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Mechanical characterization of aluminium alloys for arctic structures application

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Due to its low specific mass, mechanical resistance comparable to that of mild structural steels, the low maintenance cost and good corrosion resistance, aluminum alloys are well suited for the production of offshore structures. For the specific case of the installation of structures in arctic areas, it is necessary to verify the influence of a low ambient temperature on the mechanical performance of the alloys of interest. In particular, the present work reports the results of several investigations on two alloys widely used in the sector, the EN AW 5083-H321 and EN AW 6082-T6 at room and low temperature. The tests performed, including material investigation, tensile, fatigue and fracture mechanics testing, showed no deterioration of the material performances at low temperature, indicating how such alloys are adequate structures operating in arctic environment.

Key Words: Aluminum Welding, Low Temperature, Offshore, Tensile Properties, Fracture Mechanics, Fatigue

1 Introduction

The adoption of lightweight alloys as structural material for offshore constructions constitutes a great logistic advantage. In arctic areas temperatures as low as -60 °C may be reached and is thus of paramount importance to verify the effect of low temperature on the mechanical properties of the materials adopted. This work constitutes a revision of the results of a campaign of mechanical characterization on two of the most common alloys for MIG welded structures in the offshore industry, EN AW 5083-H321 and EN AW 6082-T6[1-3] and integrates it with novel results on the fracture mechanics performance of such alloys. The hardness profiles show how the HAZ and weld metal properties under-match the strength of the base material. This is an undesired characteristic systematically found in fusion welding of aluminium. The alloys were tested at room (25 °C) and low temperature (-60 °C) evaluating tensile resistance, fracture toughness and fatigue life. The tensile testing was executed both on the base material and on cross-welding specimens. The fracture toughness properties were obtained measuring the crack tip opening displacement (CTOD) for fatigue-cracked specimens for which the crack tip was in the heat-affected zone (HAZ). Several welded specimens have been fatigue tested at both temperatures in load control at a load ratio of R=0 and a frequency of f=10Hz. The tests were performed for plates and extruded bars ranging from 5 mm to 40 mm of thickness and no evidence of tensile properties reduction for thicknesses up to 30 mm was found, differently from what is reported in EN 1999-1-1, which imposes an increased conservativism for plates thicker than 15 mm. All the results obtained consistently present no reduction, but often improvement, of the mechanical properties with a drop of the ambient temperature. The number of studies on the fatigue and fracture behaviour of the alloys of interest available is, so far, limited, in particular with regards to the performances at arctic temperatures[4-5].

2 Specimens and material investigation

The alloys object of the study were the EN AW 5083-H321 and the EN AW 6082-T6 aluminum alloys, supplied in the form of rolled and extruded plates respectively. The plates, divided in 1000 x 200 mm elements, were welded along the long direction by semiautomatic metal inert gas (MIG) welding with 5183

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consumable wire. The joints, full penetration double V-butt geometries, were produced from plates of 5, 10, 16, 20 and 30 mm of thickness in total and the specimens obtained by cutting the welded plates in the direction orthogonal to the weld. Thermocouples were used to control the HAZ temperature during the welded process and the deposition of every new layer of weld was initiated at a temperature inferior to 100 °C. The joints resulted to be affected by an angular misalignment due to asymmetric material deposition and cooling. The dimensions of all the samples were measured and this defect was taken into consideration for the computation of the equivalent stress range applied to each specimen in the fatigue testing section. The material investigation of the joints reveals defects typically associated with fusion welded aluminum alloys, see figure 1. In particular: porosity, side wall lack of fusion and partial recrystallization at the HAZ are detected. None of these defects is found to be in abnormal proportions or affecting the validity of the tests. One of the main concerns related to the adoption of fusion welded aluminum alloys for the production of structures is the reduction of tensile strength of the weld area and HAZ, as opposed to the behavior of steel welded joints. This characteristic is signaled by the hardness of the weld metal and HAZ undermatching the hardness of the base material, see figure 2. The hardness measurements were performed at room temperature on cross-section samples prepared for metallographic investigation. The measures were taken at a depth of 2 mm from the surface on both sided of the joint and at the middle plane. The joint weakness compared to the base material was consistently found for every thickness and influences the tensile behavior as described in the following section.

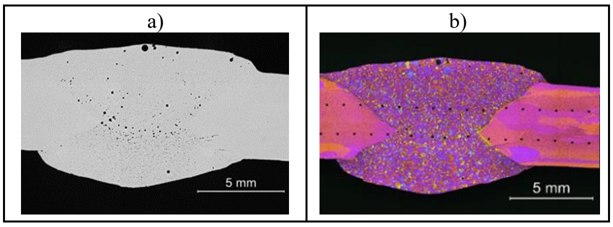

Fig. 1 The material investigation evidences (a) a normal level of porosity in the weld metal, (b) partial recrystallization of HAZ material.

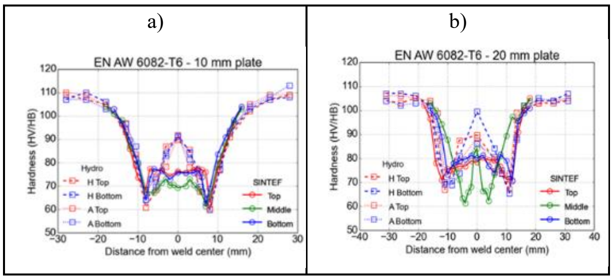

Fig. 2 Figure 2. Hardness undermatch for welded EN AW 6082-T6 alloy, weld plates 10 mm (a) and 20 mm (b) thick.

3 Tensile properties

The tensile properties of the alloys were tested for different thicknesses, temperatures and base material and welded conditions, see figures 3, 4, 5. For the base material testing, performed according to EN-ISO 6892-1-B, specimens were manufactured, in the transverse direction of the plates, to a square cross section of 12.4 x 12.4 mm for all the thicknesses but the 10 and 30 mm plates. From such plates, cylindrical specimens were produced. The tests were performed using a Zwick testing machine and a nitrogen cooled temperature chamber for the tests at arctic temperature (-60 °C). The square-section specimens were loaded at a 10 MPa/s rate, while for the cylindrical specimens a cross-head speed of 10 mm/min was set. The strains at room temperature were measured by a dual-axis laser system(6), while linear variable differential transformers were used for the low temperature testing. The temperature was controlled by a thermostat and a thermos-element placed inside a small hole practiced in the specimens. Observing the results plotted in figure 3, an influence of the thickness on the tensile properties of both alloys is detected, but more relevant in the case of the EN AW 6082 – T6 compared to the EN AW 5083 – H321 alloy, which shows also an inferior ductility. An increase of the stress level reached at arctic temperature, united to a lower ductility, compared to room temperature is observed for the former alloy, while no meaningful influence of the temperature is detected for the latter alloy. The cross-weld tensile testing followed the EN ISO 4136:2012, testing constant width specimens of several thicknesses at room and arctic temperature. The main results, summarized for both alloys in figure 4 and 5, evidence a marked reduction of tensile strength and ductility, but not a significant influence of the temperature. An increase of the base plate thickness instead, particularly in the case of the EN AW 6082 – T6 alloy, causes a reduction of ultimate ductility. All the tensile fractures occurred in the HAZ at an angle generally comprised between 50° and 60°, see figure 6. As seen from the hardness testing, the tensile testing and fractures confirm the HAZ as the weak area of fusion welded aluminum joints.

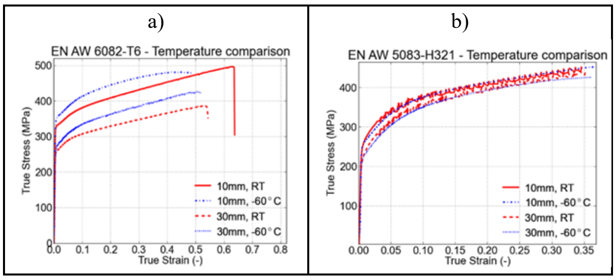

Fig. 3 Base material tensile properties temperature comparison for different thicknesses for EN AW 6082-T6 (a) and EN AW 5083-H321 (b).

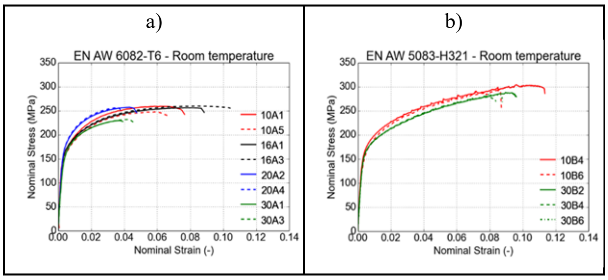

Fig. 4 Weld tensile properties at room temperature for different thicknesses for EN AW 6082-T6 (a) and EN AW 5083-H321 (b).

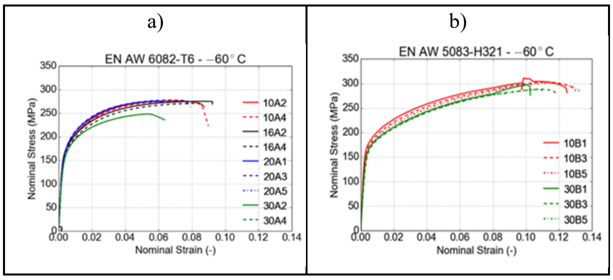

Fig. 5 Weld tensile properties at arctic temperature for different thicknesses for EN AW 6082-T6 (a) and EN AW 5083-H321 (b).

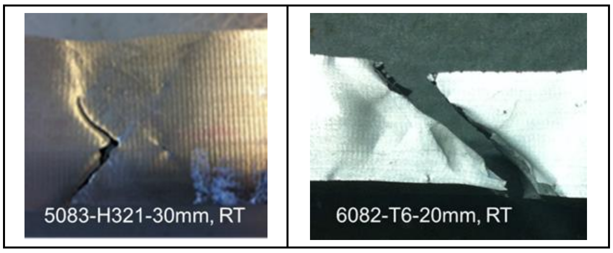

Fig. 6 The static failure occurred along the heat affected zone for both alloys.

4 Fracture toughness

A series of single edge notched beam (SENB) specimens have been manufactured and tested to evaluate the performance of a fusion welded EN AW 6082-T6 alloy in the presence of a sharp fracture at room and low temperature. The fractures were practiced in the HAZ of the weld by electric discharge machining cutting and fatigue pre-cracking to obtain a sharp crack tip, see figure 7. The crack mouth opening displacement (CMOD) and the J-integral, plotted in figure 8 and 9 against the stable crack propagation, show a slight improvement of toughness with a drop of the temperature. The crack tip opening displacement (CTOD) at maximum load (plastic tearing) is also increased at lower temperature, passing from 0.52 mm at 25 °C to 0.61 mm at -60 °C. These results confirm how a structure build of welded aluminum alloy can be used over a wide range of temperatures and in arctic environment without a decrement of the resistance to the presence of defects.

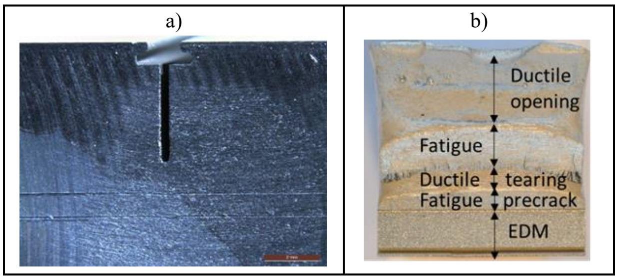

Fig. 7 Fracture mechanical testing of SENB specimens: pre-crack in HAZ (a) and fracture surface (b).

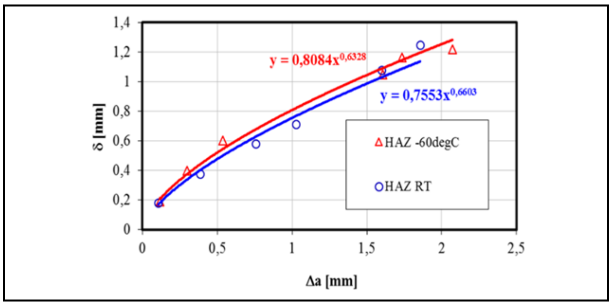

Fig. 8 Fracture mechanical testing: CTOD vs crack propagation at the HAZ.

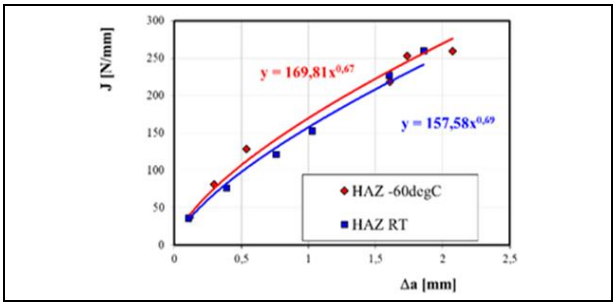

Fig. 9 Fracture mechanical testing: absorbed energy vs crack propagation at the HAZ.

Table 1 CTODm at plastic tearing.

T [°C]	Test ID	CTODm [mm]	CTODm (MOTE) [mm]
25	1	0.52	0.52
	2	0.63	
	3	0.64	
-60	4	0.67	0.61
	5	0.61	
	6	0.64	

5 Fatigue life

The fatigue testing was performed on two series of EN AW 6082 -T6 double V-butt welded joints produced from 5 mm and 20 mm thick plates. The specimens were produced by cutting the welded plates in the direction orthogonal to the weld and having a constant width of 30 mm. The welding process resulted in specimens having an angular misalignment. The deformation of every joint was then measured to correct the applied nominal stress range according to the recommendations provided by Hobbacher7), compensating for the additional stress introduced by the bending of the specimen during the clamping. The tests were performed at a frequency f=10 Hz using a MTS servo-hydraulic system equipped with a 100 kN load cell. The 5mm and 20 mm plate joints were tested at a load ratio R=0 in atmosphere at a temperature of 25 ºC and -60 ºC. An additional series of 20 mm thick plate specimens was tested at a load ratio R=0.5 in atmosphere at room temperature. The results, corrected to account for the misalignment, are summarized in figure 10. All the tests performed respect the normative requirements for their fatigue class, that is a stress range of 36 MPa at 2E6 cycles, value which has not been corrected to consider the reduction of stress ratio from the nominal value of R=0.5 to R=0 due to the thickness of the specimens and the presence of residual stresses7). Two main effects can be seen from the summary of the results: the thickness has a noticeable influence on the fatigue behavior, with the thinner specimens overperforming compared to the thicker ones and that the reduction of ambient temperature has a beneficial effect on the fatigue life of the joint, making it suitable for offshore applications in arctic regions. Figure 11 shows examples of fractures obtained in the fatigue testing, evidencing how all the failures originated at the weld toe and propagated through the HAZ.

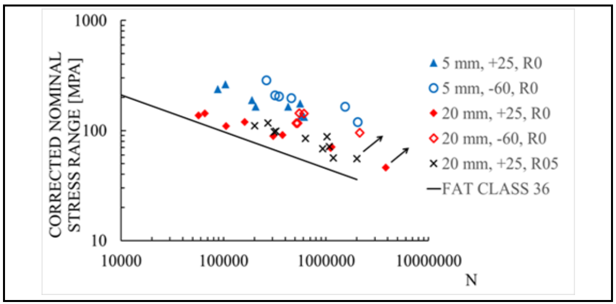

Fig. 10 Results of the fatigue testing in terms of deformation corrected nominal stress range

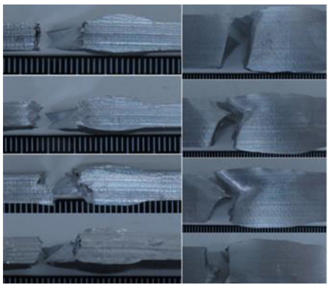

Fig. 11 Examples of fatigue cracks developing from the weld toe.

5 Conclusions

The paper presents a revision of results on the mechanical performances of aluminium alloy welded joints of industrial interest at room and arctic temperature and integrates these data with novel results on the fracture mechanics behaviour in such conditions. The hardness profile and tensile testing evidence how the weld area has an inferior tensile resistance compared with the base material. This characteristic must be considered in design of structures adopting fusion welded aluminium joints. The tensile testing shows no reduction, but often improvement, of tensile properties at arctic temperature compared to the behaviour at room temperature. No severe reduction of tensile properties is observed increasing the thickness of the welded plates from 10 to 30 mm. The same positive qualitative result was obtained from the testing of the fracture toughness of the EN AW 6082-T6 alloy, expressed in terms of CTOD and absorbed energy for crack propagation length. In addition, the fatigue testing of the same alloy confirms the excellent performance and the feasibility of the material for the production of lightweight structures to be deployed in areas characterized by arctic climate.

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