Influence of titanium and nitrogen on the fracture properties of weld metals

The American Society of Mechanical Engineers

Reprinted From
Proceedings of the 13th. International Conference on Offshore Mechanics and Arctic Engineering
Editors: M. M. Salama, M. Toyoda, S. Lui, J. F. Dos Santos, M. Kocak, E. A. Patterson, and S. Berge
Book No. H00898 — 1994

INFLUENCE OF TITANIUM AND NITROGEN ON THE FRACTURE PROPERTIES OF WELD METALS

Mustafa Koçak, Blagoj I. Petrovski, and Eckart Richter
Institute of Materials Research
GKSS Research Center
Geesthacht, Germany

G. M. Evans
OERLIKON Welding Limited
Zürich, Switzerland

ABSTRACT

The effects of titanium and nitrogen contents on the C-Mn shielded metal arc weld (SMAW) metal properties have been studied. There are still uncertainties concerning the exact role of each element and interactions between these elements with respect to the weld metal microstructure and fracture toughness properties. Therefore, systematic additions of titanium (in the range of 5 ppm to 450 ppm) and nitrogen (80, 160 and 240 ppm) were made to obtain various amounts of acicular ferrite and different microstructures which lead to varying fracture behaviours. The research programme covers the determination of tensile properties, Charpy-V notch transition curves and crack tip opening displacement (CTOD) fracture toughness values of different weld deposits containing three different nitrogen contents.

The results show that an optimum level of titanium (30 ppm) addition enhanced the formation of acicular ferrite and hence improved the Charpy-V impact and CTOD toughness values. An increase of nitrogen increased the strength but caused a drastic deterioration of both Charpy-V impact and CTOD toughness values at the upper shelf and transition regime.

Keywords: SMA weld metal, Titanium, Nitrogen, Charpy-V notch, CTOD toughness.

INTRODUCTION

In a previous investigation [1-5] jointly conducted by the GKSS Research Center and Oerlikon-Welding Ltd., the effects of nitrogen and strain aging on the microstructure and fracture properties of ferritic shielded metal arc (SMA) weld metals were studied. It was found that increasing the nitrogen content in specially prepared weld metals (containing no nitride former elements, i.e Ti, B and Al) leads to a drastic decrease of the 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 [5] suggest that the sensitivity of the Charpy-V impact and CTOD tests to static strain aging and to the amount of nitrogen is rather high. For assessing the structural significance of strain aging and nitrogen in welds and for developing the consumables, the Charpy-V impact and CTOD test results can give a very conservative bias.

Based on a detailed analysis of the microstructures of as deposited weld metals containing different amounts of nitrogen, it is observed that an increasing nitrogen content in the weld metal decreased the AF columnar size and increased the inter-columnar width [2]. This implies a decrease of the tougher AF microstructure and an increase of embrittling proeutectoid PF platelets in the case of welds with higher nitrogen. The embrittling effect due to nitrogen, particularly, when present in large amounts by way of a decrease of acicular ferrite and an increase of proeutectoid ferrite is reported by Burkhardt et al [6] and Thewlis [7]. Of all the forms, it is the dissolved nitrogen which has been found to be highly damaging as it enters the interstitials of the iron lattice like the carbon atom, but with greater effectiveness than carbon and causes dislocation pinning during deformation [8].

A balanced addition of titanium (30-40 ppm Ti in combination with 1.4% Mn) into the SMA deposit dramatically improves the as-deposited weld metal microstructure and toughness properties with an optimum degree of hardenability [9-10]. However, the addition of aluminium into this weld metal causes a change of the morphology of the non-metallic inclusions and further microstructural aspects of this Ti-Al system have recently been investigated by Evans [10]. The beneficial effect of Ti-B additions, however, on microstructure and fracture toughness has long been recognized and numerous investigations have been carried out. An optimum combination of all these elements is essential to assure improved microstructure and mechanical properties. The fundamental improvement mechanism of the Ti-B system as reported by Mori et al [11] is usually assumed as follows: active boron present at the weld metal austenite grain boundaries retards nucleation of proeutectoid ferrite while promoting nucleation of fine acicular ferrite within the grain, and Ti protects boron from oxygen and nitrogen. A systematic investigation, however, is still lacking on the role and optimum level of nitrogen in combination with the varying amount of titanium, boron, aluminium, oxygen, nitrogen and strain aging for SMA weld deposits.

The study forms the second part of an on-going joint research programme to evaluate the effects of Ti, B, Al, N (Ti-B-Al-N system) and strain aging on the fracture toughness properties of multipass ferritic SMA weld deposits. This second part of the joint research programme is particularly concerned with the effects and interactions of the micro-alloying elements (Ti-B-Al-N system) combined with the strain aging phenomena on CTOD fracture toughness. The paper, however, only presents the Charpy-V and CTOD fracture toughness results of the as-welded deposits of the Ti-N system.

MATERIALS AND EXPERIMENTAL PROCEDURE

Electrodes and Production of Welds

A balanced range of seven experimental basic iron powder type electrodes was prepared by progressively increasing the amount of titanium metal in the coating to produce three sets of welds (total 21 multipass welds) containing 80, 160 and 240 ppm nominal nitrogen contents as shown in Table 1.The core wire diameter of the electrodes thus prepared was 4 mm and the coating factor was (D/d) 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, Figure 1. 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 standardized at 200 ^{o}C.

Mechanical Testing

All weld metal tensile specimens were machined and room temperature tested for each of the 21 weld metals in the as-welded (AW) and the stress relieved (580 ^{o}C for 1hr. -SR) condition. About 35 Charpy-V notch specimens were also tested in each case to obtain full transition curves. The CTOD tests were carried out only on nine weld metals (72 SENB specimens) namely, O, W and X series as shown in Table 1 at three test temperatures of +20, -20 and -60 ^{o}C to obtain the ductile-brittle transition curves of the welds. The CTOD specimens were of the Bx2B type (B is thickness of 17 mm) and notched in the through thickness direction at the mid-weld position.

RESULTS AND DISCUSSIONS

Weld metal chemical analysis

The chemical analyses of all 21 weld metals prepared by Oerlikon -Welding Ltd. are given in Table 1. The weld metals are divided into three sets with respect to the nominal total nitrogen levels as 80 ppm, 160 ppm and 240 ppm with varying titanium contents. The formulations were adjusted to maintain the carbon, manganese and silicon contents in balance. Unfortunately, for weld metals designated as X-series, the silicon content is higher and oxygen amount is lower than the O and W series. The nitrogen content gives the total nitrogen in the weld metals. The boron and aluminium contents of the weld metals were kept at less than 5 ppm. The data given in Table 1 shows that the amount of oxygen decreases when the Ti content increases in the electrode for each nitrogen series, indicating that titanium effectively deoxidises the weld pool and forms Ti-rich oxides. The amount of silicon in higher Ti containing deposits (Ti > 300 ppm) is much higher than the low Ti containing weld metals. This suggests that Ti is reacting more readily than Si and hence it is reasonable to assume that the deoxidation products are essentially Ti-rich oxide inclusions. It should also be noted that increasing the amount of nitrogen in the welds for a given titanium did not cause a significant change in the oxygen content. However, for a constant oxgen level, higher nitrogen contents require higher titanium/oxygen ratios to satisfy oxide formation requirements, i.e. tie up nitrogen as TiN. At constant nitrogen content, the titanium and oxygen levels should also be in balance to provide optimum toughness [12].

Metallographic examination

The columnar top beads of the weld metals were optically examined and metallographic measurements were made, following the current guidelines [13] of IIW Sub-Commission IX J, to quantify the major microstructural components, namely:

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

The point count results obtained are plotted against weld metal titanium content in Figure 2 and reveal a profound effect over the micro-alloy free deposit which was essentially non-acicular and it is seen that the addition of about 30-40 ppm Ti induced a seven fold increase in AF. With increasing titanium up to the highest Ti level (400 ppm) studied, the level of AF content showed (after a slight drop at about 120 ppm Ti) only a marginal increase [9-10]. Photomicrographs of as-deposited columnar regions of the weld metals containing the lowest, 80 ppm and the highest, 240 ppm nitrogen contents (O-W-X and O2-W2-X2 series) are shown in Figure 3. The effects of Ti and N on the microstructure can further be appreciated in Figure 4 which presents typical optical micrographs of the weld metals at higher magnification (630X). Increasing the amount of nitrogen from 80 ppm to 240 ppm in the welds leads to a coarser microstructure and to a significant increase in grain boundary ferrite (FS) amount. This can clearly be seen for O and W welds, Figure 3 and 4. Increasing the Ti content from essentially Ti-free and non-acicular weld deposit (O) to weld deposit (W) containing small amount of Ti leads to a much finer microstructure with a large amount of intragranular AF which provides very good fracture toughness. A further increase of Ti obviously causes again a coarser microstructure containing an increased amount of grain boundary ferrite (FS).

Changes in the Ti and N levels have an obviously dramatic effect on the microstructure. This indicates that both elements react strongly with each other. Examining the role of nitrogen and titanium at different levels in an high heat input Gleeble simulated welds, Cuddy et al [14] conclude that at low Ti and N contents (60/30ppm) martensite formation is promoted while at higher levels (300/110 ppm) blocky ferrites were formed eliminating widmanstätten plates. At medium levels (110/60ppm) the microstructure essentially consisted of equiaxed ferrite with pearlite. In an extensive investigation by Thewlis [7] on pipeline welds over a wide range of weld chemistry, it is reported that an increase of nitrogen content in the range of 50 to 135ppm resulted in the refinement of prior austenite grain size and an increase of volume fraction of primary ferrite and a decrease of acicular ferrite in the ranges of 10 to 25% and 90 to 75%, respectively, depending upon the presence of titanium and boron amounts.

It has recently been reported by St-Laurent and L'Esperance [15] that the presence of both elements influences the composition and morphology of the inclusions. In their low N containing welds, a large amount of FCC Ti-rich phases (TiO) at the surface of the inclusions was observed. However, the formation of Ti-rich Ti(O,N) or TiN phases on inclusions of welds containing high N contents occurs at the expense of TiO or other Ti-rich oxides and the amount of N which is reacts with Ti increases with its content in the weld deposit [15].

Apparently, a further increase of in the amount of Ti (from 30-40 ppm) starts to counteract its own beneficial effect on the microstructure [9-10]. This is probably due to a change of composition and morphology of the Ti-rich inclusions with increasing Ti content. This topic is currently being investigated at various institutes to explain the basic mechanism of the Ti, B, Al and N effects on weld metal microstructure and toughness properties [16].

Tensile properties

The tensile and Charpy-V impact test results of the 21 weld deposits prepared for the Ti-N system are given in Table 2. The yield and ultimate tensile strengths are also plotted against titanium content for three nitrogen levels in Figures 5 and 6, respectively. An increase of total nitrogen caused a general increase in both yield and tensile strengths. A slight drop of strength at 30 ppm Ti level was observed for welds containing 160 and 240 ppm nitrogen as shown in Figures 5 and 6. An increase of nitrogen content from 80 ppm to 160 ppm caused a distinct increase of strength, but a further increase to 240 ppm did not produce a clear increase in strength, Figures 5 and 6. Investigating the effect of combined nitrogen Cuddy et al [14] and Yuschenko et al [17] observe that the nitrides of Al, Ti, and B either individually or in combination reduce the grain size and increase the tensile strength of the weld metals.

Hardness

Figure 7 shows the effect of nitrogen on hardness of the as-welded Ti-N weld system. The hardness measurements were made in the plate thickness direction through the middle weld passes. In general, no evidence of extreme hardenability has been observed for any of the weld deposits investigated. Nevertheless, an increasing nitrogen content increased the hardness of the O and X weld deposits, Figures 7a and 7c. For weld metals of W, containing 40 ppm Ti, the hardness values showed least scatter (except some values for top bead of the 226 ppm nitrogen weld) and basically no effect of nitrogen, Figure 7b.

The extensive microhardness investigations carried out by Achar [2] on the individual microphases (AF and PF), of Ti-B-Al free welds, revealed a distinctive increase in AF hardness with an increase in nitrogen content. The increase in hardness in the AW and SR condition are attributed to the solid solution effect-small nitrogen atoms being able to fit between iron atoms and distort the crystal lattice, thus leading to higher hardnesses [8]. However, the results of the macrohardness studies in this work did not reveal significant variations either with the nitrogen content or with the titanium content investigated.

Charpy-V notch test results

The Charpy-V notch test temperatures corresponding to an absorbed energy of 100J and 28 J for as-welded (AW) and stress relieved (SR) conditions are presented in table 2 and plotted against titanium content in Figures 8 and 9 respectively. It can be seen that an addition of about 40 ppm titanium has remarkably improved the toughness of the weld metal for all nitrogen contents particularly for the as-welded (AW) condition, Figures 8a and 9a. A further increase of titanium up to 100 ppm caused a deterioration in notch toughness for low nitrogen welds, but no further degradation in notch toughness was encountered at the higher levels of titanium even up to the 600 ppm level (this is attributed to the constant level of AF content, see Fig 2) for all nitrogen contents. Conversely, at 700 ppm Ti rather good 28J temperature was achieved for the stress relieved condition, Figure 9b. The improvements in 28J toughness brought out by stress relief heat treatement was very substantial for Ti-free weld as shown in Figures 9a and 9b. This beneficial effect of PWHT is not so visible for the 30 pmm Ti contaning weld deposit, since it already provides a very good toughness level.

The Charpy-V notch impact data on the effects of nitrogen on the ductile-brittle transition behaviours (approx. 100 J range) are also shown in Figure 8. There is a distinct increase for the 100 J test temperature for all titanium contents in AW and SR conditions. A general increase in test temperature for 28 J toughness levels with increasing weld metal nitrogen particularly for the as-welded (AW) condition is shown in Figure 9a. In general, an increase in the transition temperature of weld metals with increasing nitrogen in the AW and SR conditions are attributed to the microstructural changes viz. decreased AF and increased PF, FS and microphases [2]

Apart from titanium and nitrogen contents, weld metal boron, aluminium and oxygen contents are also obviously important in defining the optimum Charpy-V notch toughness system. All these elements are being additionally investigated as the Ti-B-Al system with varying nitrogen content and will be a topic of forth coming communications.

Effect of Ti and N on CTOD 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 (d_5) method developed at GKSS Research Center provides intrinsic toughness values based on local measurement without the need to infer from remotely measured quantities. The CTOD (d_5) values obtained for all three test temperatures are given in table 3 in terms of crack initiation ($\delta_{0.2}$) and CTOD (δ_m) values which correspond to the crack growth of 0.2mm and to the maximum load respectively. The number of tests were varied as two to four for each weld. The CTOD ($\delta_{0.2}$) values exhibit no clear dependence on the weld metal condition with respect to the nitrogen or titanium contents at any test temperatures. However, it is obvious that weld metal W (30 ppm Ti) provides highest fracture toughness values (δ_m) for any nitrogen content at -20 C test temperature.

The CTOD transition curves obtained for the nine weld metals are presented, for the sake of clarity, on two sets of graphs, namely Figures 10 and 11 to demonstrate the effects of the nitrogen and titanium contents respectively. The CTOD values obtained for Ti-free weld deposits (O-series) for three nitrogen levels are plotted against three test temperatures in Figure 10a. For a given test temperature, a detrimental effect of increasing nitrogen content is visible by achievement of the highest CTOD toughness values at the lowest nitrogen content. Similar trends also exist for weld metals containing about 30 ppm (W-series) and 410 ppm (X-series) titanium, Figs. 10b and 10c, respectively.

The detrimental influence of nitrogen can be caused either by the microstructural change or due to the soluble nitrogen content in the weld metal. With the presence of titanium in two of the welds (W and X) studied, microstructural change obviously comes from the formation of the Ti-rich (Ti-O-N) inclusions. An investigation carried out by Ito et al [18] on submerged arc weld metals containing different amount of nitrogen, reports the presence of martensite transformation for a 178 ppm nitrogen weld, in contrast to a 51 ppm nitrogen weld, in which the interstices in the ferrite structure showed a perlitic structure. It is believed that nitrogen stabilizes the austenite, which remains down to a low temperature and transforms into martensite which reduces the toughness. According to Ito et al, the main reason for the CTOD toughness deterioration is the presence of martensite islands and not the dislocation pinning effect of the nitrogen in solid solution.

In order to clearly describe the main mechanism of nitrogen embrittlement for the weld metals (Ti-B-Al-N sytem) studied in this project, a detailed electron microscopic examination is in progress.

The effect of titanium content for weld metals containing 80 ppm nitrogen can clearly be seen in Figure 11a which indicates a marked optimum of 30 ppm Ti (W-series) for all three test temperatures used. Even at the -60 °C test temperature, this weld metal produces very high toughness values of about 1.0 mm which confirm the trend obtained from Charpy-V notch tests as shown in Figure 9a. The presence of a large amount of Ti (over 410 ppm) does not improve the CTOD toughness values compared with the Ti-free weld metal, Figure 11c.

According to the CTOD results obtained at room temperature, the nitrogen sensitivity of the Ti-free and 30 ppm Ti weld metals, Figure 10a and 10b respectively, is much higher than the sensitivity of the 410 ppm titanium weld metal, Figure 10c.

It shoud be noted that the sensitivity of the 30 ppm Ti weld metal (which showed best CTOD toughness properties) to nitrogen is unexpectedly high as shown in Figure 10b occurred. With the increase of total nitrogen from 80 ppm to 240 ppm a significant reduction of toughness at all three test temperatures, Figure 10b. This aspect can also be observed in Figures 8a and 9a in that slightly larger shifts occur in the 100 J and 28 J Charpy-V test temperatures of the as-welded deposits. In contrast, the weld metals containing over 400 ppm Ti did not show such sensitivity to nitrogen by producing similar CTOD toughness values at room temperature as shown in Figure 10c. These test results therefore indicate that further investigation on the effect of strain aging on the fracture toughness properties of this system is essential. For this purpose, a large number of artificially strain aged (4% local pre-straining in compression then aged at 250 °C for 1/2 hour) CTOD specimens extracted from Ti-B-Al-N system weldments have already been prepared and the results will be a topic of forth-coming communications

CONCLUSIONS

Microstructural and fracture toughness properties of titanium and nitrogen containing manual metal arc (MMA) weld metals were investigated to determine the effects of both elements. The conclusions drawn are as follows:

1. Increasing the amount of nitrogen from 80 ppm to 240 ppm in the welds leads to a coarser microstructure and to a significant increase the amount of grain boundary ferrite (FS).

2. Increasing the Ti content from essentially Ti-free and non-acicular weld deposit (O) to weld deposit (W) containing a small amount of Ti leads to 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).

3. An increase of nitrogen increased both yield and tensile strength but caused a general deterioration of both Charpy-V impact and CTOD toughness values. For nitrogen and titanium effects on toughness properties, the standard CTOD test and the Charpy-V notch impact test responded similarly.

4. The present results confirm that a small amount of titanium (about 30 ppm) improves the as-deposited microstructure by increasing the volume fraction of acicular ferrite and hence increases the fracture toughness. Further addition of titanium in the weld metal appears to destroy its beneficial effect on the Charpy-V notch and CTOD toughness properties.
However, it should be noted that the optimum titanium content should be determined with the presence of boron and aluminium in the weld deposits for various nitrogen contents, in as-welded and strain aged conditions. Such work is in progress.

Acknowledgements - This work was jointly funded by Oerlikon-Welding Ltd, Zurich and GKSS Research Center Geesthacht, F.R.G. The authors would like to thank Mr. Mackel for his assistance with the experiments.

REFERENCES

1. Achar, D.R.G. and Koçak, M., "A review of literature on the influence of nitrogen on toughness and strain age embrittlement behaviour of steel weld metal", Under preparation.

2. Achar, D.R.G, Koçak, M and Evans, G.M, "Effects of nitrogen and strain aging on C-Mn steel weld metal microstructure", Proc. of the 3rd Int. Conf on Trends in Welding Research, ASM International, Eds. S.A. David and J.M. Vitek, June 1-5, 1992, Gatlinburg, TN, U.S.A, pp. 327-334.

3. Koçak, M, Achar, D.R.G and Evans, G.M, "Influence of shielded metal arc weld metal nitrogen content on its fracture toughness behaviour", Proc. of the 2nd Int. Conf. on Offshore and Polar Engineering, San Fransisco, U.S.A, 14-19 June 1992, pp. 239-248.

4. Koçak, M, Achar, D.R.G and Evans, G.M, "Effect of nitrogen on strain age embrittlement of shielded metal arc weld metal", Proc. of the 11th Int. Conf. on Offshore Mechanics and Arctic Eng., ASME, OMAE-92, June 7-11, 1992, Calgary, Alberta, Canada, Vol. III-part A, pp. 19-29 and IIW Doc. IIA-852-92 (1992)

5. Koçak, M, Petrovski, B, Achar, D.R.G and Evans, G.M, "Fracture mechanics and wide-plate tests for analysis of nitrogen and strain aging effects on weld metal fracture properties", Proc. of the 12th Int. Conf. on Offshore Mechanics and Arctic Eng., ASME, OMAE-93, June 20-24, 1993, Glasgow, Scotland, Vol. III - part B, pp. 741-751. IIW Doc. X - 1285 - 93.

6. Burkhardt, J., Lau, T., North T.H. and L'Esperance, G., "Effect of Al on the Ti-O-B-N balance in SAW", Welding Journal, 67, 8, (1988), 25-30.

7. Thewlis, G.,"Pipeline welds - effects of pipeline material and consumable compositions", Joining & Materials, 2, Jan., (1989), 25-32.

8. Hojo, I, "Nitrogen and Oxygen in Weld Metal-A state of the art review; Part I Nitrogen: Nitrogen in SAW weld metal", IIW Doc. II-1053-85.(1985)

9. Evans, G.M, "The effect of titanium on the microstructure and properties of C-Mn all-weld metal deposits", Welding Journal, 71(12) 1993, 447s-54s.

10. Evans, G.M, "Microstructure and properties of ferritic steel welds containing Al and Ti", IIW Doc. II-A-901-92.

11. Mori, N et al, "The behaviour of B and N in Notch Toughness Improvement of Ti-B Bearing Weld Metals", IIW Doc. IX-1158-80.

12. Lau, T.W et al, "Effect of nitrogen on properties of submerged arc weld metal", Materials Science and Technology, Jan. 1988, Vol. 4, No.1, pp. 52-61. IIW Doc. II-A-883-93.

13. Guidelines for classification of ferritic steel weld metal microstructural constituents using the light microscope, Welding in the World, 7/8, 2A, 1986, 144-149, IIW. Doc. IX-1377-85.

14. Cuddy, L.J., Lally J.S.and L.F.Porter, L.F., "Improvement of toughness in the HAZ of high heat input welds in ship steels", Proc.of Conference - HSLA Steel: Technology and Applications, Philadelphia, USA, Oct. (1983), 697-703.

15. St-Laurent, S and G.L'Esperance, "Effect of Nitrogen, Boron and Titanium on the Microstructure and the toughness of C-Mn Weld Deposits", Proc. of the 3rd Int. Conf on Trends in Welding Research, ASM, June 1-5, 1992, Gatlinburg, TN, U.S.A, pp. 527- 531.

16. Evans, G.M, private communication, 1993.

17. Yushchenko, K.A., et al, "Effect of nitrogen on the structure and properties of the HAZ in welded joints in ferritic steels alloyed with Ti & V", Welding International, 4, 3, (1970), 181-183.

18. Ito, Y et al, "Crack Opening Displacement Properties on Submerged Arc Weld Metals", The Sumitomo Search No 21, May 1979, pp. 52-67.

TABLE 1 CHEMICAL COMPOSITION OF THE WELD METALS (Ti - N SYSTEM)

Weld Designation	C	Mn	Si	S	P	N	O	Ti
	%					ppm		
O	0.074	1.40	0.25	0.008	0.007	79	475	1
W	0.077	1.46	0.27	0.008	0.007	81	459	28
	0.073	1.41	0.26	0.007	0.011	83	392	90
	0.074	1.45	0.30	0.007	0.009	84	337	120
	0.072	1.50	0.38	0.006	0.010	77	291	260
X	0.069	1.47	0.45	0.005	0.006	77	282	410
	0.070	1.50	0.45	0.005	0.006	75	294	550
O1	0.074	1.58	0.28	0.008	0.008	145	404	<5
W1	0.068	1.40	0.28	0.010	0.008	148	409	31
	0.069	1.50	0.31	0.008	0.008	160	400	51
	0.070	1.50	0.29	0.008	0.009	164	341	120
	0.068	1.51	0.39	0.007	0.009	166	278	300
X1	0.066	1.48	0.47	0.007	0.011	164	285	410
	0.070	1.50	0.45	0.004	0.006	155	297	590
O2	0.073	1.66	0.27	0.009	0.008	235	399	<5
W2	0.069	1.45	0.26	0.010	0.009	226	391	29
	0.073	1.53	0.29	0.009	0.007	243	419	46
	0.070	1.45	0.28	0.009	0.009	239	315	120
	0.067	1.48	0.40	0.006	0.008	253	286	320
X2	0.068	1.46	0.47	0.007	0.006	249	297	450
	0.066	1.47	0.43	0.005	0.006	240	322	690

TABLE 2 TENSILE AND CHARPY-V NOTCH PROPERTIES OF THE WELD METALS (Ti - N SYSTEM)

Weld Nr.	*AS WELDED*						*S.R.*	
	YS	*UTS*	*EL.*	*RA*	*ISO-V, °C*		*ISO-V, °C*	
	MPa	*MPa*	*%*	*%*	*100 J*	*28 J*	*100 J*	*28 J*
O	445	528	28.2	78.0	-14	-42	-74	-93
W	471	544	25.2	77.0	-68	-88	-70	-90
	478	540	24.2	78.9	-50	-72	-	-
	480	538	27.8	79.8	-43	-59	-56	-74
	509	578	26.4	78.9	-56	-72	-67	-83
X	504	577	25.8	79.8	-61	-77	-69	-83
	530	597	25.0	81.6	-60	-77	-63	-79
O1	473	566	24.0	77.0	+5	-24	-45	-82
W1	482	545	28.0	78.9	-41	-63	-62	-83
	522	584	26.4	78.9	-46	-68	-62	-93
	513	573	25.2	76.0	-29	-52	-54	-78
	546	611	24.0	78.0	-35	-63	-58	-82
X1	584	639	23.0	75.0	-44	-72	-58	-82
	535	599	25.6	76.0	-41	-65	-55	-83
O2	505	607	24.0	76.0	+20	-16	-29	-64
W2	492	581	25.8	77.9	-24	-48	-50	-78
	538	591	24.9	74.5	-28	-56	-50	-77
	523	599	29.2	77.0	-23	-52	-37	-67
	546	621	23.6	76.0	-24	-52	-46	-74
X2	578	631	24.6	78.0	-30	-58	-43	-72
	552	615	26.4	78.0	-28	-54	-48	-96

TABLE 3. THE CTOD (δ_5) TOUGHNESS DATA INCLUDING DUCTILE CRACK INITIATION VALUES FOR THREE TEST TEMPERATURES (SENB SPECIMENS, Bx2B, B=17mm, a/W=0.5)

Weld Nr.	YS [MPa]	UTS [MPa]	CTOD - δ_5 [mm] RT $\delta_{0.2}$	RT δ_m	-20°C $\delta_{0.2}$	-20°C δ_m	-60°C $\delta_{0.2}$	-60°C δ_m
O	445	528	0.250 0.259	1.536 1.200	0.207 0.325 0.211	1.146 1.256 1.305	 0.171 0.127	0.086 0.525* 0.347
W	471	544	0.396 0.265	2.119 1.657	0.246 0.288 0.361	**1.508** **1.563** **2.109**	0.235 0.269 0.266	0.985* 1.338 1.375
X	504	577	0.293 0.298	1.026 1.419	0.292 0.369 0.388	0.946* 1.504 1.642	- - 0.240	0.164** 0.344* 0.658*
O 1	473	566	0.320 0.295	1.504 1.177	0.268 0.275 0.223	0.335* 0.878* 1.102	- 0.135	0.056** 0.211
W 1	482	545	0.255 0.291 0.292	1.155 1.532 1.456	0.292 0.263 0.240	**1.456** **1.582** **1.549**	0.224 0.262	1.164 0.776*
X 1	584	639	0.332 0.308	1.430 1.418	0.265 0.250 0.235 0.324	0.599* 1.102 1.537 1.696	- -	0.116** 0.162**
O 2	505	607	0.289 0.258	0.748* 0.900	- 0.289 0.258	0.178** 0.748* 0.900	- - -	0.059** 0.105** 0.116**
W 2	492	581	0.234 0.244	0.972 1.095	0.187 0.253 0.211	**1.008** **1.298** **1.307**	0.211 - 0.243	0.686* 0.099** 0.660*
X 2	578	631	0.365 0.310	1.224 1.383	- 0.336 0.230	0.202** 0.917* 1.424	- - -	0.043** 0.099** 0.175**

*) δ_u **) δ_c

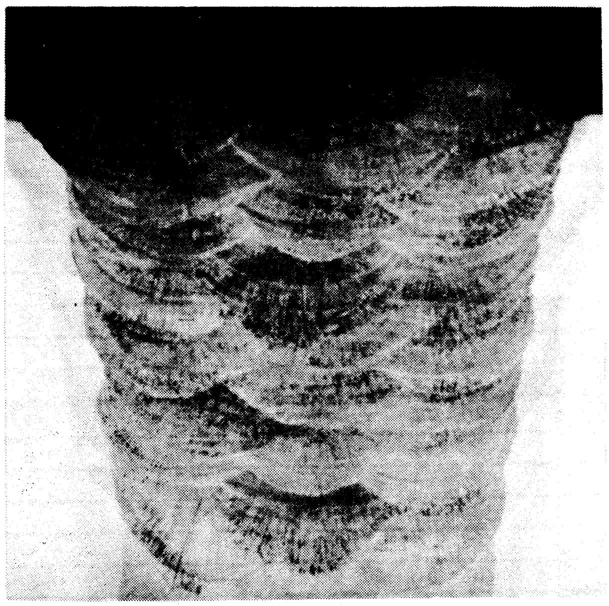


FIG. 1 PHOTOMACROGRAPH OF THE MMA WELD JOINT (X2)

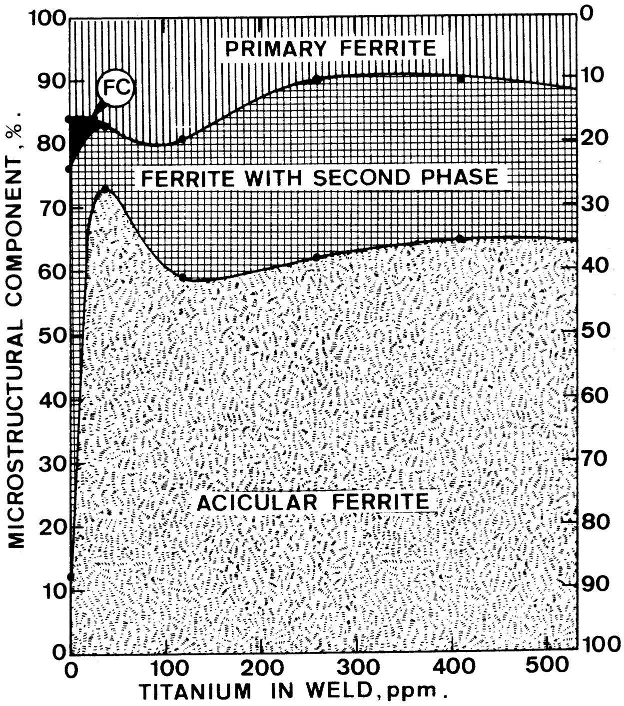


FIG. 2 EFFECT OF TITANIUM ON THE MICROSTRUCTURE OF AS-DEPOSITED WELD METAL

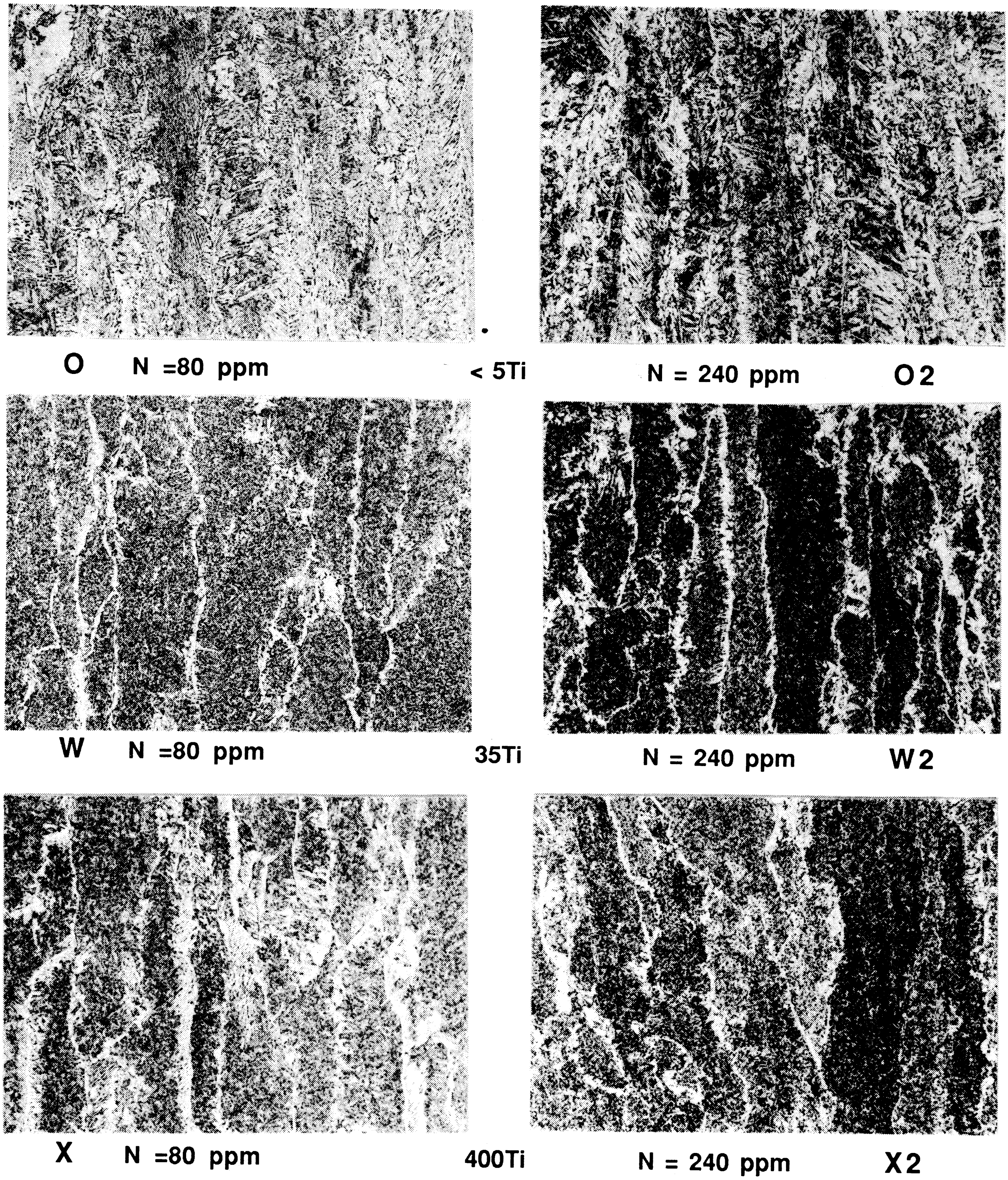
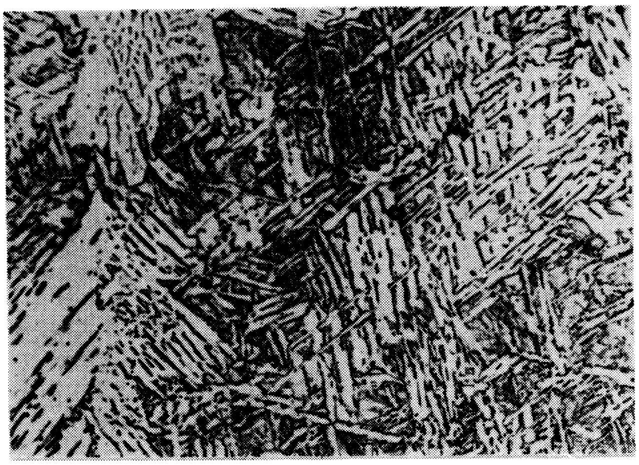
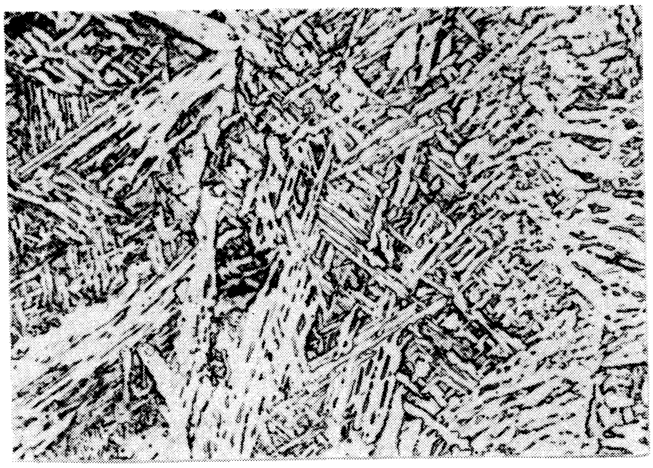
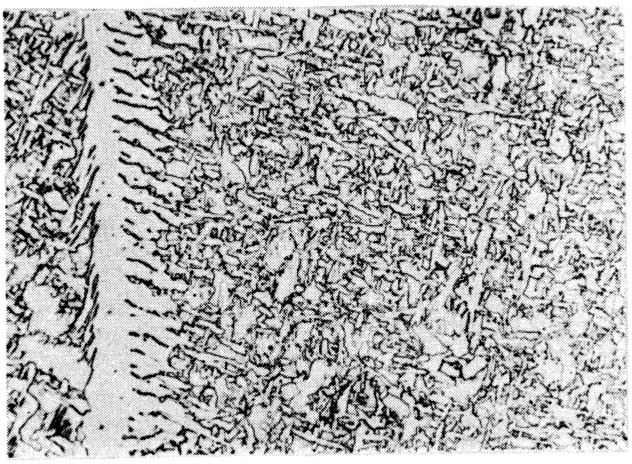
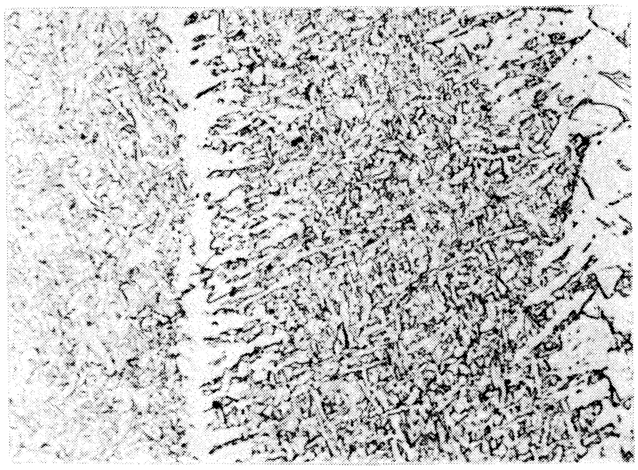


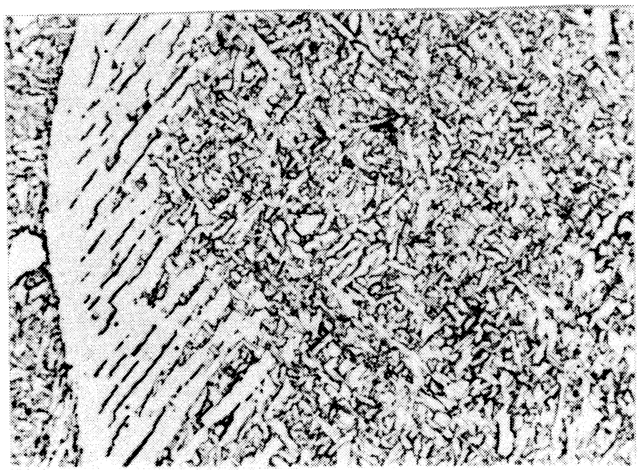
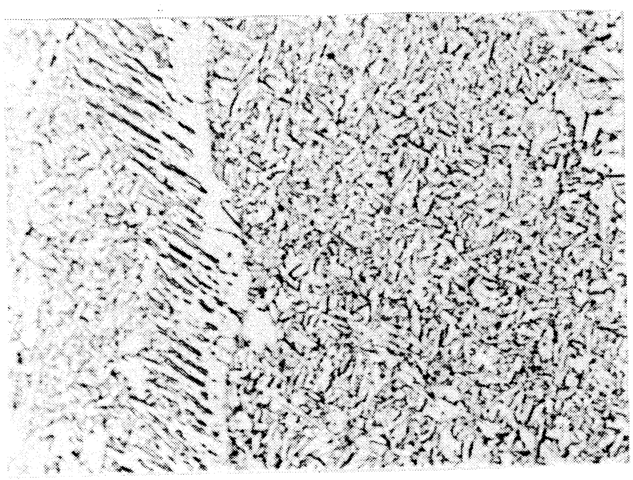
FIG. 3 PHOTOMICROGRAPHS OF TOP BEAD WELD METALS SHOWING THE EFFECT OF TITANIUM AND NITROGEN ON THE MICROSTRUCTURE (MAG. 100X)

O N =80 ppm < 5Ti N = 240 ppm O2

W N =80 ppm 35Ti N = 240 ppm W2

X N =80 ppm 400Ti N = 240 ppm X2

FIG. 4 HIGHER MAGNIFICATION PHOTOMICROGRAPHS OF TOP BEAD WELD METALS SHOWN IN FIGURE 3THE EFFECT OF TITANIUM AND NITROGEN ON THE MICROSTRUCTURE (MAG. 630X)

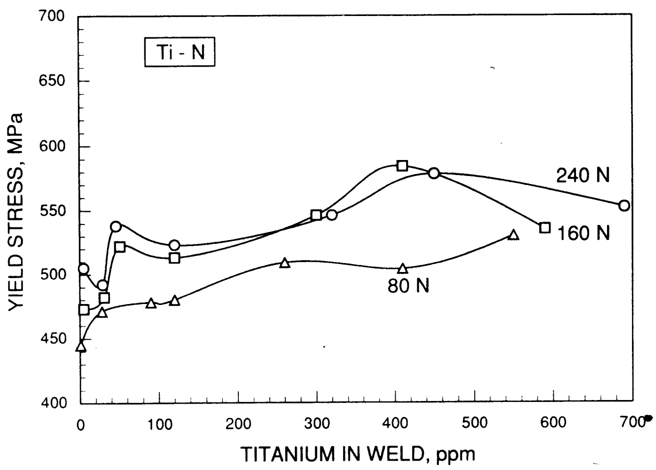


FIG. 5 YIELD STRENGTH OF THE Ti-N WELD SYSTEM PLOTTED AGAINST TITANIUM CONTENT

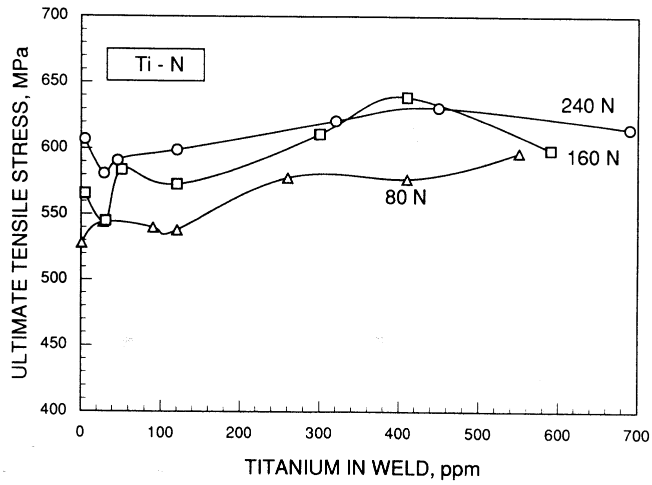


FIG. 6 ULTIMATE TENSILE STRENGTH OF THE Ti-N WELD SYSTEM PLOTTED AGAINST TITANIUM CONTENT

a)

b)

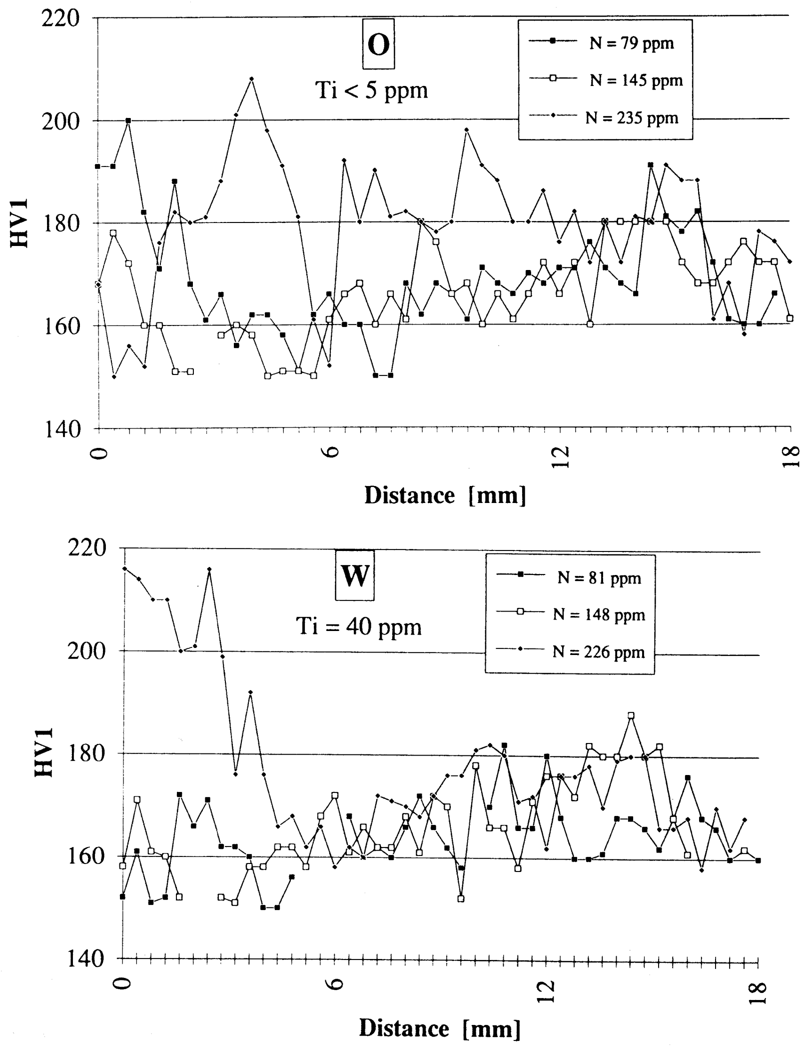
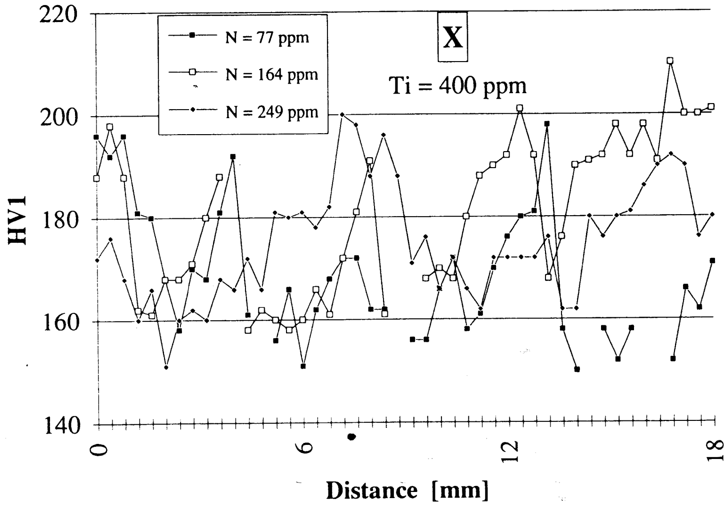
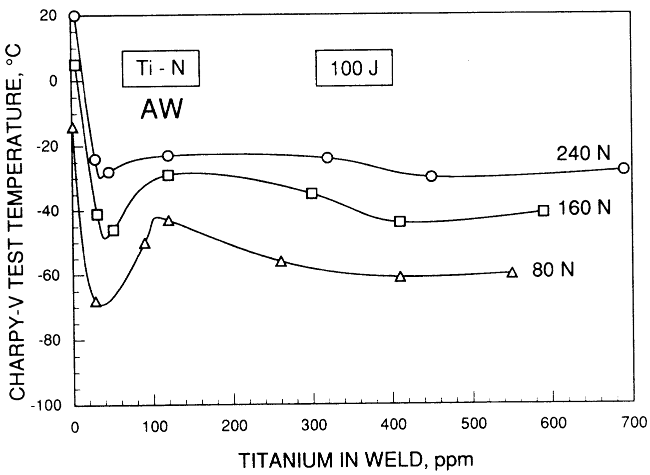
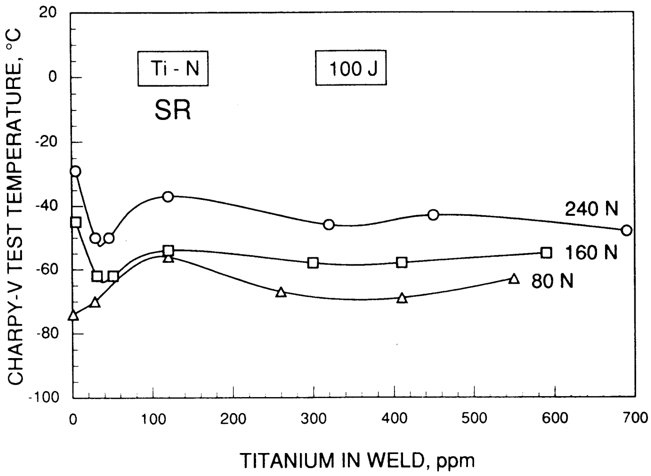


FIG. 7 HARDNESS TRANSVERSE RESULTS OF THE O, W, X WELD METALS FOR DIFFERENT NITROGEN CONTENS

FIG. 7c)

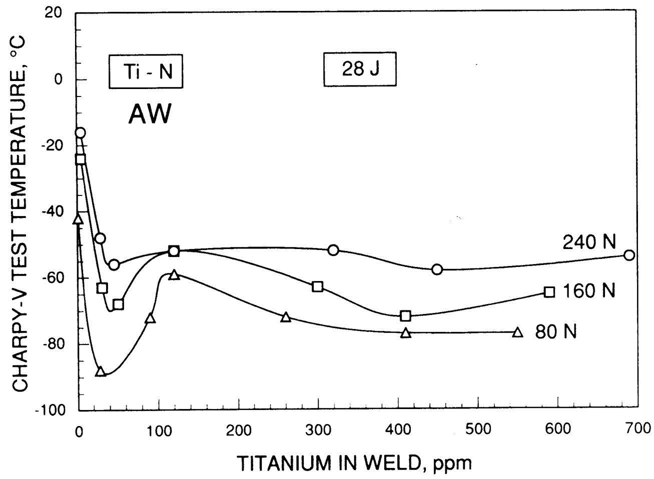


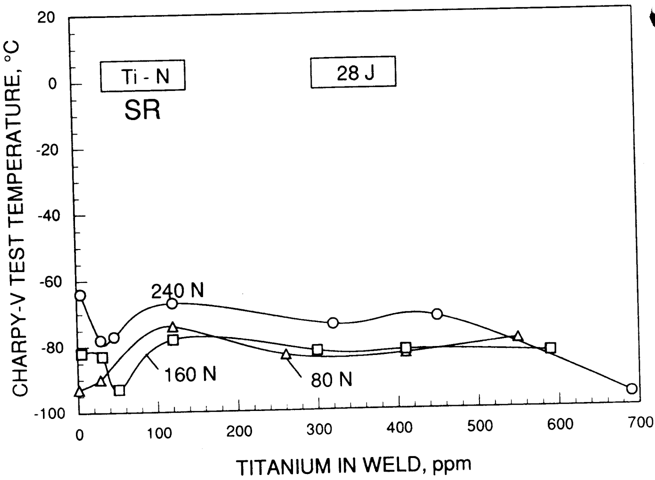




a) b)

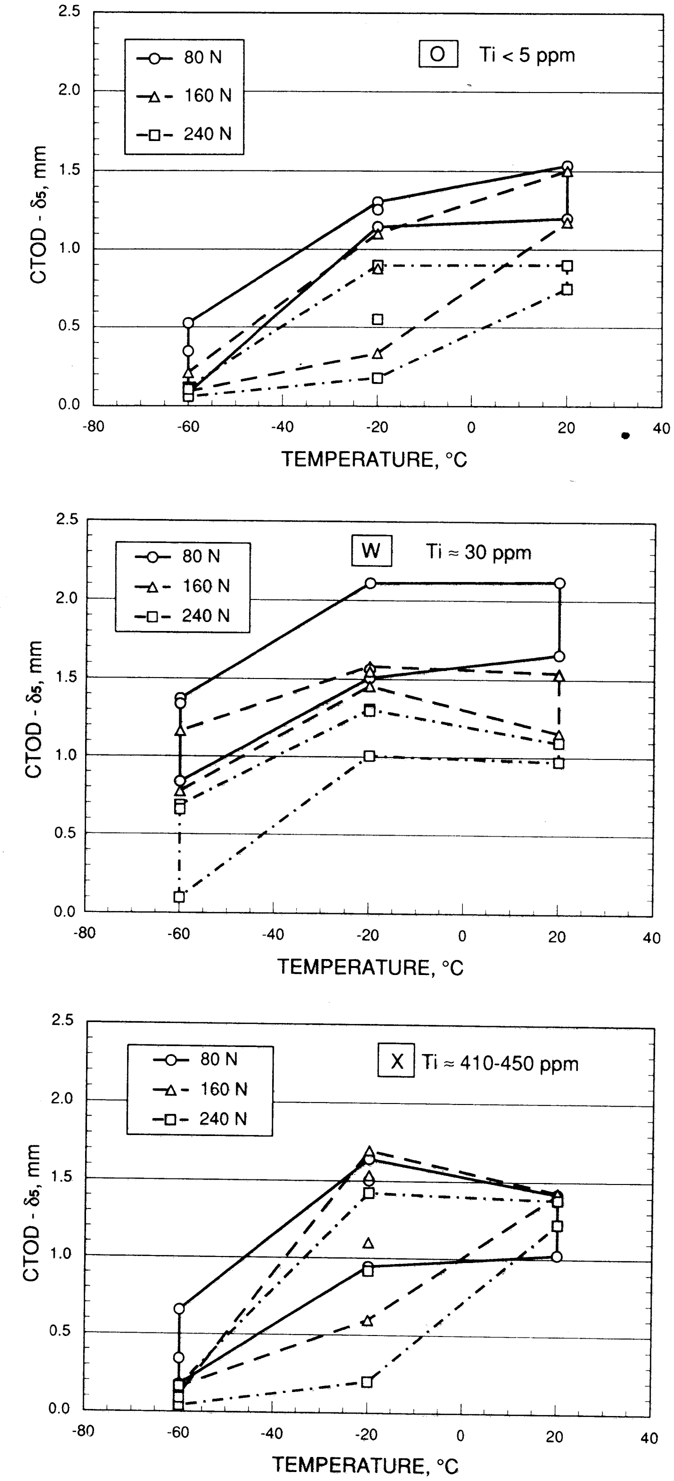
Fig. 8 EFFECT OF TITANIUM AND NITROGEN ON THE CHARPY-V TEMPERATURE CORRESPONDING TO 100 J a) FOR AS-WELDED (**AW**), b) FOR **SR** CONDITIONS





a) b)

Fig. 9 EFFECT OF TITANIUM AND NITROGEN ON THE CHARPY-V TEMPERATURE CORRESPONDING TO 28 J a) FOR AS-WELDED (**AW**), b) FOR **SR** CONDITIONS



a)
b)
c)

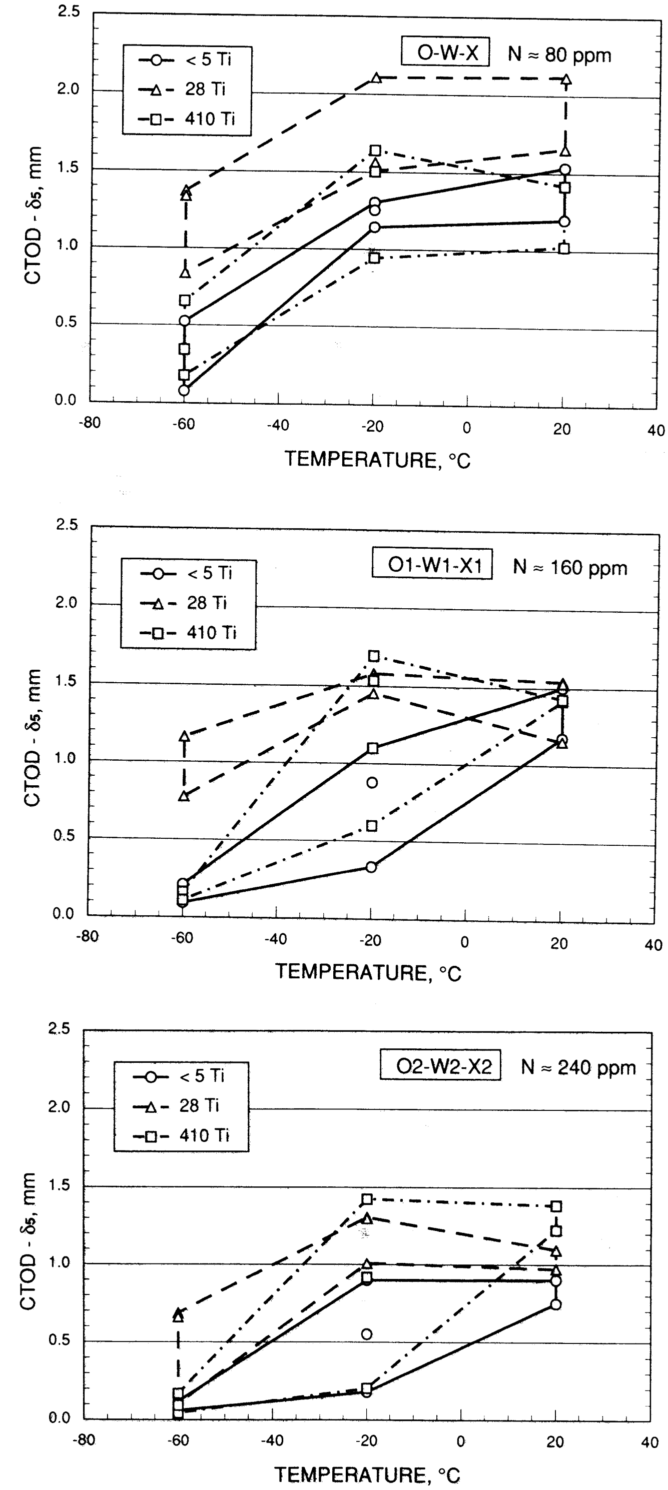


FIG. 10 EFFECT OF **NITROGEN** ON THE CTOD (δ5) TOUGHNESS OF THE WELD METALS TESTED IN AS-WELDED CONDITION AT THREE TEST TEMPERATURES
a) FOR WELD METAL **O** (Ti < 5 ppm),
b) FOR WELD METAL **W** (Ti = 30 ppm),
c) FOR WELD METAL **X** (Ti = 410 - 450 ppm)

FIG. 11 EFFECT OF **TITANIUM** ON THE CTOD (δ5) TOUGHNESS OF THE WELD METALS TESTED IN AS-WELDED CONDITION AT THREE TEST TEMPERATURES
a) FOR WELD METAL WITH **80** ppm N **(O-W-X)**,
b) FOR WELD METAL WITH **160** ppm N **(O1-W1-X1)**,
c) FOR WELD METAL WITH **240** ppm N **(O2-W2-X2)**