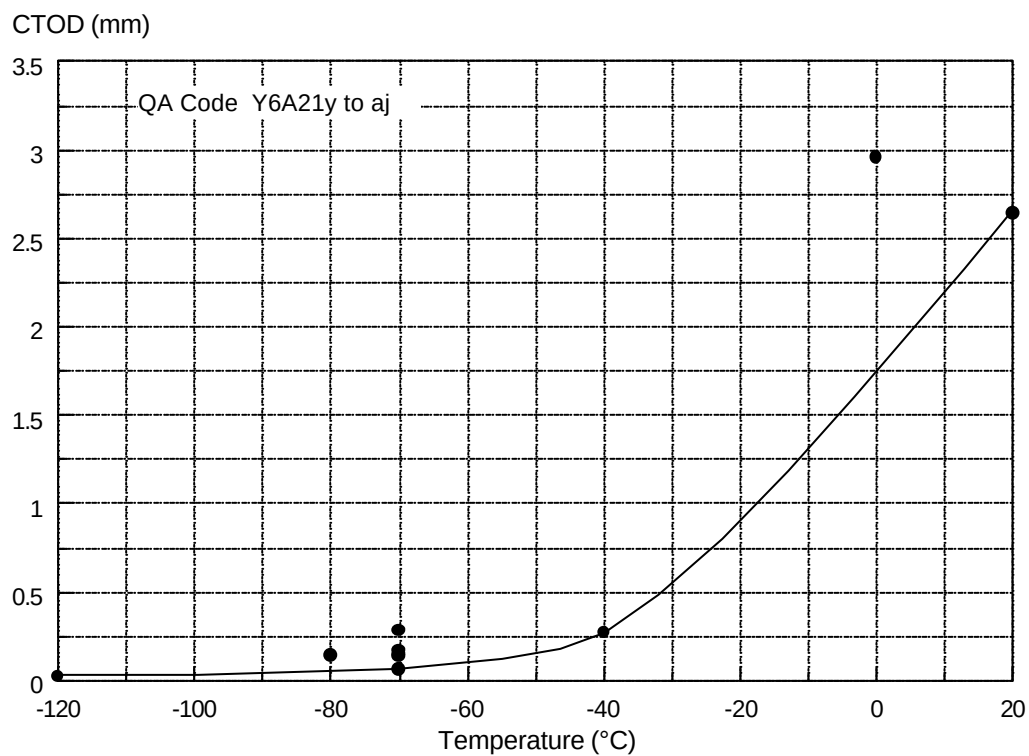


FIG. A5.8

CTOD TRANSITION DATA FOR TEMPERED RQT701 (FWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15

(D0697E21)

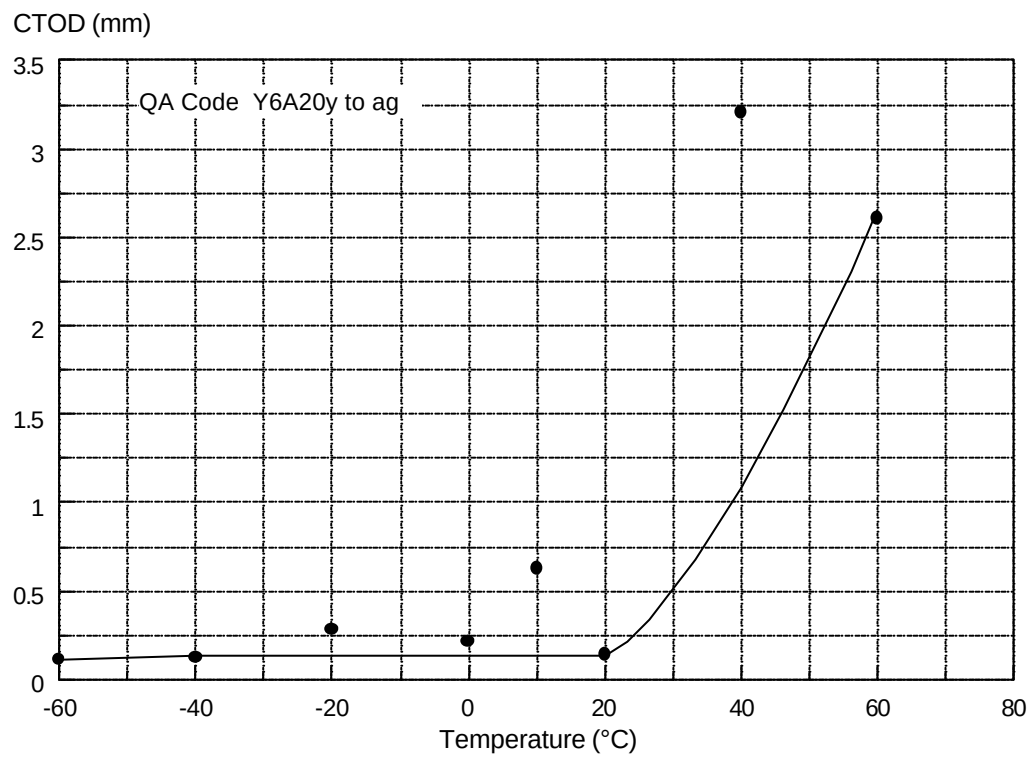


FIG. A5.9

CTOD TRANSITION DATA FOR NORMALISED RQT701 (FWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15

(D0697E21)

APPENDIX 6

CTOD TRANSITION DATA FOR FCAW WELD METALS

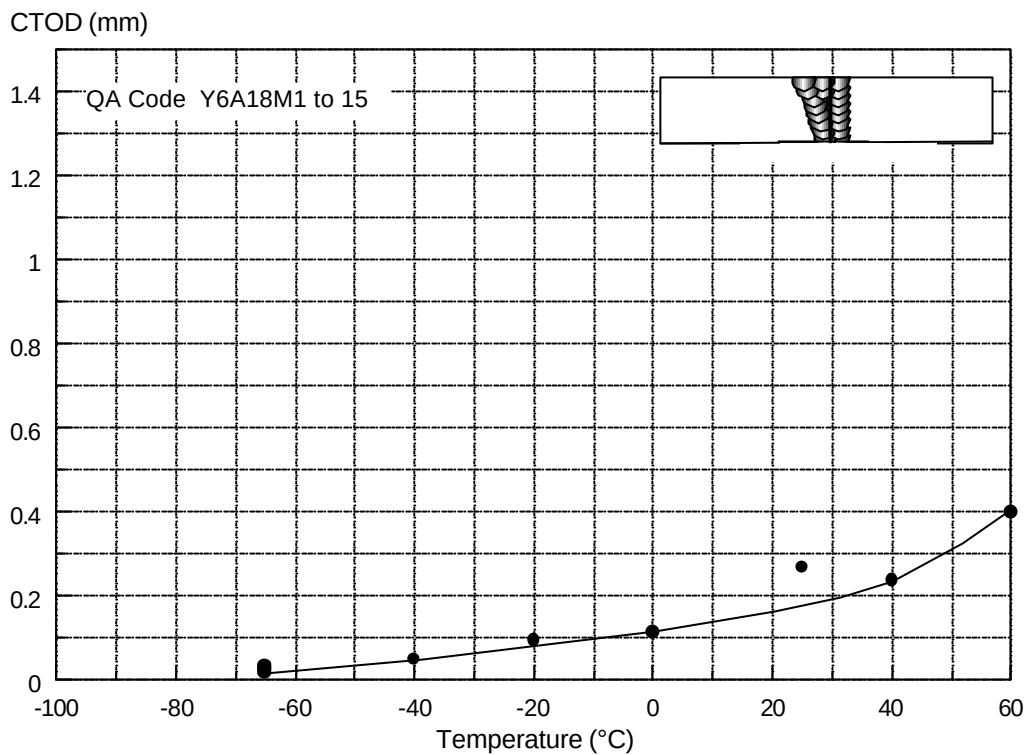


FIG. A6.1

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5 -
UNDERMATCHED CONDITION (M ~0.95)

(D0697E23)

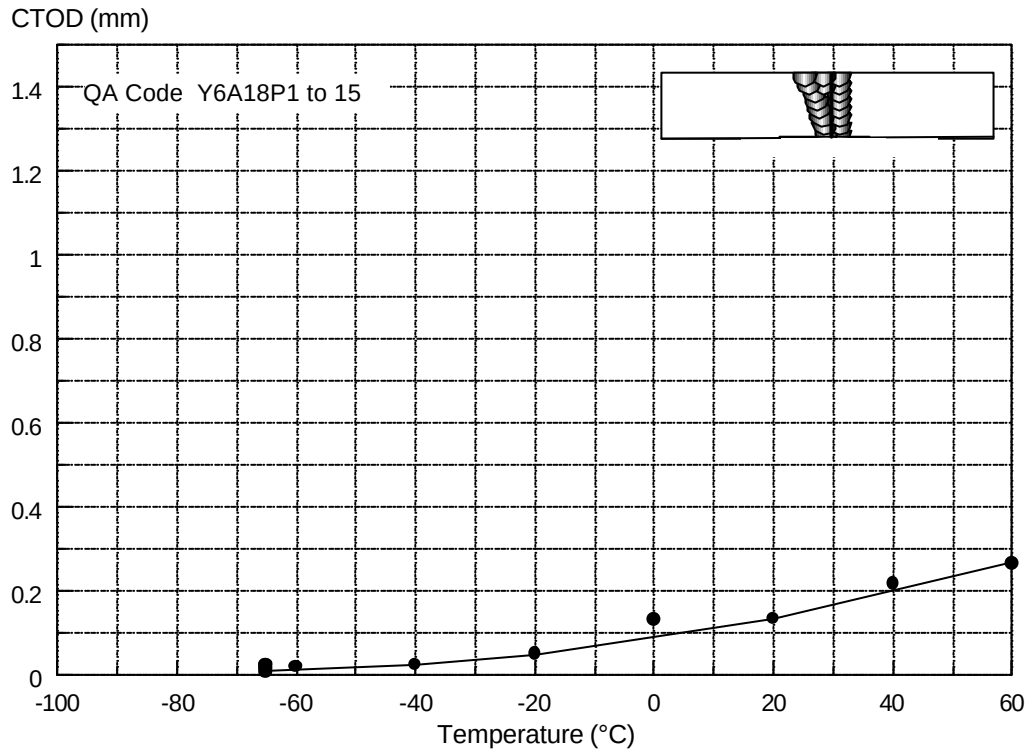


FIG. A6.2

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5 -
HIGHLY OVERMATCHED CONDITION (M ~2.15)

(D0697E23)

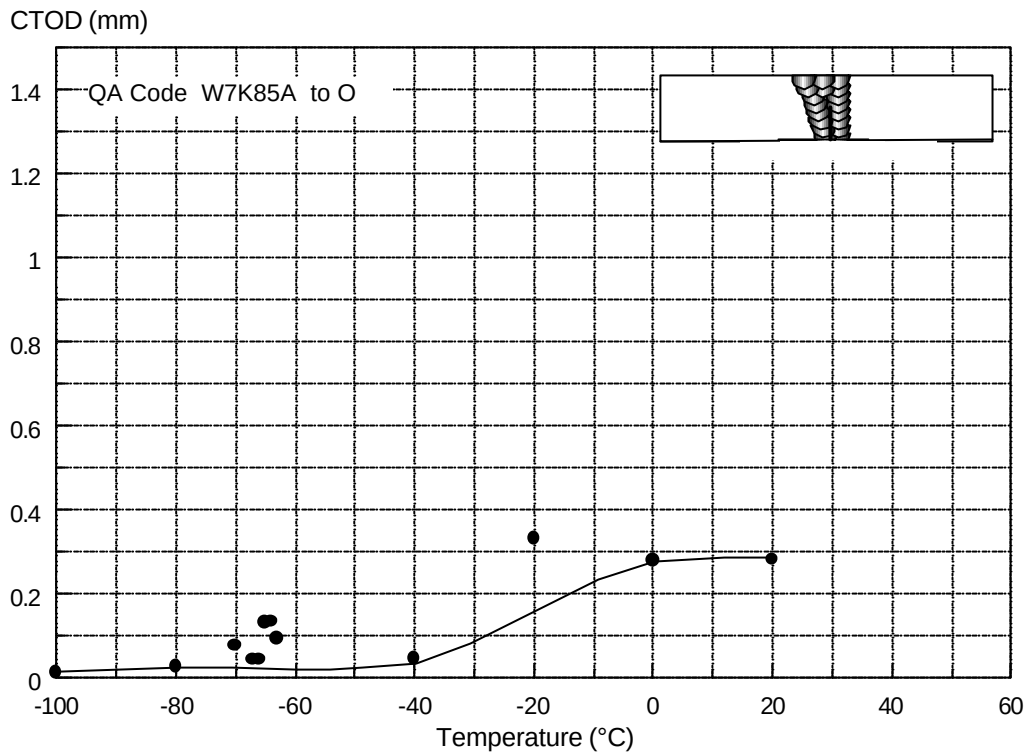


FIG. A63

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
UNDERMATCHED CONDITION (M ~0.95)

(D0697E23)

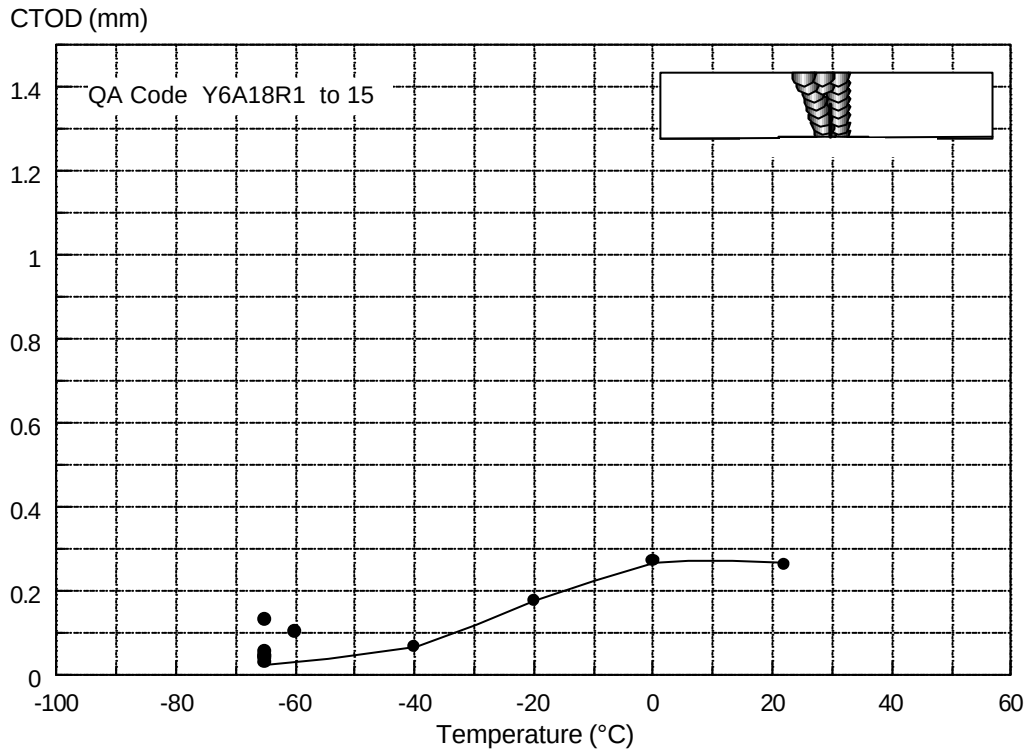


FIG. A64

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
OVERMATCHED CONDITION (M ~1.35)

(D0697E23)

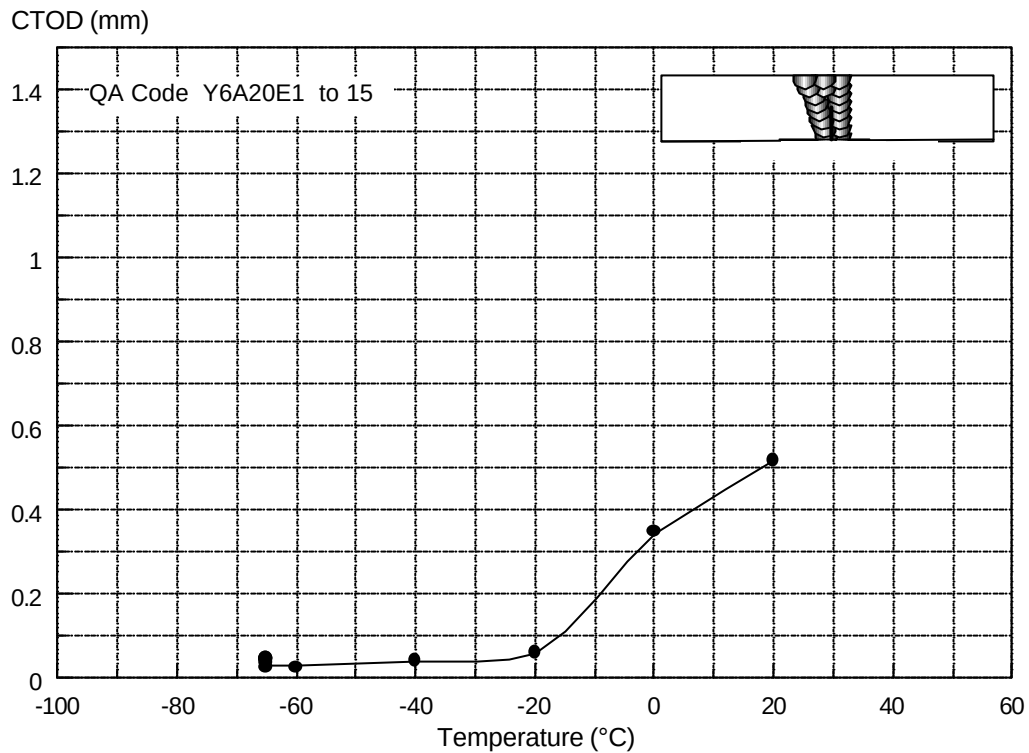


FIG. A65

CTOD TRANSITION DATA FOR FCAW/WM (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
HIGHLY OVERMATCHED CONDITION ($M \sim 215$)

(D0697E23)

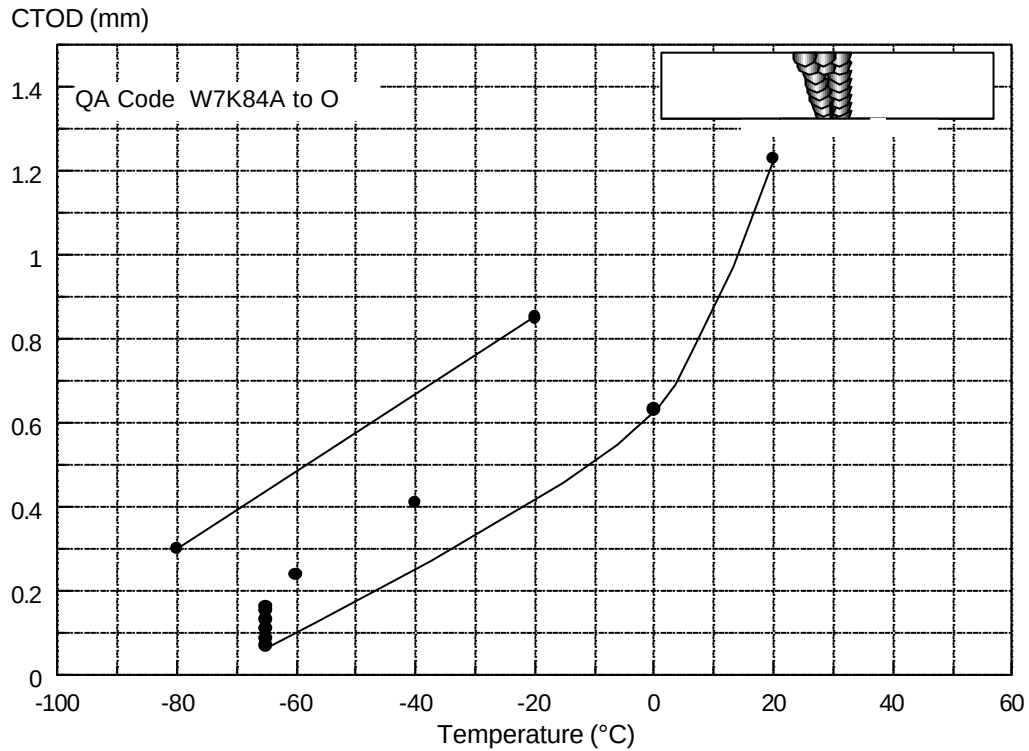


FIG. A66

CTOD TRANSITION DATA FOR FCAW/WM (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
UNDERMATCHED CONDITION ($M \sim 0.95$)

(D0697E23)

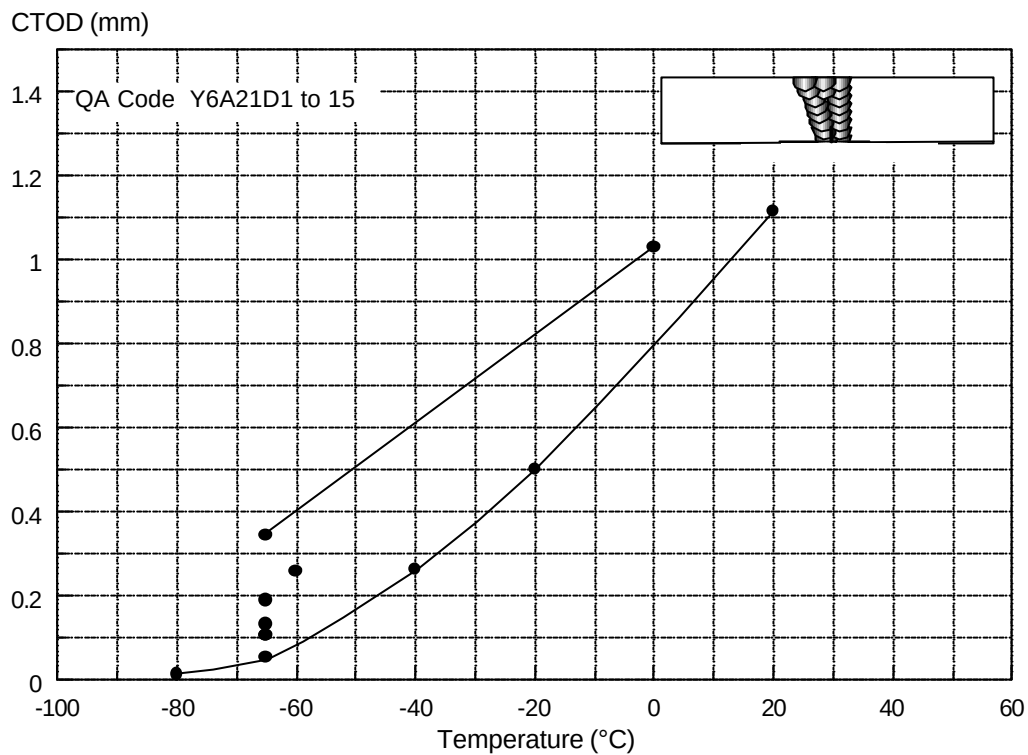


FIG. A6.7

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
OVERMATCHED CONDITION (M ~135)

(D0697E23)

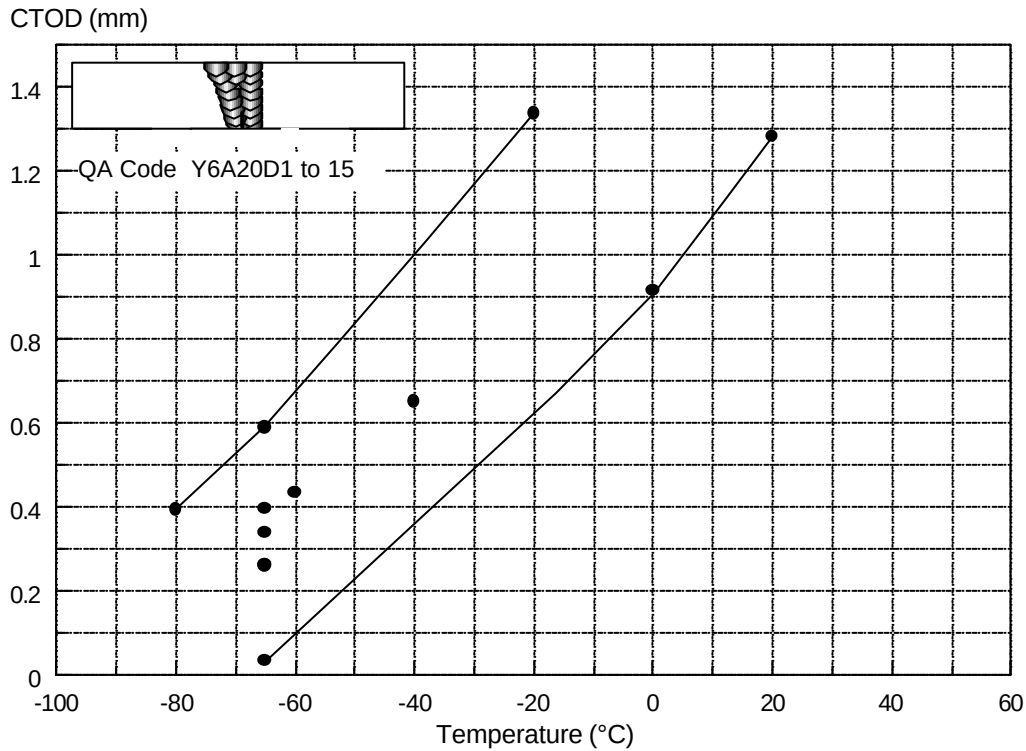


FIG. A6.8

CTOD TRANSITION DATA FOR FCAW/WM (PW-HT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
HIGHLY OVERMATCHED CONDITION (M ~215)

(D0697E23)

APPENDIX 7

CTOD TRANSITION DATA FOR FCAW HAZS

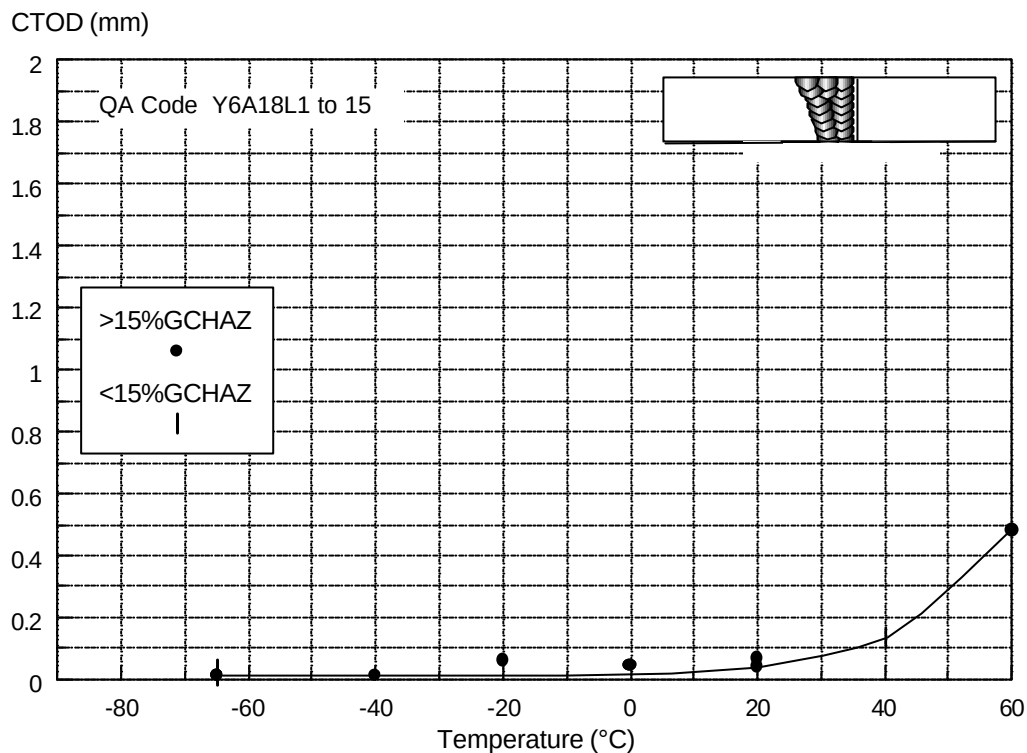


FIG. A71

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5 -
UNDERMATCHED CONDITION (M ~0.95)

(D0697E25)

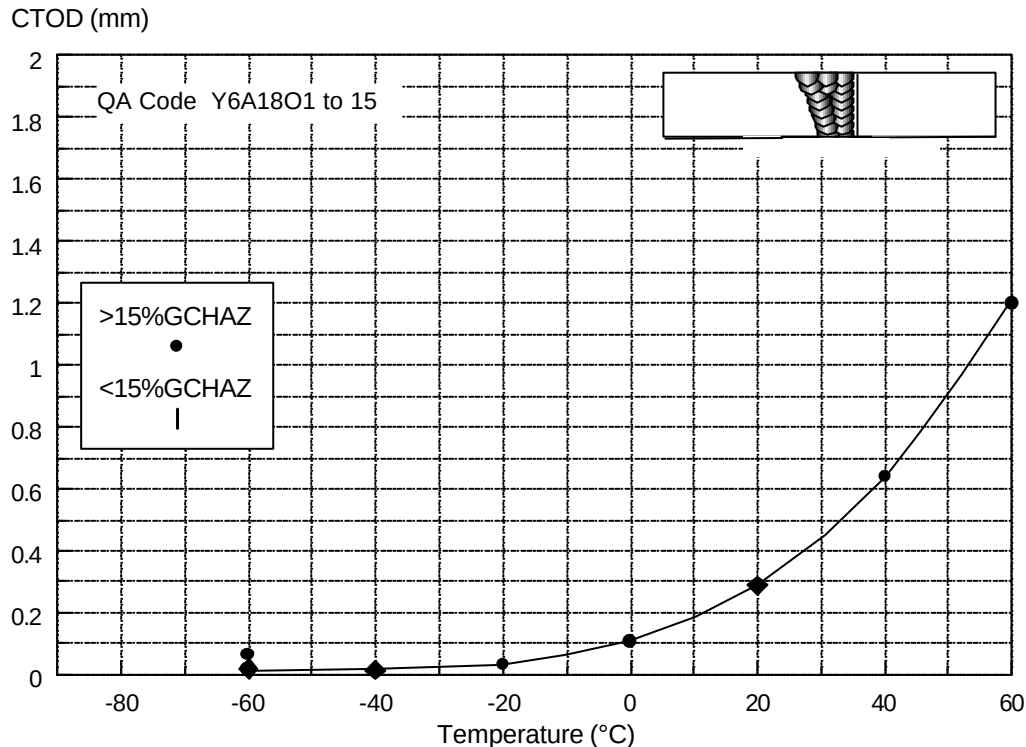


FIG. A72

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - THROUGH THICKNESS NOTCH a/w 0.5 -
HIGHLY OVERMATCHED CONDITION (M ~2.15)

(D0697E25)

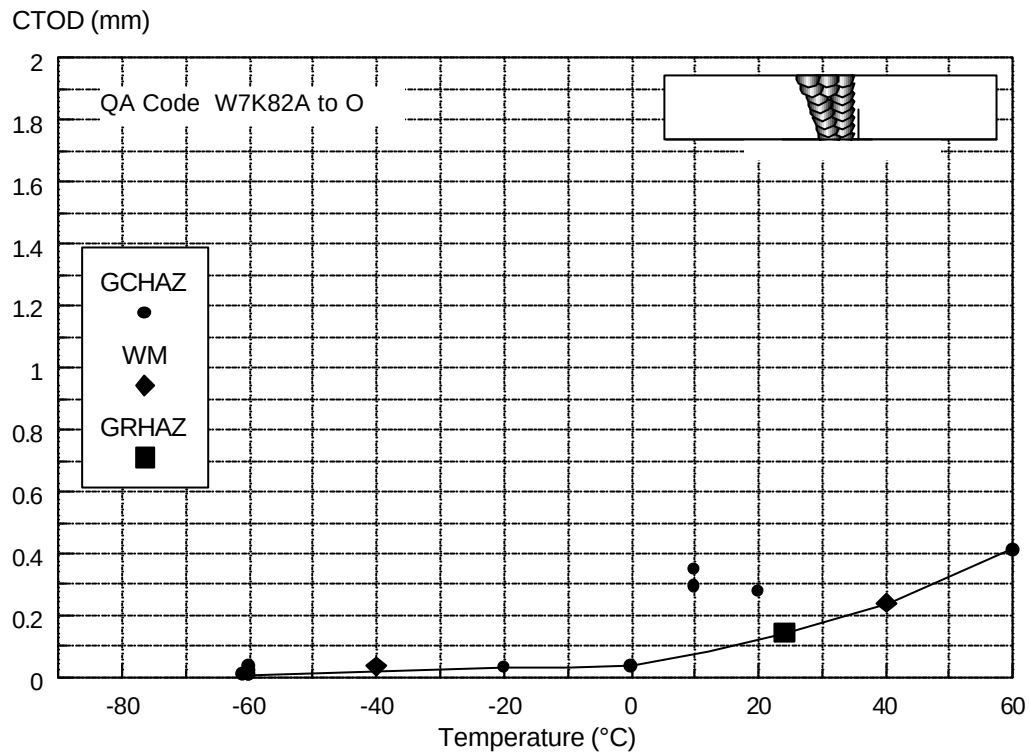


FIG. A73

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
UNDERMATCHED CONDITION (M ~0.95)

(D0697E25)

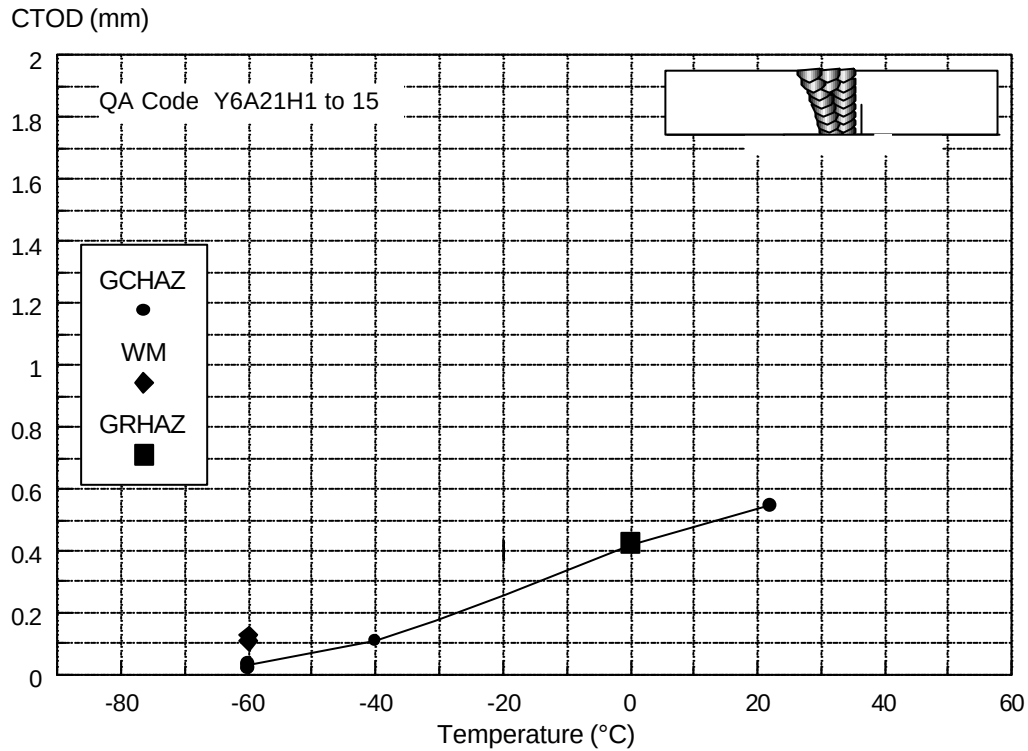


FIG. A74

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
OVERMATCHED CONDITION (M ~1.35)

(D0697E25)

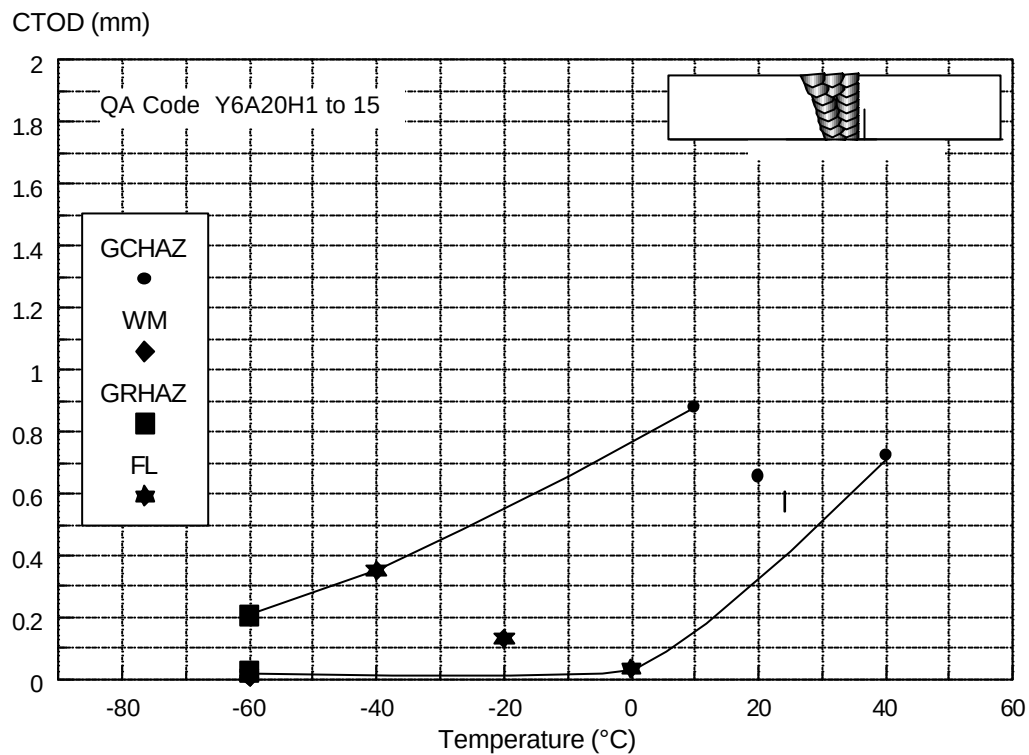


FIG. A75

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
HIGHLY OVERMATCHED CONDITION ($M \sim 215$)

(D0697E25)

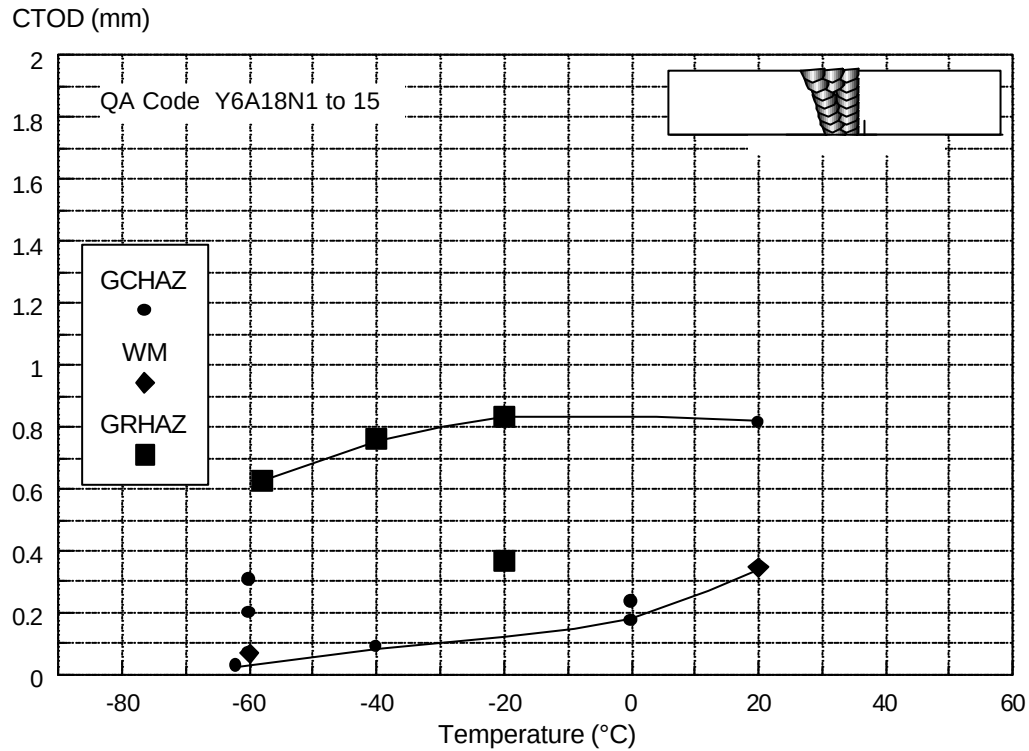


FIG. A76

CTOD TRANSITION DATA FOR FCAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
UNDERMATCHED CONDITION ($M \sim 0.95$)

(D0697E25)

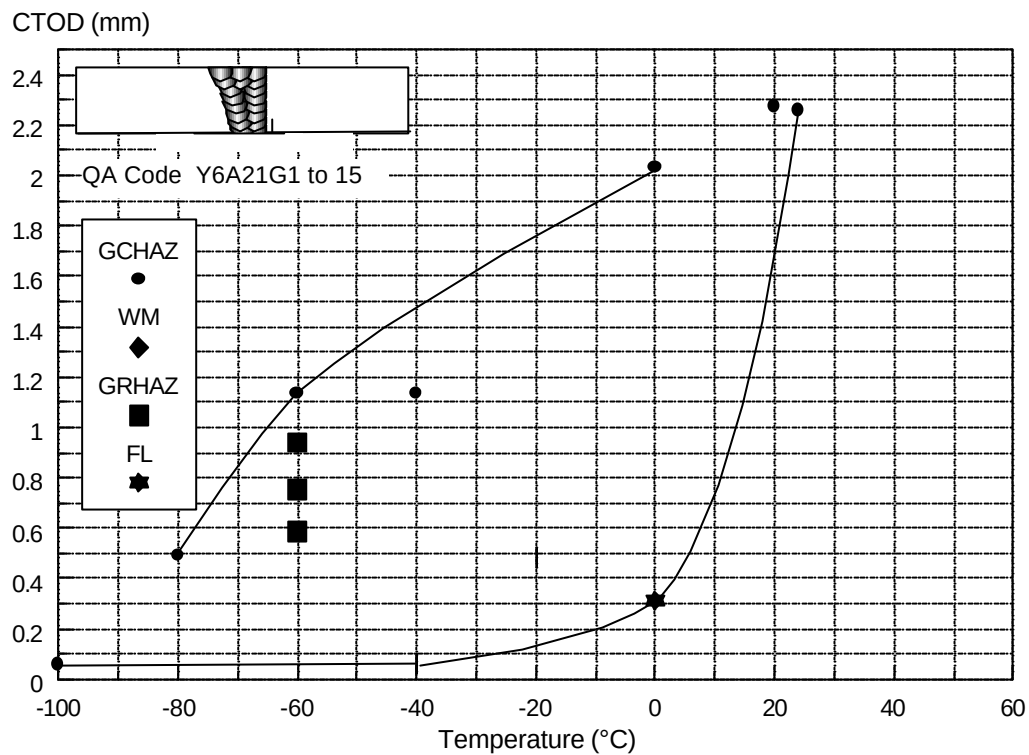


FIG. A7.7

CTOD TRANSITION DATA FOR FCAW HAZ (FWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
OVERMATCHED CONDITION (M ~135)

(D0697E25)

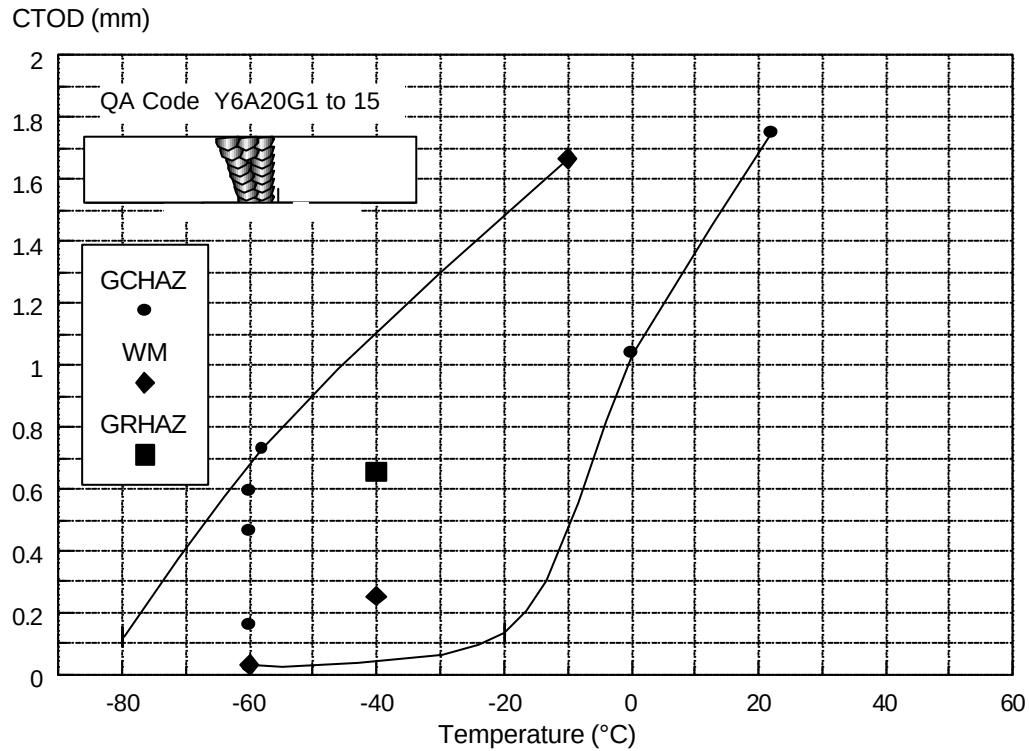


FIG. A7.8

CTOD TRANSITION DATA FOR FCAW HAZ (FWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
HIGHLY OVERMATCHED CONDITION (M ~215)

(D0697E25)

APPENDIX 8

CTOD TRANSITION DATA FOR SAW HAZS

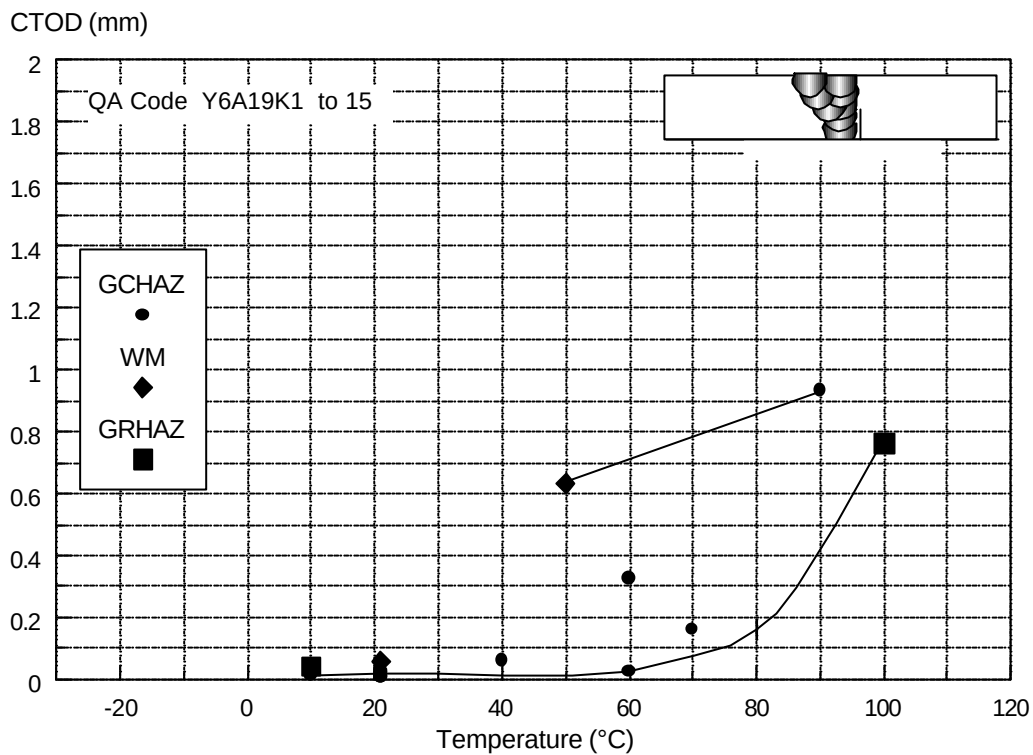


FIG. A8.1

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
UNDERMATCHED CONDITION ($M \sim 0.71$)

(D0697E27)

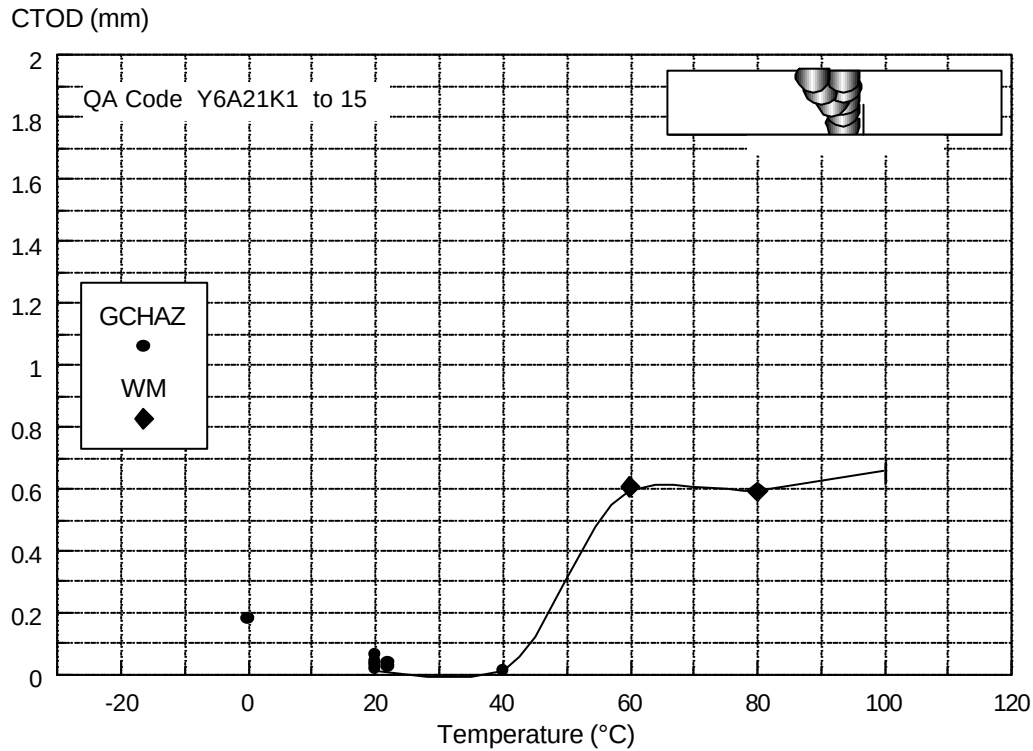


FIG. A8.2

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
MATCHED CONDITION ($M \sim 1.01$)

(D0697E27)

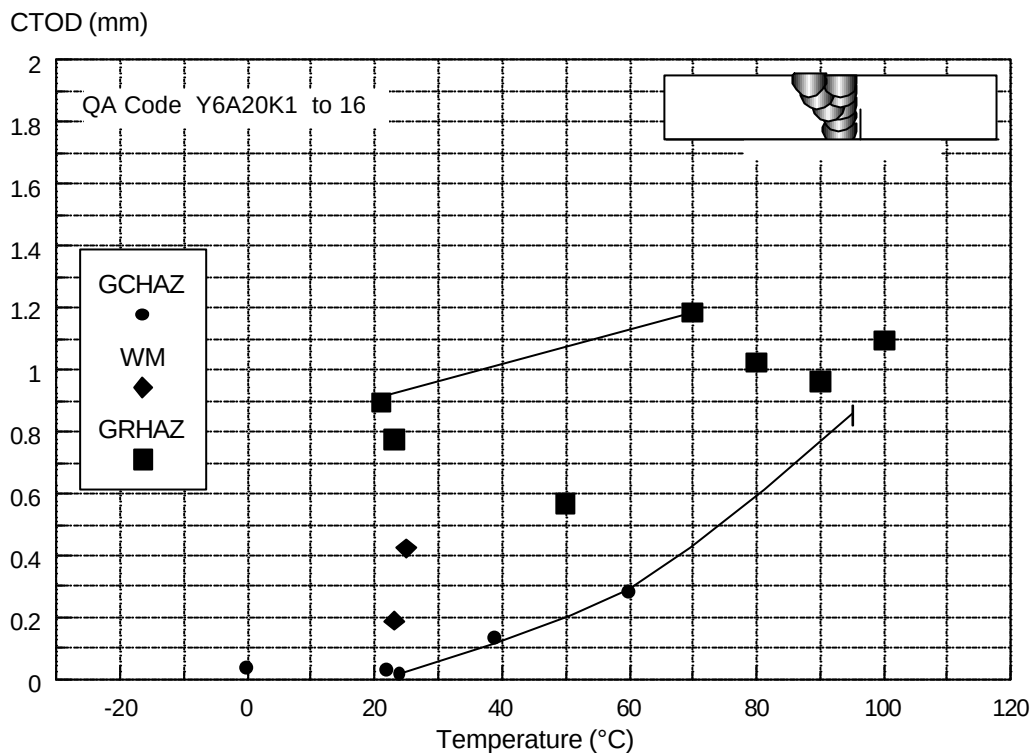


FIG. A83

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.5 -
OVERMATCHED CONDITION ($M \sim 1.62$)

(D0697E27)

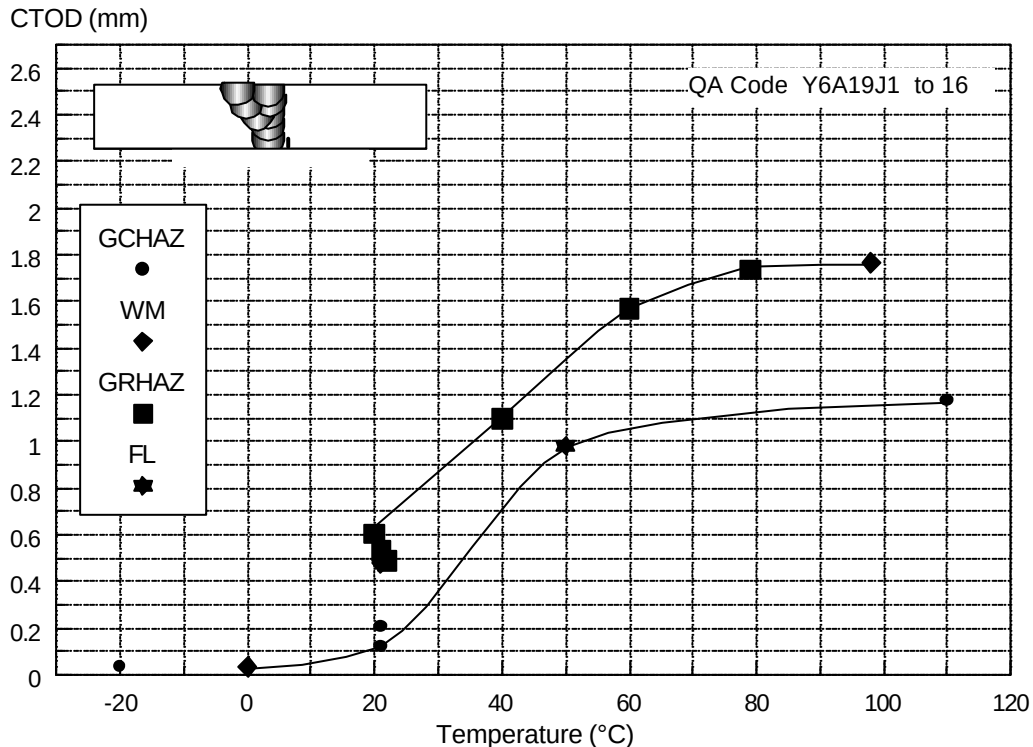


FIG. A84

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
UNDERMATCHED CONDITION ($M \sim 0.71$)

(D0697E27)

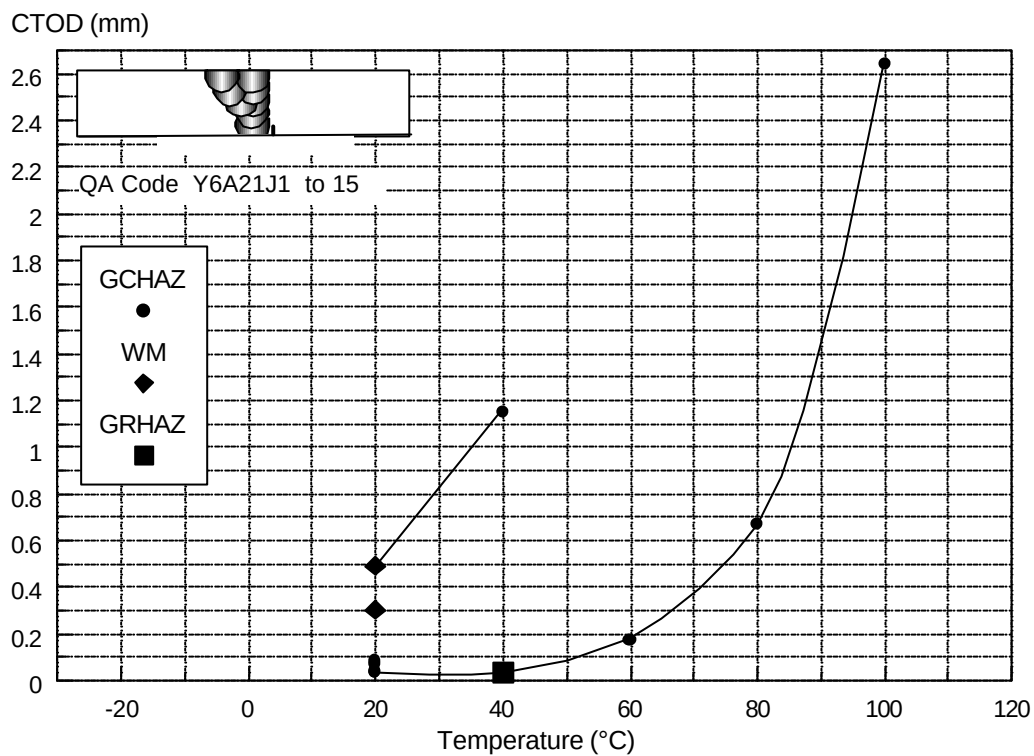


FIG. A85

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
MATCHED CONDITION (M ~1.01)

(D0697E27)

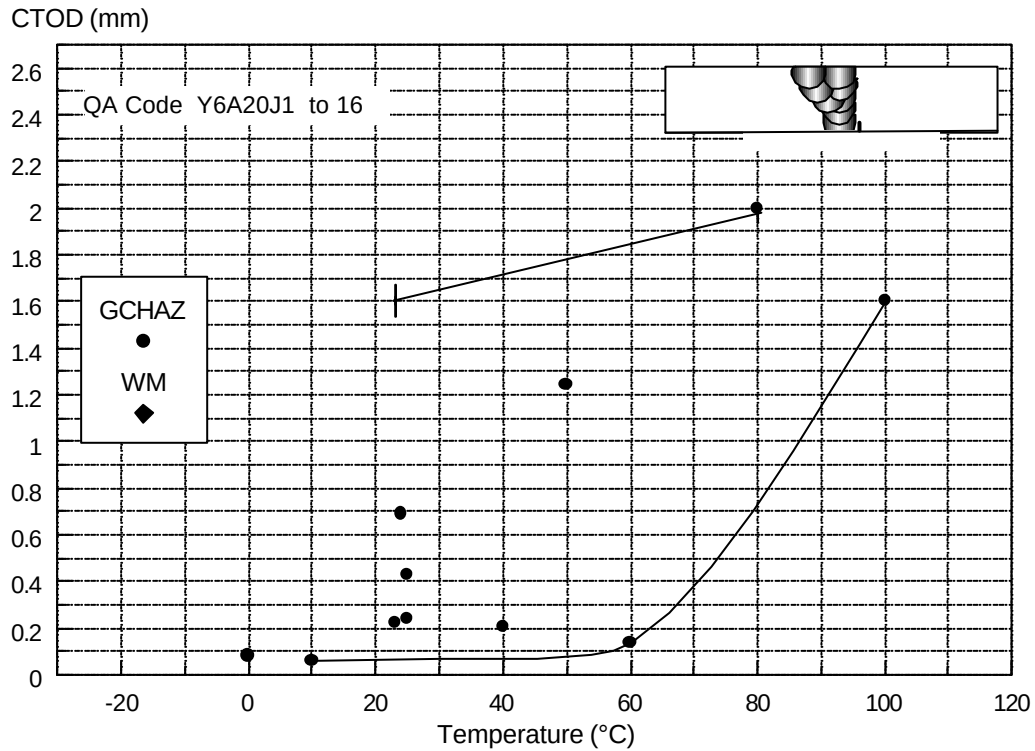


FIG. A86

CTOD TRANSITION DATA FOR SAW HAZ (PWHT) -
TRANSVERSE - SURFACE NOTCH a/w 0.15 -
OVERMATCHED CONDITION (M ~1.62)

(D0697E27)

APPENDIX 9

CENTRE CRACKED TENSILE TEST DATA FOR PARENT PLATES

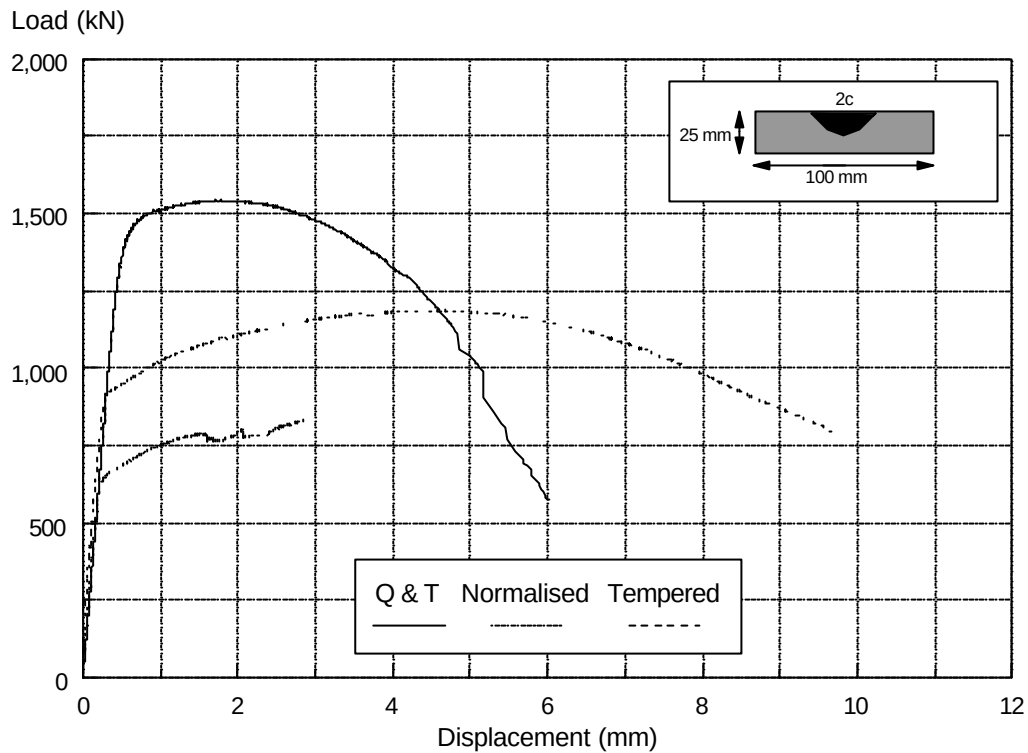


FIG. A91

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.5, a/c 0.5

(D0697E29)

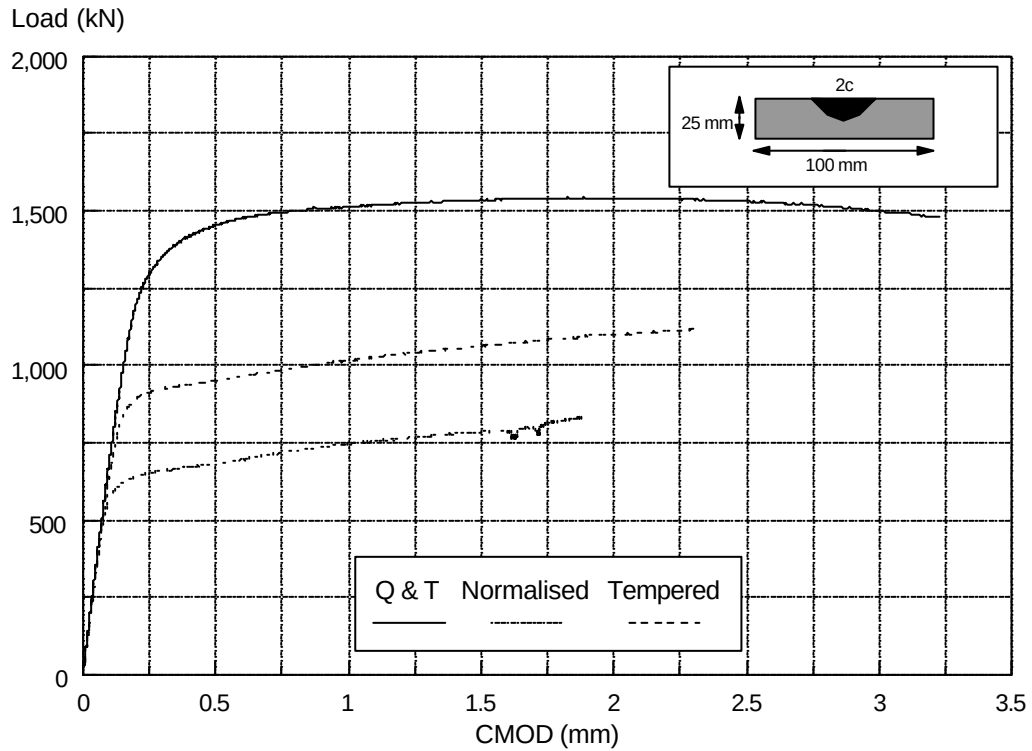


FIG. A92

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS -
TRANSVERSE - SURFACE NOTCH at 0.5, a/c 0.5

(D0697E29)

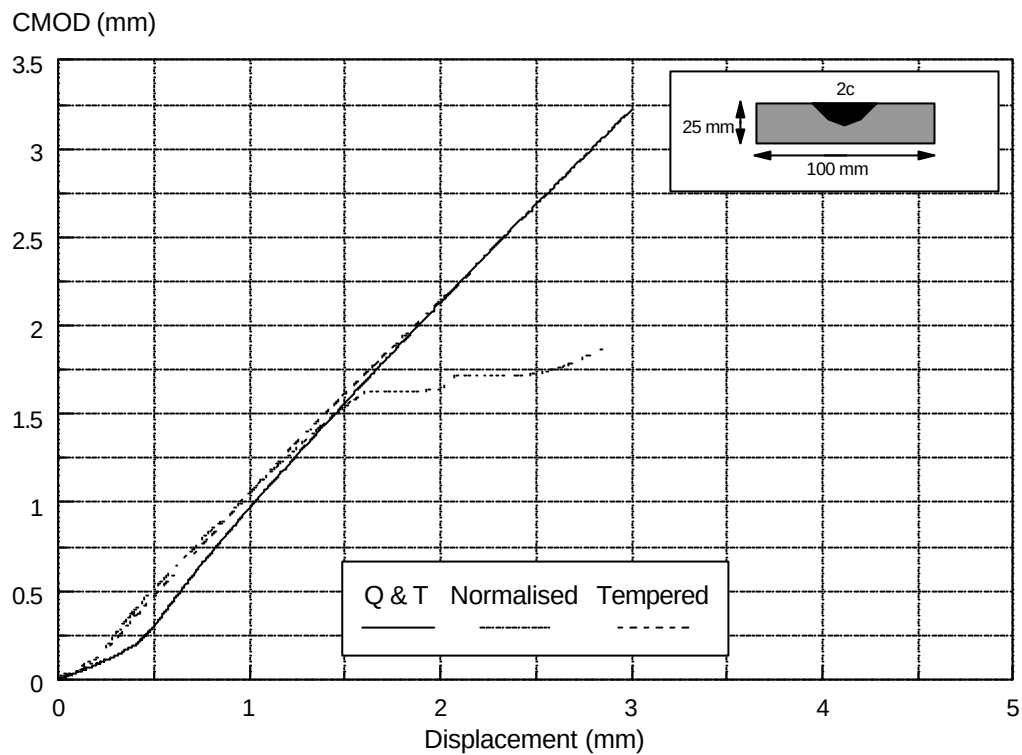


FIG. A93

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.5, a/c 0.5

(D0697E29)

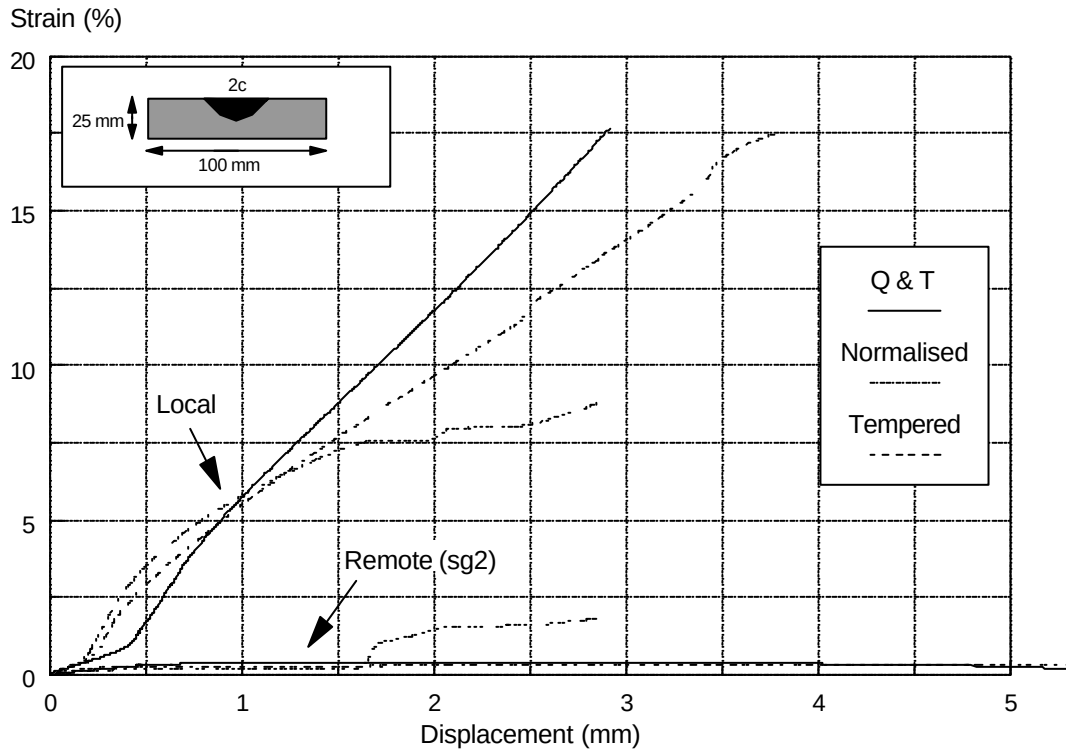


FIG. A94

OCT TEST STRAIN v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - SURFACE NOTCH at 0.5, a/c 0.5

(D0697E29)

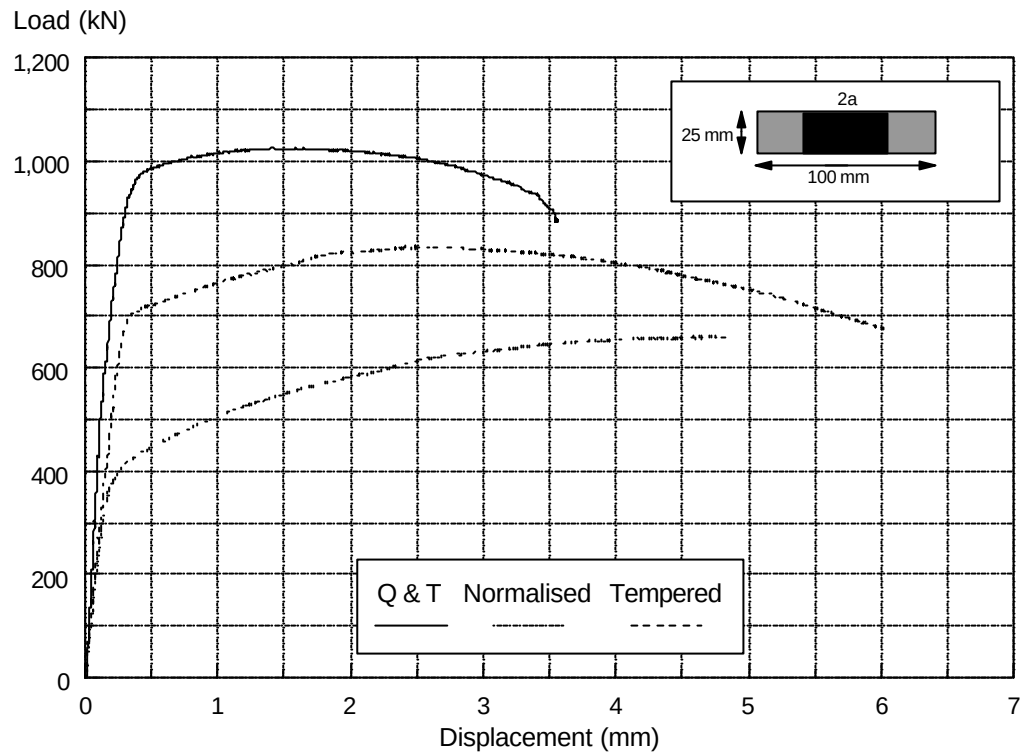


FIG. A95

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - THROUGH THICKNESS NOTCH at $t=1$

(D0697E29)

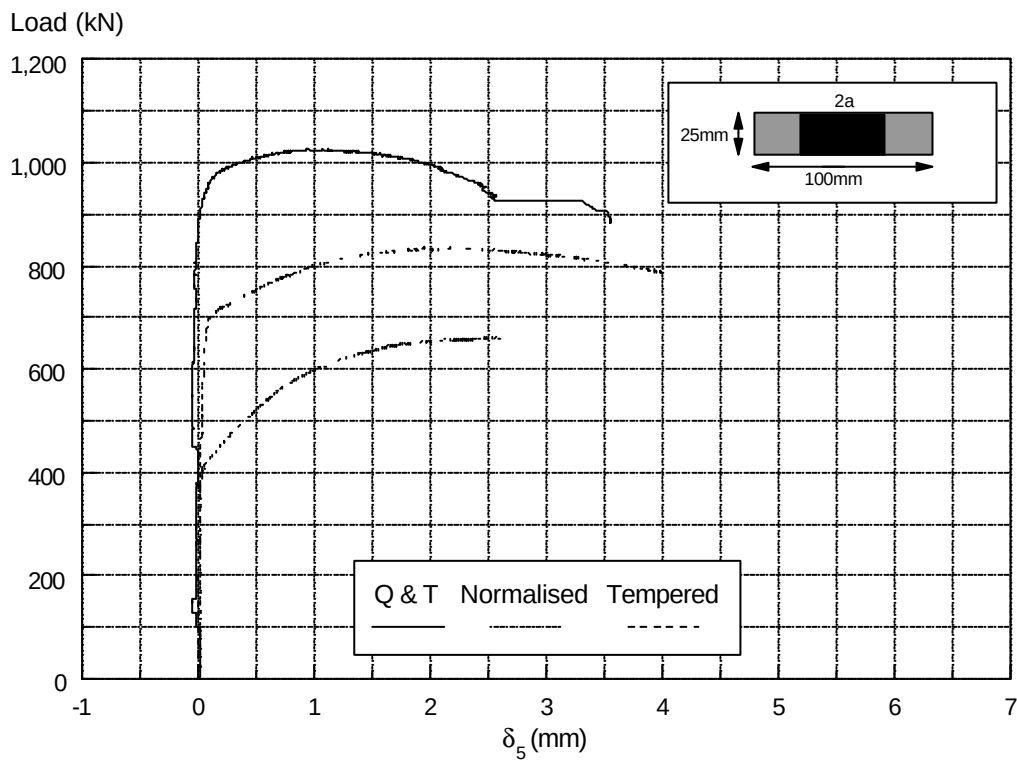


FIG. A96

OCT TEST LOAD v δ_5 DATA FOR PARENT MATERIALS -
TRANSVERSE - THROUGH THICKNESS NOTCH at $t=1$

(D0697E29)

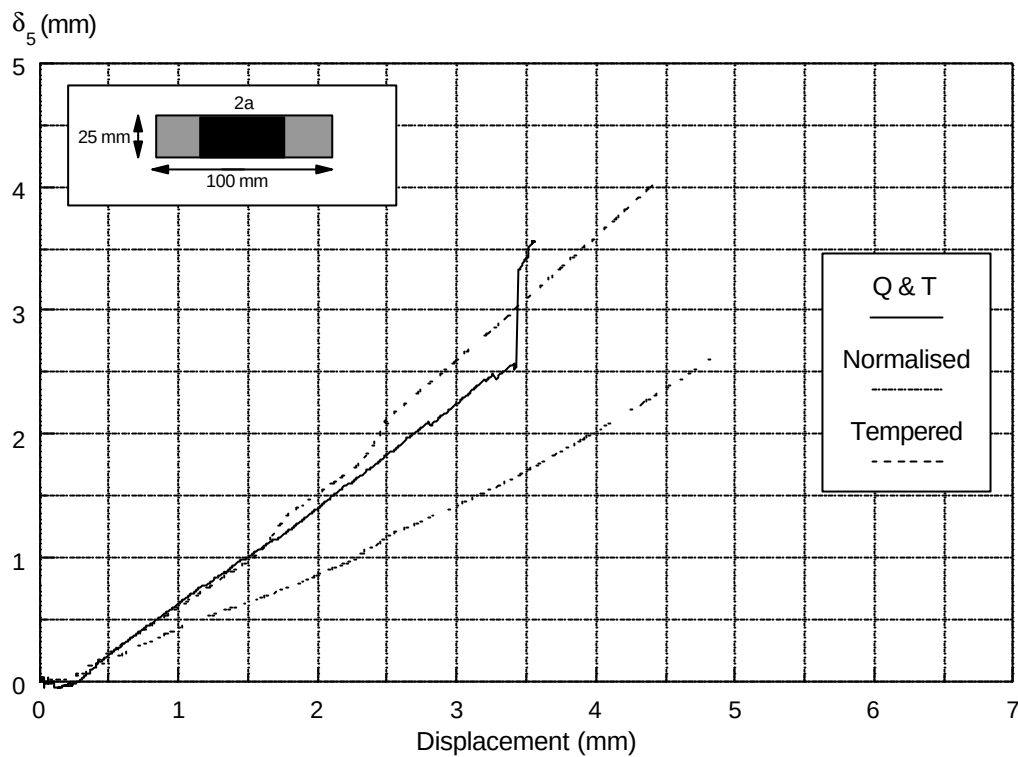


FIG. A9.7

OCT TEST d_5 v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - THROUGH THICKNESS NOTCH $a/t=1$

(D0697E29)

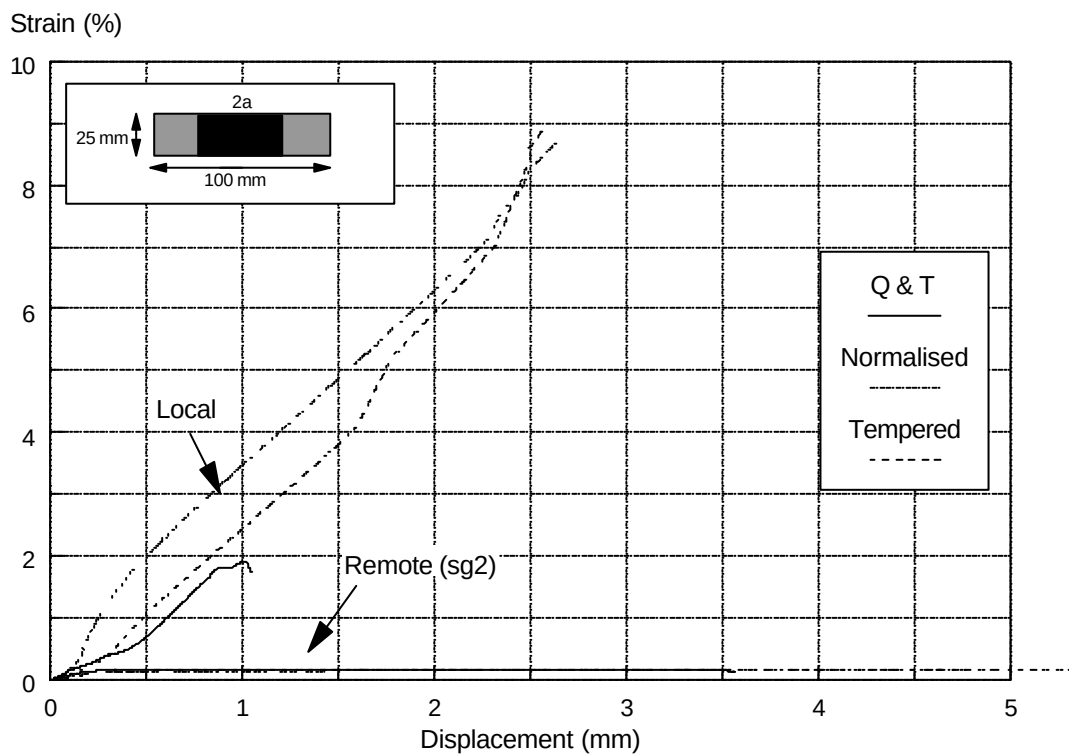


FIG. A9.8

OCT TEST STRAIN v DISPLACEMENT DATA FOR PARENT
MATERIALS - TRANSVERSE - THROUGH THICKNESS NOTCH $a/t=1$

(D0697E29)

APPENDIX 10

**CENTRE CRACKED TENSILE TEST DATA FOR TESTS
NOTCHED AT FCAW WELD METAL CENTRELINE**

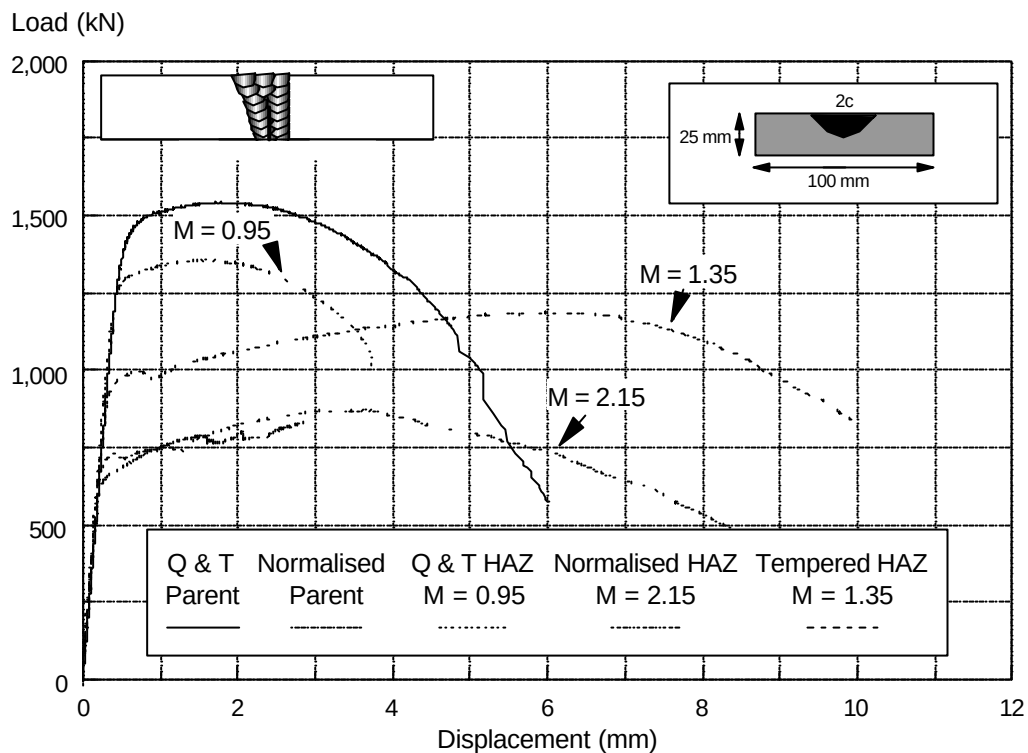


FIG. A10.1

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.5, at 0.5 - NOTCH AT WELD CENTRELINE

(D0697E31)

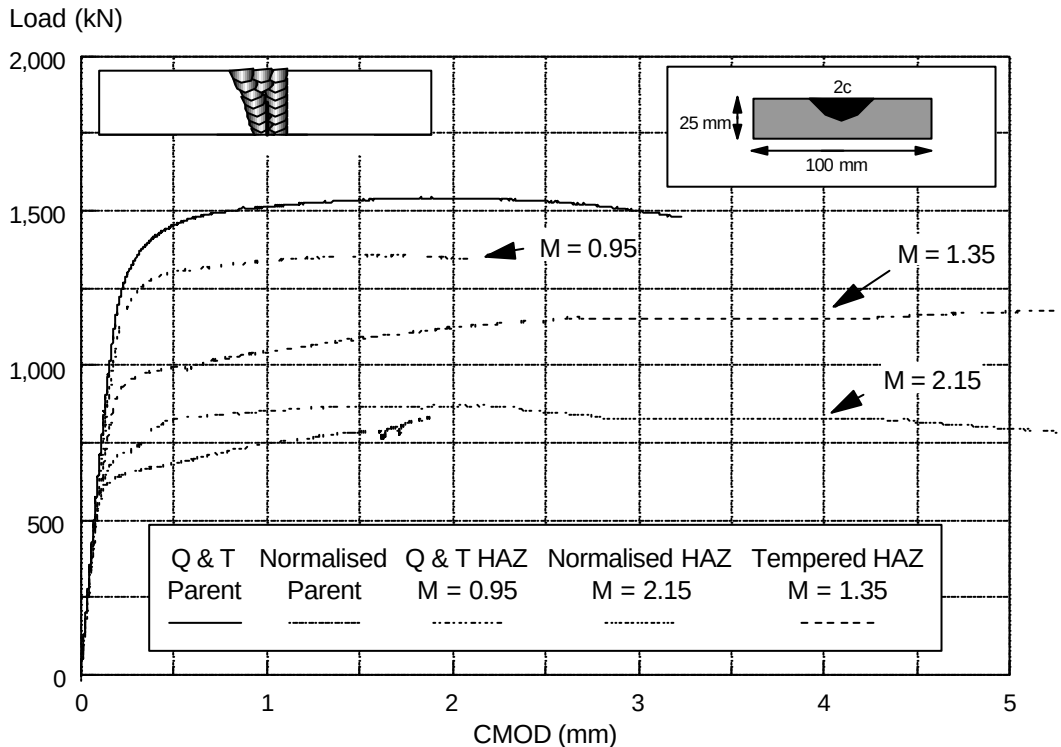


FIG. A10.2

OCT TEST LOAD v CMOD DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.5, at 0.5 - NOTCH AT WELD CENTRELINE

(D0697E31)

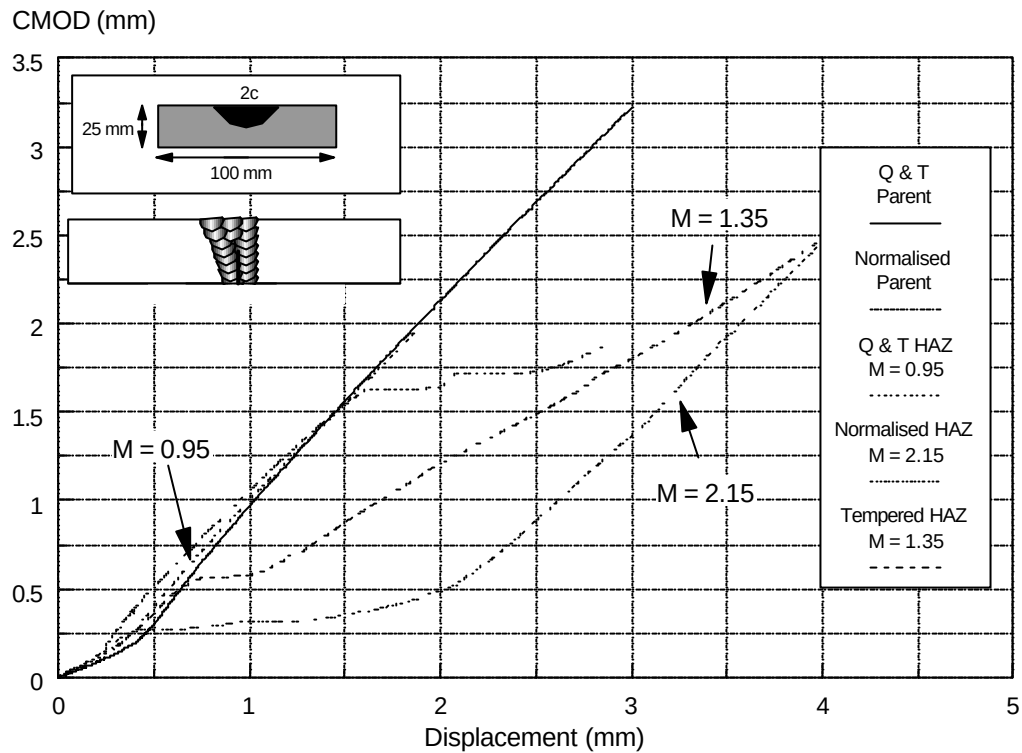


FIG. A103

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - SURFACE
NOTCH at 0.5, at 0.5 - NOTCH AT WELD CENTRELINE

(D0697E31)

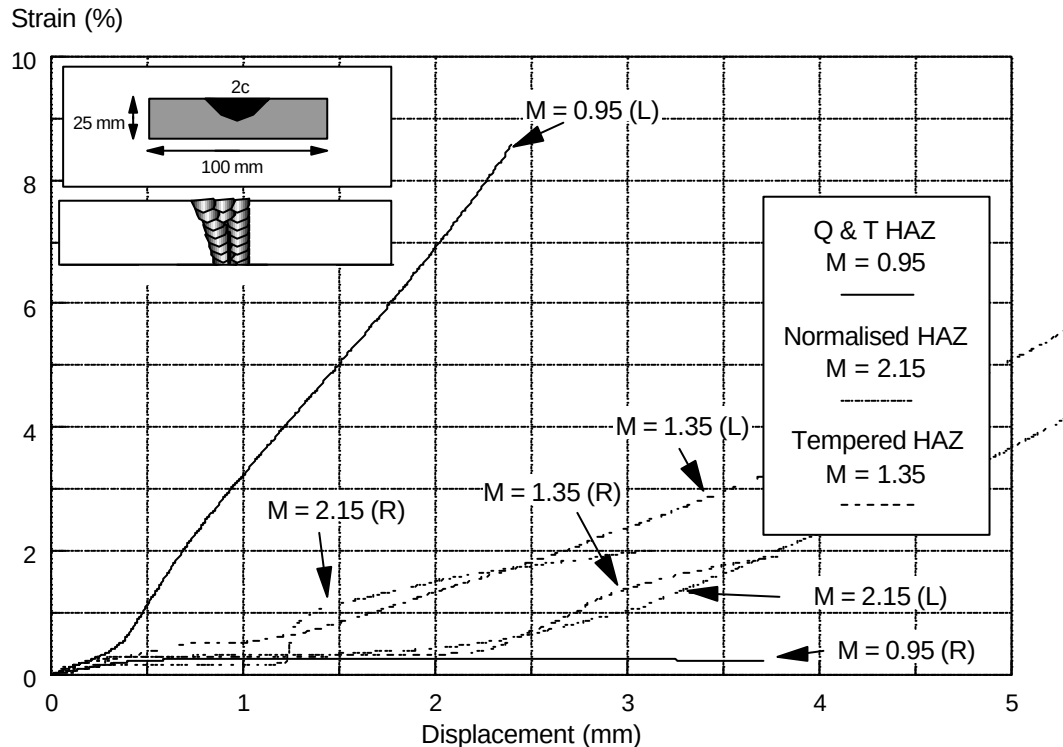


FIG. A104

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW
WELDS - TRANSVERSE - SURFACE NOTCH at 0.5,
at 0.5 - NOTCH AT WELD CENTRELINE

(D0697E31)

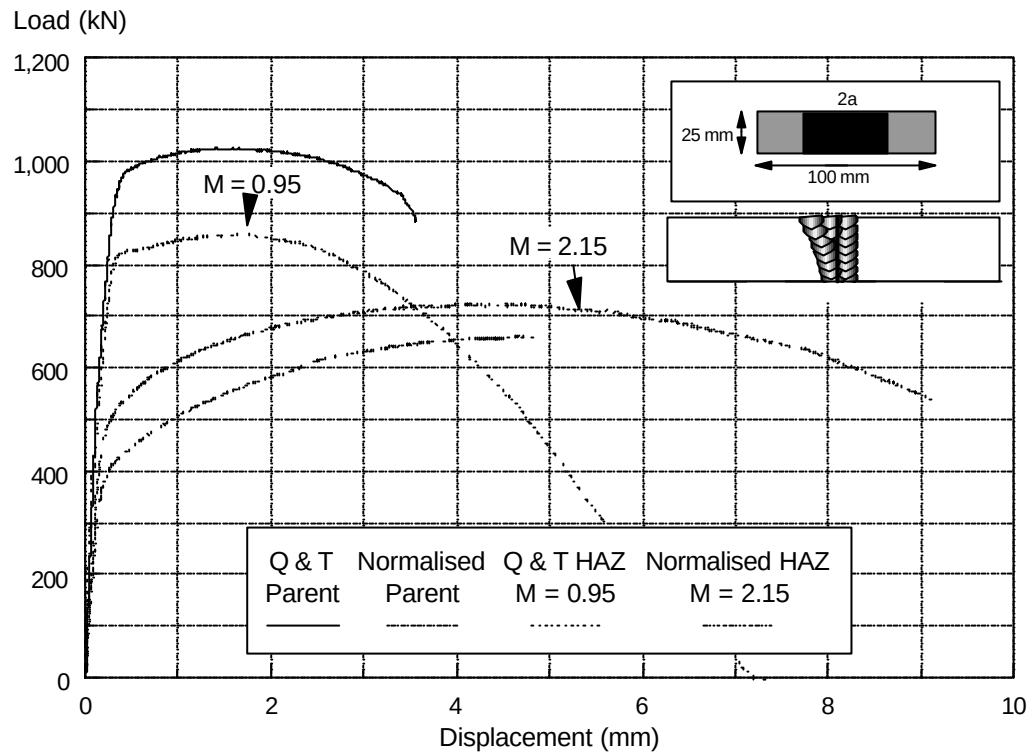


FIG. A105

OCT TEST LOAD vs DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE - THROUGH
THICKNESS NOTCH at=1 - NOTCH AT WELD CENTRELINE

(D0697E31)

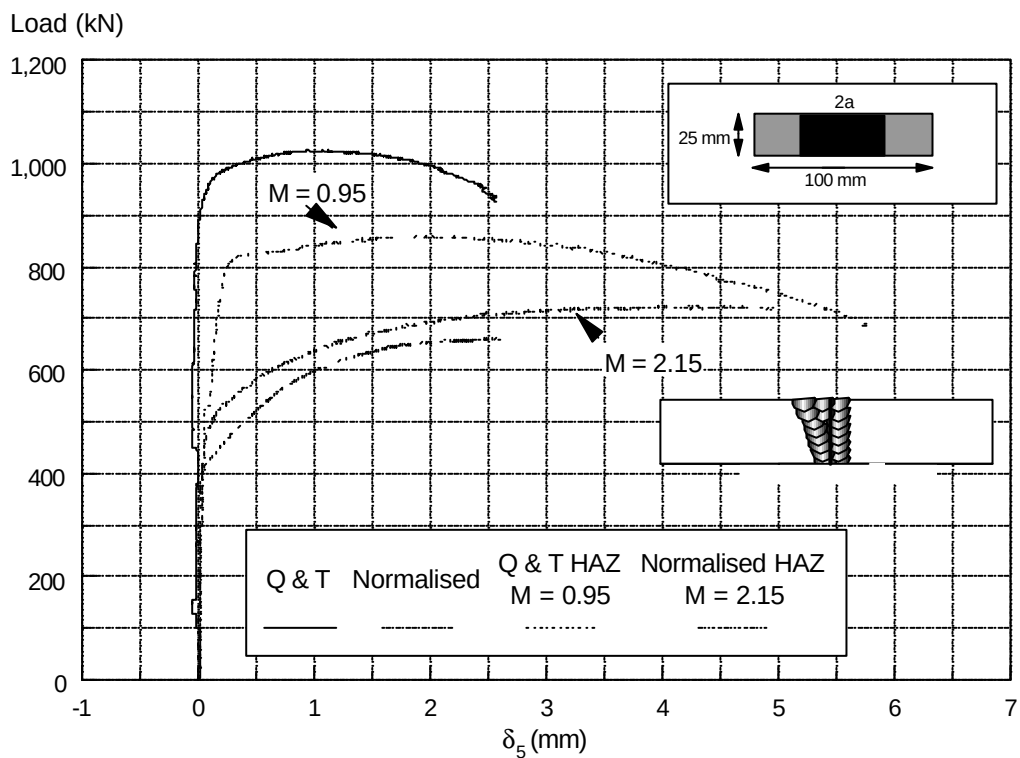


FIG. A106

OCT TEST LOAD vs d_5 DATA FOR PARENT MATERIALS AND
FCAW WELDS - TRANSVERSE - THROUGH THICKNESS
NOTCH at=1 - NOTCH AT WELD CENTRELINE

(D0697E31)

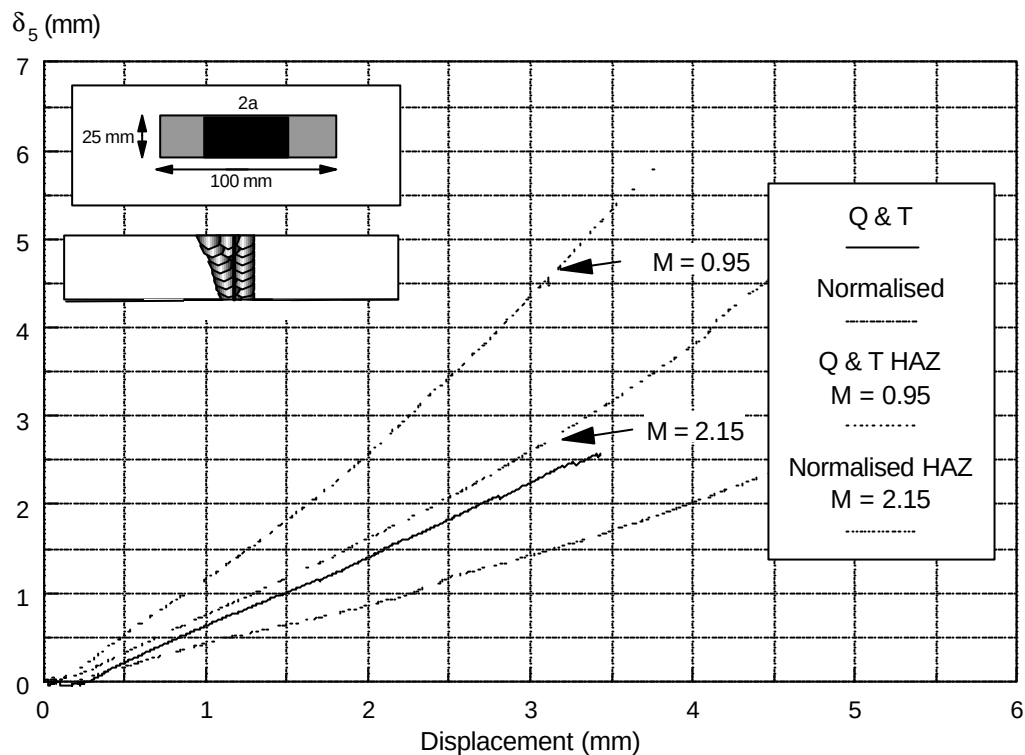


FIG. A10.7

OCT TEST δ_5 v DISPLACEMENT DATA FOR PARENT MATERIALS
AND FCAW WELDS - TRANSVERSE - THROUGH THICKNESS
NOTCH $a/t = 1$ - NOTCH AT WELD CENTRELINE

(D0697E31)

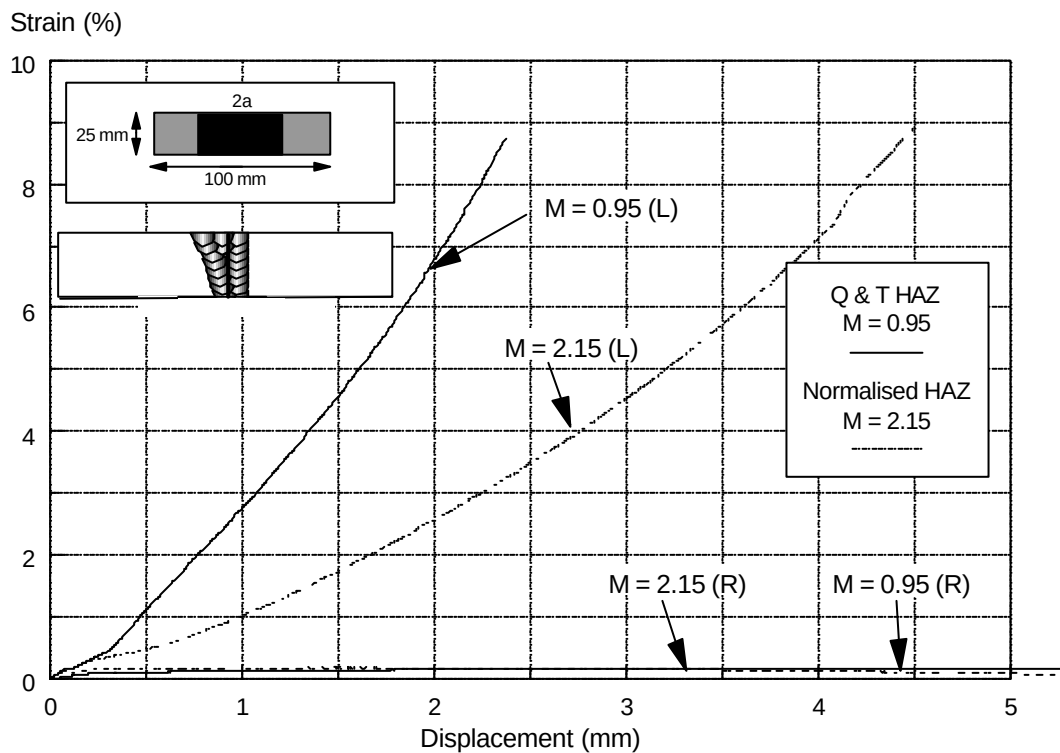


FIG. A10.8

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW
WELDS - TRANSVERSE - THROUGH THICKNESS
NOTCH $a/t = 1$ - NOTCH AT WELD CENTRELINE

(D0697E31)

APPENDIX 11

**CENTRE CRACKED TENSILE TEST DATA FOR
TESTS NOTCHED AT FCAW HAZ**

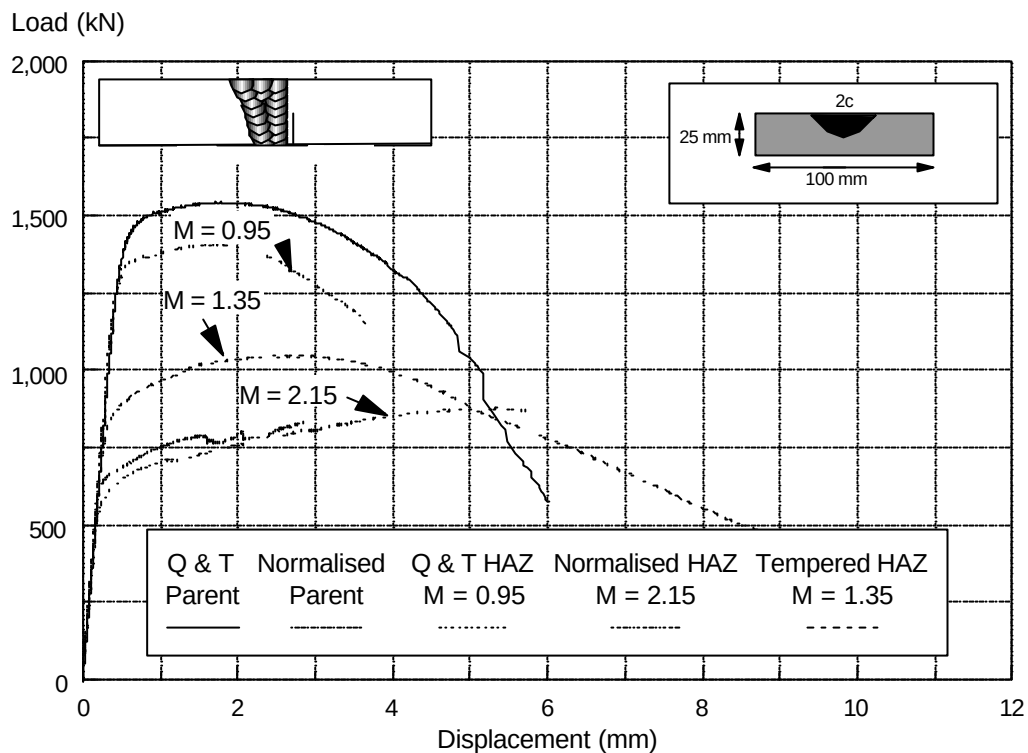


FIG. A11.1

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE -
SURFACE NOTCH, at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E33)

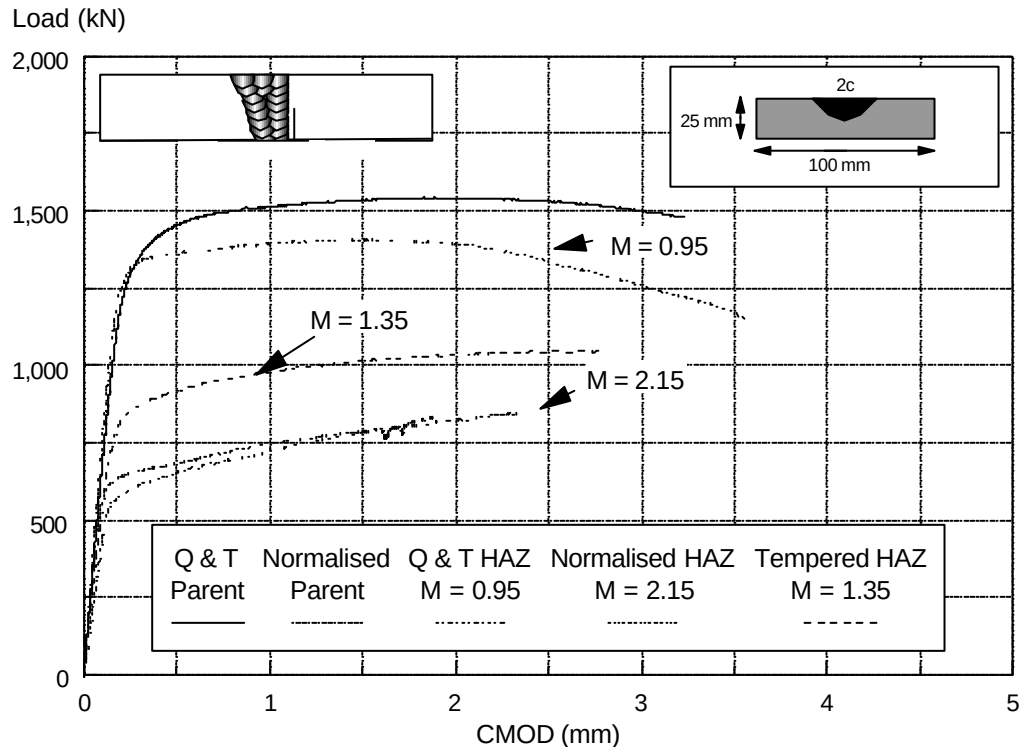


FIG. A11.2

OCT TEST LOAD v CMOD DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE -
SURFACE NOTCH, at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E33)

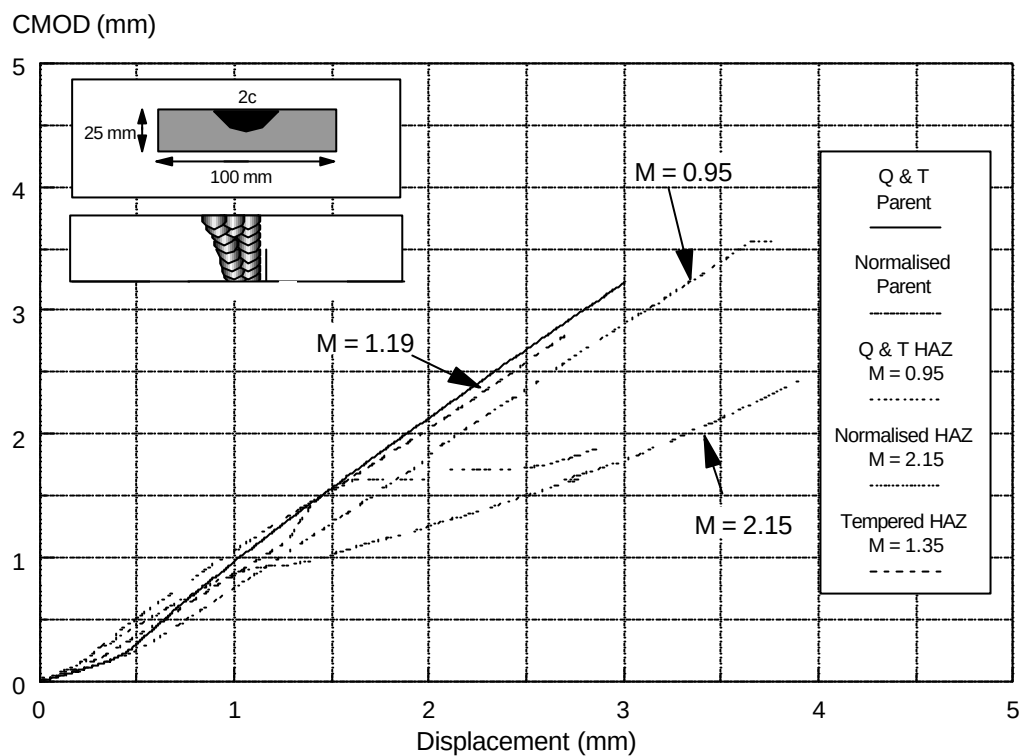


FIG. A113

OCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND FCAW WELDS - TRANSVERSE -
SURFACE NOTCH, at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E33)

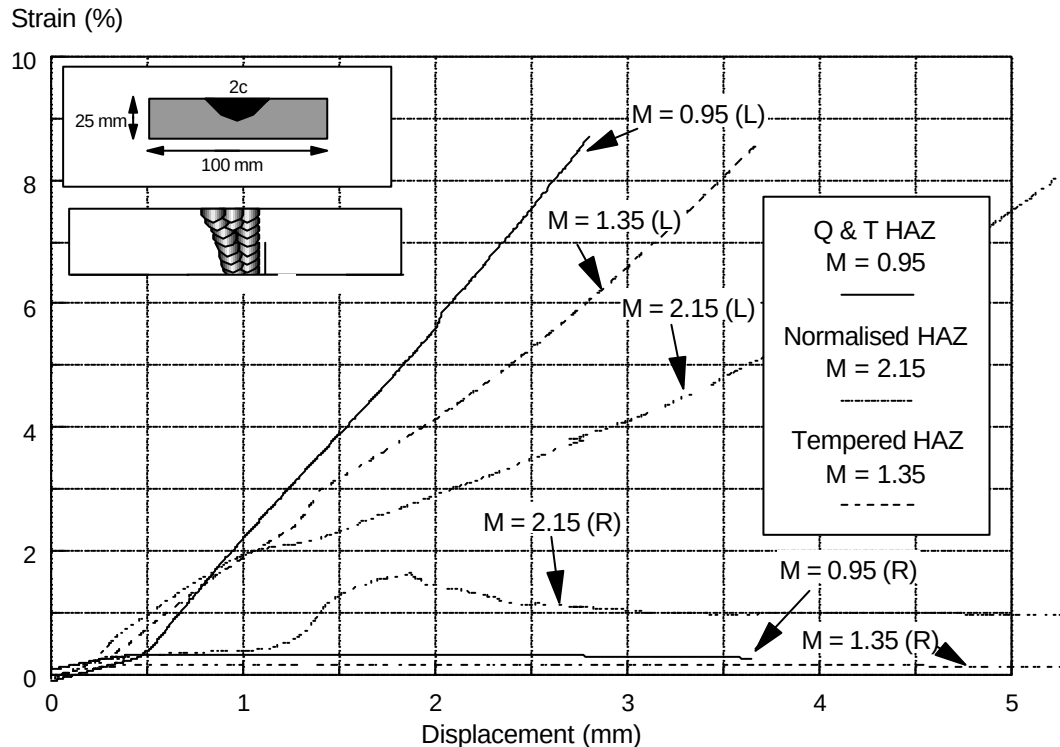


FIG. A114

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW
WELDS - TRANSVERSE - SURFACE NOTCH, at 0.5,
ac 0.5 - NOTCH IN HAZ

(D0697E33)

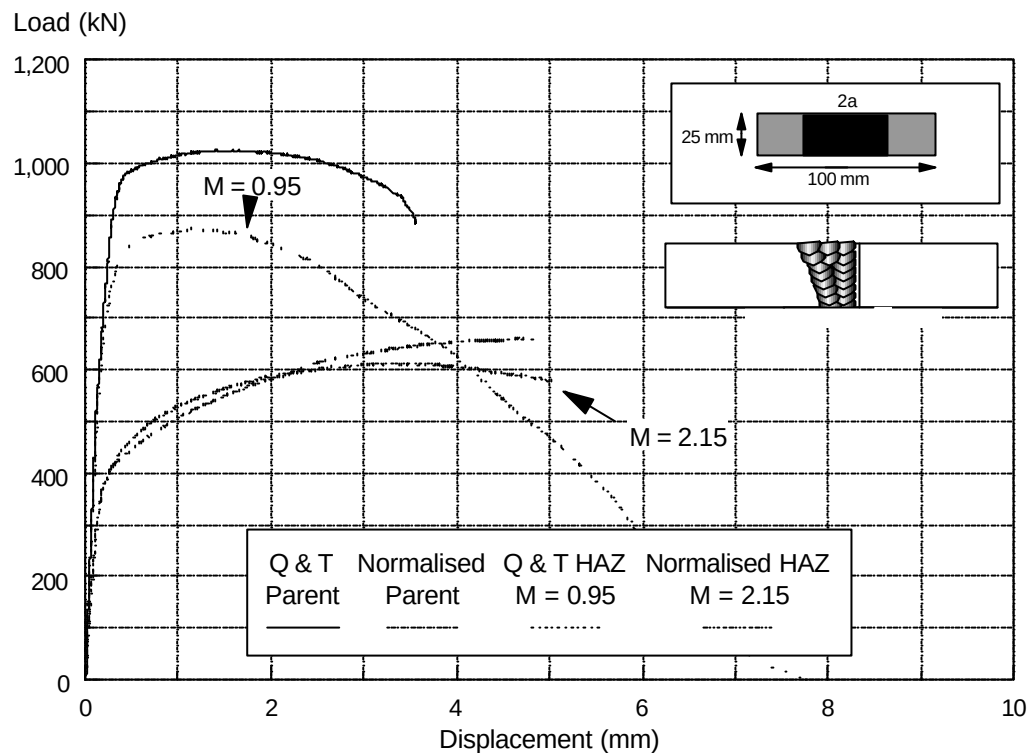


FIG. A115

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE - THROUGH THICKNESS NOTCH, $a/t=1$ - NOTCH IN HAZ

(D0697E33)

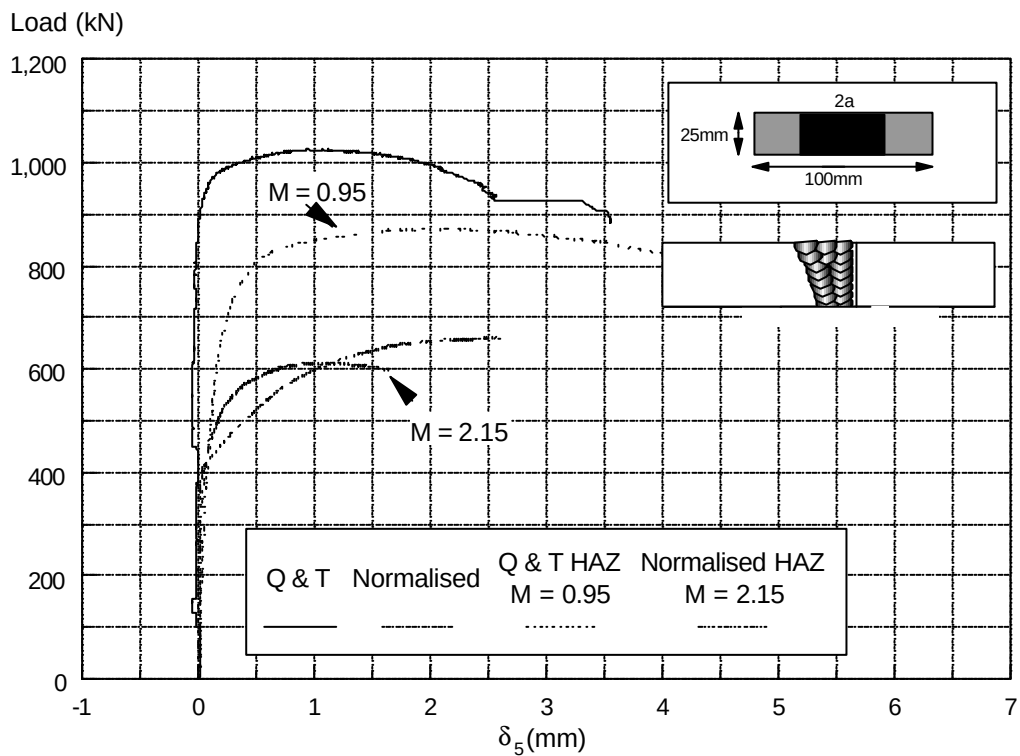


FIG. A116

OCT TEST LOAD v d_s DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE - THROUGH THICKNESS NOTCH, $a/t=1$ - NOTCH IN HAZ

(D0697E33)

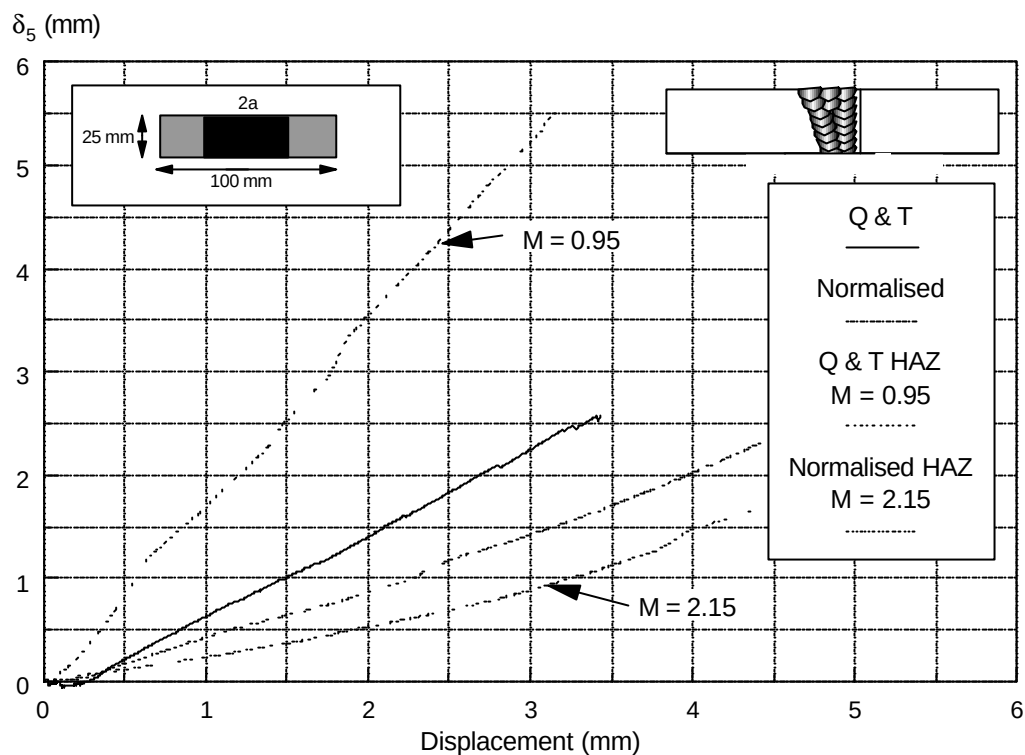


FIG. A117

OCT TEST d_5 v DISPLACEMENT DATA FOR PARENT MATERIALS AND FCAW WELDS - TRANSVERSE-THROUGH THICKNESS NOTCH, $a/t=1$ - NOTCH IN HAZ

(D0697E33)

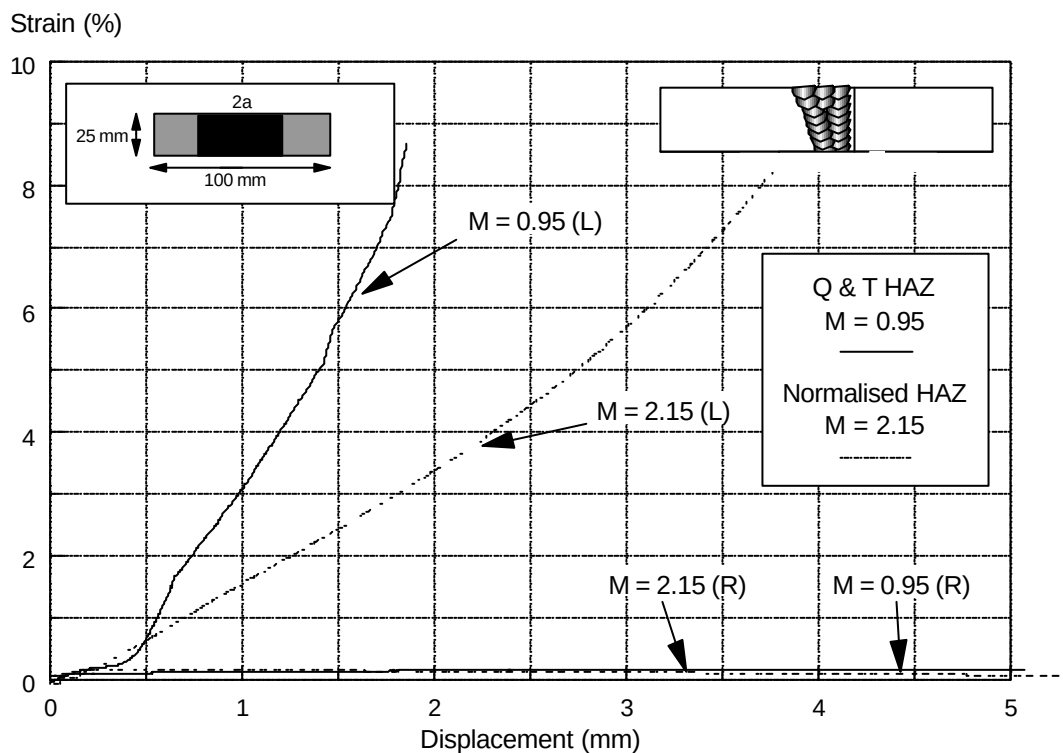


FIG. A118

OCT TEST STRAIN v DISPLACEMENT DATA FOR FCAW WELDS - TRANSVERSE-THROUGH THICKNESS NOTCH, $a/t=1$ - NOTCH IN HAZ

(D0697E33)

APPENDIX 12

**CENTRE CRACKED TENSILE TEST DATA FOR
TESTS NOTCHED AT SAW HAZ**

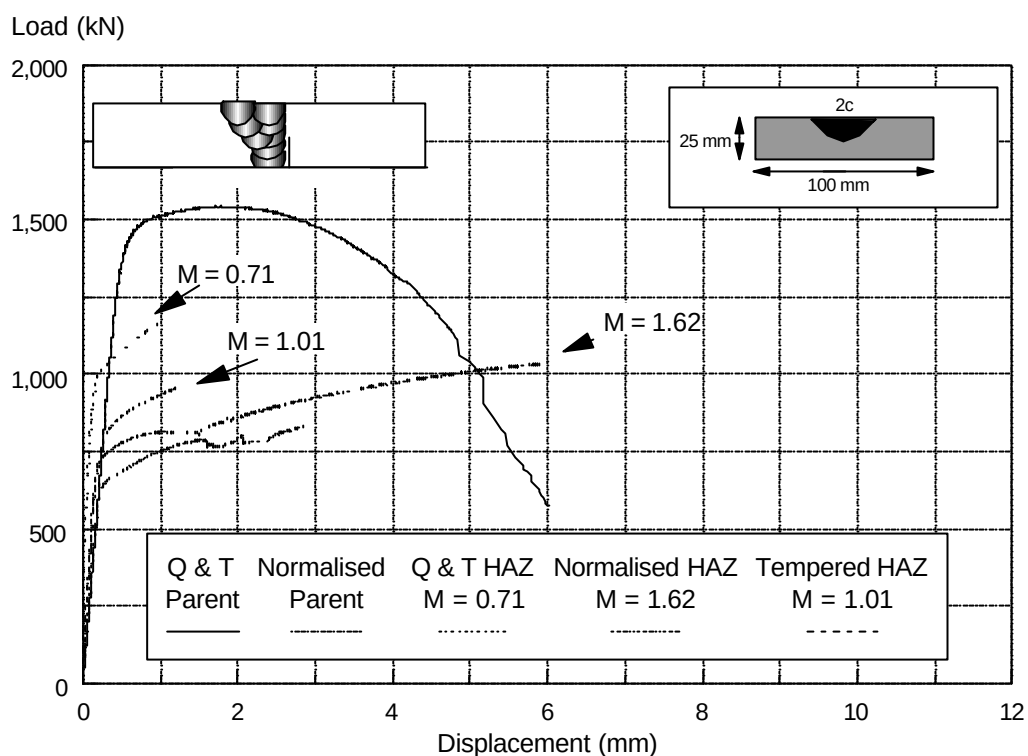


FIG. A121

OCT TEST LOAD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND SAW WELDS - TRANSVERSE -
SURFACE NOTCH, at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E35)

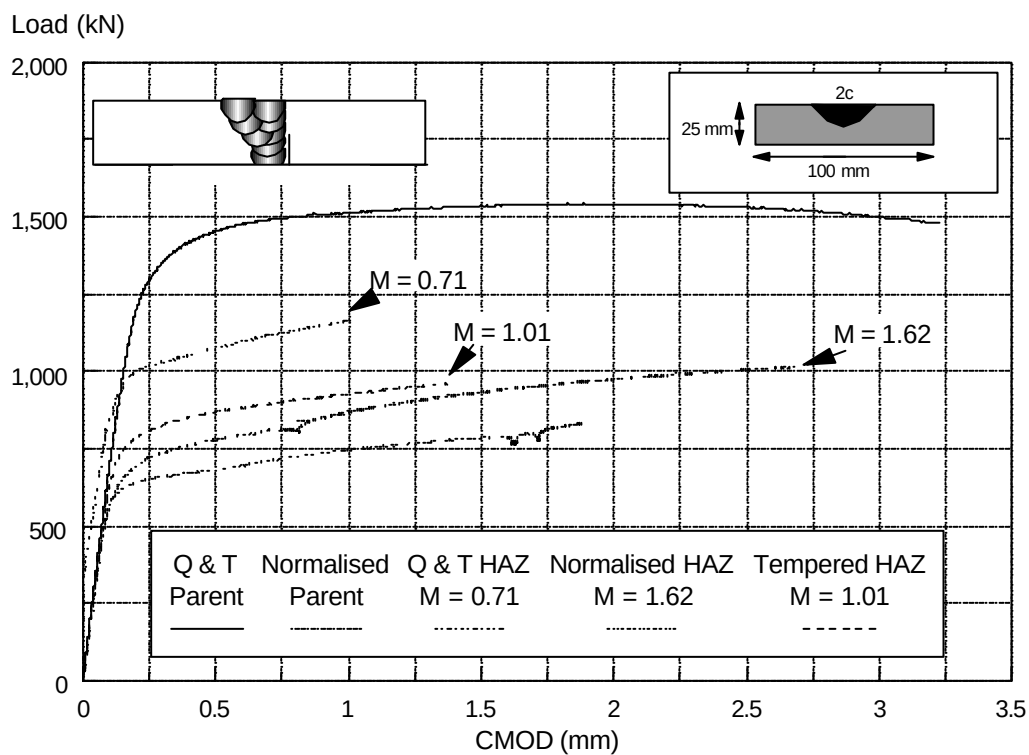


FIG. A122

OCT TEST LOAD v CMOD DATA FOR PARENT MATERIALS
AND SAW WELDS - TRANSVERSE - SURFACE NOTCH,
at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E35)

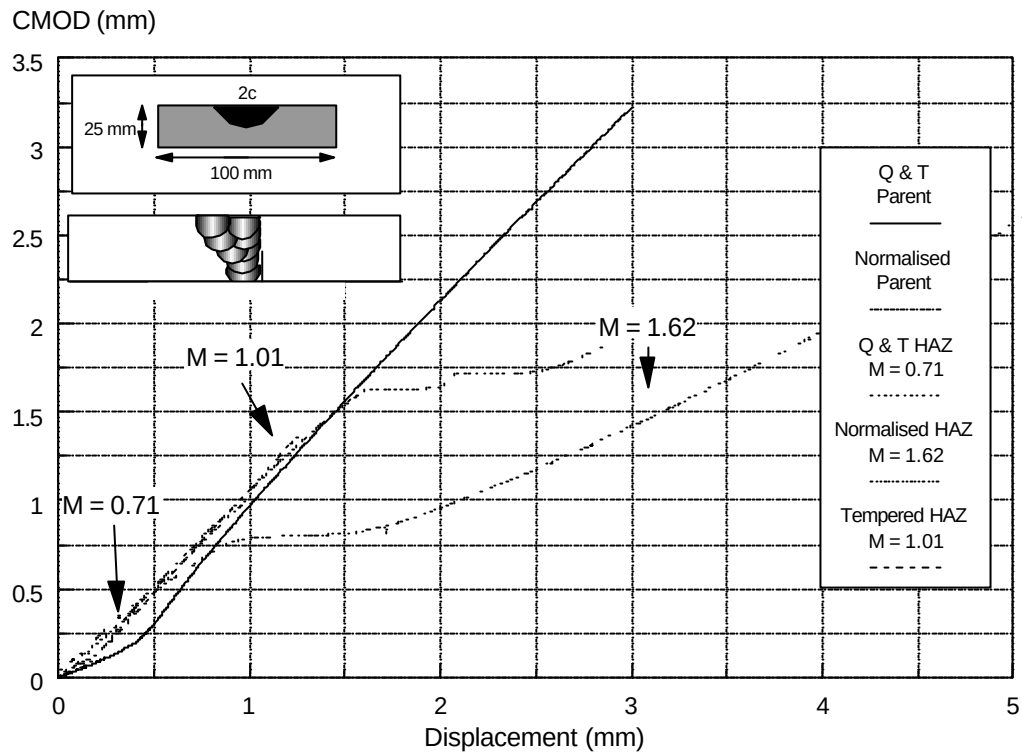


FIG. A123

CCT TEST CMOD v DISPLACEMENT DATA FOR PARENT
MATERIALS AND SAW WELDS - TRANSVERSE -
SURFACE NOTCH, at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E35)

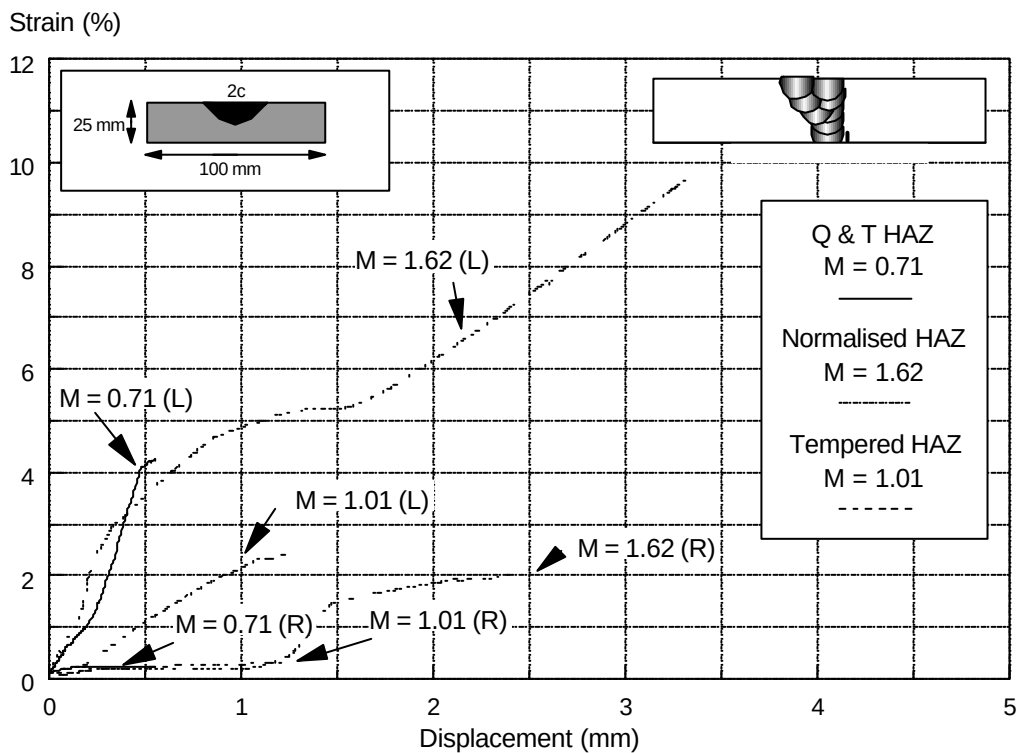


FIG. A124

CCT TEST STRAIN v DISPLACEMENT DATA FOR SAW
WELDS - TRANSVERSE - SURFACE NOTCH,
at 0.5, ac 0.5 - NOTCH IN HAZ

(D0697E35)

APPENDIX 13

MICRO-TENSILE TESTING OF MULTIPASS WELDS

SINTAP

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Task No:	1
Sub Task No:	1.3
Date:	February 1999
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Sub Task 1.3 Multi-Pass Weld Evaluation: Micro-Tensile Testing of Multi-Pass Welds

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SINTAP

Doc. Nr: SINTAP-GKSS-18

WELD STRENGTH MISMATCH EFFECTS:

MULTIPASS WELD EVALUATION

1 Introduction

SINTAP Sub Task 1.3 was set up to investigate the effects of weld strength mismatch in multipass C-Mn steel weld joints. Two weld joints (SAW and FCAW representing high and low heat input welding processes) prepared by the British Steel were sent to the GKSS for preparation and testing of the micro flat tensile (MFT) specimens, Figure 1. The objective of these tests was to determine the tensile property variation across the weld joint and hence to establish the true strength mis-match level(s) between multipass weld deposit (WM) and base metal (BM) as well as between HAZ and other parts of the weld joints. Furthermore, it is aimed to make comparisons between the tensile results obtained from simulated HAZ and real HAZ regions. It is also intended to establish the hardness vs. strength relationship for the weld joints which can be used to determine the strength of the HAZ regions.

This report includes the results of the SAW weld joints manufactured using SD3 1Ni1/4Mo wire with OP121TT flux on 25 mm thick steel plates in three conditions.

SAW weld metal tensile properties as determined from standard round all-weld metal tensile specimens at BS:

YS= 480 MPa
UTS= 591 MPa
n= 0.147

FCAW weld metal tensile properties as determined from standard round all-weld metal tensile specimens at BS:

YS= 545 MPa
UTS= 619 MPa
n= 0.111

The **base plate conditions** prior to the welding and resulting tensile properties were:

1. **High Strength Level:** Quenched & Tempered: Reheating to 930°C for 50 min. prior to water quenching and tempering at 580°C for 1hr.

YS= 675 MPa
UTS= 753 MPa
n= 0.088

Mis-match ratio for **SAW** weld metal $M= 0.71$ (Undermatching)

Mis-match ratio for **FCAW** weld metal $M= 0.95$ (Undermatching)

2. **Medium Strength Level:** High Temperature Tempering at 675 °C for 1 hr.

YS= 475 MPa
UTS= 610 MPa
n= 0.117

Mis-match ratio for **SAW** weld metal $M= 1.01$ (Matching)

Mis-match ratio for **FCAW** weld metal $M= 1.35$ (Overmatching)

3. **Low Strength Level:** Normalising heat treatment at 900°C for 1hr.

YS= 297 MPa
UTS= 510 MPa
n= 0.239

Mis-match ratio for **SAW** weld metal $M= 1.62$ (Overmatching)

Mis-match ratio for **FCAW** weld metal $M= 2.15$ (Overmatching)

Further details of the welding & PWHT conditions and standard mechanical testing results are already reported in SINTAP/BS/24.

2 Micro Flat Tensile (MFT) Testing:

The variation in local tensile properties of the joints was determined by extracting (EDM machining using 0.2 mm Cu-wire) and testing of large numbers of micro flat tensile specimens at room temperature. Figure 1 shows the basic principles of this testing procedure and specimen dimensions.

2.1 SAW welded Q&T high strength steel weld joint:

The results of the SAW welded Q&T high strength steel weld joint are given in Figure 2. The yield ($R_{p0.2}$) and ultimate tensile (R_m) strength values as well as strain to fracture values are plotted against specimen number (location). The results are clearly showing the presence of significantly wider and lower strength HAZ region due to high heat input process. The lowest yield strength level for the HAZ is about 380 MPa. This level yields a strength undermatching between base and HAZ region of 0.56 which is much lower than the mismatch level ($M=0.71$) between weld and base metals. The strength vs. hardness data developed by BS using thermal simulated specimens reveals the peak yield strength level for the CGHAZ for the SAW welds approx. 510 MPa. However, this level can not yet be confirmed and the second set of specimen results (currently at progress) will provide further data for this purpose.

These results are also confirming the BS results with respect to **undermatching** level (approx. 0.71) of the weld metal which exhibits a yield strength level of 480 MPa. Furthermore, no significant yield strength peak (for the CGHAZ) adjacent to the fusion line was observed in this specimen set. The results of the second set (W7K102-2) of specimens will confirm this trend.

The diagram also gives for each specimen the lower yield strength (R_{eL}) values (open symbols) which may slightly lower the curves at some locations.

The ultimate tensile strength (R_m) profile of the weld joint follows very similar trend as of yield strength distribution across the weld.

2.2 SAW welded normalised lower strength steel weld joint:

Figure 3 presents the strength and respective ductility across the weld joint of lower strength base metal (normalised+PWHT). The peak value of yield strength (approx. 560 MPa) was obtained for the CGHAZ region. This value is higher than the mean CGHAZ strength value of 510 MPa obtained from hardness vs. strength correlation at BS. Consequently the lower level (10%) of strain to fracture value was obtained for the MFT specimen extracted from the microstructure adjacent to the fusion line.

The strength gradient obtained for HAZ region presents the minimum yield strength of approx. 320 MPa for softened HAZ region which is slightly higher than the base metal yield strength of 297 MPa. Complete trend of strength distribution towards base plate will be confirmed or adjusted by the results of second set of specimens which is currently in evaluation stage. The arrows at the end of the yield strength distribution curves are indicating an expected trends.

The weld metal strength level obtained from MFT specimens, in average slightly lower than the levels (YS of 480 MPa and UTS of 591 MPa) obtained by using standard round tensile specimens at BS. Naturally, the MFT specimens are capable to identify local microstructural variations due to the columnar and refined/reheated weld metal regions.

Figure 3 again provides for each specimen the lower yield strength (R_{eL}) values (open symbols) which may slightly lower the curves at some locations.

2.3 SAW welded tempered medium strength steel weld joint:

Figure 4 presents a similar fashion as Figures 2 and 3, the results for medium strength level steel. For this steel weld joint, unfortunately, the first set of specimens did not reveal full HAZ strength profile due to sectioning mistake of MFT specimens. Most of the specimens were obtained for the weld metal. However, the peak strength level obtained for the CGHAZ region which gives the yield strength of 580 MPa. The HAZ strength profile will be completed with the second set of results.

The weld metal region (particularly at the middle of the weld) exhibits higher yield strength level (approx. 530 MPa) than the level determined by round tensile specimens as 480 MPa. Consequently, the level of strength mismatch established for this weld joint could be influenced and higher strength region of the SAW weld metal may lead to the undermatching condition.

3. Conclusions (Tentative)

Partial results of the micro flat tensile (MFT) specimens for the SAW process welded three steels are reported. Approximately 90 MFT specimens were tested at room temperature for determination of the strength gradient of the HAZ region of multipass welds.

The results are clearly indicating the softening nature of the real HAZ regions for all three steels and MFT specimen technique can provide the YS, UTS and strain data for respective locations.

It is shown that the hardness vs. strength correlation method used for determination of the HAZ (FL to FL+2.5 mm region) strength level can not provide real strength level of the HAZ. The minimum HAZ yield strength level determined so far (for Q&T and normalised steels) is varying between 310 MPa to 370 MPa). Therefore, an average HAZ strength level of 430 MPa given in BS report SINTAP/BS/24 is non conservative.

4. Current Work

The evaluation of the tested MFT and SENB specimens for SAW and FCAW welds are in progress. Final report will cover all these results.

Acknowledgement

We wish to acknowledge the technical assistance of Mr. H. Mackel for his careful preparation work and help to testing of large numbers of MFT specimens.

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M. Koçak

8th February 1999

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Doc. Nr: SINTAP-GKSS-18

Sub Task 1.3 Micro Tensile Testing of SAW Multi-Pass Welds

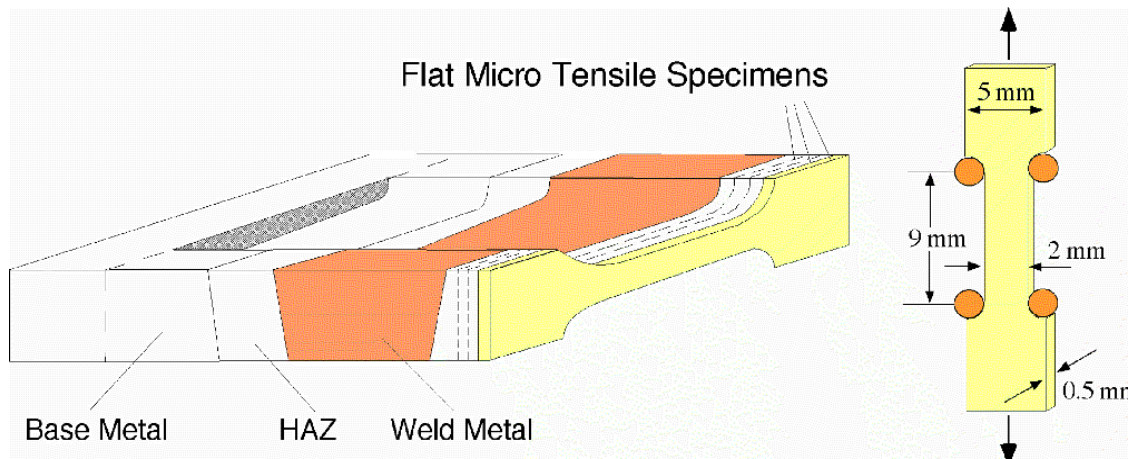


Figure 1. Extraction and testing principles of the flat micro tensile specimens to determine local variations and distributions of the tensile properties across the weld joint.

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Sub Task 1.3 Micro Tensile Testing of SAW Multi-Pass Welds

Base Plate: Q&T+PWHT

Consumables SD3 1Ni1/4Mo wire with OP121TT flux +PWHT

WELD No: W7K102-Set 1

Condition: UNDERMATCHING (UM)

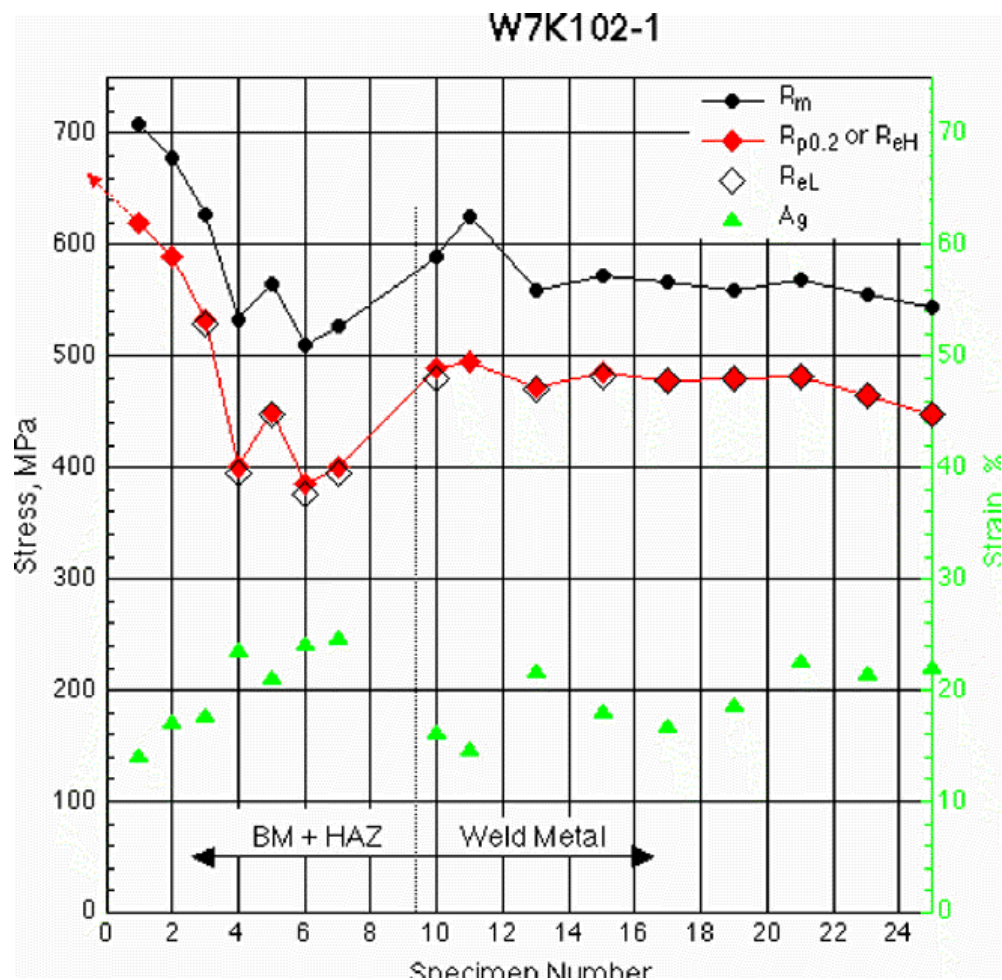


Figure 2. Distribution of the tensile properties across the SAW weld of Q&T steel

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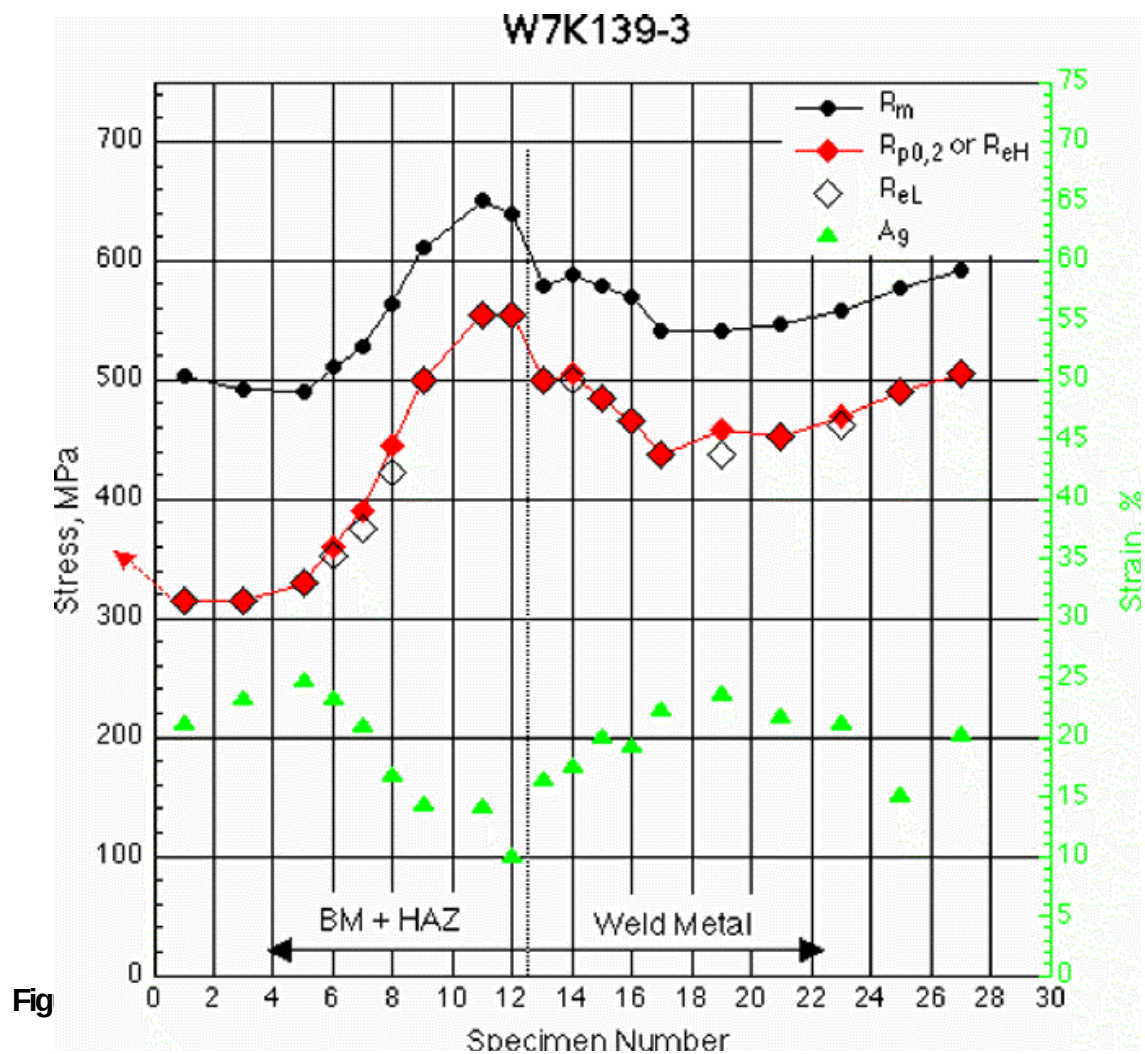
Sub Task 1.3 Micro Tensile Testing of SAW Multi-Pass Welds

Base Plate: Normalised+PWHT

Consumables: SD3 1Ni1/4Mo wire with OP121TT flux+PWHT

WELD No: W7K139-Set 3

Condition: OVERMATCHING (OM)



Fig

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Sub Task 1.3 Micro Tensile Testing of SAW Multi-Pass Welds

Base Plate: Tempered+PWHT

Consumables: SD3 1Ni1/4Mo wire with OP121TT flux+PWHT

WELD No: W7K140-Set 5, **Condition:** MATCHING (M)

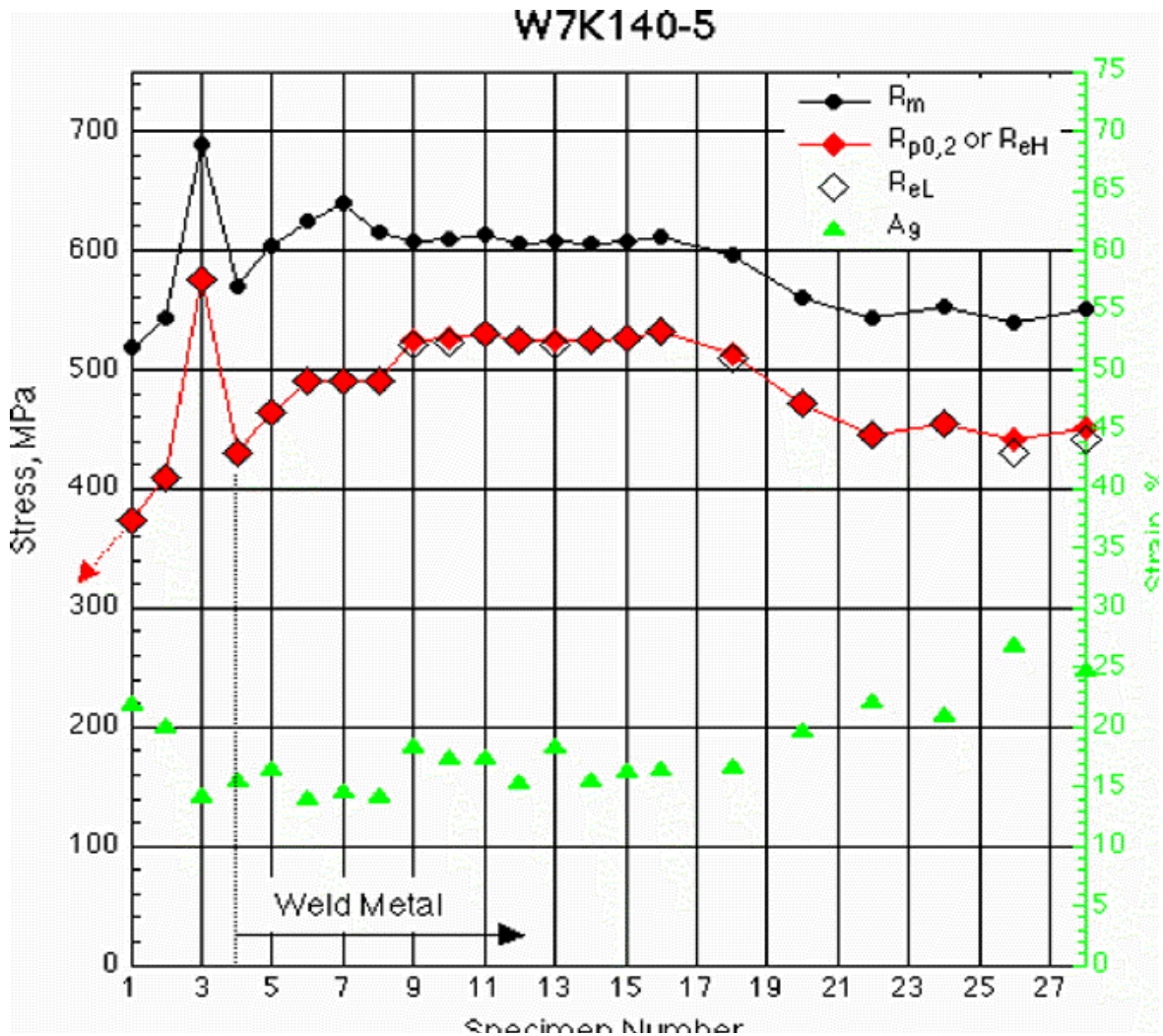


Figure 4. Distribution of the tensile properties across the SAW weld of tempered steel