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Material Performance of Ferrous Alloys in Pyro-Oil Reactors for Carbon Reduction Technologies

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Abstract - Pyrolysis technology is a method with the potential to produce valuable fuels and products from waste and remains a fundamental tenet in the circular economy. Especially the greater temperature, corrosive environment, and mechanical stress require an optimal choice of a material for designing reactors so that they maintain efficient operation and long- term service. In this study, a comparison of four alternative high-performance steel-stainless steel materials (Stainless Steel 310S, Inconel 625, 253 MA and AISI 321 or 321 SS) is carried out with regard to their application for commercial scale pyrolysis reactors. A set of criteria such as thermal stability, corrosion resistance, mechanical strength, and thermal processing ability of various feedstocks (plastics, biomass and organic waste) has been considered evaluating for each alloy for thermal processing. It indicates that Inconel 625 is the best alloy, as far as the mechanical strength and resistance to high temperature and/or chemical degradation are concerned, so it serves as a good material in a reactor used in the pyrolysis of plastics and other synthetic waste, according to the results. A good alloy suitable for continuous and high temperature operation with excellent oxidation resistance and strength is 253 MA. The lowest cost solution for comparison purposes can be Stainless Steel 310S, which can stand a good chance in the diverse applications in pyrolysis. Finally, titanium stabilization alloy AISI 321 is applied in reactors to process biomass and organic waste. The relevance of material choice enabling efficiency and performance to be highest and the maintenance cost to minimum as well as the long- term sustainability of pyrolysis technology is the significant contribution of this study. Exploration of alloy modifications by addition of elements or a surface coating, potentially serving future research into pyrolysis technology, is in accordance with emerging research and appropriate for the commercialization of pyrolysis applications.

Keywords - Metallurgy, Steel, Properties, Applications, Testing Methods

I. INTRODUCTION

The world has changed. Handling large quantities of plastics, biomass, and municipal solid waste (MSW) has intensified interest in technologies for thermal conversions that can recover energy and valuable chemicals from waste streams. The thermo-chemical decomposition processes in pyrolysis occur in an oxygen-free environment, and it is known to convert organic materials into syngas, pyrolysis oil, and solid char [1,2]. Adaptable to all types of feedstocks, as well as a fitting alternative for sustainability principles in the circular economy, pyrolysis can be a new way to deal with waste management and resource recovery. However, to fully utilize the potential of pyrolysis in the marketplace, engineering challenges lie in the reactor design plus material selection. Pyrolysis reactors need to function at a higher temperature range, generally between 400°C and 1200°C, depending on feedstock type and needed product. In addition, the process environment is often characterised by chemical exhalation of corrosive byproducts such as hydrochloric acid (HCl) generated in the degrading of chlorinated plastics. Operational conditions significantly influence material structures used in reactor constructions in terms of resistance to thermal cycling, scaling, carburization, intergranular corrosion and mechanical degradation i.e. creep or stress rupture [3,4]. Material failure of pyrolysis reactors not only reduces the safety of the process and the efficiency of the work, but it also leads to downtime and damage on a large scale. It undermines the financial sustainability of pyrolysis as a sustainability solution. Therefore, effective implementation of the high- performance alloys is critical for maintaining long-term durability, thermal stability, corrosion resistance, especially in continuous or high-output systems. The study focused on four candidates applied in high-temperature processing industries: Stainless steel 310S, Inconel 625, 253 MA, and AISI 321 (321SS). The properties of these alloys are evaluated based on their significant performance characteristics that consist of their thermal stress, oxidation and corrosion gas resistivity, thermal mechanical strength at high temperature, and compatibility to various pyrolysis feedstocks. This comparative analysis aims to offer practical guidelines for material selection in the construction of pyrolysis reactor and optimization decision making leading to an increase in the life cycle, efficiency, and sustainability of reactor. As well as reporting the materials assessed, the present paper also examined the alloy modification and surface engineering such as element doping and protective coatings as future strategies to customize materials to fit the specific needs of pyrolysis technology. With integration of material sciences and process engineering requires this study to make the contribution of the breakthroughs of strong and sustainable waste to modern energy systems. In order to extract quantitative data on key properties of the alloys, they are examined through their manufacturer datasheets, values from literature and engineering standards ASTM A240, ASTM B443 and EN 10095 [5-7].

II. MATERIALS AND MATHODS

Thus, this study aims to assess the sustainability of selected materials derived from pyrolysis reactor fabrication as well as applying a comparative assessment framework based on significant performances metrics relative to high temperature and corrosive environments. The chosen alloys are Stainless steel 310S, Inconel 625, 253 MA and AISI 321 (321SS), which used the conversions system. The selection and properties of the alloy Four different alloys, which were considered in this study reflect a spectrum of price, mechanical robustness and chemical resistance: Stainless steel 310S is austenitic stainless steel, composed of high chromium and nickel content. It is best known for its good oxidation resistance (up to 1100°C) and moderate mechanical properties. Inconel 625 is a nickel based super alloy having excellent corrosion resistance and particularly in chloride rich and reducing environments. It’s best suited for continuous operations above 1000 °C.

253 MA is an austenitic heat-resistant alloy with very high silicon and rare earth metals added. The individual is specially designed to achieve excellent oxidation resistance and strength in air up to ~ 1150 °C.

AISI 321 (321 SS) is a titanium- based austenitic stainless steel which provides resistance to intergranular corrosion with good application for thermal cycling as well as its use in environments with organic feedstocks.

A. Comparitive Evaluation of Candidate Alloys

The below table 1 explains the selected material analysis and its characteristics based on the properties of the materials [3,5].

TABLE I. COMPARISION OF SELECTED MATERIAL ANALYSIS AND CHARECTERS

Criterion	Stainless Steel 310S	Inconel 625	253 MA	AISI 321 (321 SS)
Max. Service Temp (°C)	~1,040	~982	~1,150	~925
Oxidation Resistance	Excellent (Cr-Ni rich)	Excellent (Ni-CrMo alloy)	Excellent (Si stabilized oxide)	Good
Thermal Shock Resistance	Moderate	High	High	Moderate
Carburization Resistance	Good	Excellent	Good	Moderate
Halide Resistance	Low (sensitive to chlorides)	Excellent (Cl resistant)	Moderate	Low
Sulfidation Resistance	Moderate	Excellent	Good	Moderate
Pitting / Intergranular Corrosion	Improved (low carbon)	Excellent (Mo/Nb stabilized)	High (stabilized)	Good (Ti stabilized)
Yield Strength (MPa)	~205	414–827	~310	~205
Tensile Strength (MPa)	≥520	827–1,103	~650	~515
Creep Resistance	Good up to 800°C	Excellent at high temp	Excellent	Good up to 800°C
Wear Resistance	Moderate	High	High	Moderate
Plastic Pyrolysis Suitability	Suitable for Non halogenated plastics	Excellent (even halogenated plastics)	Good (high heat, less ideal for chlorinated waste)	Suitable for non-halogenated plastics
Biomass / Organic Waste	Good performance	Excellent	Excellent	Good performance
Tar / Fouling Tolerance	Moderate	High	High	Moderate
Cost	Low-moderate	High	Moderate	Low
Best Use	General-purpose; cost-effective reactor zones	Harsh environments; halogenated plastic pyrolysis	High-temp zones; balance performance & cost	Biomass & moderate corrosion zones

With regard to the provided data for the four metals selected Stainless Steel 310S, Inconel 625, 253 MA and AISI 321 [3,4,6]. Of the four 253 MA exhibits the maximum thermal stability withstanding service temperature up to around 1150 °C which is conducive to high temperature reactor zones. Notably, Inconel 625 although was a tad lower in temperature resistance(~982°C), exhibited high overall corrosion resistance especially against halide and sulfer containing environments attributed to its high nickel, molybednium and nobium content. On the mechanical strength side, Inconel 625 has very stable tensile strength up to 1,103 MPa, and possesses excellent creep resistance, therefore it can be considered for long periods of high stress applications.

253 MA exhibited a good mechanical behaviour as well, showing that it had a good blend of tensile strength (about 650 MPa) and oxidation resistance. Stainless Steel 310S and AISI 321 offered moderate strength (about 520 MPa and about 515 MPa, respectively) and are more cost effective, making them suitable for less demanding reactor zones.

III. THERMO-CALC SIMULATION RESULTS

Thermodynamic simulations were conducted using Thermo calc software 2025a educational version with the base of Fe, Ni, Cr, C, Mn and so on. The temperature ranges from 400-1300°C relevant to commercial pyrolysis operations. The aim was to evaluate potential phase transformations and overall thermal stability. Simulations were completed in Thermo Calc Educational version (2025a) using the FEDEMO and NIDEMO databases [8]. For each alloy, essential elements, such as Fe, Cr, and Ni were used according to approximated composition. Simulations modeled each phase's stability across 400°C to 1300°C to examine the formation of FCC, BCC, and sigma phase related to reactor design.

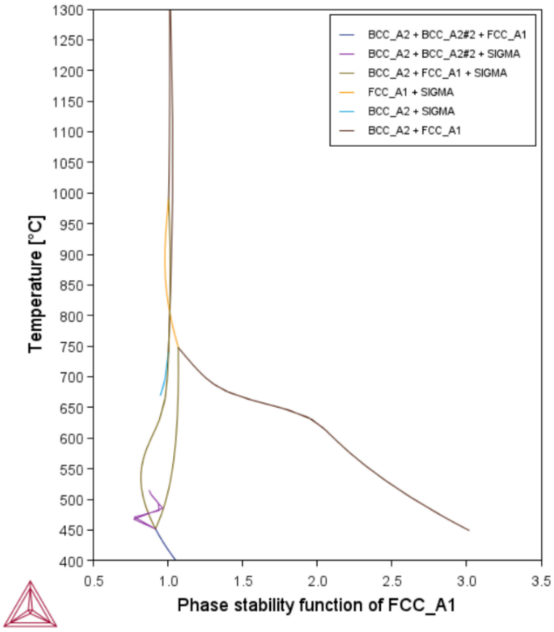


Figure 1 Phase stability of Stainless Steel 301S

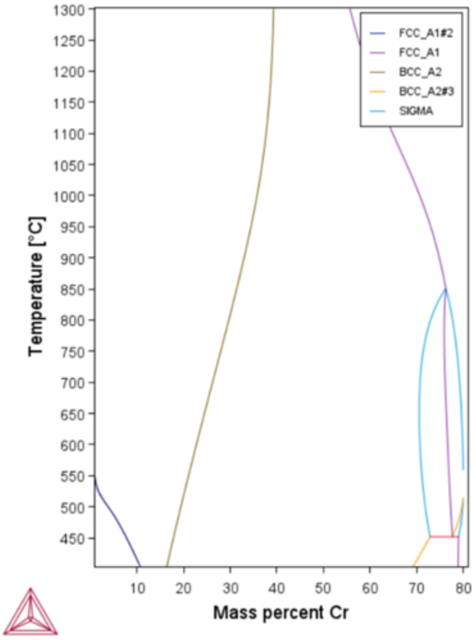


Figure 2 Mass percent of Cr in Inconel

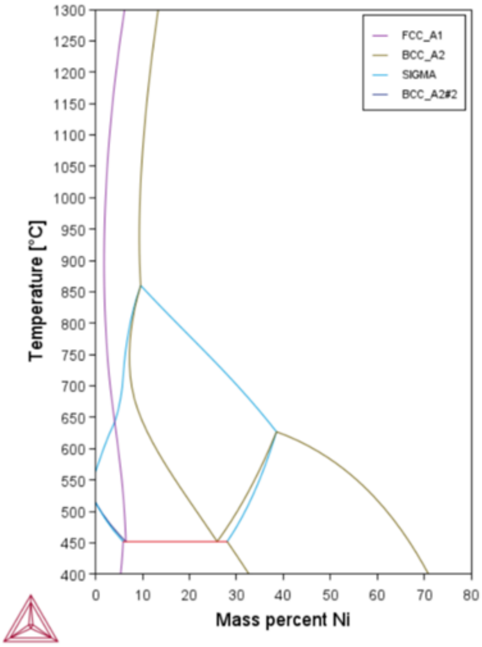
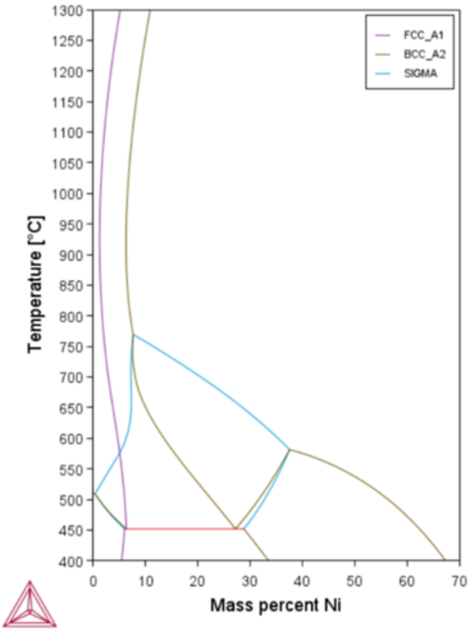


Figure 3 Mass percent Ni in 253 MA



SELECTING A TEMPLATE (HEADING 2)

Figure 4 Mass percent Ni in 321 Stainless steels

Chromium mass percent was plotted for Inconel 625 due to its direct influence on oxidation resistance in figure 2, while nickel content was analyzed for 253 MA and 321 SS due to its impact on phase stability figures 3 and 4.

IV. COMMON OBSERVATION ACROSS ALL DIAGRAMS

Thermo-Calc simulation results of these four alloys contained many similar trends. The austenitic structure, FCC_A1, was predominant in Inconel 625 and stainless steel 310S alloys with higher nickel content, which were more phase stable at higher temperature [4,9]. This austenitic phase provides better mechanical properties at higher temperatures with increased resistance to corrosion that contributes favorably. During the temperature range 700–850 °C [2,6], the sigma (σ) phase occurred in 253 MA and AISI 321, which means a high degree of plasticity and brittleness but also negative impacts on the corrosion properties. Therefore, in 253 MA and AISI 321 alloys, exposure to this intermediate temperature range could have significant effects on structural integrity. The BCC_A2 phase displaying ferritic transformation was substantially more evident in high-chromium or low-nickel alloys observed predominantly in 253 MA and 321 SS in a lower temperature range. If it is not controlled, there is risk of adverse degradation of mechanical behavior due to this phase type transformation. The simulation results indicated that temperature ranges below 850 °C are much more vulnerable to complex transformations including multiphase fields, which should be managed tightly in reactor design to not promote the undesired degradation of the materials.

TABLE II. OBSERVATION FROM THE RESULTS

Feature	**Stainless Steel 301**	**253 MA**	**AISI 321 (321 SS)**	**Inconel 625**
Ni Content	20–25%	~11%	~10%	~58%
Cr Content	24–26%	~21%	~18%	~21%
FCC Stability	Very high	High (at elevated temp)	High	Very high
Sigma Phase Formation	Very low	Moderate risk (700–850°C)	Lower risk	Very low risk
BCC Phase Formation	Minimal	Yes (450–850°C)	Yes	Negligible
High-Temp Resistance	Moderate	High	Moderate	Excellent
Corrosion Resistance	Good	Moderate	Moderate –High	Excellent

V. CONCLUSION

The results of performance analysis of four alloys, Stainless Steel 310S, Inconel 625, 253 MA, and AISI 321 were also conducted, for use in pyrolysis reactors. According to the literature and Thermo-Calc work [1,3,8], the total system performance of the Inconel 625 is ideal owing to its high-temperature and anti-corrosion activity. 253 MA proved to be the second best by exhibiting the highest thermal stability (up to 1150 °C) and mechanical strength, while its risk involved the formation of the sigma phase was moderate. Stainless Steel 310S is a perfect trade-off between price and performance, with a maximum service temperature of 1100 °C. AISI 321 SS works for the lower temperature zone, as it doesn't have endurance above 870 °C; in other words, Inconel 625 SS is used in critical high-temperature reactor zones, Stainless Steel 310 S is used for thermal sections which are cost-effective; and AISI 321 SS is not used, so long as temperature will not exceed 900 °C.

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