# Effect of Al and N on fracture properties of Ti-B containing weld metals

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# EFFECT OF Al AND N ON FRACTURE TOUGHNESS PROPERTIES OF Ti-B CONTAINING WELD METALS

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## 1.0 INTRODUCTION

Within the framework of an on-going programme to evaluate the influence of micro-alloying elements in ferritic manual metal arc deposits, a series of studies have been carried out investigating initially the individual effect of Al, Ti, B, V and Nb [1] and later on the interactive phenomena in alloying systems such as Ti-Al [2] and Ti-B [3]. However, the results of an extensive literature survey [4] and the practical aspects related to the application of the SMAW process indicated the need to extend the programme to include a systematic evaluation of the effect of nitrogen on the weld metal metallurgical and mechanical properties. The experimental matrix employed in the latter part of this research programme (i.e. the influence of alloying systems and nitrogen) is presented in Figure 1.

In a series of previous investigation [5-8] jointly conducted by the GKSS Research Centre and Oerlikon-Welding Ltd., the effects of nitrogen and strain ageing on the microstructure and fracture properties of ferritic shielded metal arc (SMA) weld metals were studied. These studies revealed that increasing the nitrogen content in specially prepared weld metals (containing no nitride former elements, i.e. Ti, B and Al) resulted in a drastic reduction of fracture toughness properties associated with a coarser microstructure (decrease in acicular ferrite-AF with the associated increase in grain boundary primary ferrite-PF and ferrite with second phase-FS) and a high amount of free nitrogen which causes dislocation pinning during deformation. The results of wide plate tests [8] suggest that the sensitivity of the Charpy-V impact and CTOD tests to static strain ageing and to the amount of nitrogen is rather high. For assessing the structural significance of strain ageing and nitrogen in welds and for developing the consumables, the Charpy-V impact and CTOD test results can give a very conservative bias.

Further investigations evaluated the fracture properties of C-Mn weld metals containing Ti at three nitrogen levels, i.e. 80 ppm, 160 ppm and 240 ppm [9]. The results of this study showed that increasing the amount of nitrogen in the welds leads to a coarser microstructure and to a significant increase in the amount of grain boundary ferrite (FS). Furthermore, increasing the Ti content from essentially Ti-free and non-acicular weld deposit to weld deposit containing a small amount of Ti resulted in a much finer microstructure with a large amount of intragranular AF which provides very good fracture toughness. A further increase of Ti causes coarser microstructures containing an increased amount of grain boundary ferrite (FS). Higher nitrogen levels increased both yield and tensile strength but caused a general deterioration of both Charpy-V impact and CTOD toughness values. In addition it was concluded that for nitrogen and titanium effects on toughness' properties, the standard CTOD test and the Charpy-V notch impact test responded similarly.

In a recent work the effect of Al and N on Ti-B weld metals on microstructure and the mechanical properties has been investigated [10]. In essence, the experiments consisted of adding aluminium, at three levels of nitrogen, to composition Y(400 Ti, 40 B), as depicted by the thick lines in Figure 1. In addition to Y, particular metallographic attention was directed towards an intermediate and a high level of aluminium, designated respectively as Z and V. The obtained results showed that the notch toughness of the deposits was dramatically affected by the interplay between Al and N and that the observed behaviour should be further investigated using a fracture mechanics approach to define the relative susceptibility of different compositional variants to embrittlement. Hence, the aim of the present study was to extend the above mentioned investigations on the fracture toughness properties to the Ti-B-Al alloying system at three levels of nitrogen.

## 2.0 EXPERIMENTAL PROCEDURE AND MATERIALS

### 2.1 Electrodes and Weld Preparation

For the standard condition different amounts of aluminium powder were added to the coatings of six basic low hydrogen Ti-B SMA electrodes. A further two sets of electrodes were prepared, with a variable fraction of the manganese metal in the dry mix being replaced with the equivalent amount of nitride manganese metal containing 7% N. The proposed aim was thus to achieve a balanced range of consumables giving three distinct levels of nitrogen in the deposits, namely 80, 160 and 240 ppm. The electrodes were extruded onto 4 mm diameter "rimmed" steel core wire (25 ppm N), using a coating factor (D/d) of 1.68.

The joint geometry was that specified in ISO 2560-1973. Welding was done in the flat position and three beads per layer were deposited. The total number of runs required to fill the individual joints prepared on the 20 mm thick mild steel was 27. Direct current (electrode positive) was employed, the amperage being 170 A, the voltage 21 V and the heat-input nominally 1 kJ/mm. The interpass temperature was standardised at 200 °C.

### 2.2 Mechanical Testing

All weld metal tensile specimens were machined and tested at room temperature for each of the 18 weld metals. Approximately 35 Charpy-V notch specimens were also tested in each case to obtain full transition curves. 17mm thick three point bend specimens (SENB) were extracted from the mid-thickness of the weld joints. The CTOD specimens were the B x 2B type and notched through the thickness direction at mid-weld position. The standard CTOD tests were carried out on nine weld metals (i.e. namely, Y, Z and V series) in the as-welded condition at room temperature and -20°C.

### 2.3 Metallography

Transverse sections of the welds were prepared and optical examination was carried out on the top beads and on the adjacent intercritically reheated zones. The top central bead of each of the weldments was optically examined and metallographic measurements were made, following the current guidelines [11] of IIW Sub-Commission IX-J, to quantify the major microstructural components, namely:

- Primary ferrite (PF)
- Ferrite with second phase (FS)
- Acicular ferrite (AF)

## 3.0 RESULTS AND DISCUSSION

### 3.1 Weld Metal Chemical Composition

Table 1 presents the chemical analysis results of 21 weld metals prepared by Oerlikon Welding Ltd.. The weld metals are divided into three sets with respect to the nominal total nitrogen levels of 80 ppm, 160 ppm and 240 ppm with varying aluminium contents.

Weld metal carbon and manganese contents were successfully balanced for different Al contents. Ti and B contents also remained substantially constant. Due presumably to the effects of aluminium vapour on the partial pressure in the arc atmosphere [2,13] the aimed nitrogen contents for the first and second series were not achieved. The average contents measured were: 65 ppm (level N), 130 ppm (level N1) and 240 ppm (level N2).

The weld metal oxygen content increased with increasing Al content up to about 300 ppm Al regardless of the titanium or nitrogen level (Figure 2). Silicon contents steadily increased indicating a reduced involvement in the deoxidation process with increasing Al contents. As mentioned above aluminium caused an imbalance in the weld metal oxygen level (Figure 2) and this should be borne in mind when assessing the changes in microstructure and properties.

## 3.2 Metallographic Examination

Figures 3, 4 and 5 present the results of the metallographic examination. In general terms it could be said that with increasing nitrogen in the weld the amount FS increased mostly at the expense of the AF. The combined effect of Al and N is however more complex. At the highest nitrogen level (app. 240 ppm) the amount of PF remained approximately constant at about 10% regardless of the aluminium content. The volume fraction AF on the other hand decreased up to 200 ppm Al, steadily increasing thereafter reaching 60% for 560 ppm Al. At the lowest and intermediate nitrogen levels Al promoted the formation of FS to values of approximately 35% at the highest Al content. In this process the amount of PF has been reduced to nearly nil. A similar suppression of PF has also been observed for Ti-B weld metals (Ti $\geq$ 120 ppm,) with increasing B contents [3]. Some of these changes are illustrated in Figures 6 and 7 for welds at low and high nitrogen contents. It is seen that aluminium addition at the normal nitrogen level led initially to the refinement of acicular ferrite (Z) and then ultimately to the coarsening (V), with a change in the aspect ratio of the laths. In addition, large cubic particles, previously identified as Al-Ti compounds [2], were again detected. The addition of nitrogen to the aluminium free weld (Y2) induced the formation of PF and a classical side plate structure. Also, Z2 contained PF but associated with a very coarse degenerate form of ferrite with second phase. Similarly, V2 in comparison to V, revealed PF and a refined acicular ferrite associated with a lesser amount of aligned second phase. Continuous, well defined sub-cell boundaries were only observed in the low nitrogen deposits.

Equivalent photomicrographs of the high temperature reheated region, directly below the top central bead, are shown in Figure 8. The addition of aluminium again caused a refinement in Z and then finally led to the formation, in V, of aligned microphases with little trace of ferrite envelopes at grain boundaries; which were otherwise well defined. The addition of nitrogen to the aluminium free weld increased the size of the pro-eutectoid ferrite envelopes. Similarly, a coarsening was encountered in Z2, with the interiors of the prior austenite grains transforming to FS. In contrast, a comparison of V and V2, shows the opposite effect, the grain interiors this time reverting from FS to an acicular type structure.

Increasing aluminium and nitrogen also modified the microstructure of the low temperature reheated region, as seen in Figure 8. An intermediate amount of aluminium (Z) caused grain refinement, whereas high Al content (V) led to grain coarsening and to the formation of aligned microphase. Nitrogen addition modified the microphase morphology and, in particular, induced grain coarsening in Z2. Further work is currently underway to resolve these changes, as part of a wider investigation involving the complete Ti-B system.

## 3.3 Mechanical Properties

### 3.3.1 - Tensile Results

Table 2 presents the results of the tensile tests. Figures 9 and 10 present respectively the effect of aluminium on the weld metal tensile and yield strengths for the three distinct nitrogen levels. In general, increased nitrogen content resulted in reduced tensile and yield strengths implying that nitrogen obviates the strengthening potential of aluminium. Compared with its effect at the lower nitrogen level (where aluminium caused strengthening), aluminium had a minor influence on weld strength, except for a slight increase in tensile strength with increasing aluminium content at the intermediate nitrogen level (N1 ≈ 130 ppm).

### 3.3.2 Impact Results

Table 2 also lists the Charpy test temperatures at 28J and 100J for the different weld metal compositions. This data has been plotted against the aluminium content for the three distinct nitrogen levels and presented in Figure 11. As it can be seen the notch toughness of the deposits was dramatically affected by the interplay between Al and N, with the intermediate Al level being the most seriously degraded; the lateral shift for 100J being exactly + 100°C. At higher Al contents (≥ 250 ppm) a reversal took place and a cross-over occurred, such that for 560 ppm Al an optimum toughness was reached at the intermediate N level (N1 ≈ 130 ppm). In other words, adding nitrogen which increased the transition temperatures (i.e. 100J level) of the basic welds (i.e. Al < 13 ppm) but on the other hand, countered the harmful influence of aluminium above 130 ppm N and at 240 ppm N was wholly beneficial. Consequently, the 570 ppm Al weld with 230 ppm N was as tough as the zero aluminium weld with 130 ppm N and tougher than the 65 ppm N weld with an aluminium content of 570 ppm. Figure 11c shows both Charpy test temperatures for 28 J and 100 J plotted against the weld metal aluminium content. This Figure shows that for all three nitrogen levels a nearly constant lateral shift of ≈ 20°C exists along the aluminium compositional range studied.

## 3.4 Fracture Toughness

The CTOD values were directly measured across the fatigue crack tip (5 mm gage length) on the side surface of the SENB specimens. The CTOD ($\delta_5$) method developed at GKSS Research Centre provides intrinsic toughness values based on local measurement without the need to infer from remotely measured quantities. The CTOD ($\delta_5$) values obtained for all two test temperatures are shown in Table 3 in terms of crack initiation ($\delta_{0,2}$) and CTOD ($\delta_m$) values which correspond to the crack growth of 0.2mm and to the maximum load, respectively. Two tests were carried out for each weld.

The data in Table 3 indicates that the CTOD ($\delta_{0,2}$) values do not show a clear dependence on weld metal aluminium or nitrogen contents. The CTOD ($\delta_m$) values obtained at +20°C and -20°C are presented as a function of aluminium in Figures 12 and 13, respectively. At +20°C low nitrogen welds (N ≈ 65 ppm) show a minor improvement in toughness up to about 160 ppm Al and then a substantial drop to values of approximately 0,5mm at 580 ppm Al. The welds containing approximately 130 ppm N experienced a decrease in toughness of approximately 0,20mm up to 160 ppm Al; further increases in Al did not produce any changes in toughness. At the highest nitrogen level the measured CTOD values were basically not affected by the aluminium content. At this test temperature the observed behaviour resembles, to some extent, that observed in the impact test results (item 3.3 above).

The CTOD ($\delta_m$) values obtained at -20°C (Figure 13) however displayed some unexpected trends. First of all the best results were recorded by the intermediate nitrogen level regardless of the Al content. A further increase in N (to level N2 ≈ 230 ppm) resulted in a substantial loss of toughness reaching a maximum at the intermediate Al (160 ppm) welds which led to a lateral shift of about 1,0mm. Increasing the Al content at this nitrogen level promoted a given recovery in toughness. The complex behaviour observed for the specimens Z is further illustrated in Figure 14 which presents the CTOD ($\delta_m$) results as a function of the nitrogen content for the specimen groups Y, Z and V.

Comparing the results obtained in the impact and toughness tests it is apparent that for the highest Al content (composition V, Al ≈ 570 ppm) the best results were achieved at intermediate N1 level followed by N2 and N. The same relative ranking can also be observed for the composition Y (Al < 13 ppm). The results of the intermediate Al level show discrepancies which require further work to be clarified.

## 4.0 CONCLUSIONS

Based on the results obtained in this study the following conclusions can be drawn:
(1) The methodology adopted in this work for the preparation of experimental electrodes was successful to a great extent in achieving the aimed variations in weld metal compositions. The lower N levels were slightly below the aimed composition presumably due to the effects of Al on arc pressure. Weld metal oxygen and silicon generally increased with increasing Al. The oxygen levels however remained approximately constant at 470ppm for specimens with 300ppm Al and higher.
(2) The observed as-deposited microstructure were substantially affected by increasing Al and N. In general , high Al and N contents resulted in higher FS participation at the expense of AF. The highest N level (≈ 240ppm) stabilised PF at about 10% regardless of the Al content. The microstructure of re-heated regions was also modified, nitrogen inducing coarsening at intermediate Al levels and refinement with increasing Al.
(3) In general, increased nitrogen content resulted in a reduced tensile and yield strengths implying that nitrogen obviates the strengthening potential of aluminium.
(4) Increasing N levels resulted in a loss of notch toughness at lower Al contents reverting this trend at the highest Al level (specimen V). The intermediate Al level was the most seriously degraded by increasing N contents; the lateral shift for 100J being exactly + 100°C.
(5) The fracture toughness test results indicated a distinct behaviour of the three Al levels in the presence of N. Specimens of the series Y (low Al contents) experienced a degradation of toughness properties. On the other hand, in the presence of high Al contents the addition of N resulted in an improved toughness. At intermediate Al levels (specimen Z), nitrogen promoted a drastic degradation in toughness.
(6) In view of the sensibility of the intermediate Ti-B-Al combination to degradation, the N level of commercial consumables should be kept as low as possible.

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| N2 Level | Code | C (%) | Mn (%) | Si (%) | S (%) | P (%) | Ti (ppm) | B (ppm) | Al (ppm) | N (ppm) | O (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N | Y | 0,070 | 1,57 | 0,45 | 0,006 | 0,010 | 390 | 39 | 13 | 83 | 308 |
| | | 0,074 | 1,53 | 0,44 | 0,007 | 0,010 | 450 | 48 | 68 | 82 | 370 |
| | Z | 0,072 | 1,56 | 0,49 | 0,007 | 0,010 | 420 | 48 | 160 | 67 | 438 |
| | | 0,071 | 1,51 | 0,57 | 0,007 | 0,012 | 460 | 51 | 310 | 60 | 482 |
| | | 0,072 | 1,53 | 0,60 | 0,006 | 0,010 | 440 | 54 | 380 | 53 | 473 |
| | V | 0,078 | 1,44 | 0,60 | 0,006 | 0,007 | 540 | 56 | 580 | 41 | 440 |
| N1 | Y1 | 0,069 | 1,48 | 0,34 | 0,007 | 0,010 | 370 | 40 | 5 | 149 | 281 |
| | | 0,070 | 1,49 | 0,34 | 0,007 | 0,010 | 410 | 36 | 61 | 150 | 382 |
| | Z1 | 0,070 | 1,45 | 0,43 | 0,006 | 0,010 | 470 | 37 | 170 | 130 | 439 |
| | | 0,066 | 1,43 | 0,43 | 0,005 | 0,010 | 490 | 41 | 330 | 120 | 489 |
| | | 0,069 | 1,44 | 0,55 | 0,005 | 0,010 | 460 | 48 | 460 | 120 | 479 |
| | V1 | 0,067 | 1,44 | 0,63 | 0,005 | 0,010 | 480 | 44 | 560 | 120 | 473 |
| N2 | Y2 | 0,069 | 1,51 | 0,36 | 0,007 | 0,008 | 410 | 44 | 5 | 232 | 292 |
| | | 0,067 | 1,38 | 0,35 | 0,007 | 0,012 | 500 | 38 | 62 | 245 | 412 |
| | Z2 | 0,068 | 1,45 | 0,50 | 0,006 | 0,011 | 470 | 45 | 180 | 230 | 440 |
| | | 0,067 | 1,44 | 0,54 | 0,005 | 0,014 | 450 | 42 | 310 | 230 | 480 |
| | | 0,069 | 1,38 | 0,52 | 0,006 | 0,011 | 410 | 35 | 380 | 225 | 478 |
| | V2 | 0,069 | 1,42 | 0,60 | 0,006 | 0,012 | 430 | 35 | 560 | 235 | 470 |

Table 1 - Weld metal chemical compositions (system Ti-B-Al-N).

| N2 Level | Code | Yield Strength (N/mm²) | Tensile Strength (N/mm²) | Elongation (%) | Reduction of Area (%) | Charpy Impact | |
|---|---|---|---|---|---|---|---|
| | | | | | | (°C at 100 J) | (°C at 28 J) |
| N | Y | 546 | 594 | 25,8 | 73 | -84 | -114 |
| | | 583 | 602 | 27,0 | 76,4 | -82 | -99 |
| | Z | 610 | 640 | 27,2 | 73,4 | -83 | -100 |
| | | 595 | 660 | 23,1 | 74,1 | -48 | -85 |
| | | 675 | 742 | 20,7 | 69,7 | -37 | -68 |
| | V | 668 | 732 | 20,3 | 69,7 | -12 | -46 |
| N1 | Y1 | 532 | 585 | 26,8 | 74,0 | -48 | -73 |
| | | 558 | 594 | 25 | 69,4 | -45 | -66 |
| | Z1 | 532 | 584 | 28,4 | 77 | -43 | -63 |
| | | 543 | 596 | 29,6 | 73,4 | -60 | -79 |
| | | 574 | 632 | 22,3 | 74,8 | -56 | -80 |
| | V1 | 571 | 644 | 25,4 | 73,5 | -64 | -93 |
| N2 | Y2 | 539 | 605 | 23,9 | 71,6 | -24 | -56 |
| | | 525 | 602 | 25,4 | 73,2 | -4 | -32 |
| | Z2 | 493 | 583 | 26,8 | 69,2 | 13 | -18 |
| | | 523 | 597 | 23,7 | 72,2 | -1 | -25 |
| | | 524 | 608 | 23,4 | 69,4 | -14 | -45 |
| | V2 | 529 | 591 | 25,6 | 73,8 | -45 | -70 |

Table 2 - Weld metal mechanical properties.

| N2 Level | Code | Aluminium (ppm) | Yield Strength (N/mm²) | Tensile Strength (N/mm²) | CTOD - δ5 | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | RT (20°C) | | - 20°C | |
| | | | | | δ 0,2 | δ m | δ 0,2 | δ m |
| N | Y | 13 | 546 | 594 | 0,289 | 0,813 | - | 1,015 |
| | | | | | 0,276 | 0,990 | - | 1,016 |
| | Z | 160 | 610 | 640 | 0,274 | 0,987 | - | 0,924 |
| | | | | | 0,270 | 1,137 | - | 1,062 |
| | V | 580 | 668 | 732 | 0,258 | 0,616 | - | 0,131 |
| | | | | | 0,196 | 0,486 | - | 0,603 |
| N1 | Y1 | 5 | 532 | 585 | 0,258 | 0,922 | - | 1,173 |
| | | | | | 0,242 | 1,050 | - | 1,212 |
| | Z1 | 170 | 532 | 584 | 0,225 | 0,825 | - | 1,19 |
| | | | | | 0,226 | 0,780 | - | 1,213 |
| | V1 | 560 | 571 | 644 | 0,230 | 0,848 | - | 0,745 |
| | | | | | 0,216 | 0,756 | - | 0,813 |
| N2 | Y2 | 5 | 539 | 605 | 0,262 | 0,668 | - | 0,704 |
| | | | | | 0,282 | 0,710 | - | 0,717 |
| | Z2 | 180 | 493 | 583 | 0,237 | 0,496 | - | 0,145 |
| | | | | | 0,267 | 0,826 | - | 0,147 |
| | V2 | 560 | 529 | 591 | 0,233 | 0,783 | - | 0,829 |
| | | | | | 0,195 | 0,734 | - | 0,692 |

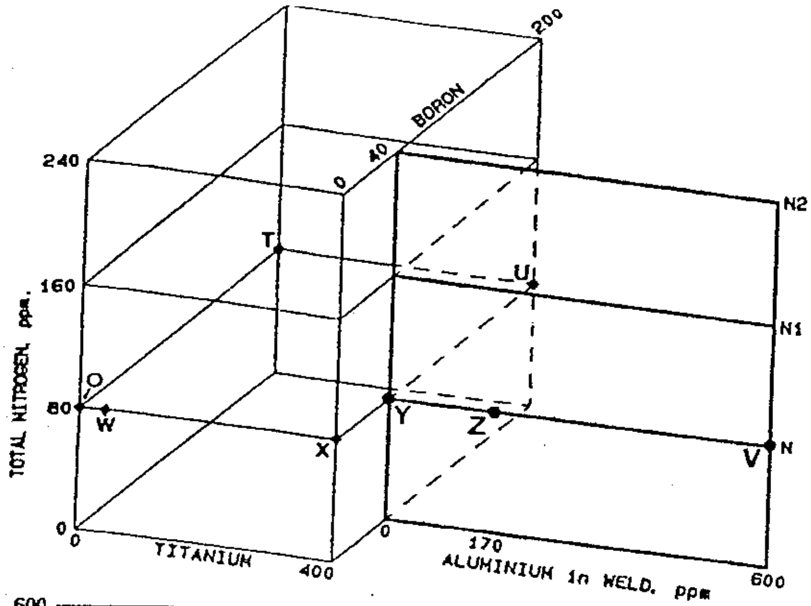


Figure 1 - Experimental matrix (Ti-B-Al-N).

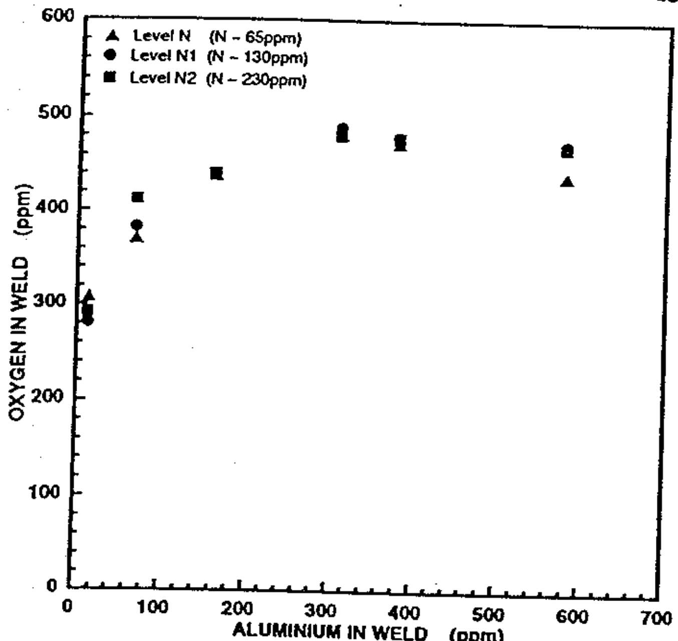


Figure 2 - Variation of weld metal oxygen as a function of the aluminium content.

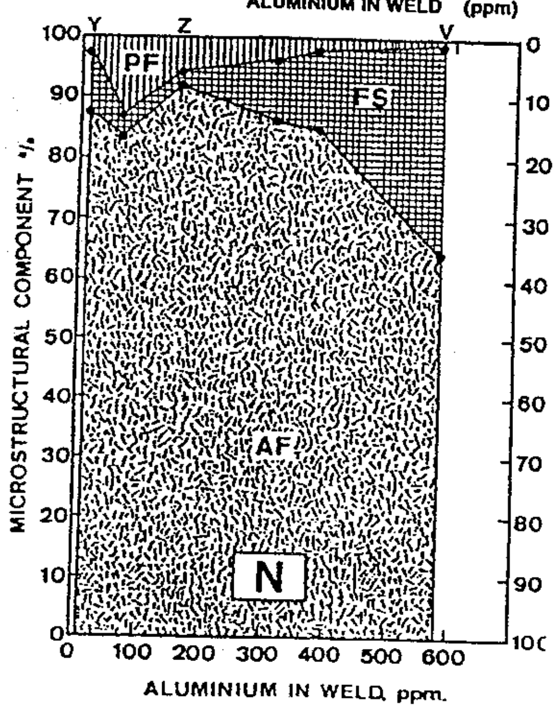


Figure 3 - Effect of aluminium on weld metal microstructure (nitrogen level N ~65ppm).

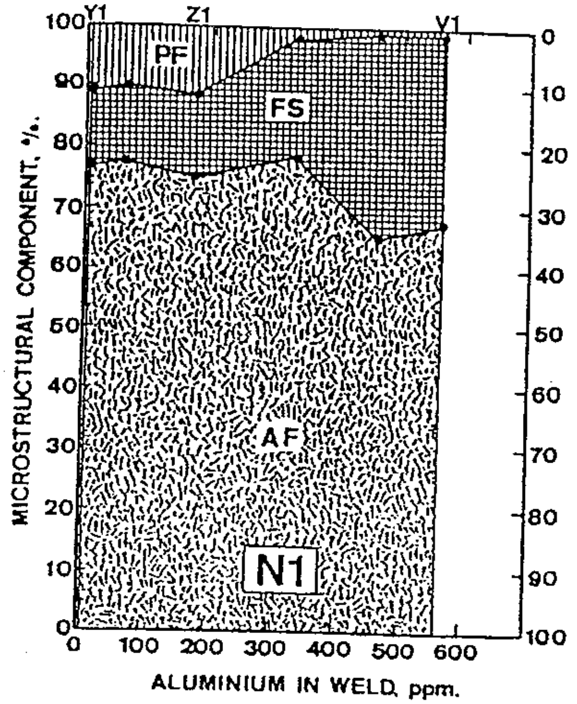


Figure 4 - Effect of aluminium on weld metal microstructure (nitrogen level N1 ~130ppm).

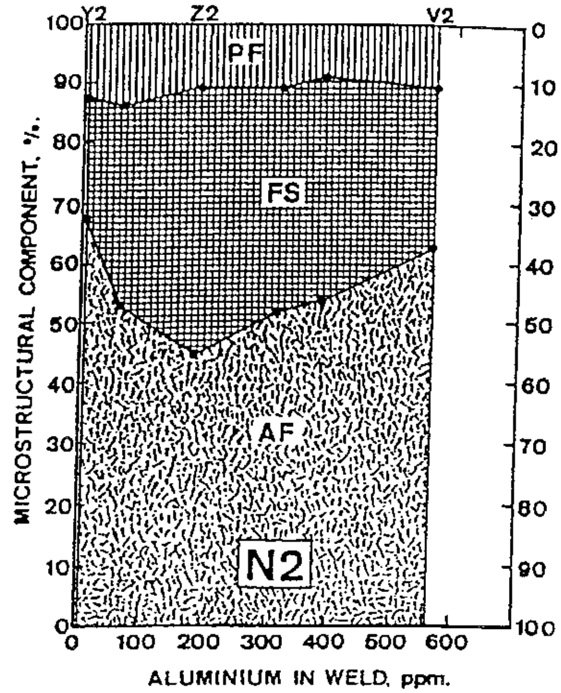


Figure 5 - Effect of aluminium on weld metal microstructure (nitrogen level N2 ~240ppm).

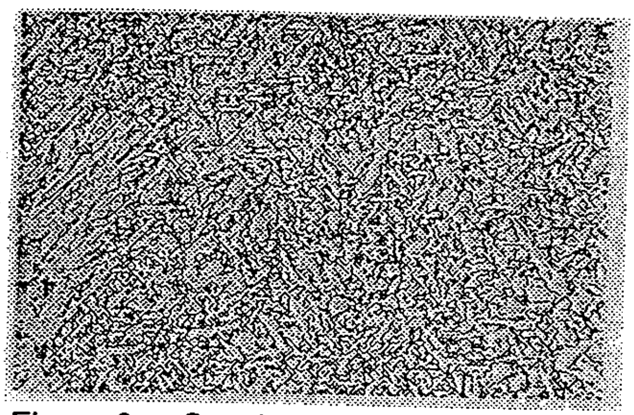

Figure 6a - Specimen Y (13 ppm Al, 83ppm N).

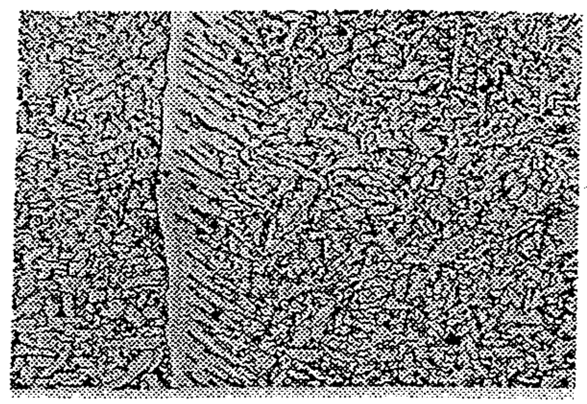

Figure 6b - Specimen Y2 (5 ppm Al, 232ppm N).

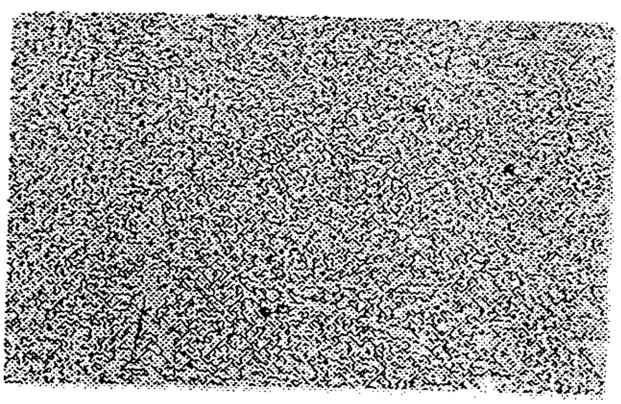

Figure 6c - Specimen Z (160 ppm Al, 67ppm N).

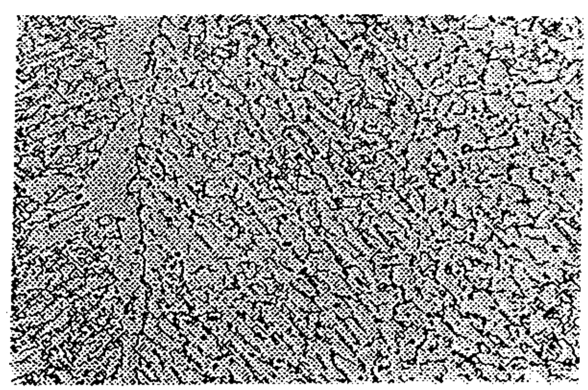

Figure 6d - Specimen Z2 (180 ppm Al, 230ppm N).

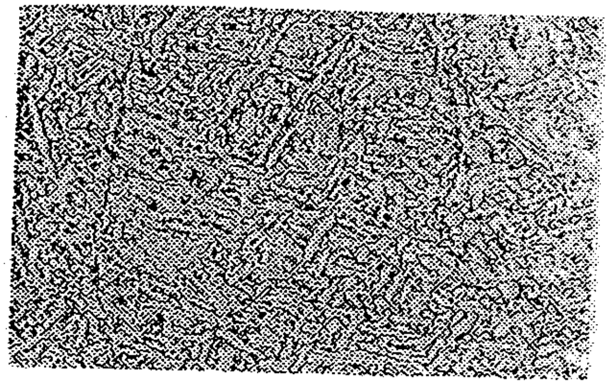

Figure 6e - Specimen V (580 ppm Al, 41ppm N).

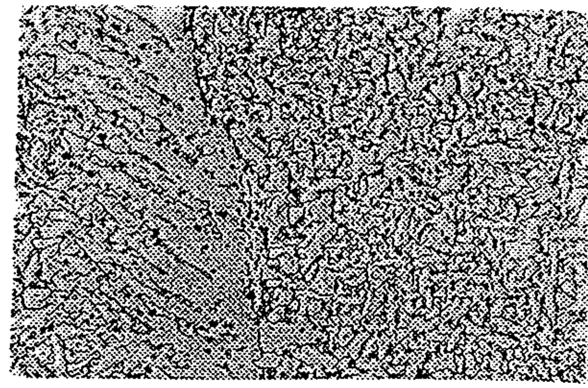

Figure 6f - Specimen V2 (560 ppm Al, 235ppm N).

Figure 6 - Micrographs of as-deposited weld metal (top beads). Magnification: x630

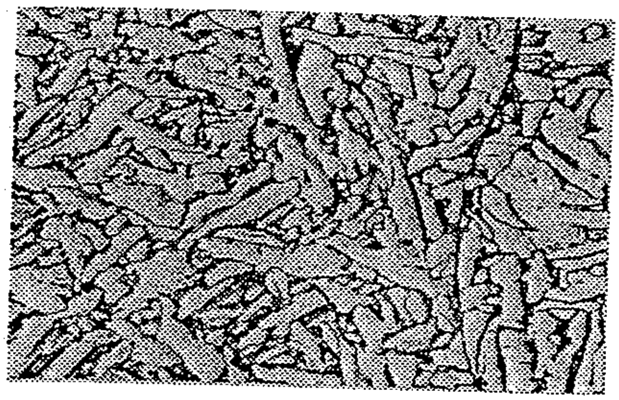

Figure 7a - Specimen Y (13 ppm Al, 83ppm N).

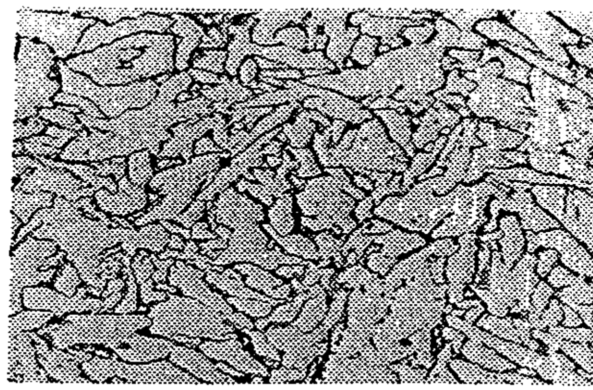

Figure 7b - Specimen Y2 (5 ppm Al, 232 ppm N).

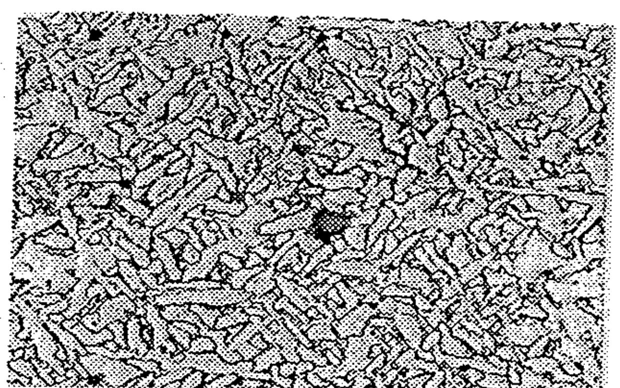

Figure 7c - Specimen Z (160 ppm Al, 67ppm N).

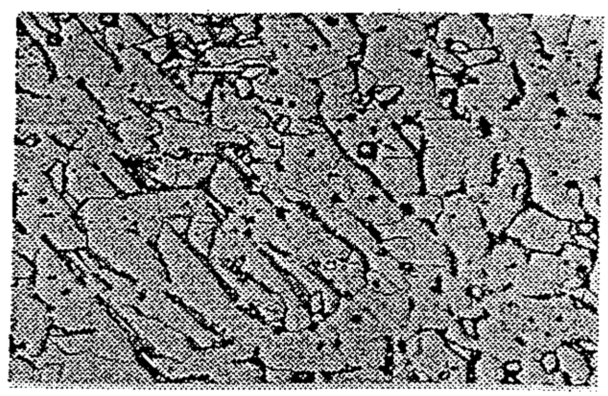

Figure 7d - Specimen Z2 (180 ppm Al, 230ppm N).

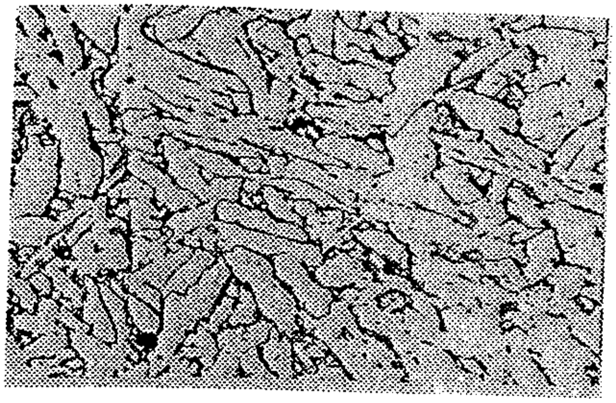

Figure 7e - Specimen V (580 ppm Al, 41ppm N).

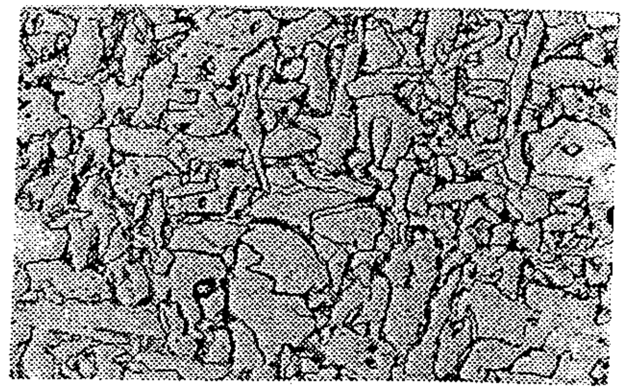

Figure 7f - Specimen V2 (560 ppm Al, 235 ppm N).

Figure 7 - Micrographs of as-deposited weld metal (top beads). Magnification: x2000

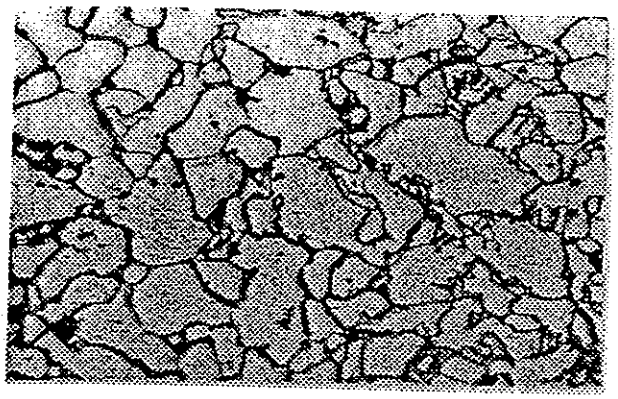

Figure 8a - Specimen Y (13 ppm Al, 83ppm N).

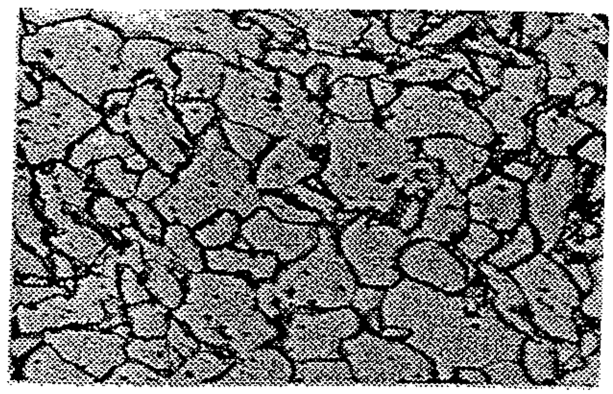

Figure 8b - Specimen Y2 (5 ppm Al, 232 ppm N).

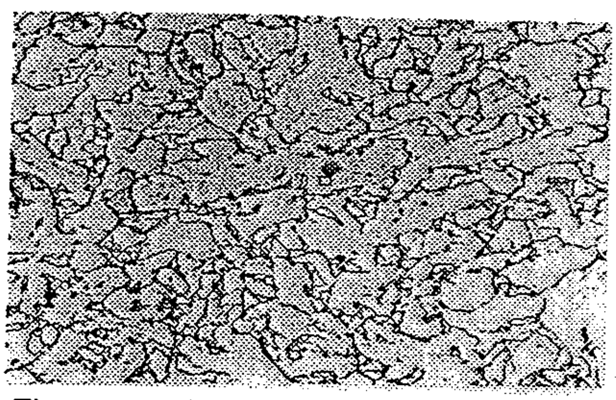

Figure 8c - Specimen Z (160 ppm Al, 67 ppm N).

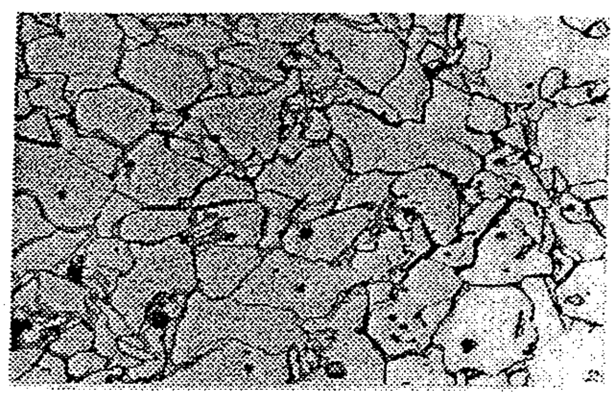

Figure 8d - Specimen Z2 (180 ppm Al, 230 ppm N).

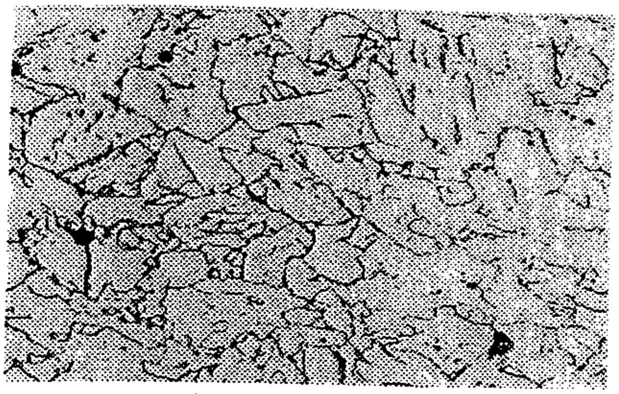

Figure 8e - Specimen V (580 ppm Al, 41 ppm N).

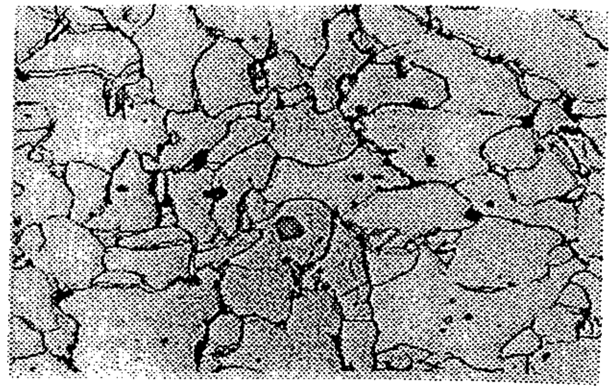

Figure 8f - Specimen V2 (560 ppm Al, 235 ppm N).

Figure 8 - Micrographs of low temperature re-heated regions. Magnification: x2000

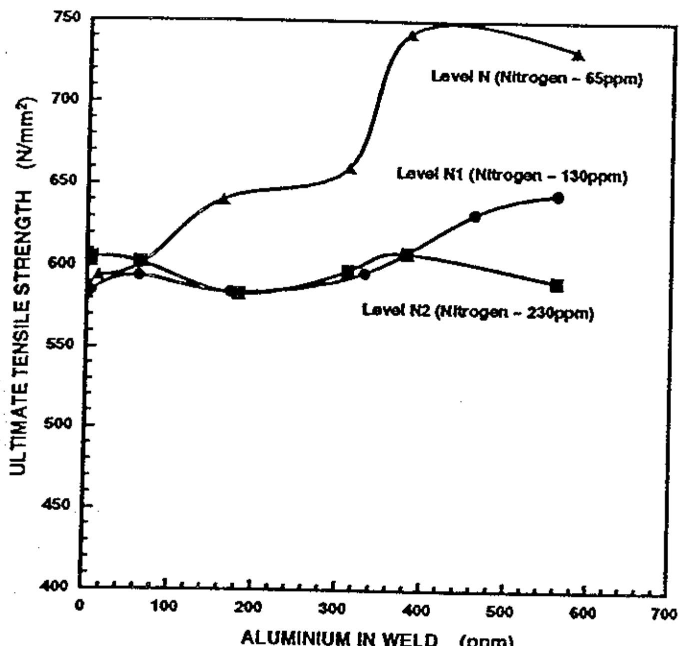


Figure 9 - Effect of aluminium on the ultimate tensile stregth at three N levels.

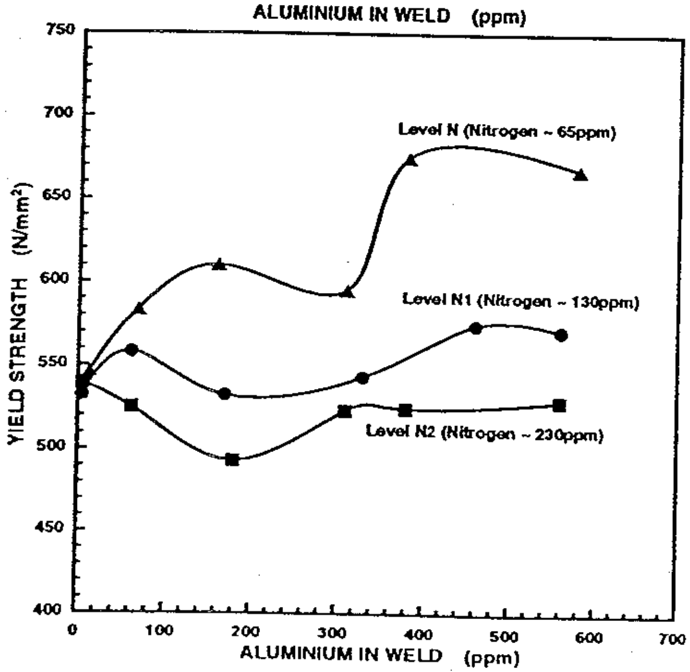


Figure 10 - Effect of aluminium on the yield stregth at three N levels.

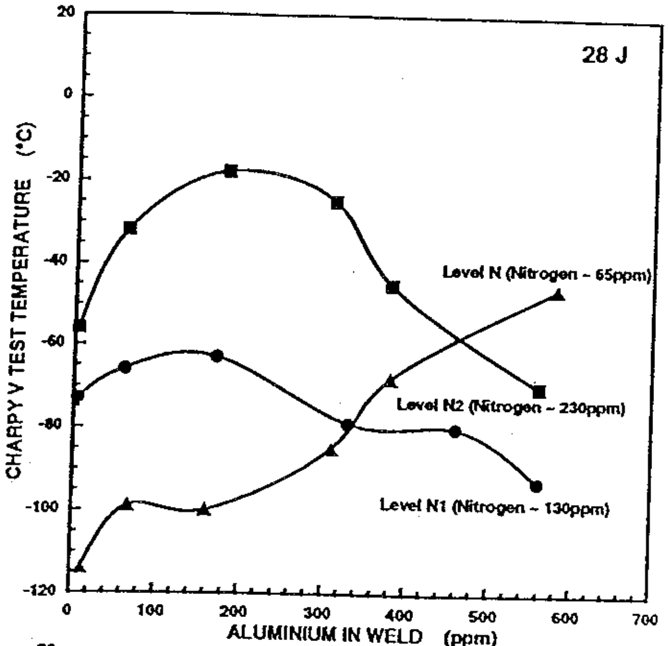


Figure 11a - Effect of aluminium on the Charpy V notch test temperature corresponding to 28 J.

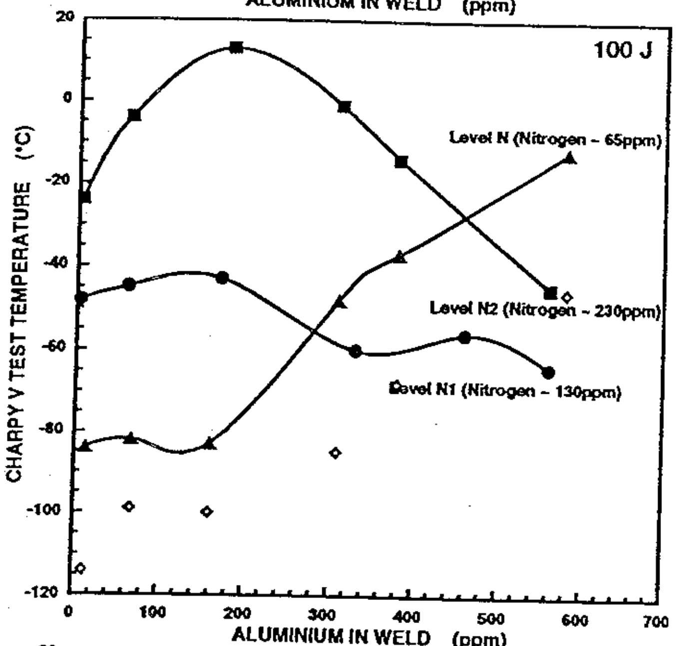


Figure 11b - Effect of aluminium on the Charpy V notch test temperature corresponding to 100 J.

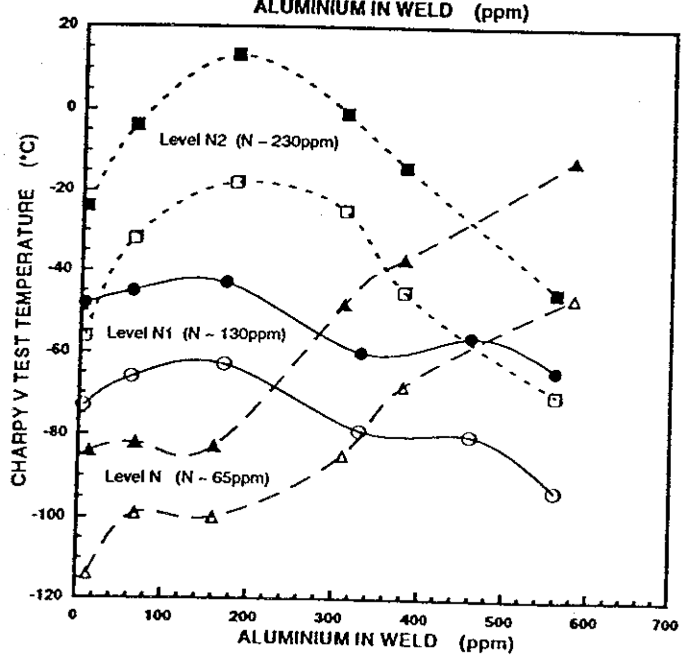


Figure 11c - Effect of aluminium on the Charpy V notch test temperature corresponding to 28 J and 100 J.

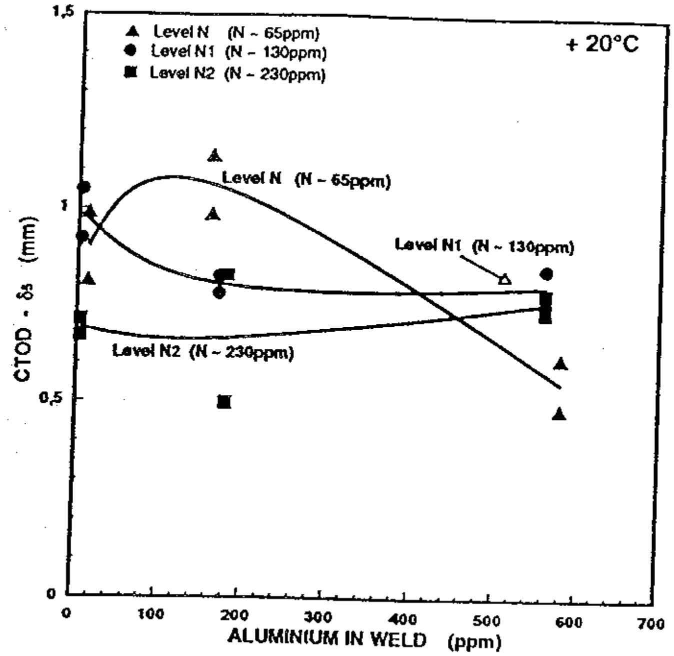


Figure 12 - Effect of aluminium on the CTOD (δ5) toughness at +20°C for three N levels.

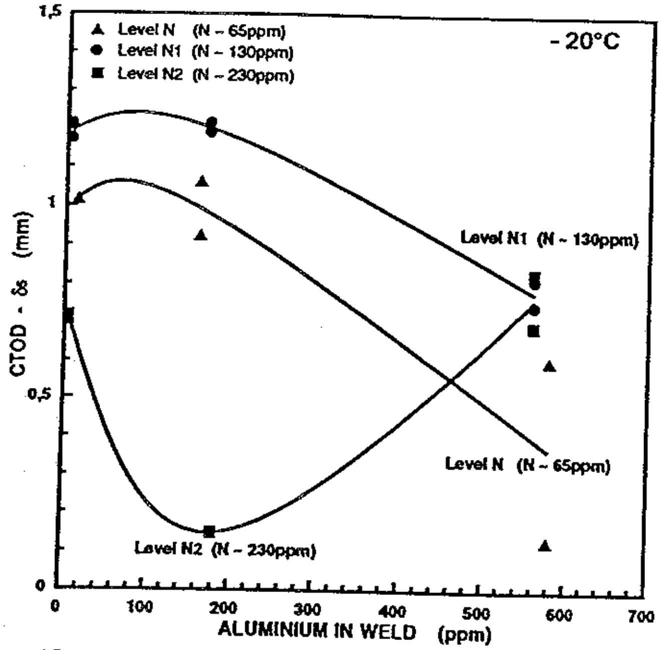


Figure 13 - Effect of aluminium on the CTOD (δ5) toughness at -20°C for three N levels.

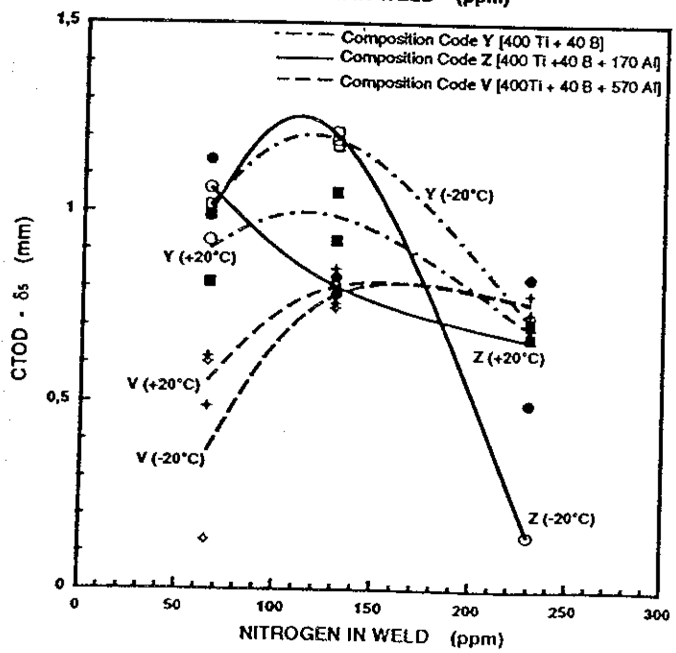


Figure 14 - Effect of nitrogen on the CTOD (δ5) toughness at +20°C and -20°C. Results plotted for three Al levels (specimens Y, Z and V).