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Thermal Stability Evaluation of Aluminium Oxide (Al_2O_3) for High-Temperature Applications

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Abstract: Aluminium oxide (Al_2O_3) is a common ceramic material widely recognized for its thermal stability, chemical inertness, and mechanical strength, and is therefore ideally suited for high temperature uses. Its stable α -phase allows it to resist extreme heating without changing structure, in turn supporting common applications in refractory linings, thermal barrier coatings, structural ceramics, electronic substrate applications, and catalytic supports. In this investigation, the thermal stability of aluminium oxide powder is evaluated using thermogravimetric (TG) and differential scanning calorimetry (DSC) techniques. The investigation shows that aluminium oxide remains structurally stable in high-temperature conditions (300-900 °C), and only experiences minor mass loss at low temperatures due to surface moisture and hydroxyl groups. These investigations demonstrate that aluminium oxide is suitable for challenging high-temperature and protective applications. Earlier investigations conducted by Toledo, Laboureur, Trunov, Vippola have pointed out alike thermal reliability thereby ensuring it functioned well in confirmation of thermal systems. Having elevated thermal resistance, mechanical hardness, and chemical non-reactivity, aluminium oxide is a flexible option of material for parts undergoing harsh thermal conditions. In summary, this study determines that aluminium oxide is a durable, thermally stable, and reliably performing material for high temperature systems, reinforcing its importance in ceramics, aerospace, electronics, and chemical industries where materials must perform and maintain their durability under extreme conditions.

Keywords: Aluminium oxide (Al_2O_3), Thermal stability, α -phase, Thermogravimetric analysis (TGA), Differential scanning calorimetry (DSC), High-temperature applications.

I. INTRODUCTION

Aluminium oxide (Al_2O_3) is a well-established ceramic material recognized for its high thermal stability, chemical inertness, and mechanical strength. These attributes make alumina suitable for a variety of applications that operate at high temperatures; it has the ability to withstand temperatures considerably beyond its degradation point[1]. Therefore, alumina is often used in refractory linings, thermal barrier coatings, structural ceramics, and as a substrate material in electronic and catalytic devices[2].

Aluminium oxide's high thermal stability is primarily driven by structural stability from its α -phase. In contrast to other forms of alumina, the α -phase of alumina does not typically undergo significant structural changes in high temperature environments[3]. This necessitates a great demand in industries that regularly experience challenging thermal conditions- situations that will likely push even tough materials to reach their critical thermal degradation temperatures. Given its microstructural stability, even in extreme thermal applications, alumina has garnered attention[4]. Past work has indicated that alumina effectively performs in harsh thermal environments, depending on relevant microstructural parameters such as particle size and method of synthesis, as well as phase composition; however, the α -phase illustrates exceptional chemical and thermal stability.

Understanding the versatility of Aluminium oxide in high-temperature systems is due not only to its chemical and thermal characteristics, but also due to its mechanical hardness and corrosion resistance[5]. This makes alumina an ideal candidate as a protective coating, structural material, or an advanced substrate in industrial applications. Thus, Aluminium oxide (Al_2O_3) will continue to be an important material in ceramics, aerospace, electronics, and other high-temperature applications[6], [7].

Aluminium oxide (Al_2O_3) is recognized for its remarkable thermal stability, chemical inertness, and varied industrial applications. In our TG–DSC results, we observed a negligible weight loss (2.2%) until 1000 °C, which corresponds well with earlier findings. For example, Toledo et al. stated that the physicochemical properties and stability of alumina are strongly inclined to complex mixing of precursor and a synthesis route, yet bulk alumina shows little degradation even at elevated temperatures[8]. Additionally, Laboureur et al. observed using DSC–TGA measurements, alumina predominantly undergoes minor dehydration at lower temperature due primarily to the removal of surface adherent moisture and not the bulk of the material, which corresponds well with our observed endothermic peak below 150 °C[9].

Furthermore, Trunov et al. indicated oxidation kinetics of alumina films varies based on the structural transformation; still, α - Al_2O_3 remains highly resistant and thermally stable with high temperature[10]. In addition, supporting the notion, Vippola et al. also performed studies on alumina based coatings and determined that the coating performs structurally under long exposure to thermal environments and remains viable for protective and refractory applications[11].

Together, these studies validate our TG–DSC observations that aluminium oxide powder possesses outstanding thermal stability, making it highly suitable for refractory linings, coatings, and other high-temperature applications.

II. METHODOLOGY

A. Sample Preparation

The material chosen for thermal analysis was Aluminium Oxide (Al_2O_3) (Figure 1). The sample was obtained in the form of fine powder and measured carefully before experimentation. It was put into a normal alumina crucible for compatibility with high-temperature testing.



Figure 1. Aluminium Oxide (Al_2O_3)

B. Instrumentation

Thermal characterization was done with Thermogravimetric Analysis coupled with Differential Scanning Calorimetry (TG-DSC). The experiment was conducted at the Sophisticated Analytical Instrument Facility (SAIF), IIT Madras, on the following instrument:



Figure 2. Thermogravimetric Analysis Machine (STA 449 F3 Jupiter)

- 1) Instrument: STA 449 F3 Jupiter
- 2) Manufacturer: NETZSCH, Germany
- 3) Purpose: Concurrent measurement of weight change (TGA) and heat flow (DSC) to analyze thermal stability, phase transitions, and decomposition behavior.
- 4) Instrument Setup: The TG-DSC analyzer employed is illustrated in Figure 2.

C. Experimental Conditions

The experimental conditions were controlled for reliable and repeatable data:

- 1) Temperature Range: 30 °C – 1000 °C
- 2) Heating Rate: 10 °C/min
- 3) Atmosphere: Inert (Nitrogen)
- 4) Sample Holder: Alumina crucible

During the test, the instrument kept a continuous record of both thermogravimetric data (weight loss %) and differential scanning calorimetry data (heat flow) as a function of temperature.

D. Data Analysis

The collected thermograms were processed to determine significant parameters including onset temperature, peak temperature, phase transition, enthalpy changes, and weight loss percentage. These results were compared with the literature to ensure reproducibility. The procedure facilitated accurate determination of thermal phenomena, validating the stability and aptness of Al_2O_3 for high-temperature and coating applications.

III. RESULTS AND DISCUSSION

Thermal characterization by simultaneous thermogravimetry (TG), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC) was performed to assess the thermal stability of the aluminium oxide powder. The data are shown in Figures 3–5, which present complementary information about the thermal behavior, phase stability, and possible applicability of the material to high-temperature applications.

A. Thermogravimetric Analysis (TGA)

The TG curve of aluminium oxide (Figure 3) shows the total weight loss of around 2.2% from room temperature to 1000 °C. Most of this weight loss is below 150 °C, and there is an inflection point at around 86 °C as indicated by the TG–DTG plot (Figure 4). This preliminary weight loss is caused by the evaporation of physically adsorbed water molecules and the expulsion of loosely bound hydroxyl groups from the particle surface. This is typical for ceramic oxide powders kept at ambient conditions since their high surface area promotes adsorption of moisture in the atmosphere.

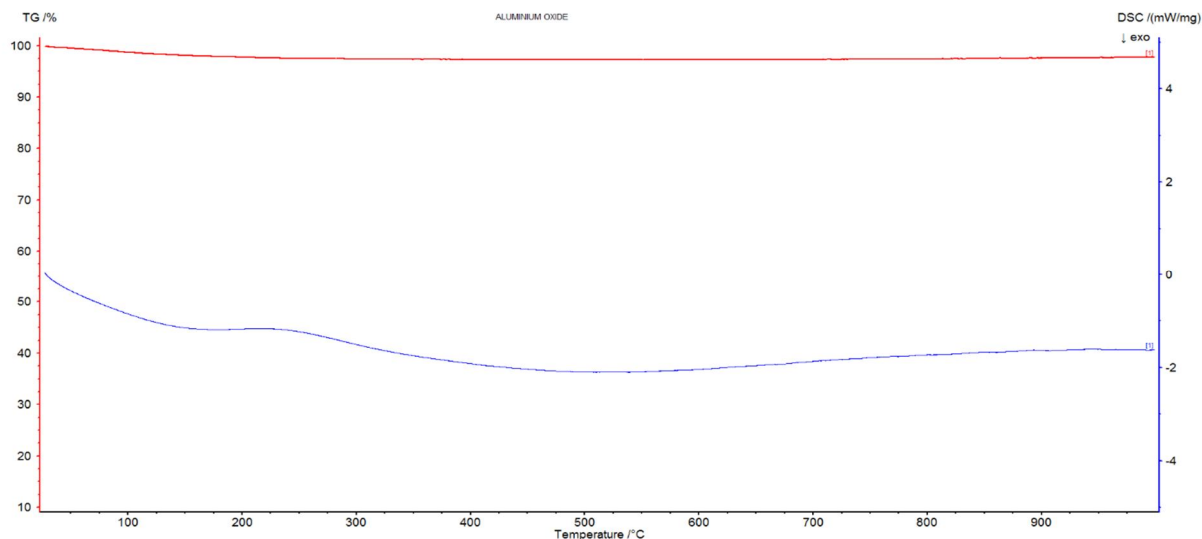


Figure 3: DSC curve of Aluminium Oxide

Above 150 °C, the TG curve levels quite flat, registering virtually no further mass change throughout the whole process of heating to 1000 °C. This very constant weight in the second stage of dehydration proves the high thermal stability of the aluminium oxide powder. The mass residue of about 97.8% at 1000 °C strongly supports that the material does not decompose or volatilize even under long heating, a basic property essential for its application in high-temperature ceramics, protective coatings, and catalytic supports.

B. Derivative Thermogravimetry (DTG)

The DTG curve (Figure 4) gives higher resolution in detecting weight loss events. A wide but shallow peak is seen below 120 °C, related to the desorption of surface water. No sharp or well-differentiated peaks are noted at higher temperatures, showing that no additional decomposition, oxidation, or phase transformation takes place within the temperature range investigated.

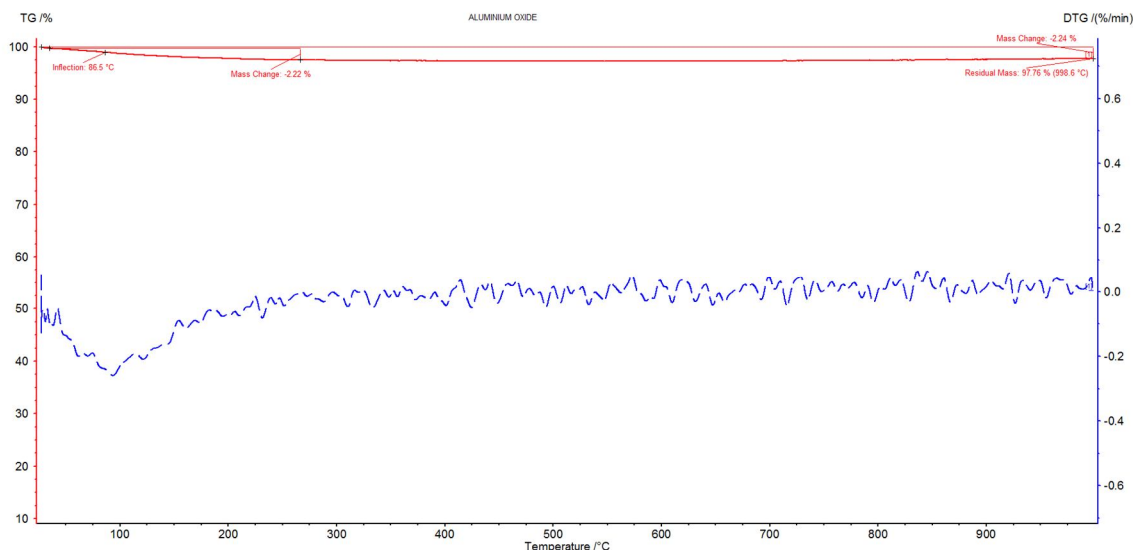


Figure 4: TG-DTG curve of Aluminium Oxide

Lack of any number of weight-loss stages or secondary peaks confirms that the aluminium oxide powder is in the stable α -phase of Al_2O_3 . This is the most thermodynamically stable form of alumina, and as opposed to its metastable variants (γ -, δ -, or θ - Al_2O_3), it has no transitions or structural rearrangements with heating. The horizontal DTG baseline above 150 °C thus reflects the chemical inertness and thermal resistance of the powder under heat stress.

C. Differential Scanning Calorimetry (DSC)

The DSC trace (Figure 5) provides supporting information for the TG and DTG data. Below 150 °C, there is a low-temperature endothermic peak representing evaporation of moisture and dehydroxylation of surface hydroxyls. The endotherm correlates with the mass loss seen in TG and with the peak in the DTG trace, establishing that these are physical processes and not related to structural degradation.

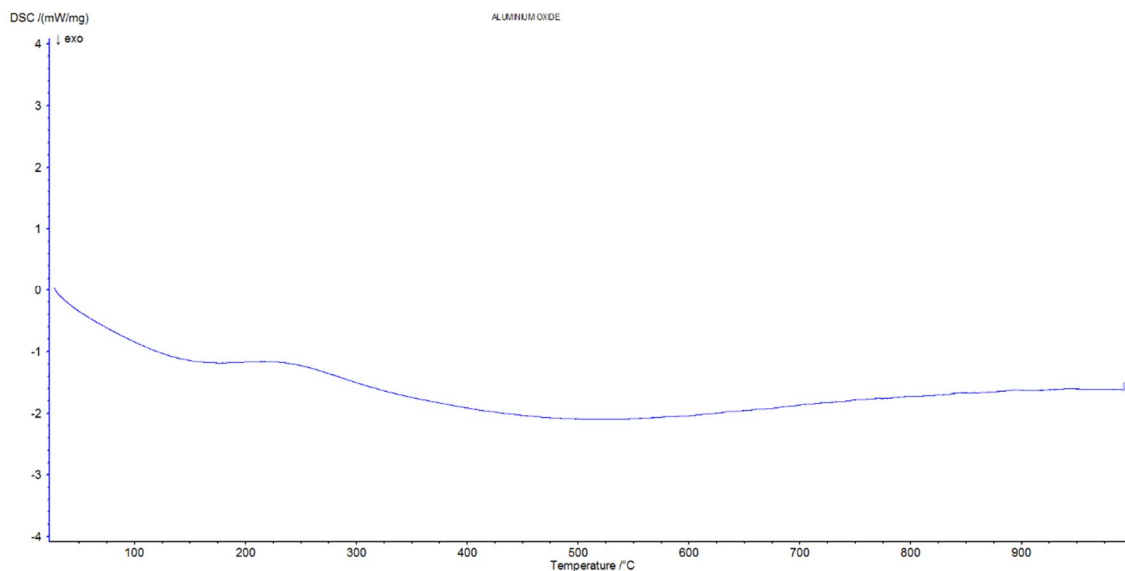


Figure 5: TG-DSC curve of Aluminium Oxide

At high temperatures, the DSC trace is virtually featureless with no indication of any exothermic or endothermic transitions. This lack of phase-change signals is evidence that the material is in a completely crystallized, stable α -alumina state and does not exhibit any crystallization, melting, or polymorphic transformations within the analyzed temperature range. Notably, metastable alumina phases like γ - or δ - under normal circumstances would exhibit exothermic peaks as a result of their transition to α -phase at elevated temperatures; the absence of such occurrences in this sample is clear evidence that the initial material is already α - Al_2O_3 .

D. Combined Discussion

The results from the thermogravimetric (TG), derivative thermogravimetric (DTG), and differential scanning calorimetry (DSC) tests confirm that the aluminium oxide powder has very high thermal stability, as evident in the TG data, which shows a total mass loss of only 2.2% at 1000 °C from surface water desorption, while the DTG traces were flat without multiple peaks, and the DSC baseline was flat with no changes or decomposition - the powder in practice exhibits a residual mass of approximately 97.8% at 1000 °C and thus could be suitable for high-temperature applications including structural ceramics, coatings, catalysts, and composites, as summarized in Table 1. These results are in agreement with previously published studies of α -alumina (Toledo et al., Laboureur et al., Trunov et al., Vippola et al.) [8], [10], [11], [12].

Table 1: Thermal Analysis of Aluminium Oxide Powder

Analysis	Observation	Interpretation	Reference
TG	Mass loss ~2.2% up to 1000 °C	Due to desorption of surface water; no decomposition	Laboureur et al., Toledo et al.
DTG	Flat trace; no multiple peaks	Confirms absence of decomposition or phase transitions	Trunov et al.
DSC	Level baseline; no exo-/endothermic peaks	Confirms thermal stability of α -alumina	Trunov et al.
Practical Implications	Residual mass ~97.8% at 1000 °C	Suitable for high-temp applications: structural ceramics, coatings, catalysts, composites	Vippola et al.

E. Applications in High-Temperature Systems

The results are a firm endorsement of the application of aluminium oxide across many high-temperature uses. The most significant application is in refractory linings, where alumina endures thermal breakdown in kilns and furnaces, thus providing long-term integrity and safe operation. It is also extensively used as a thermal barrier coating; as shown by Vippola et al., alumina-based coatings offer good protection for turbine blades and aerospace parts from intense heat, substantially prolonging their lifespan [11]. In the electronics sector, alumina is a good substrate material because it has high thermal stability coupled with outstanding electrical insulation properties, rendering it ideal for microelectronic and power device applications. Aside from these uses, alumina is critically used in the manufacture of structural ceramics and abrasives due to its hardness and thermal strength, making it a critical material in cutting tools, grinding wheels, and wear-resistant components. Together, these uses demonstrate the fundamental importance of thermally stable Aluminium oxide in applications where high-temperature performance and reliability are paramount.

IV. CONCLUSION

The thermal characterization of aluminium oxide powder by TG, DTG, and DSC methods evidently shows its superior thermal stability and crystalline quality. The overall weight loss of a mere 2.2%, primarily below 150 °C, is associated with the evaporation of adsorbed water and surface hydroxyl groups. Beyond this point, the sample is thermally inert with no indication of decomposition or phase transformation up to 1000 °C, a proof of its presence in the stable α -phase of Al_2O_3 . The level TG, DTG, and DSC traces further attest its chemical inertness and high-temperature stability

This stability renders aluminium oxide a suitable material for high-temperature coatings and thermal barrier coatings. Its melting point is high, with low thermal conductivity and high adhesion to metal substrates, which enables it to safeguard components against oxidation, corrosion, and thermal fatigue. In industrial environments—gas turbines, furnaces, and aerospace systems—aluminium oxide coatings serve as effective shields against heat, providing longer service life and reliability in performance.

In total, the combined TG–DTG–DSC results affirm that the investigated aluminium oxide powder has the thermal stability, phase steadiness, and chemical strength required for sophisticated high-temperature engineering and protective coating usage.

V. ACKNOWLEDGEMENTS

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