CRYOGENIC PROPERTIES OF ALUMINIUM 2219 ALLOY USED IN SPACE INDUSTRY APPLICATIONS

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ABSTRACT: In this paper, the results of the material characterization of Aluminium 2219 performed by Romanian Research and Development Institute for Gas Turbines COMOTI in SCOUT project are presented. Three categories of tests have been performed: in O temper (as received from producer), in T6 temper at room temperature and in T6 temper at cryogenic temperature. The material in T6 temper was spin formed prior to the tensile test pieces acquisition. The results indicated an increase of the average tensile strength (ultimate) from 153 MPa to 380 MPa after T6 heat treatment. In case of the yield strength, the increase is from 72 MPa to 273 MPa, while the elongation at break value drops from 21% to 7.7%. When subjected to cryogenic temperatures (77 K), the average of the values of the tensile strength (ultimate) is 439 MPa. The yield strength is 291 MPa and the elongation at break is decreased to 0.26%. Having in mind its properties at cryogenic temperatures, this material has been taken into account to be further used in development of equipment for space industry such as turbopump components, plasma thrusters' protective structure, cryogenic liquid storage tanks, piping sections and other equipment where strength to weight ratio is important.

KEYWORDS: SCOUT, cryogenic properties, Al 2219, pump, thruster

NOMENCLATURE
COMOTI - Romanian Research and Development Institute for Gas Turbines COMOTI
SCOUT - Sandwich Common Bulkhead for Optimized Upper-Stage Tanks
ESA – European Space Agency
FLPP – Future Launcher Preparatory Programme
USA – United States of America
ICSI – National Research and Development Institute for Cryogenic and Isotopic Technologies

1. INTRODUCTION

SCOUT is a project funded by ESA's FLPP Programme and consists in development of a Sandwich Common Bulkhead for Optimized Upper-Stage Tanks Demonstrator aimed to be used for next generations of ARIANE 6. In this project COMOTI was involved in characterization of the material used to build the upper

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and lower domes of the Tanks, both before and after the T6 heat treatment and to develop the Diffusers and Antivortex Devices of the propellant tanks.

Aluminium 2219 belongs to class 2xxx alloy. The main alloying component is Copper. It is primarily used for wrought products. Heat treating it results in higher strength, but it comes with a lower ductility. Similar to other Aluminium-Copper alloys it has a high strength, but it is less corrosion resistant and more difficult to weld comparable to other classes of Aluminium alloys [1]. Extrusion and forging are the usual methods to form Aluminium 2219, while casting is not used. It presents a good resistance to stress corrosion cracking [2,3]. Aluminium 2219 presents good properties at temperatures ranging from -250 to 250°C [4,5]. Due to these properties, it is one of the preferred materials for the creation of cryogenic propellants tanks for launch vehicles [6, 7, 8]. The material presented in this paper has been used for applications such as:

Fig. 1 AVD developed in SCOUT project

Bands that hold the filter mesh of the AVD together are created using this alloy. Another application in which this material has been used is a helicon plasma thruster, where it was used to create the mechanical supports of the magnets. The fact that its heat transfer coefficient is lower compared with other Aluminium alloys made it a preferrable choice for this application.

Fig. 2 Helicon plasma thruster magnet supports

Pump components for similitude tests model using this material are under construction.

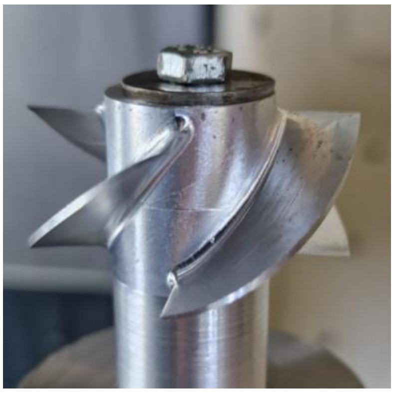


Fig. 3 Pump inducer under manufacturing

The usage of this alloy for pump components is restricted for use on oxygen pumps because accidental contact between rotor and stator during working presents a high risk of igniting the aluminium. Article [9] presents the mechanism of Al 6061 alloy ignition. Although it is focused on the Al 6061, the ignition mechanism presented in the paper is similar for other aluminium alloys aswell. Comparable to the test case presented in the paper, in case of contact between the rotor and stator, the protective aluminium oxide found on the surface of the parts is removed, reducing the ignition temperature.

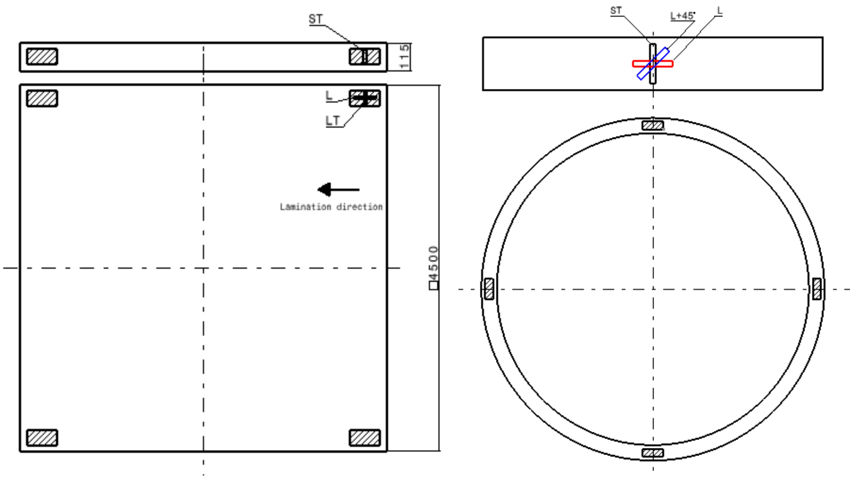
2. MATERIALS AND METHODS

The material presented in this paper is Aluminium 2219 alloy. This material has been produced by Arconic (USA) and was delivered in the form of 4500x4500x115 mm laminated plates. The material has been heat treated to temper T6 at Framatome (France). Temper O represents the designation for the alloy in annealed condition. In order to obtain this temper, the Aluminium 2219 is heated to 538°C followed by quenching in water [10]. Temper T6 represents the designation for a solution heat treatment followed by quenching, cooling and aging [11].

In order to characterize the material, three tests have been performed:

- Chemical composition test which consists in the experimental determination of the chemical composition of the alloy. For this test a Hitachi OE720 optical emission spectrometer (OES) has been used.
- Microstructural analysis which consists in taking images of the plate in order to observe the grains. It was performed using an optical microscope (Carl Zeiss: Axio Vert.A1 MAT) at 50x magnification after etching with Keller's reagent.
- Tensile tests.

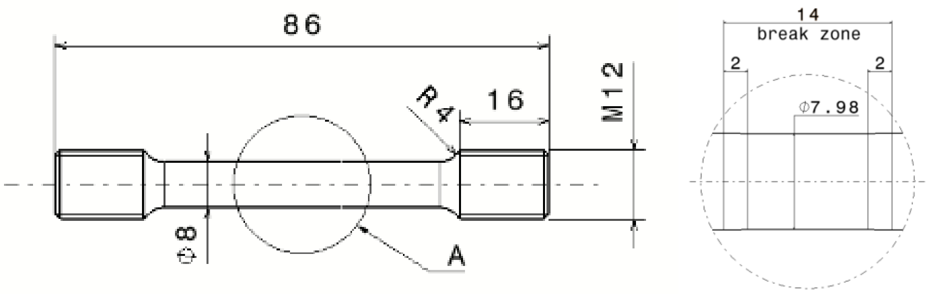
The tensile test pieces used to perform these tests have been taken from specific locations on the plates, according to Fig. 4 a) and b).



a) b)

Fig. 4 a) O temper tensile test pieces extraction locations; b) T6 temper tensile test pieces extraction locations

The tensile test pieces used for these tests are:



a b

Fig. 5 Material test pieces design: a. overview, b. detail A (break zone)

The tensile test pieces have been constructed such that they have a weak sport in the middle of the length which is characterized by a lower diameter zone. This has been imposed in order to guarantee that they will break always in this predefined location.

Three categories of tensile tests have been performed:

- Tests in O temper and at room temperature
- Tests in T6 temper and after a spin forming operation at room temperature
- Tests in T6 temper and after a spin forming operation at cryogenic temperature.

The cryogenic temperature has been chosen as 77 K, which corresponds to the boiling temperature of Nitrogen. The tests at room temperature have been performed using the Instron 8802 servo-hydraulic universal testing machine, while for the cryogenic tests has been used a LBG Italia machine. In order to cool down to the required temperature (77 K), the tensile test pieces have been inserted in a proprietary device of ICSI visible in Fig. 6.

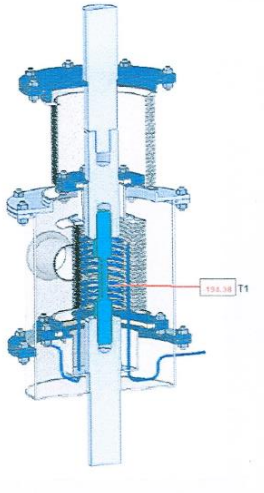


Fig. 6 Schematic of the cooling device for cryogenic tests

The tensile testing was performed according to ISO 6892-1:2019: Metallic materials — Tensile testing — Part 1: Method of test at room temperature [12]. The test parameters are:

- Preload 2MPa;
- First ramp: A tensile stress of 10 MPa/s is applied until the detection of yield strength;
- Second ramp: After the extensometer is removed, the straining rate is increased by 7.5%/min until the test piece breaks.

In order to cool down the test piece, liquid nitrogen has been circulated through the cooling device. After the temperature has been achieved, the nitrogen flow has been kept for further 5min in order to guarantee the uniformity of the cooling process. The nitrogen system has then been removed and the test has been carried out.

3. RESULTS

3.1. Chemical composition

The chemical compositions of the alloy are presented in Table 1.

Table 1 Chemical composition of the material characterized in this paper

Alloy/element, wt.%	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Ti**	**V**	**Zr**
OES-determined composition	Balance	0.08	0.153	6.189	0.255	0.037	0.097	0.15
Nominal chemical composition [3]	Balance	max. 0.2	max. 0.3	5.8 - 6.8	0.2-0.4	0.02 - 0.1	0.05-0.015	0.1 - 0.25

By analysing the differences between the nominal chemical formula and the OES-determined composition it can be observed that, for the majority of the components, the actual, measured, concentration is close to the middle of the interval of values for the given component, with the exception of the Titanium and Zirconium. The Titanium forms Al_3Ti at 300°C which allows the Al 2219 alloy to have very good mechanical properties [13], while the Zirconium boost the effects of other alloying elements and improves its corrosion resistance [14].

3.2. Microstructural analysis

The images in Fig. 7 illustrate the microstructure of the alloy in the T6 state, while Fig. 8 presents the microstructure in the O state, revealing distinct differences correlating with their respective processing conditions. The arrow represents the lamination direction.

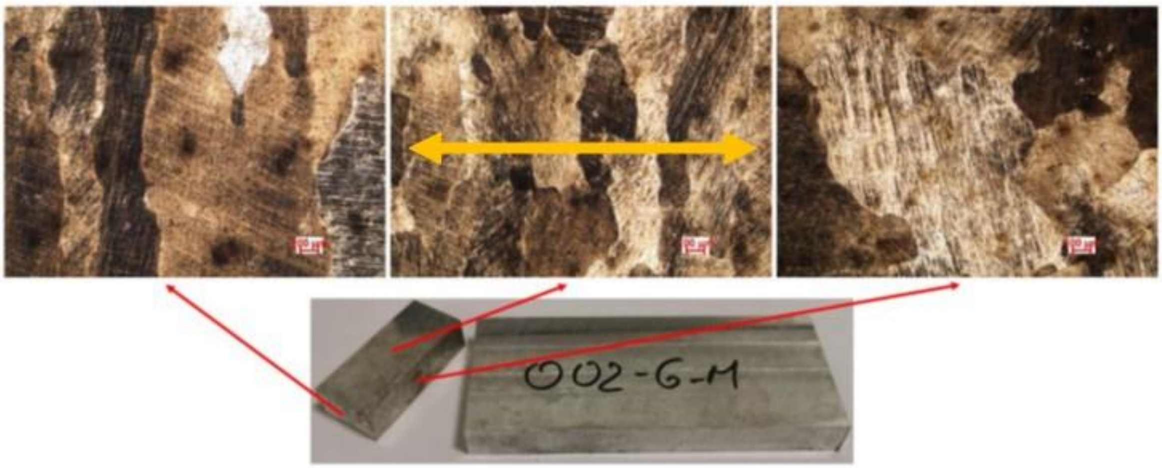


Fig. 7 T6 temper microstructural analysis

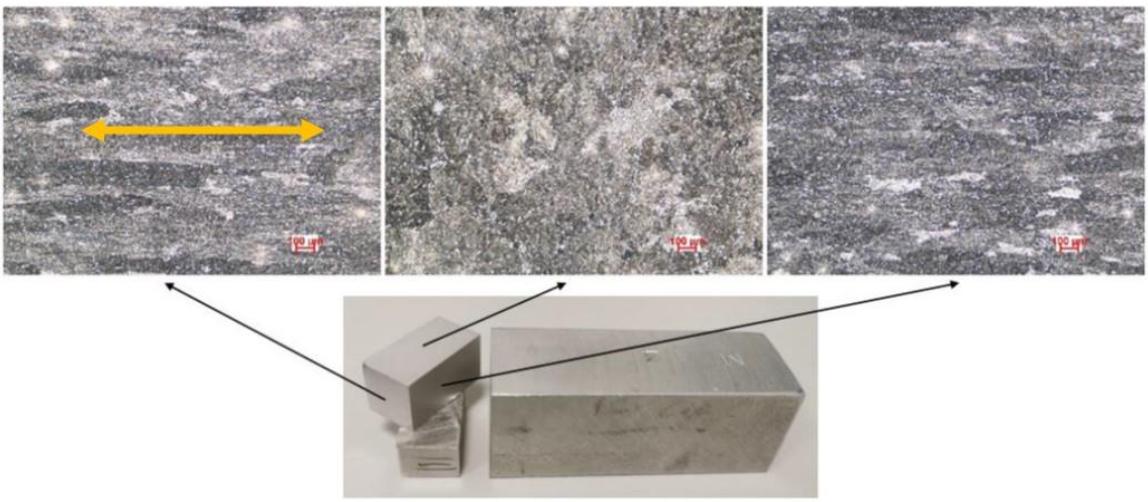


Fig. 8 O temper microstructural analysis

In Fig. 7, the metallographic sample of Aluminium 2219 in the T6 state exhibits elongated and non-uniform grains of varying sizes. The elongated grains observed suggest that the material may have retained the fibrous structure resulting from the rolling process, which could indicate that complete recrystallization might not have occurred or was insufficient. This may be due to inadequate holding time at the solution treatment temperature or possibly uncontrolled rapid cooling. Such non-uniformity in the microstructure could influence the mechanical performance of the material, especially under cryogenic conditions, where a homogeneous structure and refined grains are generally considered essential to ensure strength and durability

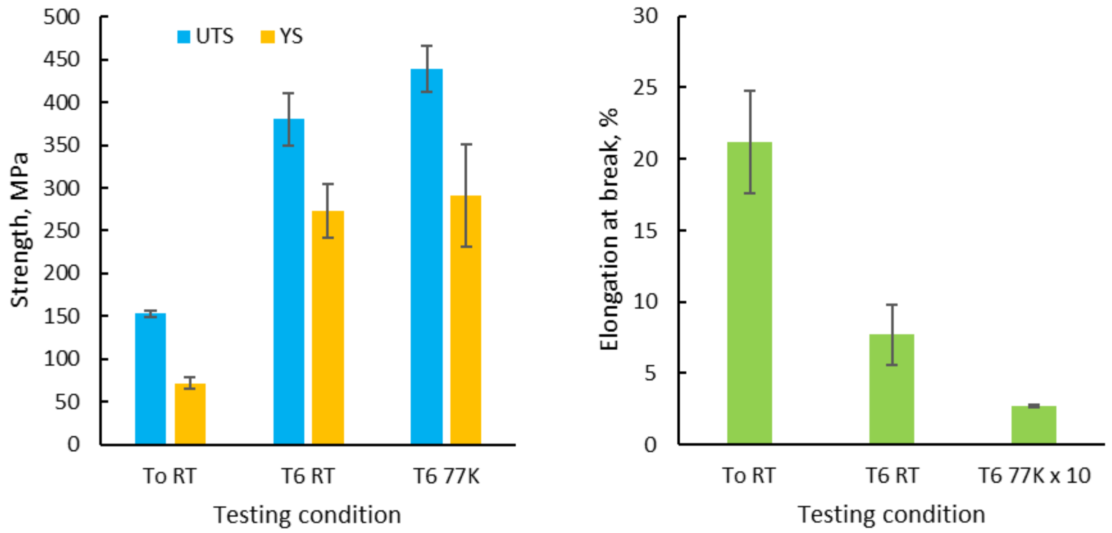
Usually, in this state, the presence of theta phase precipitates is expected within the grains and along the grain boundaries, potentially contributing to the alloy's strength through precipitation hardening. However, this may vary depending on the exact heat treatment conditions applied.

In contrast, the O state (Fig. 8) shows a microstructure that appears to have finer and more uniform grains compared to the microstructure presented in Fig. 7, possibly as a result of solution heat treatment. The absence of visible secondary phase precipitates, such as the theta phase, suggests that precipitation hardening may not have occurred, consistent with typical expectations for this condition. The alignment and fibrous nature of the grains might confirm the lamination process, potentially resulting in a ductile structure but with lower strength compared to the T6 state.

These observations may provide insights into the microstructural evolution of Aluminium 2219 under different thermal and mechanical treatments, offering a preliminary understanding of its behaviour in both ambient and cryogenic environments.

3.3. Tensile tests

A total of 73 tests have been performed on the material in the temper it was delivered (temper O) by the producer, one being a calibration test and 72 being actual tests. There have been 3 test pieces/location and orientation. In case of the material in T6 temper at room temperature and in cryogenic conditions 18 tests have been performed.



a) **b)**

Fig. 9 Tensile testing results – UTS and YS (a) and Elongation at break (b)

In Fig. 9 YS refer to yield strength of the material, while UTS refer to its ultimate tensile strength. The average ultimate tensile strength of the material is 153 MPa in case of O temper, 380 MPa after heat treatment and 439 in cryogenic conditions. The ultimate tensile strength increased by 2.5 times from O temper to T6 temper and by 1.16 times when T6 temper is subjected to the cryogenic conditions, compared to room temperature values.

The standard deviation is 3.87 in case of O temper material, 30.77 in case of T6 temper material at room temperature and 26.78 in case of T6 temper material in cryogenic conditions. While the standard deviation of the measured ultimate strength of the plates in O temper has a small value, its value for both tests of the plates in T6 temper is very big. Corroborating this information with the microstructural analysis of the T6 plates it can be concluded that the non-uniformities induced during the T6 treatment to the material structure are the ones that caused the variation.

In case of the yield strength, its value in O temper is 72 MPa and it increases to 273 MPa in T6 temper and to 291 MPa in cryogenic conditions. The yield strength increases by 3.82 times between O temper and T6 temper at room temperature and by 1.06 times between T6 at room temperature and T6 at cryogenic temperatures. The standard deviation is 7.36 for the O temper material, 31.86 for the T6 temper at room temperature and 60.33 for the T6 temper at cryogenic temperatures.

The possible explanation for the values of the standard deviation is related to the microstructural analysis finds aswell. In case of the T6 at cryogenic temperatures 2 tests presented abnormally high and low values of 507 and 183 MPa, respectively. If these are not taken into account, the yield strength drops to 283 MPa and the standard deviation to 20.06.

The average elongation at break of the material in O temper is 21.18%, while in T6 temper at room temperature it drops to 7.71%. At cryogenic temperatures, the T6 temper material has an average elongation at break of 0.27%.

The standard deviation is 3.55 in case of the O temper material, 2.09 in case of the T6 temper material at room temperature and 0.08 in case of T6 temper material at cryogenic temperature. In case of the cryogenic tests 6 test pieces had to be measured manually due to machine error. Taking into account that the manual measurements induce errors these test pieces have not been used for the calculation of the average value and of the standard deviation.

Table 2. Tensile tests results overview

Type of test	Parameter	Unit	Test values	Literature data	Difference
Temper O at room temperature	**Ultimate tensile strength**	**MPa**	153	180	27
	Yield strength	**MPa**	72	88	16
	Elongation at break	**%**	21	14	7
Temper T6 at room temperature	**Ultimate tensile strength**	**MPa**	380	420	40
	Yield strength	**MPa**	273	280	7
	Elongation at break	**%**	7.7	5.4	2.3
Temper T6 at cryogenic temperature	**Ultimate tensile strength**	**MPa**	439	-	-
	Yield strength	**MPa**	291	-	-
	Elongation at break	**%**	0.27	-	-

In Table 2 is presented the overview of the tensile tests results and a comparison between them and literature data taken from reference [3]. Tensile test results at room temperature in both T0 and T6 condition are in good agreement with literature data. Differences may be generated by the actual chemical composition of the alloys, heat treatment, specimen sizes and testing conditions.

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