DEVELOPMENT OF ADVANCED SHIP BUILDING MATERIALS

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1. INTRODUCTION

Emerging interests to decrease road traffic congestion resulted in growth in ferry transport. As the fast ferry market continues to grow, a new generation of faster, agile and bigger ferries are being built. The trend in ferry designs includes building of ferries with speeds in excess of 40 knots and lengths greater than ~80m. To achieve higher speeds, reducing the structural weight of the hull is necessary. Effective weight reduction requires both innovative designs and stronger aluminium alloys. Thus the trends in the fast ferry market in turn stimulated the development of a new aluminium alloy, Alustar. Alustar is the trade name for a commercially available, high strength, weldable, corrosion resistant, Aluminium-Magnesium type non heat treatable alloy. Several pending patent applications exist related to the Alustar alloy and to the use of it. This material has been developed by Hoogovens Research and Development together with Hoogovens Aluminium Walzprodukte GmbH at Koblenz in Germany for applications primarily in large welded structures. Since the approval of the marine grade, Alustar alloy by DNV and GL in 1997, about 1500 tons of this material have been produced. The material is currently being used in shipyards in Australia and Europe. This paper reports on the status of the Alustar alloy programme with details on the production, physical and mechanical properties of the Alustar alloy material. Furthermore, this paper also discusses the properties of the Alustar alloy extruded sections.

2. CHEMISTRY OF THE ALUSTAR ALLOY

Table 1 shown below lists the chemical compositions of the standard AA 5083[1] and the Alustar alloys. The Alustar alloy differs from the standard AA 5083 alloy in terms of its Mg, Mn, Zn and Zr

Alloy	Mg	Mn	Cr	Cu	Fe	Si	Zn	Ti
AA5083	4.0-4.9	0.4-1.0	0.05-0.25	0-0.10	0-0.4	0-0.4	0-0.25	0-0.15
Alustar	5.0-6.0	0.6-1.2	0-0.3	0-0.4	0-0.5	0-0.5	0.4-1.5	0-0.2

Table 1 : Chemistry window

contents as can be seen from table 1. A relatively higher Mg-content present in the Alustar alloy helps to achieve higher strength levels after welding. Together with an increased Mn-content, a higher Mg content improves the ductility. Zr addition in Alustar alloy enables the formation of a beneficial, fine grain structure in the fusion line and heat affected zone. In general, susceptibility of an aluminium alloy to corrosion depends on not only the electrochemical nature of intermetallics present in the material but also on the grain structure of the material. Especially, in the context of corrosion of Al-Mg based alloys, the following three factors are of primary importance: the Mg content of the alloy, the fabrication history and the environment to which the material is being exposed. The Mg % in the alloy determines the amount of anodic AlMg intermetallics present in the alloy. Fabrication history plays a crucial role in determining the grain structure of the plate. Grain boundaries are the preferred sites for the undesirable precipitation of anodic AlMg intermetallics which renders the grain boundaries susceptible to corrosive attack. To compensate the deterioration in corrosion resistance caused by the presence of a higher Mg-content, which is needed to achieve higher strength, in the Alustar alloy an optimum amount of Zn is added.

3. PRODUCTION OF ALUSTAR ALLOY PLATES

Plates for ship building are produced at Koblenz using a route consisting of DC casting, hot rolling, cold rolling, annealing and stretching. The state of the art remelt and refining technology enables the production of Alustar alloy plates with extremely low Fe- and Si-contents. This ensures an improved fatigue performance of the Alustar alloy welded panels. A 4-high reversible, 148"(3.75m) hot rolling mill, one of the salient features of the production facility at Koblenz, enables production of upto 3.3m wide plates. Cold rolling using another 148" mill further guarantees the production of plates meeting tight dimensional tolerances and optimum thermomechanical treatments. Annealing/stabilisation treatments are carried out using a sophisticated horizontal heat treatment furnace which provides consistency to microstructure and hence to properties along the plate dimensions. Plate stretchers with strengths upto 8000t aid the production of flat and tension free plates. Modern saws cut the plates into their final dimensions which is one of the unique modern facilities available at Koblenz. Using the CNC-segment saw, plates can be cut to shapes close to the required final dimensions.

4. PHYSICAL PROPERTIES OF THE ALUSTAR ALLOY

Table 2 lists the some of the physical properties of the Alustar alloy and compares with that of the standard AA5083 alloy[1]. A rudimentary comparison shows that for all practical purposes, the physical properties of the Alustar alloy can be taken as similar to that of the AA5083 alloy.

PROPERTIES		AA5083	ALUSTAR
Density at 20°C [g/cm³]		2.66	2.64
Approximate Melting Range [°C]		574-638	568-636
Coefficient of Linear thermal expansion [μm/m.K]	20-100°C	24.2	23.0
	20-200°C	25.0	24.5
	20-300°C	26.0	25.9
Specific heat at 20°C [J/kg.K]		900	890
Electrical conductivity at 20°C [% IACS]		29	27.1
Electical resistivity at 20°C [μΩ cm]		5.95	6.3

Table 2: Physical Properties of AA5083 and Alustar alloys

5. MECHANICAL PROPERTIES OF THE ALUSTAR ALLOY PLATES

In this section, the following mechanical properties of the Alustar alloy will be discussed:

- tensile properties [before and after welding]
- fatigue strength and bendability [before and after welding]

5.1. Tensile Properties of the Alustar alloy plates before Welding

Figure 1, compares the minimum values for tensile properties of the AA5083, AA5383 and Alustar alloys. From this figure, it is evident that the Alustar alloy is significantly stronger than the other two

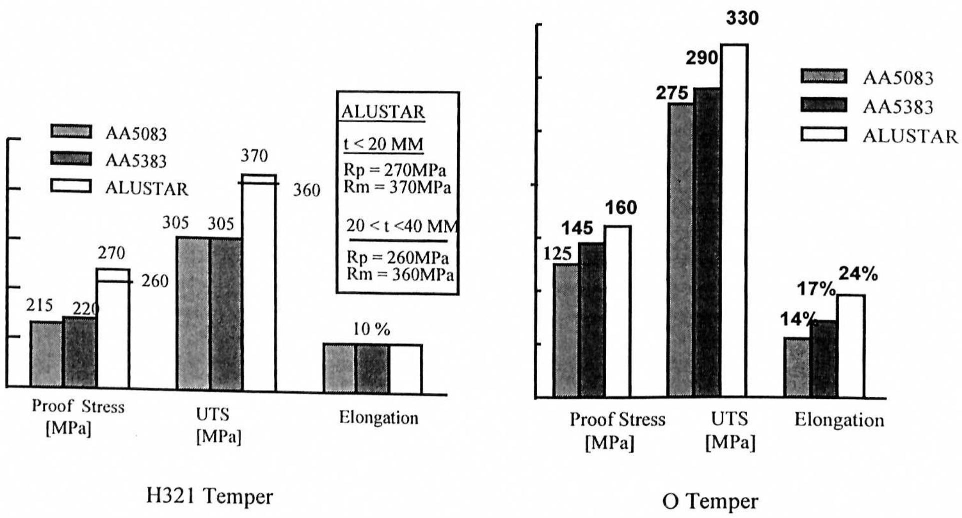

Figure 1 : Minimum Tensile properties

alloys in both the soft and in strain hardened tempers.The increased strength of the Alustar alloy in the strain hardened temper primarily stems from the Mg additions whereas the combined effects of Mg and Zr accounts for the strength in the soft temper. Figure 2 shows the LT direction, typical tensile properties of the H321 temper Alustar alloy plates in the gauge range 4-32 mm, produced at Hoogovens Aluminium Walzprodukte GmbH. Tensile tests were carried out according to ASTM B557[2] standards and the range shown in the figure 2 is obtained from the data collected over 400 lots of the Alustar alloy material.

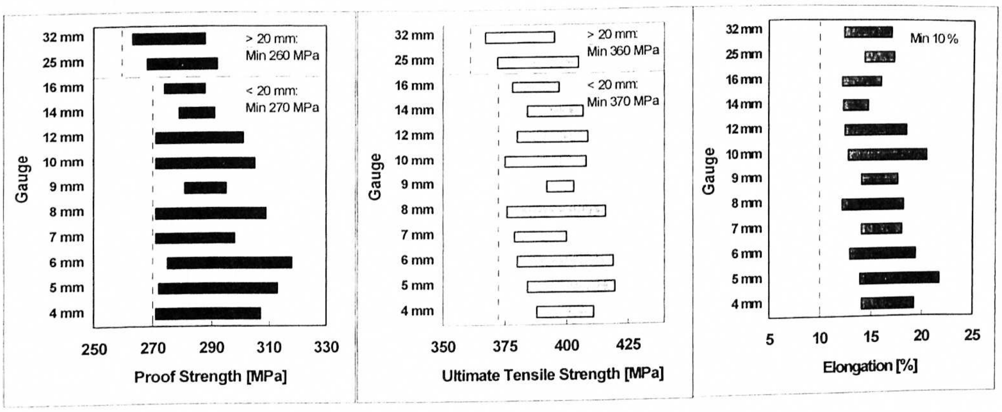

Figure 2 : Tensile Properties of several lots of H321 temper Alustar alloy material

5.2. Tensile Properties of the Alustar alloy plates after Welding

To determine the strength of the Alustar alloy in the welded condition, a large number of cross weld tensile tests have been carried out on samples machined out from welded panels produced at various shipyards and commercial aluminium welding places. Although tensile testing using various gauge length have been carried out, most of the data collected so far have been produced using a gauge length, specified in Det Norske Veritas rules [i.e: the greater of the following two : a gauge length of 3 x thickness or 2 x thickness + width of the weld seam][3]. Thus, a large set of weld strength data, corresponding to various welding positions, gauge thickness and welding conditions, has been collected. The Alustar alloy has a minimum of 160 MPa for proof strength, 300 MPa for tensile strength in the welded condition. When tested according to the DNV's specifications, typically the proof strength in the welded condition falls in the range 165 -175 MPa whereas the UTS value were measured to be in the range 300-325 MPa [see figure 3]

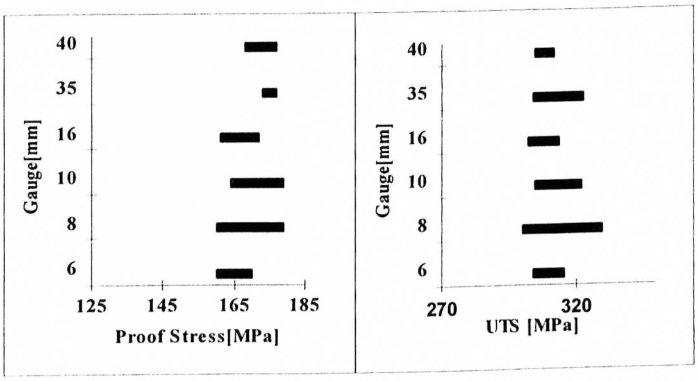

Figure 3 : Typical tensile properties obtained from cross weld tensile tests

Microstructural investigations on the welded joints revealed the presence of very fine recrystallised grains both in the fusion line and heat affected zone of Alustar alloy welded panels and this could explain why the Alustar alloy is stronger than AA5083 alloy in the welded condition.

5.3. Fatigue Strength of the Alustar Alloy plates in the Welded condition

In order to determine the fatigue strength of the Alustar alloy in the welded condition, Alustar and AA5083 [H321 temper, 8mm thick] alloy plates were welded using a three pass welding procedure. Flat samples with the weld bead were produced and tested for fatigue strength. The test conditions were provided by the DNV Oslo which are as follows: Range : 10^5-10^7 cycles; Constant frequency ~70-120Hz; Axial Loading; R-ratio = 0.1; Number of stress levels = 5. Tests were carried out until either fracture occur or the sample is incapable of reacting to full test load. The outcome of the tests is shown as the plot of maximum stress as a function of number of cycles [See figure 4]. From this figure, it is evident that the minimum allowable stress at 10^7 cycles can be increased by ~20MPa if Alustar is used in place of the standard AA5083. Investigations into fatigue strength of other weld details of the Alustar alloy are in progress.

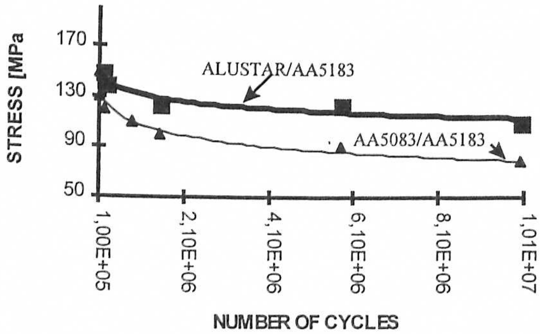

Figure 4: S-N curves

5.4. Bendability of Alustar alloy plates before and after welding

To assess the bendability of plate materials, the standard three point bend test was used. Samples produced from both L and LT directions were tested. To produce the bend test specimens, plate strips of dimension 250 x 30 x thickness mm were sheared and the edges were rounded off [1-2mm]. A mandrel diameter of 6 x thickness was used for those tests involving H321 temper materials. In order to determine the bendability of the 16, 35 and 40 mm gauge Alustar alloy welded panels, side bend tests were carried out. More than 200 samples from H321 temper materials have been tested in the welded condition with none showing any evidence of cracks. Alustar alloy H321 temper in typical thicknesses have been cold formed to various shapes typically used in shipyards, thus illustrating the good formability of the Alustar alloy.

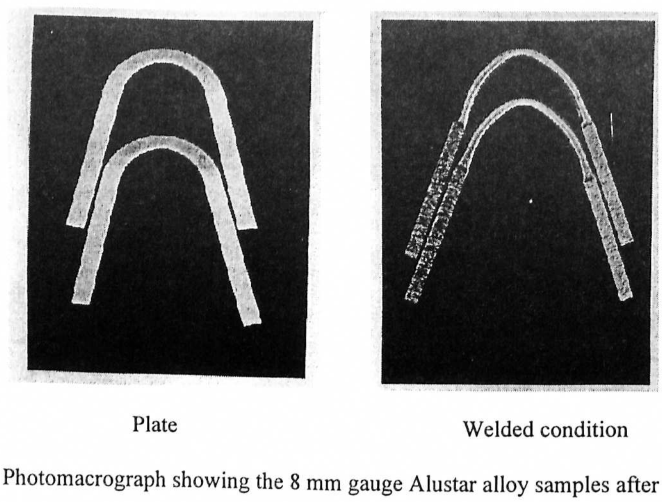

Plate Welded condition

Figure 5: Photomacrograph showing the 8 mm gauge Alustar alloy samples after bend test

6. WELDABILITY OF THE ALUSTAR ALLOY

Alustar alloy plates have been welded at various shipyards and commercial aluminium welding places. Successful Alustar alloy welded panels have been produced using the standard filler wire alloys such as AA5183, AA5356, AA5087 etc. Alustar alloy welded panels have been produced using typical ranges in, a wide variety of welding parameters such as current, voltage, welding machines, shielding gases [for example : Ar, Ar+He]. Figure 6 illustrates the effect of welding current on the resultant quality of weld seam. Similar graphs are available for other combinations of welding parameters. Alustar alloy welded panels are stronger [see figure 1], tougher [see figure 4] bendable [see figure 5] and have good corrosion resistance which will be discussed in the following section.

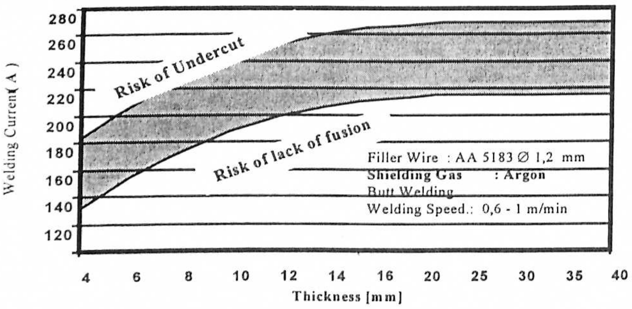

Figure 6 : Effect of Welding Current on the weld quality

7. CORROSION RESISTANCE OF ALUSTAR ALLOY PLATE

7.1. Pitting, Exfoliation and Stress Corrosion Resistance

Resistance to pitting, exfoliation and stress corrosions is an important prerequisite for a marine grade aluminium alloy. The resistance to pitting and exfoliation is commonly determined using the ASSET test[ASTM G66][4]. The resistance of the Alustar alloy to pitting and exfoliation corrosion in both the welded and unwelded conditions has been tested. The test results clearly demonstrate that the Alustar alloy is better than AA5083 with respect to ASSET test. ASSET-testing of samples artificially aged at 100°C, indicates the same corrosion resistance of alloys such as AA5083 and Alustar after long term service[5,6]. Figure 7 shows optical micrographs of the ALUSTAR and AA5083 alloys after heat treatments at 100°C upto 10 days. Absence of exfoliation in the heat affected zone in figure 7,

ALUSTAR AA5083

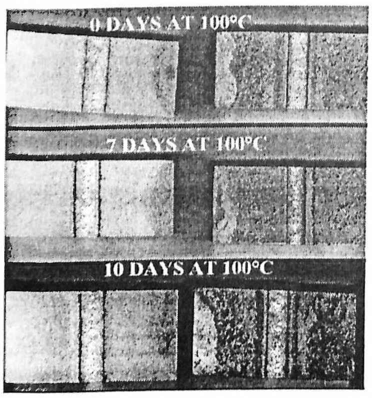

Figure 7 : Surfaces of sensitised samples after the ASSET test

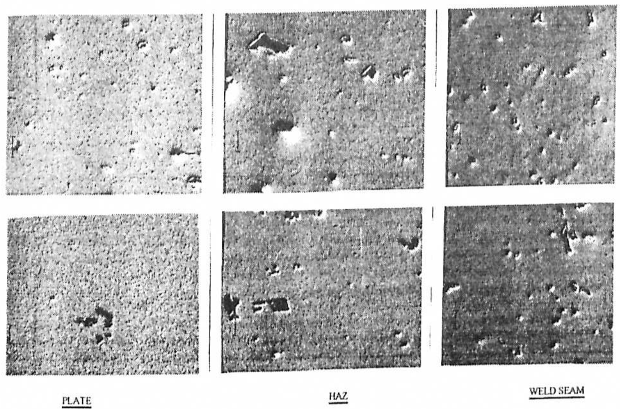

Figure 8 : Microstructures of sensitised Alustar and AA5083 alloys
[Top : AA 5083 and Bottom : Alustar]
[Magnification : 1 cm = 6.25μm]

plus the absence of any continuous network of boundary precipitates in figure 8 clearly demonstrate that the Alustar alloy has a good long term corrosion resistance. To further assure a good corrosion resistance of the Alustar alloy in the welded condition, about 100 lots of the Alustar alloy H321 temper plates, produced at Hoogovens Aluminium Walzprodukte GmbH, have been tested with results clearly demonstrating the absence of exfoliation in the heat affected zone. Values obtained in nitric acid weight loss test [ASTM G 67][7] indicate resistance of AA5083 type alloys to intergranular corrosion.

A value less than 15mg/cm^2 is typically obtained for the Alustar alloy H321 temper plates clearly indicates the resistance to the intergranular corrosion. In addition to the above mentioned investigations, salt spray tests according to ASTM B117[8] have been carried out with results alloys showing no evidence of exfoliation on the welded and unwelded coupons after having been in the salt spray cabinet for a period of 2 months.

Using the procedures specified in ASTM G39[9], an extensive SCC test programme was carried out at BODYCOTE MATERIALS TESTING in the Netherlands. SCC tests have been carried out both on sensitised[100°C/7days] and un-sensitised samples. The fact that no cracks were found after a period of 1000h in a four point bend, SCC test, carried out under the surveillance of DNV, clearly demonstrates that the resistance of the ALUSTAR alloy to SCC is as good as AA5083. In addition to this, a constant load, alternate immersion, stress corrosion test according to AIR 9048-147 specification[10] was carried out at Hoogovens Walzprodukte GmbH. A cycle, consisting of 10 minutes of immersion in 3.5 wt% NaCl solution and a 50 minutes dry period was used for the SCC test. During the dry period, samples were exposed to 50-60% relative humidity and to a temperature of 21-23°C. Welded and the unwelded samples were stressed respectively to 130 MPa and 195 MPa. After a test period of 1000hours, no evidence of SCC was observed on the Alustar alloy samples. This result again confirms the excellent resistance of the Alustar alloy to SCC.

7.2. Corrosion Potential

Following ASTM G69-81[11] procedures, the electrolytic solution potential of the Alustar alloy samples were measured using Fieldcorr apparatus from EG&G. A 0.1N saturated calomel electrode in an aqueous solution containing 58.5g NaCl plus 9 ml H_2O_2 per litre was used. The potential of 8mm, Alustar alloy H321 plate was determined to be -1.00V. In a separate investigation, corrosion potentials of, the plate and weld seam of 8mm, Alustar alloy welded panel were determined using ASTM G69-81 specification and found to be -1.005 and -0.984V respectively. The welded panel used in this experiment had been produced using AA5183 filler wire.

8. ALUSTAR ALLOY EXTRUSIONS

The extrusion facilities available at Hoogovens Aluminium Rods and Hard Alloys at Duffel, Belgium allows the Alustar alloy to be extruded to solid sections in the H112 temper. Extrusions for stiffeners in shipbuilding are produced at Duffel using a route consisting of DC casting, extrusion and controlled stretching. The use of channel induction heated remelt furnaces, state of the art metal treating and filtering, and 100% ultrasonic control on billets ensures improved performance of the Alustar alloy. Extrusion size is restricted to a circle of 260mm, whereas the minimum wall thickness should be 4mm. Typical profiles which can be manufactured at Duffel are bulb or T shapes in lengths of 6 meters as shown schematically in figure 9.

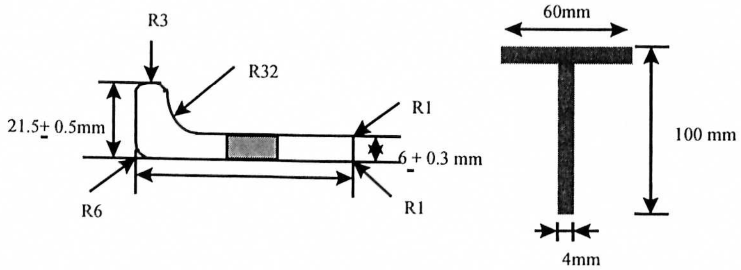

Figure 9: Typical Profiles produced at Hoogovens Aluminium N.V. Extrusions Hard and Soft Alloys

Consistency in product properties is realised by controlling the variables related to extrusion preheat and extrusion speed. Due to the higher Mg content, Alustar alloy shows higher deformation resistance which consequently leads to higher extrusion force, lower extrusion speed, broader tolerances and more sensitive surface finish [for example, in comparison with AA6061 T6 extrusions]. The severity of these problems is enhanced due to the requirements on smaller wall thickness which in turn call in for higher extrusion ratios. In spite of being difficult to extrude, the Alustar alloy extruded sections are quite stronger than AA5083 alloy sections. Typically the proof strength in the unwelded condition is in the range of 234-277MPa whereas the ultimate tensile strength is in the range of 354-381MPa. The tensile elongation falls in the range 12.8-16.8%. In the welded condition, typically the proof and ultimate tensile strengths fall, respectively, in the range 162-172MPa and 302-320MPa. Figure 10 shows the Alustar alloy profiles after the ASSET test. It is evident from this figure that there is hardly any corrosion attack on the surface.

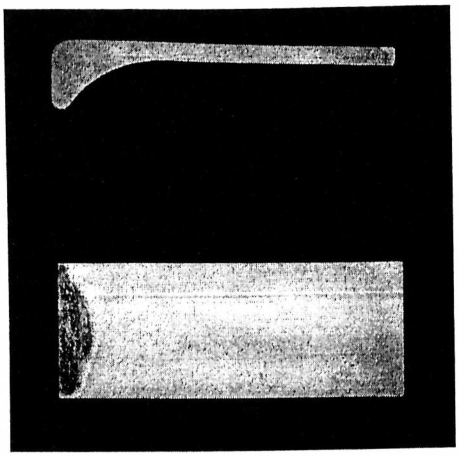

Figure 10 : Samples from Alustar alloy extruded sections after ASSET test

9. STATUS SUMMARY

- Alustar alloy plates are stronger than AA5083 alloy both before and after welding. In addition, they also have good pitting, exfoliation and stress corrosion resistance similar to that of the AA5083 alloy.
- The bendability of the Alustar alloy in both the welded and in unwelded conditions is comparable to that of AA5083.
- Alustar alloy has been successfully extruded to produce simple solid sections in H111 temper. Similar to the case of plates, the extruded sections are not only stronger but also resistant to pitting and exfoliation corrosion.

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