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AlMgSc alloy 5028 status of maturation

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Abstract
This paper gives an overview of the maturation activities for AlMgSc alloy 5028. The alloy shows interesting potential for non-pressurized launcher primary structures. Various parametric studies for structural performance are presented. For reasons of chemical compatibility the alloy is equally interesting for (satellite) propellant tanks using green propellants. The alloy has been tested for its base material properties as well as various welds. Those tests included strength and fracture tests and tests for chemical compatibility. A demonstrator tank is currently under construction. This tank will be used as a non-flight item for cryogenic functional tests and will primarily be made out of 5028.

1. Introduction

The AlMgSc alloy 5028 is a lightweight alloy developed at the beginning of years 2000s for application in airframe structural design. In space structures the alloy came into focus some 10 years later for conceptual studies of both primary and secondary launcher structures. In the newer history, AlMgSc alloy became interesting for reasons of chemical compatibility with various propellants and demisability i.e. the requirement to completely burn up during uncontrolled atmospheric re-entry as a means of post-mission disposal.

This paper gives an overview of the studies performed for the potential applications. Those concentrated especially on the primary launcher structures using the paradigm of Ariane 5. Comparison will be shown for pressurized structures (main tanks) as well as unpressurized structures (inter-tank structures). The potential of the alloy for (satellite) propellant tanks will also be examined. The perspective of structural mass optimization (performance) will be exposed both based on simple analytical comparisons as well as on the background of multi-parametric numerical studies.

In the second part of the paper the current status of maturation concerning material properites and manufacturing technologies are presented. Those include strength dimensioning properties as well as fracture properties. Base materials and welded materials are presented including FSW welds. Environmental compatibility is analysed supported by test results.

2. Properties of alloy 5028

Al alloys with Sc addition were intensively investigated and industrialized in Russia and the former Soviet Union [6]. In the Western world the alloy has been investigated through 1990s mostly on AlMgSc basis. In Europe this resulted in development of the 5024 alloy and its stronger version 5028 [1]. A comprehensive overview of the developments and metallurgy of Sc can be found in [2,3].

Alloy 5028 is a low density high strength aluminium alloy on AlMg basis with additions of Sc. Chemical composition is given in Table 1. Apart from good mechanical properties the alloy exhibits good weldability, good corrosion resistance and is easily formable. The alloy is currently procurable in sheet and plate form in thicknesses up to 12mm.

Table 1: AlMgSc alloys 5028 chemical composition (Al content to balance).

Si	Fe	Cu	Mn	**Mg**	Cr	Zn	Ti	Zr	**Sc**
0.0-0.30	0.0-0.40	0.0-0.20	0.30-1.0	**3.2-4.8**	0.05-0.15	0.05-0.50	0.05-0.15	0.05-0.15	**0.02-0.40**

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The typical mechanical properties are less to those of 2219 or 7075 at room temperature. On the other hand, the density of 5028 is significantly lower while the E-modulus is slightly higher, see Table 2 and Table 3. Although the alloy may not appear as attractive on the basis of absolute strength values, the relative values gaged by density and E-Modulus make the 5028 an interesting candidate.

Table 2: Properties of AlMgSc 5028 to other structural aluminium alloys. Typical values.

	5028 H116	2219 T87	2195T8	7075T73	
Thickness	5mm	6mm	6mm	6mm	mm
Ultimate strength	400	440	600	462	MPa
Yield strength	325	360	550	393	MPa
Elongation	12	10	11	8	%
E-modulus	74	73	76	72	GPa
Density	2.67	2.84	2.71	2.81	g/cm3

Table 3: Relative properties of AlMgSc5028 to other structural aluminium alloys.

	5028 H116	2219 T87	2195T8	7075T73
Relative strength σ/ρ	150	154	221	165
Relative yield σ/ρ	122	126	203	140
Relative global stiffness E/ρ	27.7	25.6	28.0	25.7
Relative local stiffness $E^{1/3}/\rho$	1.57	1.47	1.56	1.49

3. Structural performance

3.1 Applicability of 5028 to various structures

The potential applications for 5028 include main (primary) structures of a launcher and propellant tanks, primarily for satellite propulsion modules.

Other applications are conceivable but do not appear as attractive. Those include esp. the various secondary structures for a launcher and propulsion modules. An application can be considered for large secondary structures like electronics platform support structure, cable bridges or ducts. Such structures are often riveted from sheet metals, typically using aluminium alloy 2024.

Current production forms of 5028 are not compatible with small secondary structures like brackets, supports and extensions. The 5028 alloy is offered as sheet metal and plates up to 12mm thickness. On the other hand, the small secondary structures are prevalently milled from thick plates (>50mm) or rods. Those product forms are not available in 5028. Assuming that such product forms would be available in future the mass advantage would need to be traded in very detail. As of 2017 the mass advantage gained may not be in relation esp. with the procurement costs, which are elevated against standard alloys (7xxx class).

3.2 Main launcher structures

Under the main structures both the main tanks as well as unpressurized structures were studied. There were multiple purposes of that activity, in particular:

- Support technology maturation projects.
- Identify performance for selected bare tank configurations.
  - o Ariane 6 upper propulsion module bare tank, Figure 1.
  - o VEGA 4th stage, Figure 2.
- Manufacturing Processes.

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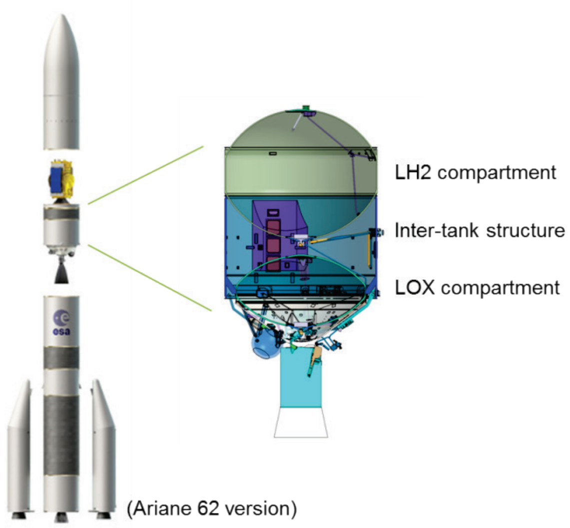

Figure 1: Ariane 6 launcher with upper propulsion module.

Figure 2: VEGA launcher a 4th stage.

The material candidates considered for those studies were aluminimum alloys:

- 2219. This is the main structural alloy for Ariane 5 with high level of industrialization.
- 2195. Alloy implemented e.g. for SLWT for high mass savings and included in Ariane 6 development.
- 5028. The studied candidate; currently not in use for space applications.

The purpose of the study was to prepare basic information for further development steps. Those are typically performed by the tank design authority and include:

- Mass performance evaluation and compliance with system mass targets.
- Analysis and projection of development and recurring costs.
- Performance of technological maturation, qualification and industrialization.
- Identification of technical and programmatic risks related to the choice made.

The study was performed with means of parametric semi-numerical tools. Those consider various architectures, geometries, load boundary conditions and material properties. The Tables 4 and 5 show the results of the study. Those are expressed as relative masses of some structures against the baseline. The baseline for structures has been taken aluminium alloy 2219.

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Table 4: Relative masses for A6 upper propulsion module for various alloys.

Ariane 6	**2219T87**	**2195T8**	**5028H116**
	Relative Masses		
LH2 Compartment	1	0.99	1.00
Inter Tank Structure	1	0.95	***0.94***
LOX Compartment	1	0.94	1.02
Total	**1**	**0.96**	**0.99**

Table 5: Relative masses for VEGA 4th stage for various alloys.

VEGA	**2219T87**	**2195T8**	**5028H116**
	Relative Masses		
NTO Compartment	1	0.91	1.03
Inter Tank Structure	1	0.94	0.95
MMH Compartment	1	1.03	1.15
Total	**1**	**0.96**	**1.05**

The relative mass ratios with respect to 2219 show either performance increase (ratio < 1.00) or performance decrease (ratio > 1.00). As is visible from Table 4 the alloy 5028 appears interesting for large intertank/interstage structures, where the relative mass for 5028 is the lowest. For the total upper stage structure the alloy appears only marginally better than the baseline 2219 solution. The AlLi alloy 2195 appears the most mass performant solution out of the three materials. It should be noted that the 7xxx materials have not been included in this preliminary study. Those are usually applied for the non-pressurized structures and were included in later detailed investigations using FE-modelizations.

3.3 Propellant tanks

The relative performance of 5028 for a propellant tank (not main structure) can be drawn from Table 5. The VEGA tanks are similar by size to those typical used in satellites (at least large ones). Obviously, the 5028 relative performance (1.03 to 1.15) is worse than that of the baseline 2219 (1.0) which makes the AlMgSc alloy not attractive from mass point of view.

However, propulsion modules for satellites and other spacecraft normally use aggressive propellants like NTO, hydrazin or MON and the tank materials must be compatible with the applied propellants. Obviously, the chemical compatibility is often driving. In frame of the maturation for Green Propellants those standard hypergolic propellants will be replaced. The green propellants are usually defined on H_2O_2 basis.

Whereas the structurally performant Al-Cu alloys are at least sufficiently compatible with many hypergolic propellants they are not compatible with H_2O_2. In this perspective the structurally less performant 5028 becomes interesting. A study performed by NASA for AlMgSc alloy C557 has shown good compatibility in both virgin and welded condition [4,5]. In order to confirm the compatibility of 5028 with H_2O_2 dedicated tests have been performed with good results. This is described in the next chapter.

4. Material testing

4.1 Base material

Various tests with base material have been performed. Those tests included tensile testing, fracture testing and metallographic analyses. The tests were performed at room temperature (RT) as well as cryogenic temperatures (77K, 4K). All the mechanical tests at RT, LN2 temperature (-196°C) and LHe temperature (-269°C) were performed according to ASTM E-9 for tensile testing and according to ASTM E-1820 using an universal testing machine. For the presented test results 5mm thickness have been tested. Both L and LT directions were investigated.

DOI: 10.13009/EUCASS2017-633

4.2 Tensile and fracture properties

Tensile tests were performed according to ASTM E9 for room temperature. The cryogenic tests were performed in analogy to that standard. The measured stress-strain curves have shown significant irregularities during the work hardening, Figure 3. This discontinuous deformation is typical for aluminum alloys with Mg as the primary alloying element (the 5xxx series) and is known as Portevin–Le Chatelier (PLC) effect. It is marked by the formation of localized deformation bands that not only leave undesirable traces on the surface, but also reduce the ductility of the alloy. The general consensus explains the origin of the PLC effect as the dynamic interaction between the moving dislocation and the diffusing solute atoms. The mobile dislocations which are carrier of the plastic strain move jerkily between the obstacles provided by the other defects. When the testing temperature is lowered the PLC effect decreases and disappears when the temperature is low enough.

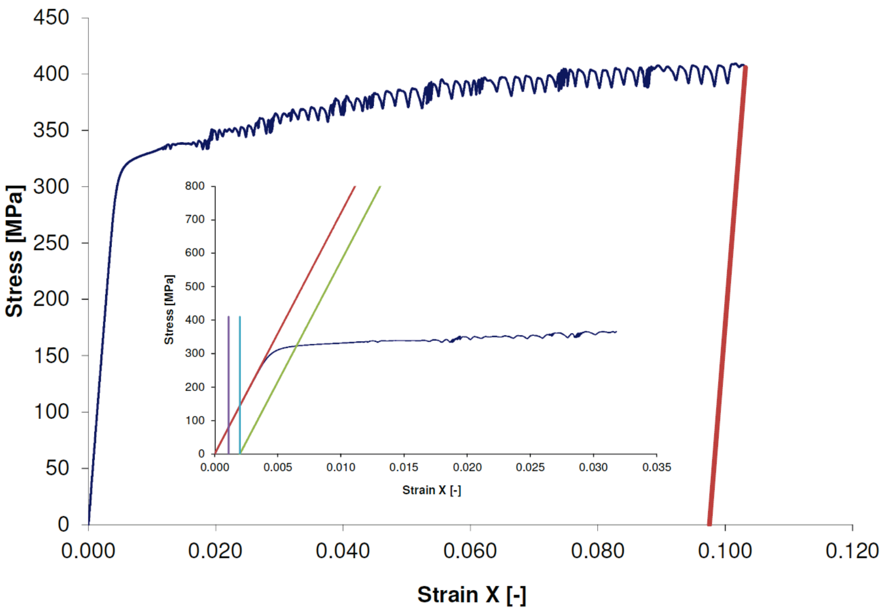

Figure 3: Typical stress-strain curve at room temperature.

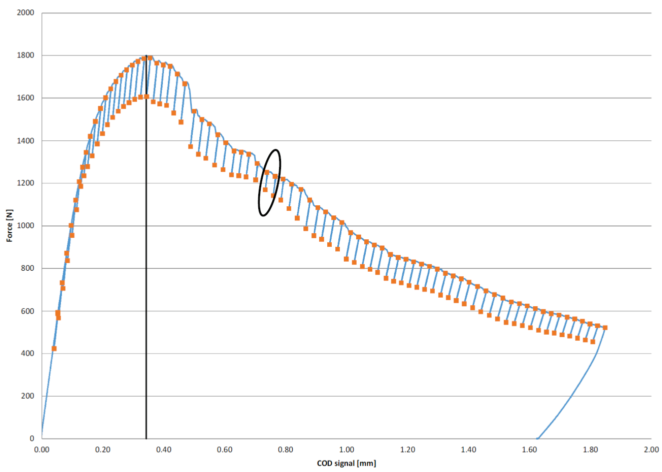

Figure 4: Typical force-COD curve at room temperature.

Fracture tests were performed to evaluate the fracture toughness. It was observed that the crack length was constant up to the maximum load for all specimens in both directions, Figure 4. A growth of the crack was observed for all specimens in both directions after the maximum load has been reached. Therefore all samples show an unstable crack growth and the evaluation of the J-Integral vs. crack length (up to the maximum load) was not possible (according to ASTM E1820). Instead of that the J-Integral at constant crack length was determined out of the elastic part Jelastic and Jplastic. The summary of the tensile and fracture properties is given in Table 6, as average values.

DOI: 10.13009/EUCASS2017-633

Table 6: Tensile and fracture properties of 5028H116. Average values.

Direction	Temperature [K]	E [GPa]	Rp0.2 [MPa]	Rm [MPa]	A [%]	KJQ [MPa√m]
L	RT	71	322	409	9	48
LT	RT	72	326	413	16	46
Direction	Temperature [K]	E [GPa]	Rp0.2 [MPa]	Rm [MPa]	A [%]	KJQ [MPa√m]
L	77K	77	379	525	24	47
LT	77K	77	390	521	21	46
Direction	Temperature [K]	E [GPa]	Rp0.2 [MPa]	Rm [MPa]	A [%]	KJQ [MPa√m]
L	4K	79	431	665	19	52
LT	4K	81	443	650	19	45

For the base material properties the following can be summarized:

- The stress strain behavior is very similar for the two different directions except that the strain to failure at RT is higher for the rolling direction (L).
- For both directions the Yield strength and fracture strength Rm increases when the temperature is decreasing.
- For both directions the strain to failure is highest for 77K.
- The total J-Integral and KJQ shows limited dependence on the temperature and on direction.

4.3 Metallographic analysis

Metallographic analysis was performed for specimens in both rolling and perpendicular direction. The results have shown the expected laminar texture, see Figure 5 and Figure 6.

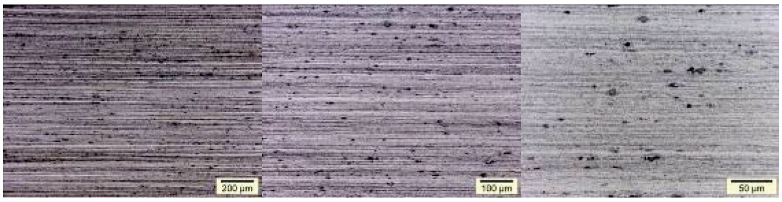

Figure 5: Metallographic analysis in rolling direction (L).

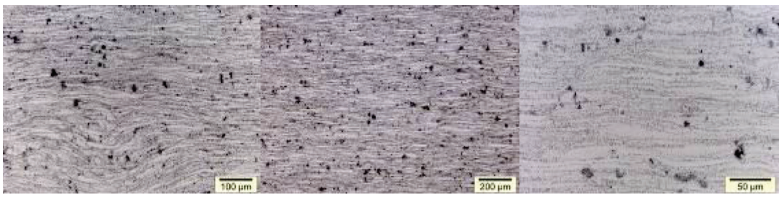

Figure 6: Metallographic analysis in perpendicular direction (LT).

4.4 Welds

The primary focus for investigations of welds was put on FSW (friction stir welding). Among others, the FSW technology allows high weld efficiency factors against fusion welded process. However, AlMgSc are generally easily weldable with fusion welding technologies like TIG. This allows good repair and alternative weld end-closure solutions. Therefore, further tests for TIG and EB welding are running or planned. For FSW process the microsections are presented in Figure 7.

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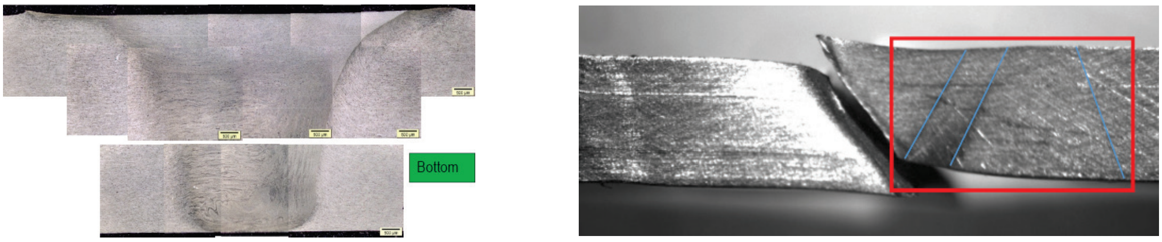

Figure 7: FSW microsections of 5028H116. The blue lines indicate the position of weld zone. Fracture started from the edge of the weld zone under an angle of 45° in direction of the base material.

In the presented activities no detailed maturation of the process has been performed. Nevertheless, the study allowed to observe the following findings:

- the yield strength and ultimate strength increase when the temperature is decreasing. The increase in strain to failure with decreasing temperature is a typical phenomenon in some material of face centered cubic structure.
- the strength properties and strain to failure is lower for the welded material (without due maturation yet):
    - weld factor ~0.87 for Rp0.2,
    - weld factor between ~0.90 for Rm.
- the plastic J-Integral, total J-Integral and KJQ shows a positive and strong dependence on temperature – nearly linear increase with increasing temperature.

4.5 Environmental compatibility

The 5028 alloy has previously been tested for standard exfoliation corrosion and stress corrosion properties. The alloy has shown very good properties with no show stoppers against the rigid space requirements.

For the chemical compatibility tests were performed for with H2O2. NASA has tested alloy C557 for compatibility with H2O2 in both virgin and FSW welded condition, and compared to the baseline alloy 5254 (rated as Class 1). The C557 has been found Class 1. For 5028 tests have been performed under increased temperature 50°C and 98% concentration H2O2. The alloy did not show any degradation in the subsequent testing, Figure 8.

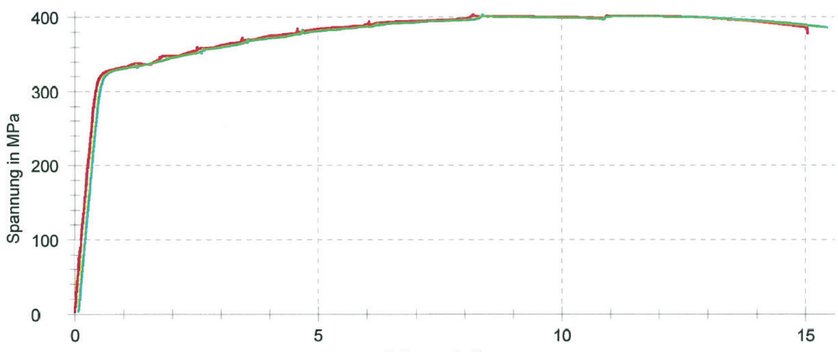

Figure 8: typical stress-strain curve of virgin base material (RED) and after H2O2 four weeks exposure (GREEN).

5. Demonstration

The alloy 5028 appears most interesting for non-pressurized primary structures or for tanks where chemical compatibility with H2O2 is the driving requirement.

As a technological demonstrator a dedicated tank is now under development. The primary purpose is to perform functional propellant management studies with liquid hydrogen. The secondary purpose is a demonstration of manufacturing technologies with AA5028. Since the tank is aimed to be used in a laboratory environment a robust

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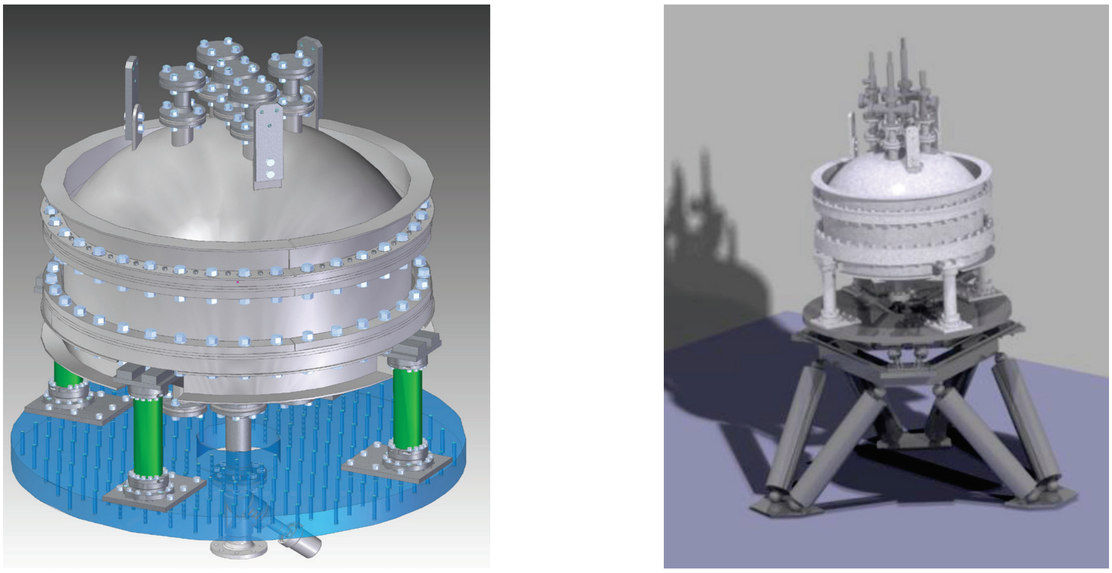
design according to the European pressure vessel regulation was chosen. The inner tank shape is a scaled-down version of the Ariane 6 launcher's LH2 tank. The tank is nearly made of full AlMgSc and is currently in the manufacturing phase.

The Figure 9 below shows two renderings of the AlMgSc tank. In the first rendering it is visible that the tank consists of spherical domes and an exchangeable cylindrical tank element such that the tank size can be adapted to different capacity needs or launcher configurations.

Main challenges in the tank manufacturing are the hot forming of the tank domes and the different welding processes which are used at the flanges. For the tank demonstrator, 5028 will be welded using the welding processes tungsten inert gas welding, metal inert gas welding, and friction stir welding. Since the material 5028 is not standardized in any pressure vessel code, detailed test campaigns for each welding process will be done to validate the material properties after welding.

In Figure 9b) the tank in the final experiment configuration is shown without insulation. The liquid hydrogen sloshing experiments with the tank will be performed at the hexapod system of the Institute of Space Systems of the German Aerospace Center (DLR) in Bremen. More details on the laboratory environment can be found in [7].



a) AlMgSc-Tank mounted on the mounting plate

b) AlMgSc tank mounted atop the DLR hexapod

Figure 9: Different artist renderings of the AlMgSc tank mounted atop the mounting plate and the DLR hexapod system at the Institute of Space Systems' hexapod of the German Aerospace Center (DLR).

6. Conclusion

The AlMgSc alloy 5028 offers interesting advantages over the other aerospace aluminimum alloys. Those advantages consist in particular in:

- Lightweight design of non-pressurized structures, like inter-tank and inter-stage structures.
- Chemical compatibility with H2O2.

Material tests are being performed for full characterization of the alloy for various manufacturing and operational conditions. The results are promising and confirm initial assumptions.

A demonstrator tank is currently being manufactured. The tank design is 5028 -based and uses various forming and welding technologies.

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