



# Thermite-for-Demise (T4D): charge shaping exploratory tests

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Thermite-for-Demise (T4D) is an innovative approach to aid spacecraft demise during re-entry by leveraging thermite-based materials to enhance structural demisability. This study investigates the initial steps in developing thermite-based materials tailored for Design-for-Demise (D4D) applications. Two fabrication techniques were explored: pelletization of thermite powders with or without polymeric binders and embedding thermite in a polymer matrix for casting. The pelletization of fuel rich thermite formulations, with the addition of polymeric binders resulted in lower porosity. However, compression tests revealed the mechanical limitations and variability of the produced pellets, emphasizing the necessity for further processing to improve the mechanical performances. Thermite dispersion in acrylonitrile butadiene styrene (ABS) demonstrated promising pyrotechnic behavior at thermite concentrations equal or higher than 15%. This work establishes a foundation for future exploration of thermite-based structural reactive materials to mitigate ground casualty risks due to spacecraft uncontrolled re-entry.

## I. Introduction

The need for sustainable, safe, and economically sound spacecraft disposal is a hot topic in space research. In the last decades, the launch costs decreased so significantly [1] that the operative paradigm in the space sector completely changed. The cheaper access to space, and to Low Earth Orbit (LEO) in particular, enabled the entrance of private actors in the sector, giving birth to the mega-constellations that are being deployed in these years. Although these changes are providing new services to society and new opportunities for economic growth, the drawbacks of these activities should be considered. Periodic reports from ESA [2] and IADC [3] are showing the impressive rise of the number of space debris in orbit. In a more and more crowded space environment, the risk of dangerous conjunctions increases, leading to the need for better shielding technologies and more frequent collision avoidance maneuvers. Even if in the short term this will result only in higher operational costs, it has been postulated that human access to space could be jeopardized due to space junk. Indeed, the increase in the number of derelict space objects could lead to the Kessler syndrome [4], a condition in which a cascade of collisions would dramatically increase the object density in LEO, with each collision that increases the probability of further collisions. To avoid this scenario, international guidelines and national standards (e.g., [5]-[8]) impose space debris mitigation measures for space actors operating in protected regions. For LEO spacecraft, the main mitigation strategy is the atmospheric re-entry after the end of the operative life. A maximum timespan between the end of the operative life and the removal from orbit is set, usually 25 years [5]. Recently, both the Federal Communications Commission (FCC) [7] and the European Space Agency (ESA) [8] restricted this timeframe down to 5 years, in line with the increasing concern about space junk of the research community. Other typical requirements on spacecraft decommissioning are on the minimum disposal reliability (e.g. > 90%) and on the maximum casualty risk on ground (e.g.,  $<10^{-4}$ ) [5]. In particular, the last one is paramount in the definition of the re-entry strategy. Each re-entry inherently poses a threat for people and goods on the ground, should it not demise completely during the process. If this risk overcomes a certain threshold (typically 1 in 10000), a final high-thrust maneuver is imposed to direct the derelict spacecraft over uninhabited areas, hence avoiding possible victims. In contrast, if the limit is respected, uncontrolled re-entry is allowed, with the consequent advantages for the mission in terms of costs and complexity.

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The design solutions aiming at the reduction of the casualty risk on ground and, in this way, at the enlargement of the spacecraft share which can access to an uncontrolled re-entry strategy, are named Design-for-Demise (D4D). D4D is the intentional design of the space system such that its destruction during the re-entry process will be maximized, limiting the consequences of its impact on ground. This research field has been flourishing in the recent years, with numerous techniques that have been proposed [9][10]. Most of them focus on the minimization of the surviving mass, either by minimizing the heat load needed to reach complete demise, maximizing the available enthalpy, or optimizing the heat exposure of the most robust equipment. Only some approaches focus on the minimization of the casualty area on ground by keeping all the fragments together. A rather unexplored technique to maximize the available heat on board is represented by Thermite-for-Demise (T4D). In this concept, a thermite charge is placed on the spacecraft and is triggered during the re-entry phase, acting as an additional source of enthalpy. Thermites are chosen thanks to their high energetic density, wide tunability, and intrinsic safety. The possible techniques based on this concept are numerous, and in this paper the basis of an innovative approach will be explored. Usually, thermites are produced in powder form: it is evident that the use of a granular media in space-like environment implies the need for an encapsulation. The thermite could then be embedded into the structural voids of the spacecraft or of the single component, or into a dedicated vessel. In this work, the first steps to embed thermites into structural reactive materials for space systems will be outlined. Two approaches will be discussed. In the first one, the thermite is pelletized with or without a limited fraction of binder, aiming at a formulation that could be later sintered. In the second one, the incorporation of the pyrotechnic powder in a polymer to obtain a castable material is explored.

In Section II, a brief background on the T4D concept, the state-of-the-art research on Structural Reactive Materials (SRM), and the production technologies addressed in this work is provided. The selection of the used materials, as well as the description of the methods explored is provided in Section III. Then, the obtained results will be discussed in Section IV, highlighting the advantages and limitations of each technique. Finally, Section V presents the main conclusions that can be derived from this work.

## II. Background

### 1. Thermite-for-Demise

The use of exothermic reactions to aid spacecraft demise has been investigated only to a limited extent even if conceptualized more than 10 years ago. CNES filed a patent [11] on the topic in 2011, followed by ESA in 2018 [12]. The same institutions funded the research projects that investigated the T4D concept up to date. Monogarov et al. tested the CNES concept of a thermite pellet, in direct contact with a titanium plate and shielded over the other sides, selecting the  $\text{Al}/\text{Co}_3\text{O}_4$  as the best performing one in perforating the plate [13]. During the same study, different granulometries and shapes of the aluminum powder were explored, confirming the possibility to tune the thermite ignition temperature (from  $869 \pm 5$  °C for the micron-sized powder to  $592 \pm 5$  °C for the nano-sized one). The same research group tested this concept in a hypersonic wind tunnel, successfully perforating a curved titanium alloy plate of thickness 0.8 mm using an encapsulated thermite pellet [14]. A similar approach was investigated by ESA in the Exothermic Reaction Aided Spacecraft Demise (ERASD) [15] and Spacecraft demise during re-entry expedited using various exothermic reactions (SPADEXO) [16] projects. In these cases, the thermite powder was embedded in the structural voids of robust component mock-ups, with the objective of verifying the efficacy of the concept, the passive ignition of the energetic material, and the predictions of a dedicated extension of the SCARAB numerical model [17][18]. The outcomes of these projects indicate that T4D is an effective D4D solution. Thermite-induced demise was verified in hypersonic wind tunnel tests and appropriately described by the numerical tool, both in terms of ignition and effects. An appropriate selection of the thermite ingredients and of its production method (i.e. mechanical activation) allowed the control of its ignition temperature. In a real application, this ability of tuning the passive ignition of the reactive charge would reflect in the possibility of selecting the re-entry phase in which the reaction would happen. The main challenge identified during the SPADEXO activity is the pressure build-up that was observed in the confined geometry that was placed in the wind tunnel. As thermites are typically produced in the form of powders, a certain degree of confinement is necessary for their practical use. Even if the ingredients are properly selected and hence the gas generated is limited, the risk of an uncontrolled fragmentation persists. This challenge was identified independently by another ESA-funded activity that is still ongoing, Design-for-Demise Exothermic Reactions (D4D-ER) [19].

However, the possible thermite-based D4D techniques are various and not all of them necessitate a limited gas generation. A concept that has been formulated but not tested yet is the use of gas-generating thermites to create a thermal torch. In this case, the thermite combustion would take place in a confined geometry, resulting in a hot jet ejected by a nozzle which would impinge on the target substrate. This technique could be particularly effective to

provoke early demise, concentrating the available enthalpy on the structural connection of the space platform. Again, the main concern that prevented the experimentation was the risk of an uncontrolled fragmentation of the thermite vessel. Another thermite-based concept which would need a high-gas generating formulation is the potential use of thermites to induce the separation of the sub-components of particularly robust equipment. An example of this application is the one proposed by Ehinger et al. [20]. During an ESA-funded study on the demisability of reaction wheels, this research group identified the important role of sub-elements separation in the demise process of these components, which could be triggered by a strategically placed thermite charge.

In all these applications, one of the main requirements is the need to confine the thermite to avoid its dispersion. A different concept, which is the focus of this work, is the use of thermite to create Structural Reactive Materials (SRM). According to this approach, the thermite could be either sintered or embedded in a polymer, giving birth to a thermite-based material able to withstand mechanical loads. This solution would enable the use of the thermite without encapsulating it in a closed vessel, avoiding in this way the possible problems connected to gas generation. Moreover, the thermite-based SRM could be used as a structural material itself, should its properties be sufficient for the loads that the component must withstand.

## 2. Thermites

Thermites are a subset of energetic materials composed by a metal and a metal oxide, typically produced in powder form. When an appropriate energetic stimulus is provided (e.g., thermal, mechanical, electrical), these mixtures react exothermically, resulting in the oxidation of the starting metal and in the reduction of the starting oxide. The most used mixture is based on aluminum and iron oxide, but the selection of different components can grant a wide spectrum of properties [21]. The main parameters which are considered when a thermite couple is selected for a particular application are its adiabatic flame temperature, energetic density, sensitivity to external stimuli, and the amount of gaseous products generated. While the thermodynamic properties of the reaction and the resulting products are determined only by the chemistry of the formulation (i.e. the selected thermite couple), other characteristics of the powder have a central role in determining its reactivity and kinetics. The granulometry, surface finishing, and shape of the grains can be used to tune its properties as close proximity between the metal and the metal oxide can improve thermite reactivity performances. Moreover, production processes can be used to alter these characteristics or create nanostructured powders [22]. For example, high-energy mechanical activation [23][24] is a production process which can enhance the reactivity of micrometric thermites. The properties of the powders produced through this process are similar to the ones of nano-sized thermites, even if their micrometric size is preserved. Standard micrometric powders are placed in a closed jar, together with a milling tool and (possibly) a Process Control Agent (PCA). The most common milling tool is a set of steel spheres, but its material and shape can be changed to alter the results of the process. The PCA is usually a liquid that is removed at the end of the process and whose objective is to limit the temperature reached inside the vessel during the milling or to control the intensity of the impacts inside the vial. The powder is then milled by agitating the closed jar, and the resulting powder shows an enhanced reactivity owing to changes in the granulometry, surface finish, shape, and nanostructure.

## 3. Structural Reactive Materials

Structural Reactive Materials are a class of materials designed to withstand mechanical loads and release energy when triggered by an appropriate stimulus. Their typical applications are in the defence field. An example of their possible use is in the structural parts of ammunitions, where the reaction of a case made of SRM could contribute to the energy release of the explosive charge. An extensive literature review on this class of materials can be found in [25]. The most common SRM, often considered as reference, are composites of aluminum and polytetrafluoroethylene (PTFE). The mechanical properties of these materials are limited, but the gas generation and the energy release are attractive. The typical production process starts with the blending of aluminum and PTFE powders, their consolidation through uniaxial pressing, and successive sintering to obtain cross-linking of the polymeric material [26]. Various efforts have been conducted over the years to obtain thermite-based SRM. Nanostructured powders of metal-metal oxide composites have been realized using mechanical milling, increasing the thermite reaction rate [27] and improving the capability of these powders to produce hydrogen when in contact with water [28]. Other techniques were explored to obtain consolidated geometries, such as cold spray [29], ultrasonic consolidation [30], and uniaxial pelletization. The latter strategy will be discussed in Section II.4. Typically, the most important parameters of merit are the porosity of the composite, which correlates with its mechanical properties and energetic content, and its characteristic burning time. For some defence applications, the heat release rate of the SRM should be very fast (up to 2900 m/s), should the energy be released in concomitance with the impact of an ammunition. For D4D applications, this requirement can be strongly relaxed as the characteristic time of re-entry phases is typically of the order of seconds

or minutes. Instead, a slow reaction could be preferred to limit the pressurization rates if the thermite-based material is (even partly) confined.

#### 4. Investigated production technologies

The first technique explored in this work to shape thermite is uniaxial compression. Previous research on this topic was conducted by Stamatis et al. [31][32]. In their work, fuel-rich Al/MoO<sub>3</sub> and Al/CuO were uniaxially compressed at room temperature, using Teflon spray to lubricate the die surface. The compaction pressures used were in the range of 105-500 MPa. In some tests, PolyEthylene Glycol (PEG) or indium were used in small amounts as binders. The produced pellets showed densities higher than the 90% of their Theoretical Maximum Density (TMD). Moreover, thermal initiation tests conducted on Al/MoO<sub>3</sub> pellets indicated that their reactivity was preserved in the compression process. A further development of this technique could be the successive sintering of the thermite pellets, which could improve the mechanical properties of the consolidated material. In this way, the metal particles could be exploited to create a matrix capable of withstanding mechanical loads. A comprehensive overview of composites sintering can be found in [33]. For this class of materials, it is suggested to limit the volumetric fraction of the inert phase to 30%. Moreover, even if greens made of bimodal powders can reach a higher packing density, it is reported that a better densification is usually obtained sintering composite powders of similar granulometry. Considering Al-based thermites, the most straightforward strategy would be aluminum sintering, starting from fuel-rich compressed greens. The main process parameters to be considered are sintering temperature, duration, pressure, and atmosphere [34]. Typically, sintering temperature can vary between 560 to 625 °C and the process can last up to a few hours. Moreover, the atmosphere should prevent further oxidation of the Al particles. For this reason, the sintering process is typically conducted in high-vacuum or nitrogen atmosphere.

A second strategy explored in this paper for the creation of a thermite-based material capable of maintaining a desired shape is the incorporation of the reactive mixture in a polymer. The incorporation of powders in polymers is common in technologies such as solid propellant manufacture [35] and Fused Deposition Modeling (FDM) 3D printing (e.g., [36]). The presence of the powder modifies the mechanical and thermal properties of the composite. In the field of energetic materials, while castable solution can reach high solid loading, it is still not clear if FDM can achieve comparable results [37]. In this work, a polymer commonly used for 3D printing rapid prototyping was selected and its filling with thermite was explored, with the objective of verifying the lowest loading percentage for which a pyrotechnic behavior during combustion could be observed.

### III. Materials and methods

#### 1. Materials

The ingredients used to produce the thermite-based materials presented in this work are reported in Table 1. The standard thermite was produced mixing the Al and Fe<sub>2</sub>O<sub>3</sub> powders using a Resodyn LabRam acoustic mixer. The activated thermite was produced starting from the same ingredients and following the procedure described in [24]. For the pelletization tests, the ingredients mass ratio was varied depending on the investigated formulation (see Section III.2). Instead, for the tests involving thermite dispersion in polymers, the reactants were mixed in stoichiometric ratio.

**Table 1: Starting ingredients to produce thermite-based materials.**

Material	Characteristics	Supplier	Batch
Al	Spherical, 30 µm	AMG Alpoco	N.A.
Fe <sub>2</sub> O <sub>3</sub>	-325 mesh (≤44 µm)*	Thermo Scientific	M22H036
PMMA	Molecular weight: 400,000 to 550,000	Thermo Scientific	N04H030
PEG	Molecular weight: 4,000	Alfa Aesar	10216306
ABS	Pellet granulate	Smartfil	N.A.

\*: D(0,5) = 0.454 µm, measured with Malvern Mastersizer 2000, Hydro 2000S.

#### 2. Methods

Two approaches have been explored to give structural integrity to thermite. The first one consists of uniaxially pressing the thermite powder in a cylindrical steel die using a MTS 810 universal testing machine. Prior to its filling, the die surface was lubricated using Teflon spray. The mixture was pressed for 5 minutes on each side. Different

pressure levels and binders were explored to assess the resulting porosity and mechanical properties. Table 2 reports the formulations explored, the binder used (if any), the pressure level, and the number of pellets later undergone compression tests. The use of two binders, PolyMethyl MethAcrylate (PMMA) and PolyEthylene Glycol (PEG), was explored. Two thermite formulations were used, one composed of 80% Al and 20%  $\text{Fe}_2\text{O}_3$  by weight, and the other in stoichiometric ratio. From a volumetric viewpoint, the inert phase is respectively around 10% and 60%. The binders were added to the thermite mixture as a fraction of its weight, as shown in Table 2, and incorporated using a Resodyn LabRam acoustic mixer. After the pelletization process, the weight and the dimensions of the pellets were measured to compute their density as a percentage of their TMD. This method was preferred to the volumetric method due to the risk of powder detachment from some of the pellets in the liquid. Therefore, the measured density should be considered as a lower boundary, as shape defects are not considered. Two pellets, one composed of pure Al, and the other of 80% Al and  $\text{Fe}_2\text{O}_3$ , were sintered after compression at 300 MPa. After an initial temperature rise at 10 °C/min, they were maintained at 600 °C for one hour and then brought back to room temperature at a cooling rate of 20 °C/min. The sintering process was conducted in high-vacuum.

The second production method explored in this work is the dispersion of the powder in a polymer, Acrylonitrile Butadiene Styrene (ABS). ABS was chosen thanks to its good mechanical properties and solubility in non-toxic solvents such as acetone. Firstly, the polymer is stirred in acetone until its complete dissolution is reached. Then, the thermite is introduced in the solution and the compost is stirred until the composition is uniform. Lastly, acetone is removed by heating the composition at 60 °C. The formulations used for these tests are reported in Table 4. Only in two cases, a fraction (5%) of ABS was substituted with PEG and the samples were allowed to slowly dry in open air.

**Table 2: Formulation and compression pressure of the thermite pellets. The binder is in excess with respect to the powder weight.**

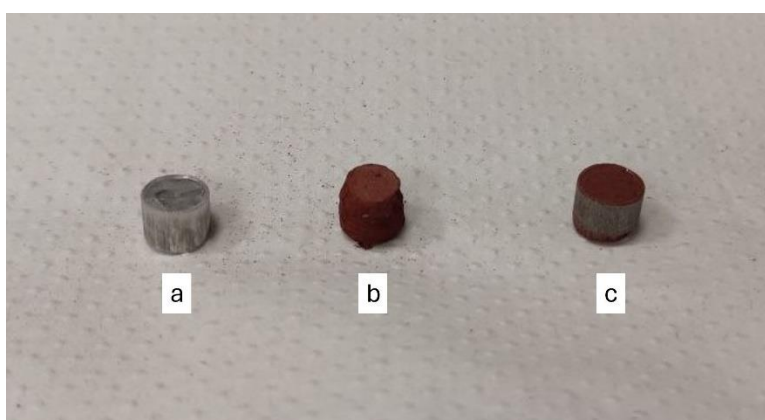
Test ID	Formulation, w%	Binder, w%	Pressure, MPa	N° of pellets
F1	100% Al	No	300	6
			400	1
F2	80% Al + 20% $\text{Fe}_2\text{O}_3$	No	200	1
			250	1
			300	3
			400	1
F3	80% Al + 20% $\text{Fe}_2\text{O}_3$	5% PMMA	200	1
			300	1
			400	1
F4	80% Al + 20% $\text{Fe}_2\text{O}_3$	10% PMMA	200	1
			300	1
			400	1
F5	80% Al + 20% $\text{Fe}_2\text{O}_3$	5% PEG	300	1
F6	25% Al + 75% $\text{Fe}_2\text{O}_3$	10% PMMA	300	1
			400	1
F7	Act 25% Al + 75% $\text{Fe}_2\text{O}_3$	No	300	3
F8	Act 25% Al + 75% $\text{Fe}_2\text{O}_3$	10% PMMA	300	4

			400	4
F9	Act 25% Al + 75% Fe <sub>2</sub> O <sub>3</sub>	5% PEG	300	5

## IV. Results and discussion

### 1. Thermite pelletization

In **Errore. L'origine riferimento non è stata trovata.** three examples of the obtained pellets are shown. The Al pellet does not present geometrical defects and can withstand limited loads typical of handling or applied with a spoon. The one composed of pure thermite, without any use of binder, is dusty and qualitatively appears more fragile. The one in which PMMA is included in the composition is neater and more robust, similarly to the one of pure aluminum. The external surface of the pellet comprising PMMA is brighter, showing a color and finishing typical of aluminum. This is not true for the one made of simple thermite, but this could be due to damages resulting from its low mechanical properties.



**Figure 1: Examples of pellets obtained through uniaxial compression. From the left to the right, according to the nomenclature presented in Table 2: a) P6 b) P9 c) P17.**

The first parameter of merit of the produced pellets that has been investigated is their density. The higher the density, the higher the expected mechanical properties before and after sintering. The density values in terms of percentage of the TMD are reported in Table 3 and Figure 2. It is possible to see that for a higher aluminum mass fraction a higher density is obtained. Moreover, the use of a binder improves this parameter. PMMA seems to be more effective than PEG in improving the density of fuel-rich formulations. The use of the 10% of PMMA is not associated with a significant improvement in density with respect to the samples containing just 5% of the same binder. Moreover, the pellets composed of activated thermite showed higher porosity than the ones made of standard thermite. This could be due to the irregular shape of the milled powder, induced by the mechanical activation process.

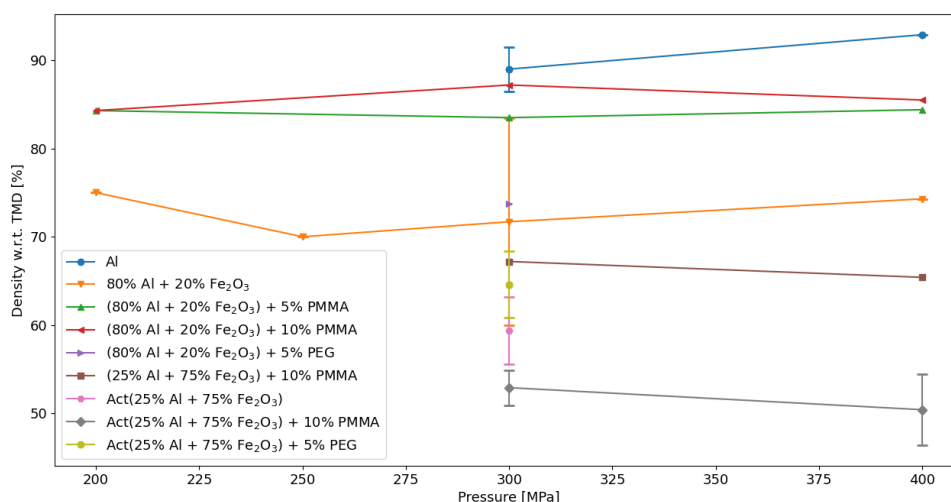
The mechanical properties of the pellets were studied through compression tests. The obtained Young's modulus and compression strength are reported in Table 3. Even if higher compression and the inclusion of a polymeric binder generally result in better mechanical properties, the measured results show very high variability. For this reason, the creation of a thermite-based material capable of maintaining its shape during the typical life cycle of a space system by simply compressing thermite, even with a limited fraction of polymeric binder, seems unrealistic. Therefore, an approach to thermite sintering was attempted.

**Table 3: Results of the compression tests.**

Formulation	Pressure, MPa	Test ID	Density w.r.t. TMD	Young's modulus, MPa	Compression strength, MPa
F1	300	P1	90.2%	493	88.41

		P2	91.4%	2221	68.75
		P3	88.0%	1844	59.11
		P4	86.2%	1107	46.39
		P5	89.3%	2878	76.11
	400	P6	92.9%	1362	88.66
F2	200	P7	75.0%	248	11.52
	250	P8	70.0%	1013	25.33
	300	P9	78.9%	208	7.44
		P10	72.6%	329	13.38
		P11	69.7%	1172	28.79
	400	P12	74.3%	374	22.53
F3	200	P13	84.3%	2356	49.39
	300	P14	83.5%	3590	70.50
	400	P15	84.4%	2671	56.11
F4	200	P16	84.3%	2346	68.48
	300	P17	87.2%	3328	78.52
	400	P18	85.5%	4267	104.73
F5	300	P19	73.7%	1892	47.73
F6	300	P20	67.2%	1525	28.21
	400	P21	65.4%	1397	30.64
F7	300	P22	59.7%	1113	54.28
		P23	57.8%	1043	33.13
		P24	60.8%	1389	60.17
F8	300	P25	52.2%	2582	325.80
		P26	53.9%	1675	238.77
		P27	51.6%	2206	270.12
		P28	54.1%	1769	251.84
	400	P29	47.0%	1930	189.51
		P30	49.8%	2539	203.87
		P31	52.6%	2248	226.73
		P32	52.0%	2093	235.73

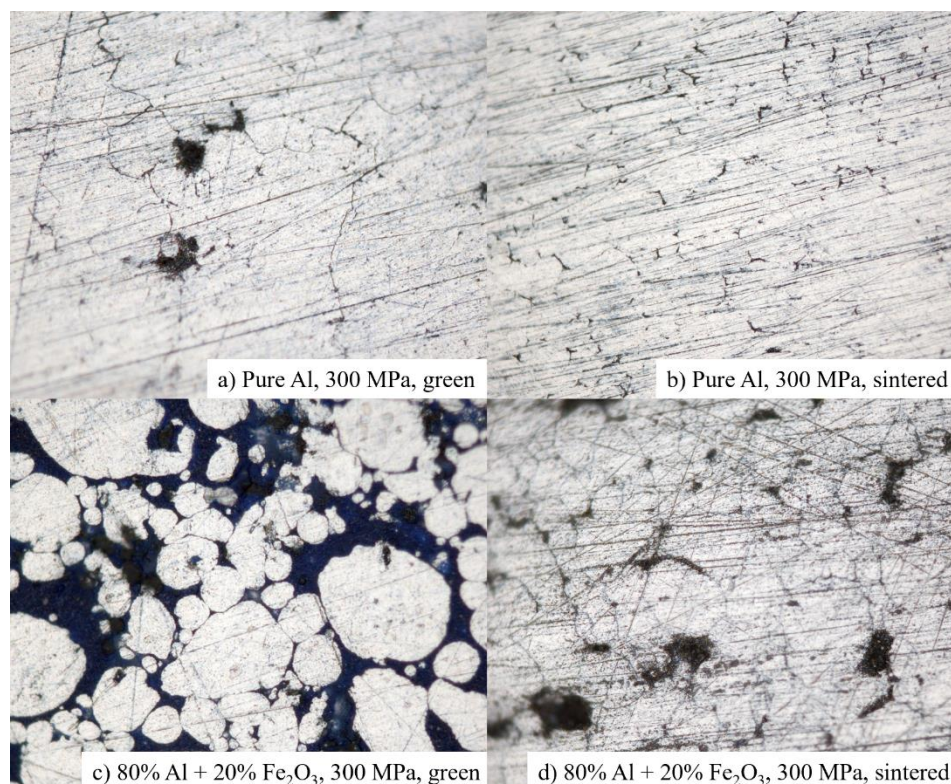
F9	300	P33	59.4%	2263	65.22
		P34	65.6%	1239	50.05
		P35	66.6%	915	35.82
		P36	66.7%	2201	206.60
		P37	64.9%	899	48.37



**Figure 2: Density of the produced pellets as a function of compression and formulation.**

Exploratory sintering tests were conducted on two pellets, one made of pure Al and one of 80% Al and 20%  $\text{Fe}_2\text{O}_3$ . Both pellets were compressed at 300 MPa prior to sintering. For these tests, the use of polymeric binders was excluded to limit the number of variables. Figure 3 presents the appearance of the green and sintered pellets at the optical microscope with a 50x magnification. The aluminum particles can be clearly individuated in the Al green pellet. Their polygonal shape highlights the mechanical deformation resulting from the previous compression. Once sintered, the Al grains can be steel recognized, but necks are formed between the particles. As for the thermite pellet, a clear difference can be seen before and after the sintering process. While before sintering the Al particles are clearly separated, connections between the Al grains appear after the thermal treatment. After the sintering process, the color of the pellets changed from red to black. This suggests the transition of iron oxide from  $\text{Fe}_2\text{O}_3$  to  $\text{Fe}_3\text{O}_4$ . The oxygen loss would probably result in a degradation of the energetic properties (see [21]), but a thermite reaction would be still possible. The mechanical properties of samples prepared following this procedure will be tested in further research, as well as their reactivity.





**Figure 3: Images of the green and sintered pellets (Al and 80% Al + 20% Fe<sub>2</sub>O<sub>3</sub>) obtained through optical microscopy, 50x magnification.**

## 2. Thermite dispersion in ABS

Figure 4 shows two examples of the samples obtained by dispersing activated thermite in ABS, respectively with a powder mass loading of 15% (Fig. 4a) and 90% (Fig. 4b). Combustion tests were performed to identify the lower powder filling showing pyrotechnic behavior. The results of these tests are reported in Table 4. In the table, the Go / No Go result refers to the detection of a pyrotechnic behavior, shown in Figure 5 and Figure 6. Only the samples D1 and D2, containing respectively 5% and 10% of thermite, showed a combustion behavior similar to the one of pure ABS. However, the samples produced using only thermite and ABS highlighted the tendency of the powder to precipitate during the drying process. Moreover, the samples dried in oven presented some cavities, probably due to the too fast evaporation of the acetone. For these reasons, two additional samples (D8 and D9) were realized introducing PEG as dispersant in the formulation and allowing the acetone to slowly evaporate in open air. Figure 7 shows a comparison between a sample that did not contain PEG and dried at 60 °C (D6) and the two samples that did contain a PEG fraction and dried in the open air. While the first one presents gradients in the powder concentration, because of deposition, samples D8 and D9 are more homogeneous. Moreover, the two samples that dried slowly in open air did not show cavities or similar shape defects. The combustion of these samples showed a two-step behavior, with thermite combustion anticipated by the ignition of the polymers (Figure 8).



**Figure 4: Appearance of the samples obtained with thermite dispersion in ABS. From the left to the right, according to the nomenclature defined in Table 4: a) D3 b) D7.**

**Table 4 Formulation and combustion behavior of the thermite dispersed in ABS.**

Test ID	Formulation, w%	Go / No Go	Comments
D1	5% Act Th + 95% ABS	No Go	Similar to combustion of pure ABS
D2	10% Act Th + 90% ABS	No Go	Similar to combustion of pure ABS but more sustained
D3	15% Act Th + 85% ABS	Go	-
D4	20% Act Th + 80% ABS	Go	-
D5	30% Act Th + 70% ABS	Go	-
D6	40% Act Th + 60% ABS	Go	-
D7	90% Act Th + 10% ABS	Go	-
D8	75% Th + 20% ABS + 5% PEG	Go	-
D9	75% Act Th + 20% ABS + 5% PEG	Go	-

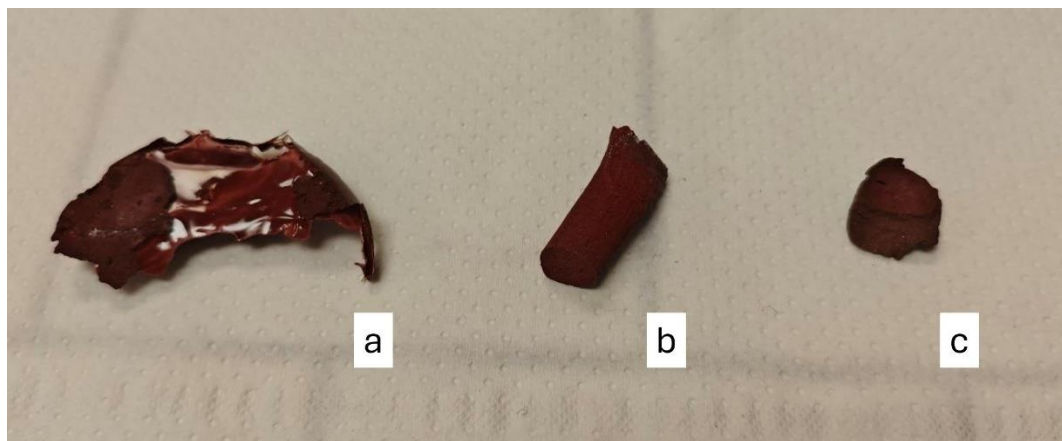




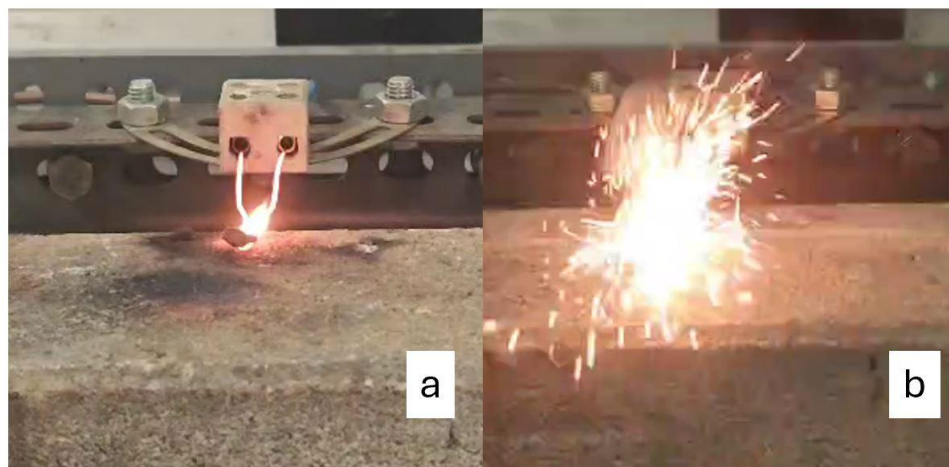
**Figure 5: Combustion of sample D3.**



**Figure 6: Combustion of sample D7.**



**Figure 7: Comparison between sample D6 (a), D8 (b), and D9 (c). The samples containing 5% PEG by mass result more uniform and compact.**



**Figure 8: Combustion test of sample D9. a) Polymer ignition. b) Thermite ignition.**

## V. Conclusion

The first steps toward the creation of thermite-based materials for D4D applications were described in this paper. Two techniques were explored. The first one consisted in the pelletization of thermite, with and without the use of a polymeric binder. Reference pellets of pure Al were realized to compare the results obtained with two thermite formulations, one composed of 80% Al and 20%  $\text{Fe}_2\text{O}_3$ , and the other in stoichiometric ratio. The pellets were uniaxially pressed at pressures in the range between 200 and 400 MPa, in some cases including a fraction of PMMA or PEG up to 10% of the powder mass as binder. Lower porosity was observed for the fuel rich formulation with the use of binder. However, compression tests highlighted the variability of the Young's modulus and compression strength of the produced pellets, suggesting that further processing is necessary to obtain a thermite-based material capable of withstanding the typical mechanical loads associated with the life cycle of a space system. Therefore, exploratory sintering tests were conducted on two pellets, one composed of pure Al, and the other of 80% Al and 20%  $\text{Fe}_2\text{O}_3$ . The pellets were sintered in high-vacuum at 600 °C for one hour. Optical microscopy revealed an appearance change after sintering for both the formulations, highlighting the formation of necks between the Al particles in the pellets. Even if this phenomenon was more evident for the pure Al pellet, it was observed also for the fuel rich thermite case. A second technique explored for shaping the thermite formulation was its embedding in a polymer (ABS) to enable successive casting. After the dissolution of ABS in acetone and the introduction of thermite powder in the solution, the obtained material was dried at 60 °C to remove acetone. Samples containing up to 90% thermite by mass were realized. Combustion tests showed that for thermite fractions equal or higher than 15% pyrotechnic behavior can be observed. However, powder deposition during the drying process was observed, as well as shape defects induced by the rapid evaporation of acetone. Two additional samples were realized introducing PEG as dispersant and allowing the mixture to slowly dry in open air. The resulting samples showed a homogenous texture and no shape defects, and combustion tests results confirmed their reactivity.

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