NIOBIUM IN STEEL CASTINGS

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Synopsis

Recent developments in large steel node castings are described briefly, and the advantages offered by the use of cast nodes are illustrated. The development of high integrity castings has been made possible by steelmaking developments and developments in foundry technology. This paper describes the metallurgical aspects of the development of nodes, which necessitates deviations from the conventional manufacture of steel castings. The microstructural and mechanical properties attained are compared with those of plates used in fabricated structures.

Introduction

The exploitation of offshore oil reserves has fostered the development of large steel or reinforced concrete structures. Steel jacket structures for use in the North Sea are being developed for application in deeper waters with more hostile environments. The move to deeper waters requires the design and fabrication of larger structures, and dramatically increased plate thicknesses are necessary to give adequate stiffness, or more complex joints with internal stiffeners are needed. Problems arise concerning the quality and integrity of welded joints in the fabricated node, relating to fatigue and corrosion fatigue properties, and to regions of stress concentration in the vicinity of the weld.

The advantages of the cast steel component over fabricated alternatives are being exploited by the British Steel Corporation, either as a direct substitution, or as part of a total structure designed to optimise the use of castings. Initially, development work was concentrated upon the development of nodes which could be substituted in a structure designed as welded fabrication. In order to avoid problems of incompatibility between the cast node and adjoining tubular members, both the chemical and material property specifications for the cast node need to be similar to those of the structural plate currently used. The basic objective was to develop a cast steel based upon the plate specification BS4360 grade 50D. The present paper describes metallurgical aspects of the development work.

Advantages of Cast Nodes

A large (25 tonne) node casting manufactured in the River Don Foundry is shown in Figure 1. The wall thickness can be varied from one part of the casting to another to accommodate stresses. It is clear that very complex shapes can be produced as shown in Figure 2, and what is more, stiffeners and cross braces can be made as an integral part of the casting. The manufacture of such nodes offers a number of advantages over the fabricated node as follows.

Stress concentration

By producing the node as a casting, it is possible to introduce optimum fillet profiles which reduce local stress concentrations. A section through a node casting is shown in Figure 3. The smooth profile fillets are clearly shown. High stress concentrations of up to x12 may be observed near the toe of a welded joint (1). The addition of large fillets in a welded structure has a stiffening effect and reduces stress concentration factors at the center of the fillet but concentrates the stress to a similar degree (x11) in other areas. The adoption of a smooth profile fillet in a casting gradually running out into the chord reduces stress concentration factors to about x3. Measurements of stress concentration factors have been obtained using strain gauges and photoelastic stress analysis on acrylic and epoxy resin models respectively. Typical results are shown in Figure 4 confirming the low stress concentration factor attainable with the smooth fillet profiles.

Figure 1. A 25 tonne Cast Node.

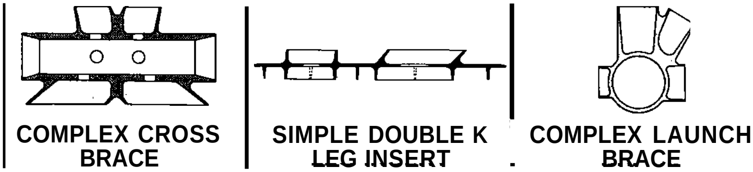


Figure 2. Complex Node Shapes

Figure 3. Section through a Cast Node showing Smooth Profiled Fillets.

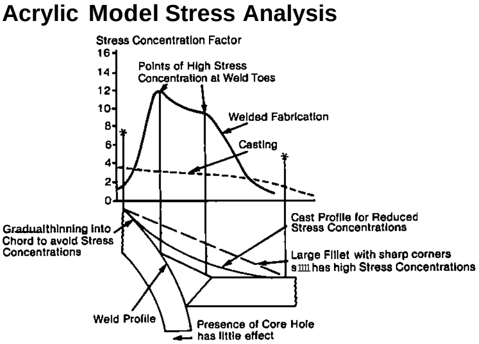


Figure 4. The fatigue life of welded fillet joints is restricted by the presence of crack–like defects, residual stresses and high stress concentration factors at the weld toe. The use of cast steel for a node enables rounded fillet profiles with significantly lower stress concentration factors to be developed for improved fatigue life.

Fatigue properties

The reduction in stress concentration factors gives an accompanying improvement in the fatigue behavior of the cast components. It should be emphasized that this advantage derives from the design of the fillet profiles, etc. in the component and the absence of weld toe defects, and is not produced by any change in the material properties. Measurements of fatigue performance have been made for both welded and cast cruciform type joints **(1).** The cast cruciforms showed significantly improved fatigue lives, even when they had been weld repaired. The implications of the improvements in stress concentration factors and component fatigue life are shown in Figure 5. Improvements in life of up to x18 have been estimated for certain components based upon improved fillet profile but neglecting the improvement resulting from the absence of weld toe defects.

Isotropy of properties

The node steel, being in the cast state, shows isotropy of properties thereby avoiding the problems which arise in transverse and short transverse directions in plate products, and which can lead to lamellar tearing because of the reduced through thickness ductility.

Cost advantape

Significant reductions in platform construction costs can be attained, of the order of 20 percent, and greatly reduced "in-service" inspection and maintenance charges accrue as a consequence of the improved reliability of the product and the fact that all the primary welds are the easily accessible circumferential welds located in lowly stressed regions.

Metallurgical aspects

As indicated in an earlier section of this paper, the initial development of the node steel was based on the requirement to substitute cast nodes for fabricated ones in existing structures, and to make the nodes compatible with the BS4360 grade 50D steel used for the structural tubulars. In order to ensure adequate weldability, a maximum CEV of 0.48 was specified. The basic composition is as follows:

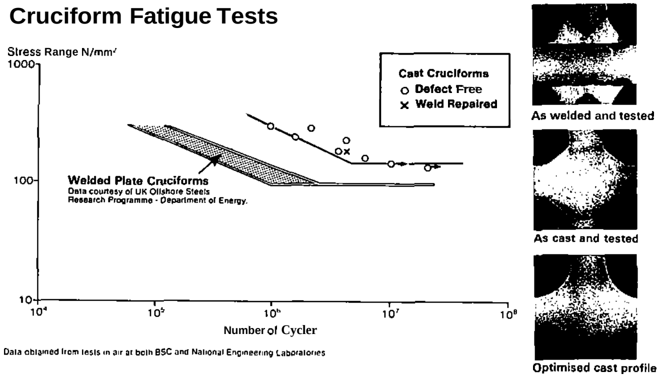


Figure 5. Fatigue Test Results.

C	Mn	Si	S	P	Ni	Mo	V	Nb
0.18x	1.2/1.6	0.5x	0.01x	0.02x	0.5x	0.2x	0.08x	0.04x

x indicates the maximum level.

The casting is annealed, normalized, and finally stress relieved at 600 C.

Deoxidation practices

Conventional deoxidation practices for large steel castings involve heavy deoxidation with aluminum in order to avoid producing porous castings. This led to the problem of rock-candy fracture (2) which is an intergranular fracture caused by intense plate-like precipitation of aluminum nitride on the austenite grain boundaries. In order to overcome the problem of rock-candy fracture, additions of zirconium or titanium were made to fix the nitrogen in the form of cuboids. Zirconium and titanium form extremely stable nitrides, the cuboids separating out in the liquid prior to solidification, thus preventing the formation of intergranular plates of aluminum nitride.

One of the prime requirements of node steels for use in the North Sea is low temperature impact properties. Zirconium and titanium additions were considered undesirable for low temperature toughness. One view is that the large cuboids act as crack initiation sites for cleavage fracture. Nevertheless, aluminum is desirable as a deoxidant and also to provide grain growth inhibition (3). Niobium is also a useful grain refiner in normalized steels (4). It it important to recognize this distinction from the role of niobium in wrought plate, where it acts as a dispersion strengthener and affects prain refinement by retarding recrystallization and austenite grain growth during hot rolling (5). In order to establish the appropriate levels of these elements, test blocks were prepared which had been subjected to similar thermal cycles to those experienced by the casting during solidification and subsequent thermal treatments.

Because of the extremely slow cooling rates associated with large castings of up to 60 tonnes in weight cast and cooled in sand, the precipitation processes suffer little undercooling. A knowledge of the appropriate solubility data for niobium carbide and aluminum nitride is available from extensive studies based on wrought products (6) and is pertinent to both intergranular fracture and grain refinement. Solubility data for these compounds in austenite are given by the following equations:

$$\log_{10} [Al] [N] = -6,770/T + 1.03 \tag{1}$$

$$\log_{10} [Nb] [C] = -6,770/T + 2.26 \tag{2}$$

where [x] is the concentration of the element in solution (wt%) and T is the absolute temperature (°K).

The relevance and application of these solubility relationships are given in the following sections.

Behavior of Aluminum Nitride in Large Castings

The solubility equation for aluminum nitride, equation 1 was used to construct the solubility diagram shown in Figure 6. The isotherms indicate the limits of aluminum and nitrogen that can be held in solution at a given temperature. In the case of a large steel casting cooling slowly from a high temperature, the chemical composition will dictate the temperature at which aluminum nitride will become stable and will start to precipitate under equilibrium or near equilibrium cooling. Higher aluminum and nitrogen contents will result in precipitation starting at higher temperatures. With precipitation of aluminum nitride, the loss of aluminum and nitrogen from solution will occur according to the stoichiometric ratio i.e. 27:14 as indicated in Figure 6. It is thus possible to trace the extent of precipitation in a given steel as a function of temperature, provided that the cooling rate is slow enough to give a reasonable approach to equilibrium. Such precipitation curves are shown in Figure 7 for steels with 0.01 percent N and various aluminum contents. It is clear that an increase in aluminum content inceases the bulk precipitation temperature range. At 0.06 percent Al, the bulk (74%) of the precipitation occurs at temperatures above 1100 C. As the aluminum content is lowered, the bulk of the precipitation occurs at temperatures below 1100 C. Provided that the aluminum content remains in excess of stoichiometry, the nitride content at low temperatures in the austenite range is only slightly affected by aluminum, thereby giving greater opportunities for grain refinement. In studies of grain refinement (7), it has been shown that the critical particle size above which grain growth can occur is related to the volume fraction of particles, f, as shown in the following equation:

$$r_{crit} = 6 \frac{R_o f}{\pi} \left(\frac{3}{2} - \frac{2}{Z}\right)^{-1} \qquad (3)$$

where R_o is the austenite grain size and Z is the ratio of the diameter of a large grain to that of its neighbors and describes grain size heterogeneity.

For a given austenite grain size established during the normalizing treatment, and a given grain size heterogeneity, increasing the volume fraction of particles increases the critical particle size above which grain growth will commence. This means that the workpiece can be held at temperature longer, or can maintain a finer grain size, than a steel with a lower volume fraction of particles. On the other hand, particles which are formed at high temperature in steels with high aluminum nitride contents will coarsen rapidly and may exceed the critical particle size before reaching the heat treatment stage. This aspect would be particularly relevant to aluminum nitride precipitated on the as cast grain boundaries in the plate form, such as would give rise to rock-candy fractures.

Experimental test blocks of suitable dimension were cast and heat treated. Notched bend tests were carried out at ambient temperature. Coarse facets were observed on the fracture surfaces of steels containing high aluminum contents. Scanning electron microscopy revealed coarse dendritic patterns in the facets, Figure 8. Carbon extraction replicas were taken from these surfaces and revealed extensive intergranular precipitation of a plate-like precipitate, Figure 9. The precipitate was identified as aluminum nitride by electron diffraction, and by Auger electron spectroscopy on fractured surfaces. As the aluminum content was reduced, the occurrence of coarse facetting was also reduced and the aluminum nitride plates became more particulate and isolated Figure 10.

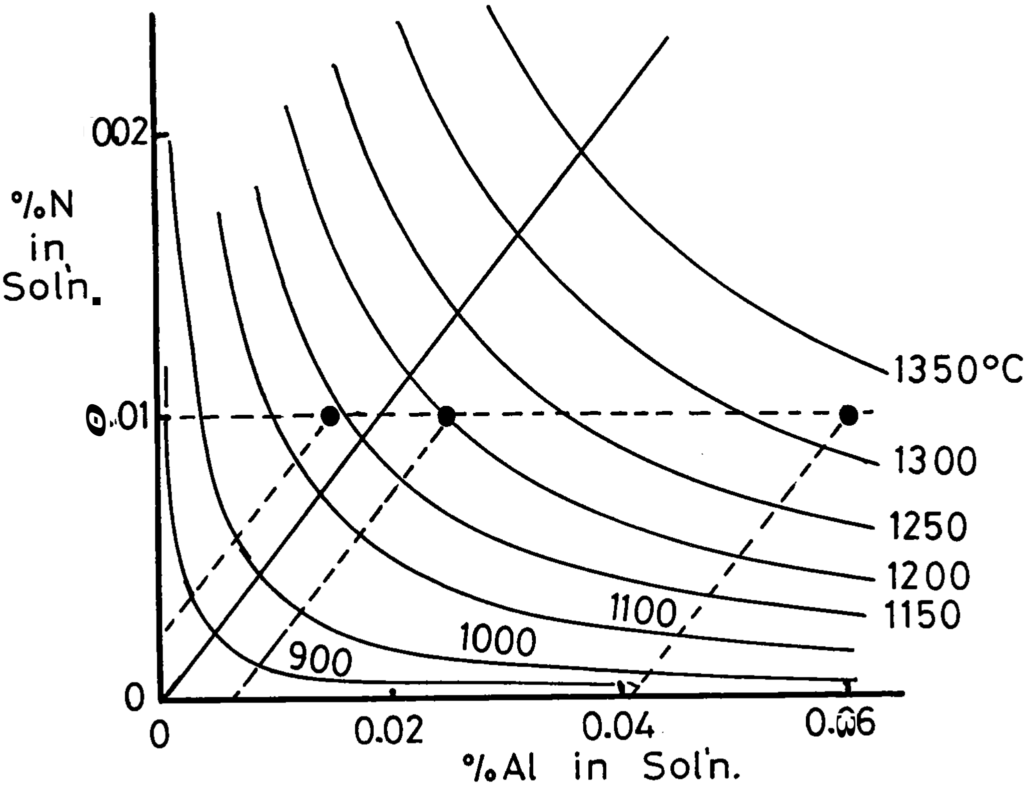


Figure 6. Solubility of Aluminum Nitride.

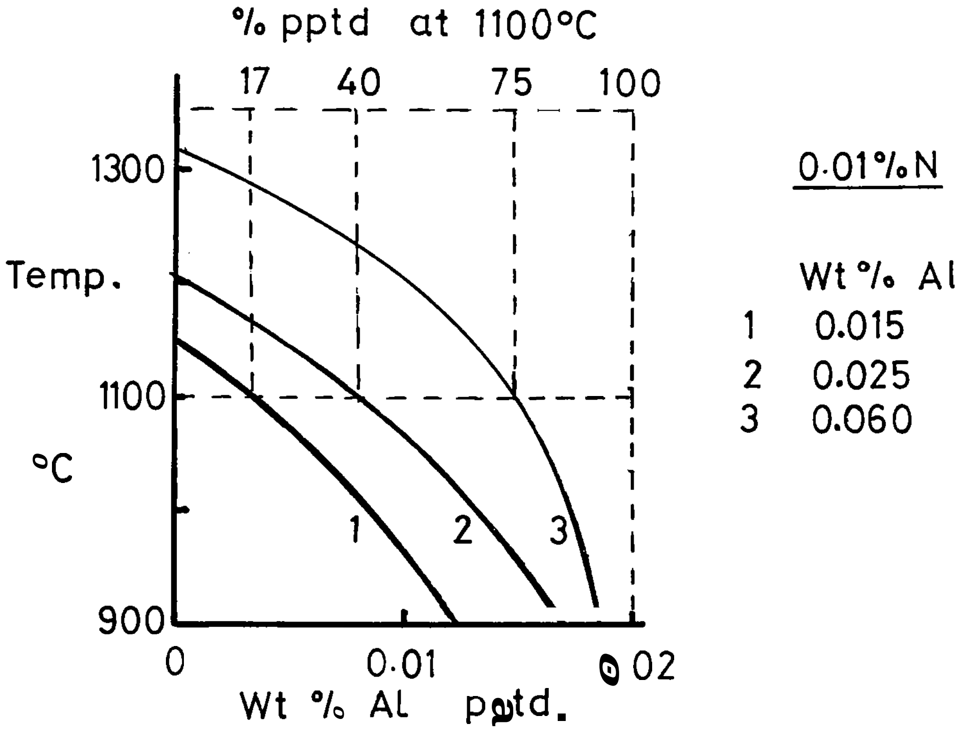


Figure 7. Precipitation Curves for Aluminum Nitride.

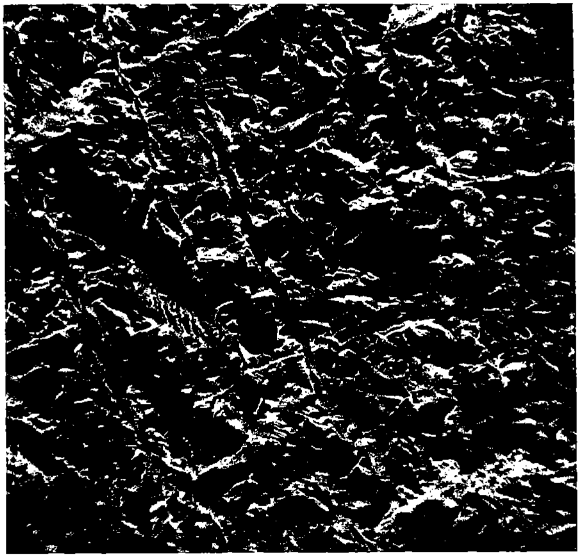
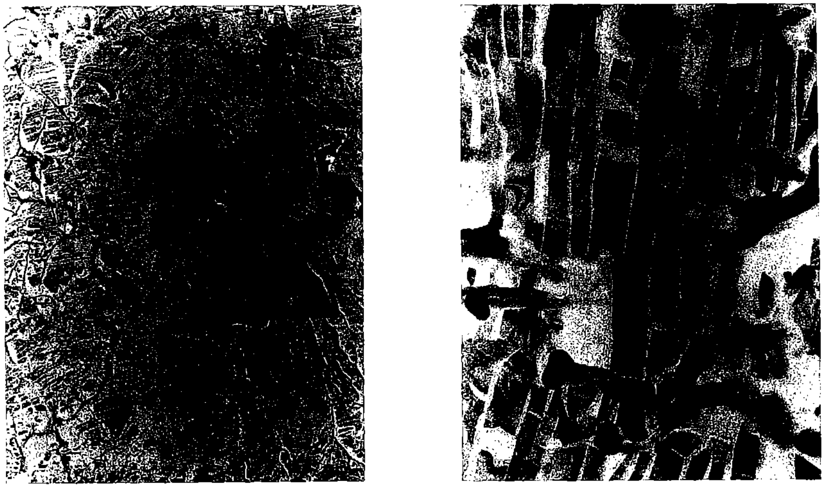


Figure 8. SEM of a High **Aluminum Steel Fracture Facet** x500.



9 (a). x2,000

9 (b). x40,000

Figure 9. **Aluminum Nitride Plates** on As **Cast Boundaries in High Aluminum Steel.**

Figure 10. Particulate Aluminum Nitride in a Low Aluminum Steel x40,000.

Behavior of niobium carbide in large castings

The solubility data expressed by equation 2 was used to construct the solubility diagram shown in Figure 11. A feature of this diagram is the vast excess of carbon (at 0.15 wt%) over that required by the stoichiometric ratio for niobium. The solubility of niobium at low temperatures is virtually independent of the niobium content. Precipitation-temperature curves were prepared Figure 12 which shows the niobium solubility and the effect of niobium content on the precipitation temperatures. The volume fraction of niobium carbide precipitated at low temperature can be seen to be independent of the niobium content. Increasing the niobium content merely increases the total volume fraction of niobium carbide by increasing the high temperature precipitation. Fractographic studies revealed the presence of extensive intergranular flakes of niobium carbide in steels with high niobium contents, Figure 13. As the niobium content was reduced, the incidence of the plate form was also reduced, and tended to become more particulate, Figure 14.

It should be pointed out that the additions of both aluminum nitride and niobium carbide would contribute to the volume fraction of particles expressed in equation 3 and would increase the critical particle size and hence the grain coarsening resistance.

Mechanical Properties of Cast Nodes

Thick section test blocks were cast using steel of suitably restricted niobium and aluminum contents. Properties obtained on these thick section test blocks are shown in Figure 15. As can be seen, the tensile yield strength and elongation values, and the Charpy Impact Energy at *40* C met the required plate grade specifications. Figure 16 shows the mechanical properties determined on a 25 tonne production node which was sectioned for destructive testing under the supervision of Lloyds Register Inspectors. Test positions A, B and C relate to the chord, brace, and intersection; the changes in strength observed at various positions reflect the section thickness. Impact energy levels met the plate grade specification. Fracture toughness testing was carried out at -10 C and COD values are compared with those obtained from corresponding plate products in various orientations. It can be seen from Figure 17, that the COD value taken from the casting was comparable with the longitudinal value for plate material, and is of course isotropic.

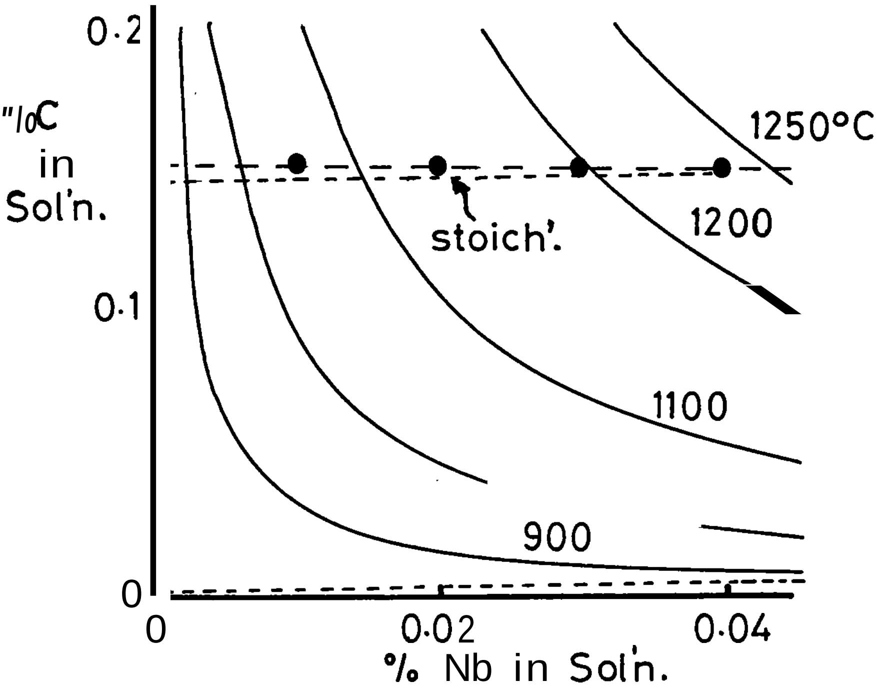


Figure 11. Solubility of Niobium Carbide.

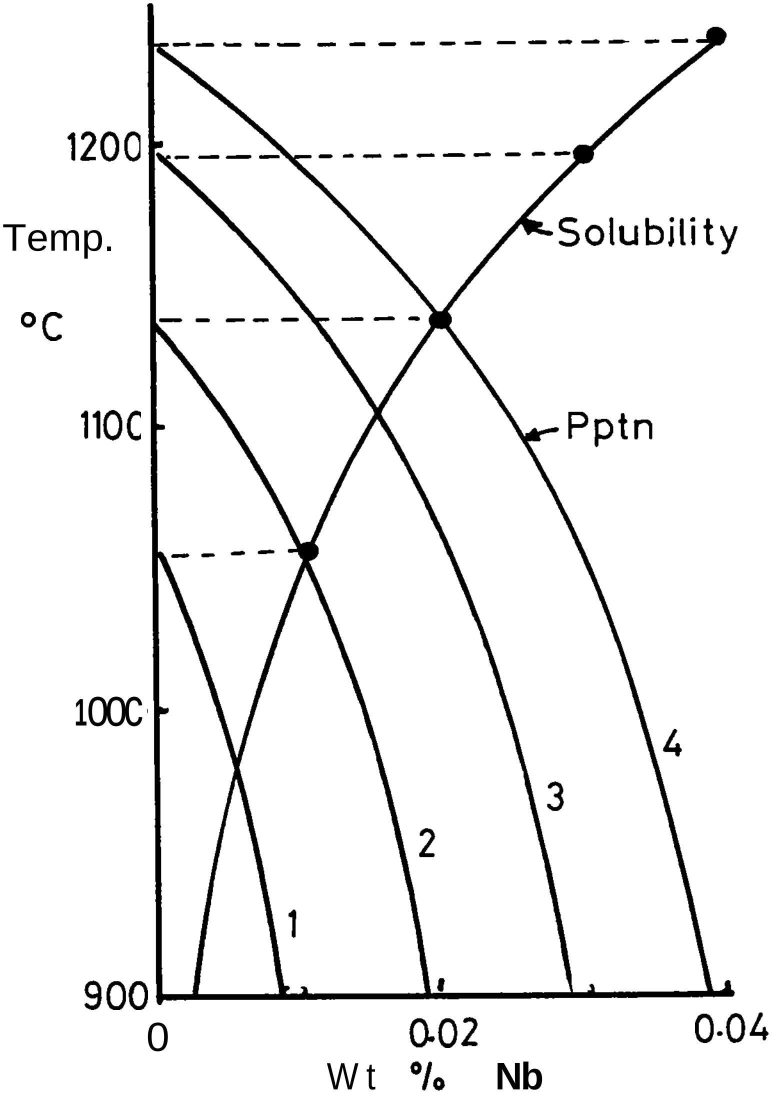


Figure 12. Precipitation Curves for Niobium Carbide at 0.01% (1), 0.02% (2), 0.03% (3) & 0.04% (4) Niobium

Figure 13 (a). x2,000.

Figure 13 (b). x10,000.

Figure 13. Grain Boundary Flakes of Niobium Carbide in a High Niobium Steel.

Figure 14 (a). x2,000.

Figure 14 (b). x10,000.

Figure 14. Reduced Incidence and more Particulate Morphology of Niobium Carbide Flakes in a Low Niobium Steel.

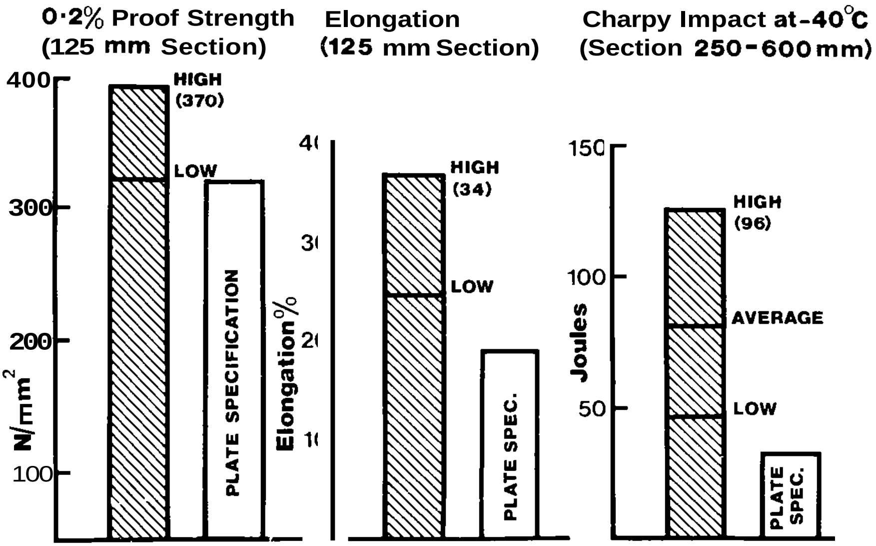


Figure 15. Typical Mechanical Property Data from Thick Section Test Blocks.

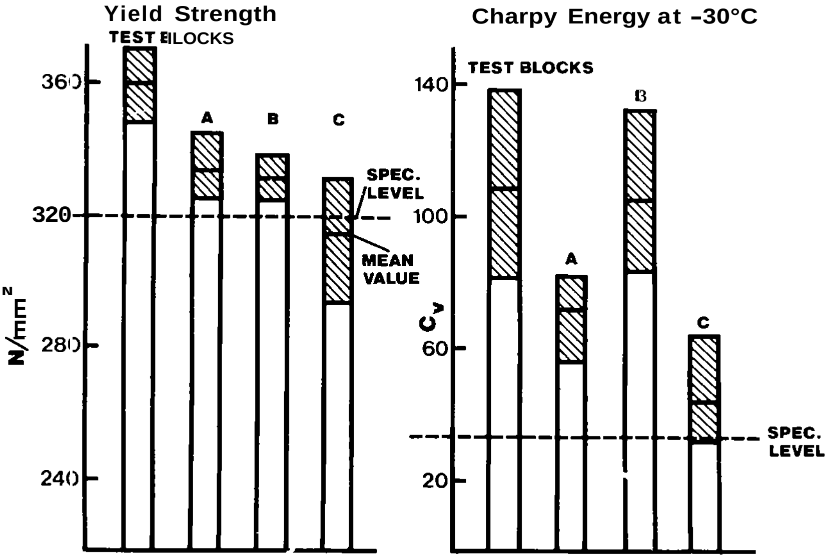


Figure 16. Properties of a 25 Tonne Production Node.

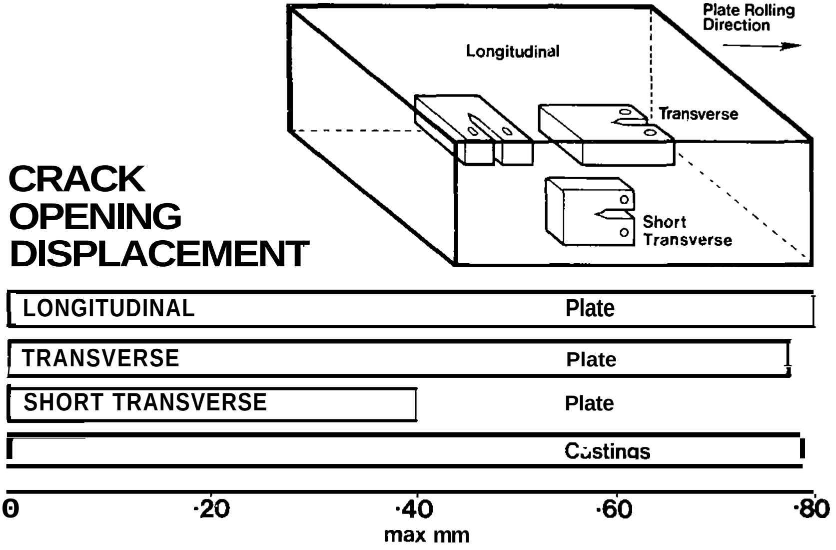


Figure 17. Comparison of COD Results from Cast Node Steel and Wrought Plate.

Summary

A brief description of a development program for cast nodes has been given, emphasizing the particular advantages of reduced stress concentration and improved component fatigue properties, together with the economic advantages of easier fabrication and maintenance.

The metallurgical aspects of controlling the structure and properties of node steel by control of aluminum and niobium contents are described in some detail. Excessive use of these elements can give rise to high temperature intergranular precipitation phenomena resulting in hot cracking or low energy fracture mechanisms at ambient temperature. Suitable control of these elements has been attained by the use of modern developments in secondary steelmaking and in foundry technology.

The mechanical properties obtained in a 25 tonne production node have met the required levels for both strength and toughness.

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