Niobium Bearing Structural Steels
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SELECTION AND WELDING OF NIOBIUM BEARING STRUCTURAL STEELS IN SOME RECENT UK SHIPBUILDING CONTRACTS

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Abstract

Within the UK shipbuilding sector the use of niobium (Nb) bearing steels tend to have been limited to high stress areas, where minimum strengths of 350MPa were commonly applied. As thicker gauge steels were used in these areas, the steel always contained Nb to develop the desired strength/toughness combinations. In traditional naval contracts strengths of 270MPa were the norm, but recent vessel designs have been very sensitive, which has resulted in these steels being displaced by the higher strength/superior toughness steel grades. The reasons of which are discussed in this paper, as is the chemical composition of the steels used.

The paper presents some of the recent Nb-bearing steels that have been used in the build and fabrication recent naval vessels. The welding of these, predominantly Nb-bearing, steels is also described particularly with reference to the heat affected zone toughness. An evaluation of laser welding these steels is described, as a significant proportion of these steels used have been thin plate (<8mm). The selection of a 460MPa strength steel for the flight deck and hanger of an upcoming aircraft carrier contract is described as is the evaluation of the submerged arc welding of steel processed by two different manufacturing routes.

Introduction

During the last 20 years the shipbuilding industry in the UK has contracted significantly. It now consists of two build sites concentrating on naval ship contracts, one build site on submarines, and the remainder of the build sites on smaller specialised craft. There are a number of other sites which concentrate on the ship repair sector. The two sites of BVT Surface Fleet are at Portsmouth on the south coast of England and the other is at Glasgow on the River Clyde on the west coast of Scotland. Although commercial build has largely disappeared from these sites, the vessels built there are now constructed to standards which more resemble commercial build requirements.

Naval contracts completed about 10 years ago mainly used relatively low strength / low toughness steels such as the Lloyds Grade A and some Lloyds Grade D shown in Table 1. This was typical of the steels used on frigates such as the Type 23 shown in Figure 1. Other offshore patrol vessels and frigates for far eastern naval contracts used the same steel type combinations.

Table 1. Comparison of Lloyds Grade A and Grade D steels.

Steel grade	%C	%Si	%S	%P	%Mn	%Al	%N_2	YS MPa	UTS MPa	Toughness J at X°C	X°C	Plate Thickness (mm)
Lloyds Grade A	0.15	0.20	0.015	0.018	0.82	0.035	0.0055	290	450	170	20	12
Lloyds Grade D	0.11	0.23	0.005	0.011	0.64	0.039	0.0050	298	428	204	-20	11.5

Figure 1. HMS Argyll – a Type 23 Frigate.

The most recent UK naval contract for six destroyers was initially based on the use of Lloyds Grade D steel, a typical analysis of which is shown in Table 1. This had a higher toughness requirement but the same strength as the Grade A steel. Failure to meet the build weight requirements at this stage of design meant that a decrease in plate thickness had to be obtained without compromising structural integrity.

The option of using aluminium in the superstructure was not considered to be viable, as the UK Royal Navy had concerns related to fire resistance of the material, based on previous experiences. At this stage superstructures produced from composite materials are not an option, but will probably materialise in the future, based on work being carried out in USA. The option of replacing areas of the D grade steel with higher strength, thinner DH36 was adopted. As a result, 82% of the plates used in the design were Lloyds Grade DH36, and this resulted in a significant amount of 4 and 5mm thick plate being used. The first ship of the class, HMS Daring is shown in Figure 2, preparing for sea trials.

Figure 2. Type 45 Destroyer – HMS Daring.

Type 45 Destroyer

The steel for this contract was sourced primarily from two European steel mills. The 4 and 5mm thick plates originated from the only plate rolling mill in Europe capable of producing 4mm thick plate. The mill contains what is ostensibly a 4-stand hot rolling mill. The remainder came from a very modern east European mill, with a high level of rolling automation incorporated into it.

The typical chemical analysis of the various plate thicknesses are shown in Table 2. Very small additions of niobium are made to the 4 and 5mm thick plate product to ensure the minimum yield strength can be guaranteed by at least 40-50MPa, thus highlighting the potency of Nb-microalloying. Prior to adopting the microalloying addition, the product yield strength was too close to the specified minimum. In the case of the plate above 8mm thick, niobium is added to ensure the strength/toughness properties are met. However, no niobium is added to the 6 and 7mm thick product as the properties appear to be generated through the action of the rolling reduction process on a much higher C -Mn-Al steel. Typical plate mechanical properties are also shown in Table 2. Where toughness is shown it has been corrected from the certificated figure by using the accepted conversion factors for test specimen size found in Lloyds Rules for the Manufacture, Testing and Certification of Materials.

Table 2. Typical steel plate chemistry and properties at various thicknesses from different mill supply.

Grade	**(mm)**	**%C**	**%Si**	**%S**	**%P**	**%Mn**	**%Nb**	**%Al**	**%N_2**	**YS (MPa)**	**Impact Energy (J@-20^{o}C)**
DH36	4, 5	0.100	0.20	0.008	0.013	1.30	0.012	0.035	0.0050	440	90
	6	0.165	0.35	0.009	0.017	1.44	0.001	0.037	0.0045	415	204
	>6.5<8	0.150	0.35	0.005	0.016	1.31	0.030	0.045	0.0050	415	190
	>8	0.110	0.27	0.008	0.023	1.26	0.032	0.032	0.0040	493	68

The proportion of thin plates (<8mm thick) in this vessel was 63%, and the main concern in the fabrication of thin plate structures is to ensure that distortion is minimised. As a result, practices such as minimising cutting heat and welding heat input were put in place. In addition a number of other critical factors were identified as contributing to thin plate distortion [1-3].

One of the possible process routes to reduce thin plate distortion is to apply some form of laser welding to the structure. Therefore an investigation was carried out into the capability of welding DH36 plate over a range of thicknesses. This work has been reported in detail elsewhere [4], but Table 3 summarises the outcome of the work carried out. The chemical analysis of the steel used was a 0.013%C-0.42%Si-0.006%S-0.013%P-1.35%Mn-0.025%Nb-0.035%Al-0.005%N_2-0.017%Ti, which was common to all plate thickness. It is generally accepted that the potential for thin plate distortion to occur will increase in the process order; autogenous CO_2 laser - CO_2 laser assisted MIG – Nd-YAG laser assisted MIG – SAW. As can be seen in Table 3, this is related to the increase in the 10mm thick equivalent weld metal volume for the welding process. Also shown in Table 3 is the beneficial effect of using an assisted MIG process compared to the autogenous laser process on the weld metal toughness. There is a tendency for the autogenous laser welding process to generate high hardness areas in the weld metal, which relates to the poorer toughness seen here.

The best option for a shipyard would be a laser assisted MIG process, to allow variations in the weld joint fit up to be accommodated, plus the ability to alter the weld metal chemistry. The secondary option would probably involve adopting the fibre optic technology of the Nd-YAG process over the CO_2 process. For this specific situation, there is obviously scope to further fine tune the laser assisted process to build in improvements in weld metal toughness. While it would be highly desirable to be able to apply this type of technology, a financial justification to install a laser welding facility could not be sustained on the basis of reduction in distortion rework reduction.

Friction stir welding may also hold some promise, where maximum temperatures of around 930^{o}C were measured [5] about 4mm from the centre of the weld. Microhardnesses were less than 200 on HSLA steel. However, there are a significant number of issues related to tool wear [6] and achievable plate thicknesses that need to be resolved before this technology can be considered as being suitable for shipbuilding.

The outcome was to tackle the problem of distortion at what were known to be its root causes using the current arc welding processes [1-3]. One of the outcomes of a study [7,8] using Artificial Neural Networks (ANN) was that higher tensile, less ductile steel was less susceptible to distortion or buckling. It was generally regarded that the inherent stiffness of the higher strength steel was a dominant factor in resisting distortion/buckling. From this work it is hoped to develop a study to consider higher strength thin plate steels (probably of Hot Strip Mill origin), with ductility at the lower end of the acceptable range. This type of steel would obviously be niobium treated. The level could be around 0.05%. Some similar work has been reported [9] in Australia using X80 type Hot Strip Mill steel, with some very positive effects.

From the initial discussion it should be noted that niobium is present in a number of shipbuilding steels possibly by default, and in some instances an unwillingness to change. There is no specific technological reason why other alloying systems with or without niobium [10] could not have been used in the Type 45 destroyer programme steels – from a purely technological point of view. Steelmaking, casting and processing have all advanced very significantly in the last 30 years, and some of the reasons for adding specific microalloying elements may now be in a position to be questioned. Titanium, for example, was never considered to be a serious contender as a microalloying element [8], but that was based on data generated before the wholesale implementation of secondary steel making techniques. Although there are still some issues with nitrogen control, the issue is nowhere nearly as severe as it was in the past. These techniques have also led to an ability to control titanium to very tight limits. With the cost of titanium being very favourable, a case could be presented in the future to justify its wider scale use. It would have one significant advantage in the control of HAZ toughness. It is in the HAZ that niobium has a somewhat mixed reputation [11-14] and the beneficial use of a Ti-Nb microalloying is successfully used to limit the HAZ [16]. However, as long as any potential drop in toughness in the HAZ can be catered for in the parent plate properties then niobium will continue to be used in shipbuilding steels.

Table 3. Data generated from laser weld test welding of DH36 plate.

Plate Thickness (mm)	**Welding Process**	**Weld Metal Toughness (J@-20°C)**	**HAZ Toughness (J@-20°C)**	**Weld Metal Microhardness**		**Weld Metal Area (mm^2)**	**10mm Equivalent Weld Metal (mm^2)**
				Average (Hv0.1)	**Maximum (Hv0.1)**		
15	CO_2 Laser	32	43	300	350	38.6	24.4
12		37	73	330	375	25.4	21.2
10		35	53	360	375	21	21
12	CO_2 Laser Assisted MIG	64	42	280	325	44.6	37.2
9		85*	43	290	340	27.3	30.3
6		57	47	286	340	19.9	33.2
8	Nd:YAG Laser Assisted MIG	57	45	255	280	42.2	52.8
6		52	40	248	265	28.2	47.6
4		53	49	250	270	18.7	46.8
10	SAW	49	72	199	224	180	180

Future Projects

The most immediate new build project involves two aircraft carriers for the UK Royal Navy [15]. These vessels are being built in four major block sections at four construction yards within the UK. The final assembly is planned to be carried out at Babcock Engineering Services at Rosyth on the east coast of Scotland. This is potentially a complex project, and its successful completion will depend on a robust project management approach. Figure 3 shows a conceptual illustration of the vessel.

Figure 3. An artist's impression of the future aircraft carrier.

In terms of thickness this project is diametrically opposed to the work on the destroyer programme, although the bulk of the steel is DH36 grade. However, within the build there is a sizeable tonnage of EH46 steel, which will be used on the flight deck and the hanger deck. Although the initial design plate thickness was around 35mm maximum, through various iterations areas of the flight deck were decreased to about 22mm thick by the use of EH46 plate. This was developed from a base case which originally had EH36 grade designed into the flight and hanger decks. There are two potential basic plate processing routes for the EH46. One was a quench and temper (QT) process route and the other was a thermo-mechanical-control-process (TMCP) plate. The overall assessment using EH36, as the base case for these areas is shown in Table 4.

Table 4. Material route assessment for flight deck steel.

Steel Grade	**EH36**	**EH46 (QT)**	**EH46 (TMCP)**
Tonnage	3,051	2,593	2,593
Unit cost index	85	100	91
Overall cost index	259,335	259,300	235,963
Welding Time	Baseline	Approx. 27% shorter	Approx. 27% shorter
Consumable cost index	Baseline	17% higher	17% higher
Consumable usage	Baseline	29% lower	29% lower
Welding overall	Baseline	Cheaper	Cheaper
Weldability	Baseline	More complex	Baseline
OVERALL ASSESSMENT			**BEST OPTION**

What this showed was that the desired plate thickness/weight reductions could be achieved through the use of the higher strength steel. The QT plate had a number of drawbacks, such as preheat requirements, cost, and availability. Overall the use of EH46 – TMCP generated the best combination benefits for the project, and also cost savings.

The initial evaluations of EH46 were carried out using 20mm thick plate to assess a variety of welding consumables and processes at each of the potential construction yards to be involved in the total project. The chemical analysis of the plate is shown in the first row of Table 5(a), and it is typical of the TMCP steel used for offshore applications, which are Cu-Ni-Nb-V low carbon steels. In this specific plate there was a 0.01 addition of titanium to protect [16] the HAZ toughness.

Table 5(a). Chemical analysis of EH46 steel plate.

(mm)	Mill	%C	%Si	%S	%P	%Mn	%Nb	%Al	%N_2	%Ni	%Cu	%V	%Ti
20	A	0.09	0.37	0.003	0.010	1.61	0.037	0.048	0.0055	0.300	0.210	0.077	0.010
35	A	0.13	0.49	0.004	0.018	1.49	0.035	0.039	0.0063	0.019	0.012	0.071	0.003
35	B	0.046	0.31	0.005	0.007	1.62	0.041	0.033	0.0040	0.012	0.011	0.002	0.013

Table 5(b). Mechanical properties of EH46 steel plate

Plate Gauge (mm)	Mill	YS (MPa)	Impact Energy (J@-40°C)
20	A	485	70
35	A	468	96
35	B	468	407

Overall the heat affected zone Charpy toughness and fracture toughness were satisfactory, for each of the welding processes shown in Table 6. The inclusion of an MMA welding assessment was purely for completeness, as it was not envisaged it would be used in some of the shipyards. The main area of concern was the submerged arc welding process with its inherently higher heat input. However, as the design of the vessel was refined it was identified that some areas of the deck would be increased in thickness back up to 35mm thick. For this, plate was sourced from two mills, one using a TMCP process where the 20mm thick plate had been sourced from. The other plate was sourced from a mill operating a TMCP and accelerated cooling (AC) practice.

The chemical analyses of the two plates are shown in Table 5(b). The TMCP only steel is a Nb-V steel, and the TMCP-AC is a very low carbon titanium treated Nb steel. The effects of accelerated cooling are very marked with the exceptionally high toughness. The complete toughness-temperature data for the AC steel is shown in Figure 4.

The situation with the two supplying mills was one which raised some interesting issues. The mill producing the TMCP only steel was a conventional plate mill, which had been subject to some upgrading over a long period of time, but was incapable of producing the 35mm thick plate. The 35mm thick plate was produced on another plate mill within the same company, and due to its configuration utilised the different chemistry shown in Table 5(a). However, the TMCP+AC plate was rolled in a modern mill operating well within its design attributes. Brammer [17] has highlighted the dangers in attempting to extend the initial production range beyond the attribute levels. This can lead to inconsistencies in geometric control and mechanical properties of the product being produced.

Welded test plates from the two rolling processes for the 35mm thick steel were produced using identical welding passes as the plates were lined up together to produce the macrograph shown in Figure 5.

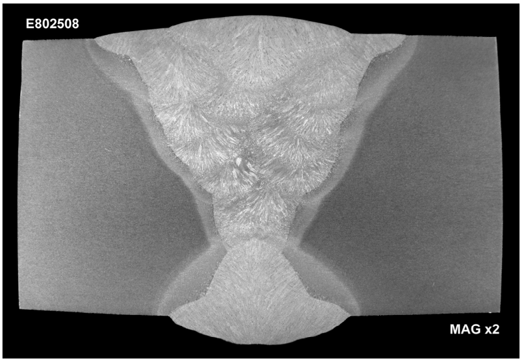


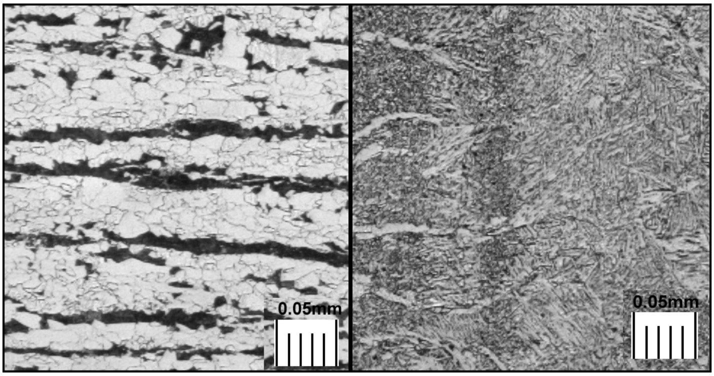
Figure 5. Submerged arc weld of 35mm thick EH 46 plate.

The results of the HAZ toughness tests at -40°C are shown in Table 6. This shows the effects of the welding process on heat affected area of the parent plate. It also demonstrates the need to maintain parent plate toughness significantly in excess of the actual specified requirement. Additionally some fracture toughness testing was also carried out, although not a contractual requirement. This data is shown for the HAZ in Table 6.

Table 6. Heat affected zone (HAZ) properties for submerged arc welded EH46 plates.

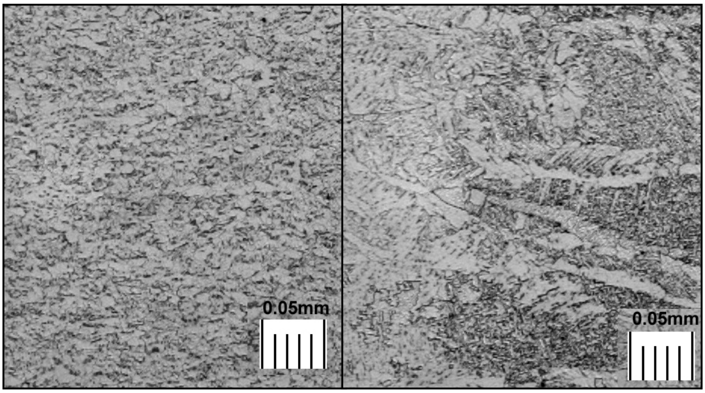
	20mm thick plate (TMCP)			**25mm thick plate (TMCP)**			**35mm thick plate (TMCP+AC)**		
Welding Process	**Toughness (J@-40°C)**	**Maximum Hardness**	**CTOD at -10°C**	**Toughness (J@-40°C)**	**Maximum Hardness**	**CTOD at -10°C**	**Toughness (J@-40°C)**	**Maximum Hardness**	**CTOD at -10°C**
SAW	120	256	0.365	58	266	0.44	201	218	0.72
FCAW	134	285	0.61	-	-	-	-	-	-
MCAW	113	301	0.61	-	-	-	-	-	-
MMA	154	270	0.66	-	-	-	-	-	-

Representative optical micrographs of the two 35mm thick plate parent plates are shown in Figures 6 (a) and (c). The very fine grain structure of the AC steel in Figure 6 (c) is in contrast to the banded structure of the higher carbon TMCP only steel, and also demonstrates the beneficial effect of the reduction in the carbon content of the steel from 0.13% to 0.046%, which would also have a positive benefit on toughness.



(a) (b)

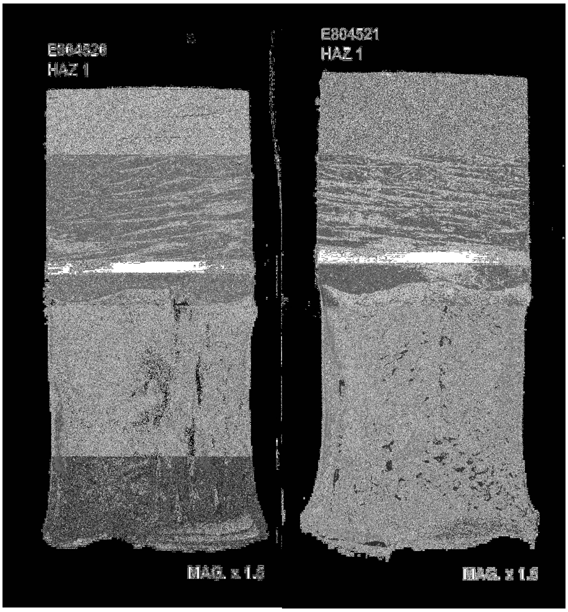
Figure 6. Optical microstructures of 35mm thick EH46 TMCP plate.



(c) (d)

Figure 6. Optical microstructures of 35mm thick EH 46 TMCP+AC plate.

The HAZ show some differences too, as would be expected from the toughness data shown in Table 6. Both HAZ samples show ferrite outlinement of the prior austenite grain boundaries, and probably more evidence of ferrite side plate development in the material that had been accelerated cooled. The remainder of the structure was dominated by acicular ferrite. The HAZ hardness increased by 36% for the TMCP steel and by 18% for the TMCP+AC steel. There was evidence of Type II pop-in delamination on the TMCP only CTOD test fracture faces. This was not present on the TMCP+AC test pieces. Examples are shown in Figure 7. According to Wiesner and Piskarski [18], the pop-ins are caused by splits in a plane perpendicular to the fatigue pre-crack.



(a) (b)

Figure 7. Fracture faces of HAZ CTOD test pieces. (a) TMCP only showing Type II pop-ins in parent plate section of sample (b) TMCP + AC showing no evidence of Type II pop-ins.

In such cases it is acceptable to ignore Type II pop-ins. It is now generally accepted that such delaminations are related to crystallographic texture to and can be typical of TMCP steel. At the final rolling temperatures there is a tendency for recrystallisation to be suppressed, creating a flattened and elongated austenite grain structure parallel to the plate surface. Thereafter, the phase transformation from oriented austenite to ferrite, develops a situation where the ferrite grains have a preferred orientation to the plate surface too. Through thickness reduction in area testing of the 35mm thick parent plates gave 85% reduction in area for the TMCP + AC, and 67% for the TMCP only plates. Clearly the delaminations did not create planes of weakness within the plates, and were related to grain structure and not related to previously identified sources such as steel cleanliness and segregation.

Cost Considerations

There has been a move in specific sectors of naval shipbuilding to reduce plate weight. This is primarily achieved through a reduction in plate thickness and other weight and control measures. As stated earlier the weight reduction is achieved through reducing the plate thickness and in turn increasing the strength of the plate.

As an example an 8mm thick plate of D grade steel can be replaced with a 7mm thick plate of DH36 grade steel, i.e.12.5% reduction in weight. It has been established that the cost differential between the grades is that DH36 steel is £50/tonne more expensive. This is equivalent to a 7% increase in cost. It is therefore a cost effective action for this particular situation, as it was in the case of the carrier. In addition the thickness reduction could lead to some decreases in the welding time. The effect of this from a microalloying viewpoint is that there is a predominant need for elements such as niobium to generate the required higher strength of the thinner plate.

It should be stressed at this stage of this particular debate that this effect would be more marked in commercial shipbuilding, where the cost of a typical commercial cargo carrier is very much towards the steel, and the reverse is the case in the case of naval ship-builds. Typical differences are shown in the indicative data shown in Figure 8.

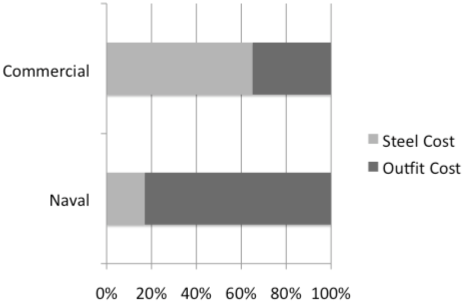


Figure 8. Steel value in a naval and a commercial vessel.

Conclusions

The use of microalloyed steels in naval shipbuilding is showing an upward trend mainly due to the progressive use of thinner steel.

Niobium currently is the major microalloying element being used in naval ship building steels, either alone for high strength steel, or in combination with other microalloying elements on higher strength steels.

There is still an issue with the variability of toughness effects seen in the heat affected zone of niobium microalloyed steels.

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