RESEARCH ON VARIOUS FERROUS METALS FOR PYRO-OIL REACTOR AS ENVIRONMENTAL DECARBONATIZATION

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Abstract

Pyrolysis technology represents a viable strategy for the conversion of waste into valuable fuels and products, which remains a core tenet of the circular economy. Notably, higher temperatures, corrosive environment, and mechanical stresses warrant careful material selection in constructing reactors in order to ensure operational efficiency and durability. This work presents a comparison of four candidate high-performance steel alloys: Stainless Steel 310S, Inconel 625, 253 MA and AISI 321 (also known as 321 SS) in relation to their applicability for commercial scale pyrolysis reactors. Each alloy has been assessed based on a set of criteria including thermal stability, corrosion resistance, mechanical strength, and suitability for thermal processing of a variety of feedstocks (plastics, biomass, and organic waste). Results suggest that the best alloy, in terms of mechanical strength and resistance to high temperatures and/or chemical degradation, is Inconel 625, making it favourable for a reactor employed in the pyrolysis of plastics and other synthetic waste. A favourable alloy for continuous, high-temperature operation with good oxidation resistance and strength is 253 MA. The cost-effective option for comparative purposes is Stainless Steel 310S, which could find a niche in a variety of applications in pyrolysis. Lastly, an alloy with titanium stabilization, AISI 321 is suitable for reactor processing biomass and organic waste. The importance of materials selection permitting maximum performance while minimizing maintenance costs and impacting the long-term sustainability of pyrolysis technology is an important contribution of this study. Exploration of alloy modification through the addition of elements or surface coating, applicable for developing future pyrolysis technology research, is in line with emerging research and a useful consideration for commercial pyrolysis applications.

Keywords: Metallurgy, steel, properties, applications, testing methods

1. INTRODUCTION

The world has changed managing enormous volumes of plastics, biomass, and municipal solid waste (MSW) has accelerated interest in thermal conversions technologies capable of recovering energy and valuable chemicals from waste streams. Among these technologies, pyrolysis has a thermo-chemicals decomposition processes occurring in the absence of oxygen and has been recognized for its ability to convert organic materials into syngas, pyrolysis oil, and solid char [5, 8]. Its versatility in handling diverse feedstocks and compatibility with circular economic principles makes it a promising solution for sustainable waste management and resources recovery.

However, realizing the full potential of pyrolysis on a commercial scale presents a number of engineering challenges, especially with regard to reactor design and materials selection. Pyrolysis reactors must operate at higher temperatures, typically from 400°C to 1200°C, depending upon the type of feedstock and desired product needs. Moreover, the process enviroinment is usually chemically aggressive with crossive byproducts such as hydrochloric acid (HCL) released during the degradation of chloinated plastics. These operational conditions plays a significant role on demands of the structural materials used in reactors constructions inclusing resistance to thermal cycling, scaling, carburization, intergranular corrosion, and mechanical degradation such as creep or stress rupture [2, 3].

Materilas failure in pyrolyis rectors are not only compromises safety and efficiecy of the processes it also results in costly downtime and maintanence. It weakers the economic viability of pyrolysis as a sustainalble solution. Thus, careful selection of the high-performance alloys is essential to ensure long term durability,, thermal stability and corrosion resistance particularly in continious or high output systems.

This study focoused on four candidates widely used in high temperature processing industries: Stainless steel 310S, Inconel 625, 253 MA and AISI 321 (also called as 321SS). These alloys are assesed based on the critical performance metrics inclusing their charectersitcs such as thermal stress, resistance to oxidation and corrosion gases, mechanical strength at elevated temperatures and adaptability to different pyrolysis feedstocks. The goal of this coparitive analysis is to provide practica guidences for material selections in pyrolyis reactor constructions and design decisions that enhances reactor life span, efficiency and sustainability.

In addition to presentig the materials performed assessments, the article also considered grwing directions the alloy modification and surface engineering such as element doping or protective coatings as future plans to tailor materials to the unique demands of pyrolyis technology. By integrating material sciences with process engineering needs this study to contribute the advancedments of robust nad sustainable waste to energy systems.

The alloys are evaluated using manufacturer datasheets, literature values and engineering standards like ASTM A240, ASTM B443, EN 10095 [4, 6] to extract quantitative data on key properties.

2. MATERIALS AND METHODS

To evaluate the sustainability of selected materials from pyrolysis reactor construction, this study adopts a comparative assessment framework based on key performances criteria related to the high temperature and corrosive environments. The selected alloys are Stainless steel 310S, Inconel 625, 253 MA and AISI 321 (also called as 321SS) choosen based on their conversions system.
The four alloys are considered in this study represenmts a spectrum of cost, mechanical robustness and chemical reistances:

Stainless steel 310S is an austentic stainless steel with high chromium and nickle content. Its is widely known for its good oxidation reistance upto ~ 1100°C and reasonable mechnical properties.

Inconel 625 is a nickle based supper alloy offering execeptional corrosion resistance and it’s particularly in chloride rich and reducing enviroinments. It is best suitable for continious operations above 1000 °C.

253 MA is a austenic het resistant alloy with high silicon and rare earth metals additions. It is specially designed for it own excellent oxidation resistance and strength in air upto ~ 1150 °C.

AISI 321 (321 SS) is a titanium bassed austenic stainless steel which provides resistance to intergranualr corrosion and it is commonly used for thermal cycling applications and enviroinmement with organic feedstocks.

Comparitive evaluation of candidate alloys were selected according reseracher Mohan Kumar [6]. The below table explains the selected material analysis and it’s charectresistics based on the properties of the materials [6, 9].

Table 1 Comparision of the selected materils. [6, 9] .

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-Cr-Mo 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/IG Corrosion	Improved due to low C	Excellent (Mo/Nb stabilized)	High	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	Suitable for non-halogenated plastics	Excellent – even for halogenated plastics	Good – handle 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; cost-effective high-performance balance	Biomass & moderate corrosion zones

Based on the above given data of the four selected metals Stainless Steel 310S, Inconel 625, 253 MA, and AISI 321 [2, 4, 7]. Among all of these four 253 MA shows the highest thermal stability withstanding continious service temperature up to approximately 1150 °C making it particularly well-suited for high temperature reactor zones. Inconel 625 while slightly lower in temperature resistance(~982°C), excelled in overall corrosion resistance especially against halide and sulfer containing enviroinments due to its high nickle, molybednium and nobium content. In terms of mechanical strength, Inconel 625 outperformed all other materials with a tensile strength of up to 1,103 MPa and excellent creep resistance, making it highly reliable for prolonged, high-stress applications. 253 MA also exhibited strong mechanical performance, offering a good balance of strength (~650 MPa tensile strength) and oxidation resistance. Stainless Steel 310S and AISI 321 offered moderate strength (tensile strength ~520 MPa and ~515 MPa, respectively) and are more cost-effective, making them suitable for less demanding reactor zones.

3. RESULT AND DISCUCCION

3.1 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 relevent to commercial prolysis operations. The aim was to evaluate potential phase transformations and over all thermal stability. Simulations were completed in Thermo-Calc Educational version [1]. Campbell F. C, was using the FEDEMO and NIDEMO databases [1]. 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.

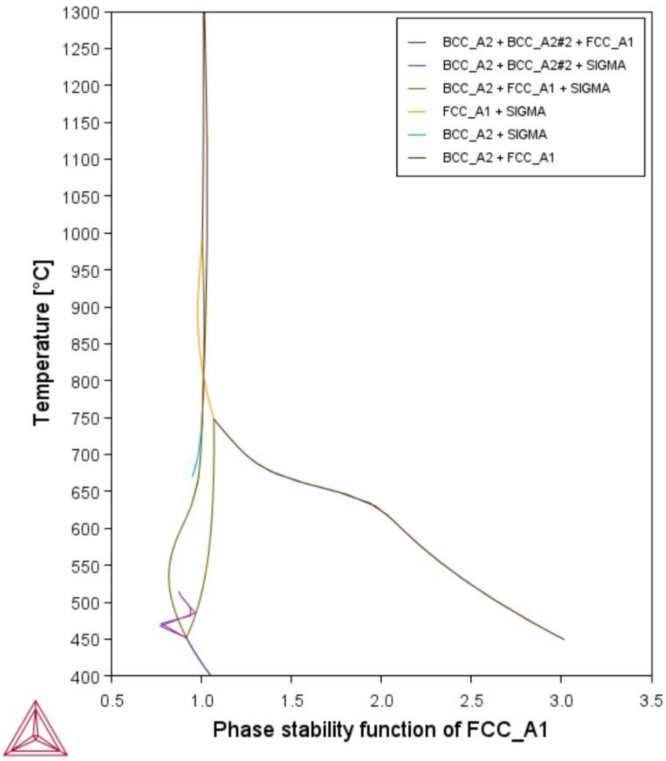

Figure 1 Phase stability of Stainless Steel 301S

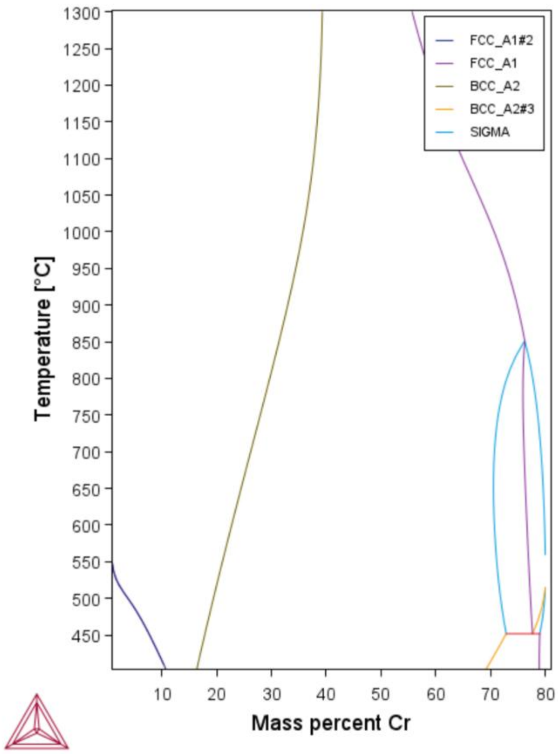

Figure 2 Mass percent of Cr in Inconel 625

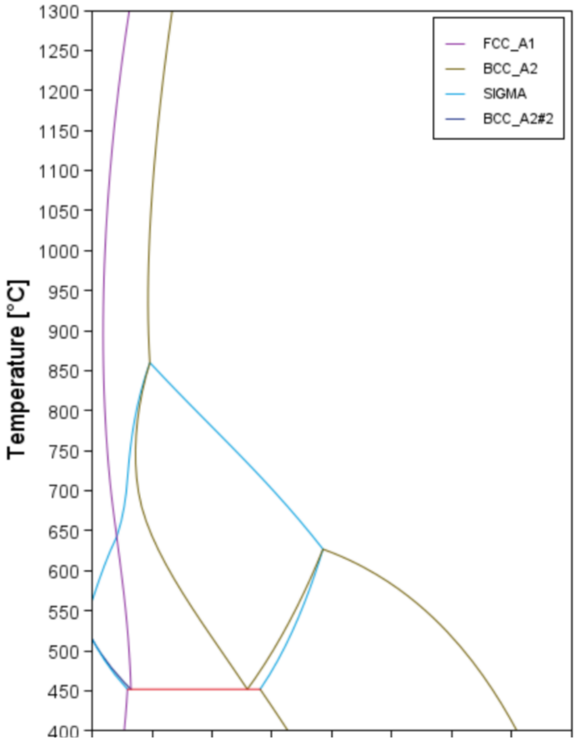

Figure 3 Mass percent Ni in 253 MA

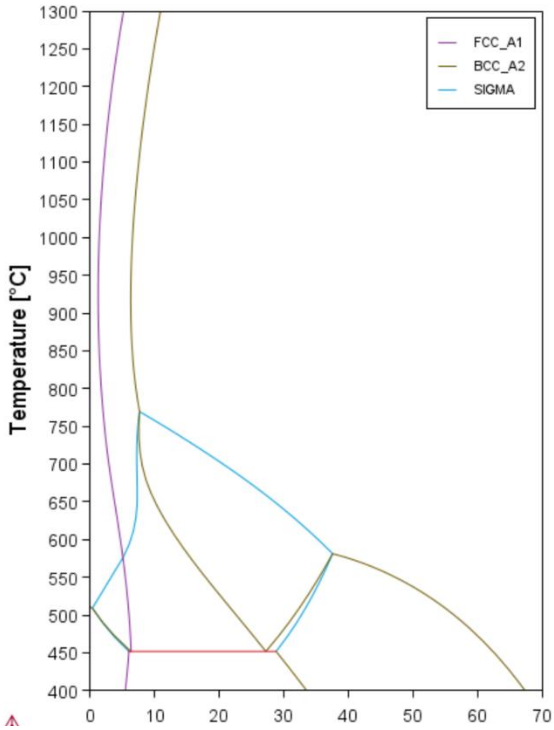

Figure 4 Mass percent Ni in 321 Stainless steels

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.

3.2 Common observation across all diagrams

The simulation results produced by Thermo-Calc for these four alloys exhibited numerous common patterns. The FCC_A1, which represents the austenitic structure, was more dominant in Inconel 625 and Stainless Steel 310S alloys with higher nickel content, reflecting that they were more phase stable at higher temperature [1, 2]. This austenitic phase offers enhanced mechanical performance at elevated temperatures and improved corrosion resistance, which is valuable. The sigma (σ) phase, which indicates plasticity but is brittle and negatively impacts corrosion properties, appeared when the temperature range was 700–850 °C [1, 2]; in 253 MA and AISI 321. Therefore, exposure in this intermediate temperature range could cause structural integrity issues in 253 MA and AISI 321 alloys. The BCC_A2 phase that showed ferritic transformation was much more prominent in high-chromium or low-nickel alloys seen mostly in 253 MA and 321 SS at a lower temperature window. Transformation to this phase type could lead to negative changes in mechanical behavior if not managed. Overall, the simulation results suggested that temperature ranges below 850 °C are much more susceptible to complex transformations, including multiphase fields, which require careful management in reactor design to avoid unwanted degradation of materials.

Table 2 Observation from the results [1, 2].

Feature	**301 S**	**253 MA**	**321 SS**	**Inconel 625**
Ni Content	20-25	~11%	~10%	~58%
Cr Content	24-26	~21%	~18%	~21%

FCC Stability	Very high	High at 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

4. CONCLUSION

This investigation analyzed four alloys—Stainless Steel 310S, Inconel 625, 253 MA, and AISI 321—concerning their performance in pyrolysis reactors. Following literature sources and Thermo-Calc operations, the general performance of Inconel 625 is best because of its high resistance to corrosion and its high-temperature properties. 253 MA is the next best option and demonstrated the highest thermal stability (up to 1150 °C) and mechanical strength despite a moderate risk of sigma phase formation. Stainless Steel 310S offers a balance between cost and performance, and allowed for a maximum service temperature of 1100 °C. AISI 321 SS will only function in lower-temperature zones, due to being limited for endurance above 870 °C. In summary, Inconel 625 SS is suitable for critical high-temperature reactor zones, Stainless Steel 310 S is suitable for cost-effective thermal sections; and AISI 321 SS alloys should not be considered unless the temperature are constrained to less than 900 °C.

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