HIGH PERFORMANCE ALLOY APPLICATIONS IN ADJACENT MARKETS

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EXECUTIVE SUMMARY

This report explores opportunities to leverage research activities funded by the National Energy Technology Laboratory (NETL) Crosscutting High Performance Materials program, in the development of high performance alloys (HPAs) for applications in fossil energy (FE) outside of coal plants, as well as “adjacent”, that is, non-fossil energy (FE) markets. Much of the research sponsored by the High Performance Materials program targets innovations for coal plants, but is also directly translatable to natural gas applications such as natural gas combined cycle (NGCC). An in-depth review of market data and market reports for the HPA applications identified the four most relevant industry segments, accounting for 92.5 percent of the current and predicted HPA usage by volume, globally. Exhibit 1 below indicates the global percentage by volume of the most important market opportunities adjacent to fossil energy.

Exhibit 1- 1 Adjacent Markets for High Performance Alloys

Aerospace	51.8%
Industrial Gas Turbine	27.5%
Industrial and Chemical Processing	7.8%
Automotive	5.4%

Superalloys largely originated in the aerospace, industrial gas turbine and traditional FE market, driven by the respective original equipment manufacturers and government support. End users of superalloys often have foundry subsidiaries or partnerships. Many alloys found in FE applications were previously developed for other applications in adjacent industries. The HPA properties are mature, and their use in those markets is largely saturated and optimized.

In summary, the non-FE superalloy applications are

- Extremely high performance – Only used in limited niche applications
- Expensive – Only extreme performance benefits justify the additional cost
- Mature – Industry stakeholders in adjacent markets are currently not investing heavily in superalloy development

The list of specific alloys used in these industries was compared and correlated with the list of alloys investigated in the NETL High Performance Materials program. Opportunities for technology transfer in the adjacent markets based on the program’s investments exist in:

- Computational materials development, and process and property modeling
- Welding technology improvement; in particular, dissimilar alloy joining
- Characterization of materials properties, performance, and evolution under operating conditions
- Additive manufacturing for improved component performance, functionality, and reliability

This report reviews the potential translational benefits of FE-supported alloy development for broader applications in industries beyond coal-based steam cycle applications.

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ACRONYMS AND ABBREVIATIONS

Al	Aluminum
AM	Additive manufacturing
AUSC	Advanced ultrasupercritical
CMC	Ceramic matrix composite
Co	Cobalt
Cr	Chromium
Cu	Copper
DOE	Department of Energy
FCC	Face-centered cubic
Fe	Iron
FE	Fossil energy
Hf	Hafnium
HPA	High performance alloy
HPT	High pressure turbine
IGT	Industrial gas turbine
LPT	Low pressure turbine
M	Million
MESA	Mission Execution and Strategic Analysis
mm	Millimeter
Mn	Manganese
Mo	Molybdenum
MPa	Megapascal
N_2	Nitrogen
NGCC	Natural gas combined cycle
Nb	Niobium
NETL	National Energy Technology Laboratory
Ni	Nickel
ORNL	Oak Ridge National Laboratory
psi	Pounds per square inch
R&D	Research and development
SA	Superalloy
Si	Silicon
SiC	Silicon carbide
TBC	Thermal barrier coating
Ta	Tantalum
Ti	Titanium
TTP	Time temperature pressure
U.S.	United States
USC	Ultrasupercritical
V	Vanadium
W	Tungsten
°C	Degrees Celsius
°F	Degrees Fahrenheit

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1 INTRODUCTION

High performance alloys (HPAs) are metals that display superior characteristics in high temperature and corrosive environments. Properties include chemical stability and mechanical strength at temperatures up to 70 percent of the melting temperature for prolonged periods. These materials are critical components of extreme environment processes, and are expensive to develop and produce. They enable processes to run at higher temperatures and pressures, improving performance and efficiency. Advanced materials are critical to plant reliability under cyclic operation.

The United States (U.S.) Department of Energy (DOE) has directed significant efforts toward the development of advanced fossil energy (FE) conversion systems and technologies that feature improved efficiency, increased durability, reduced capital investment and maintenance cost complemented by advanced emissions control capabilities. A variety of research, development, and technology transition initiatives are addressing critical challenges, facilitating progress toward these goals. One route to improve the reliability and efficiency of coal-fired power plants is operation at advanced ultrasupercritical (AUSC) steam conditions (760°C/35MPa or 1,400°F/5,000psi), a significant increase of process temperature and pressure from the currently used ultrasupercritical (USC) steam cycle. A limiting factor for the development and deployment of AUSC power plants is the lack of a supply chain for HPAs capable of operating reliably in these extreme process environments. HPAs are approaching the properties needed for AUSC operational environments but use rare and costly alloying elements, employ difficult manufacturing processes, and lack adequate weldability or joining. Availability is also a concern, as these alloys are limited by a proprietary manufacturing and supply chain landscape.

The development and qualification of suitable and affordable HPAs remains a core focus of research and development (R&D) programs supported by DOE. Drivers of these HPA development activities are the National Energy Technology Laboratory (NETL) and Oak Ridge National Laboratory (ORNL), working closely with industry consortia and industry partners in the power plant, turbine, and metals manufacturing community. Because of the high investment in development, understanding opportunities to expand the application of HPAs is valuable. Benefits considered in this analysis are performance advantage at comparable component cost, and cost savings at comparable component performance, to utilize and transfer NETL technology and expertise to relevant non-FE industry partners.

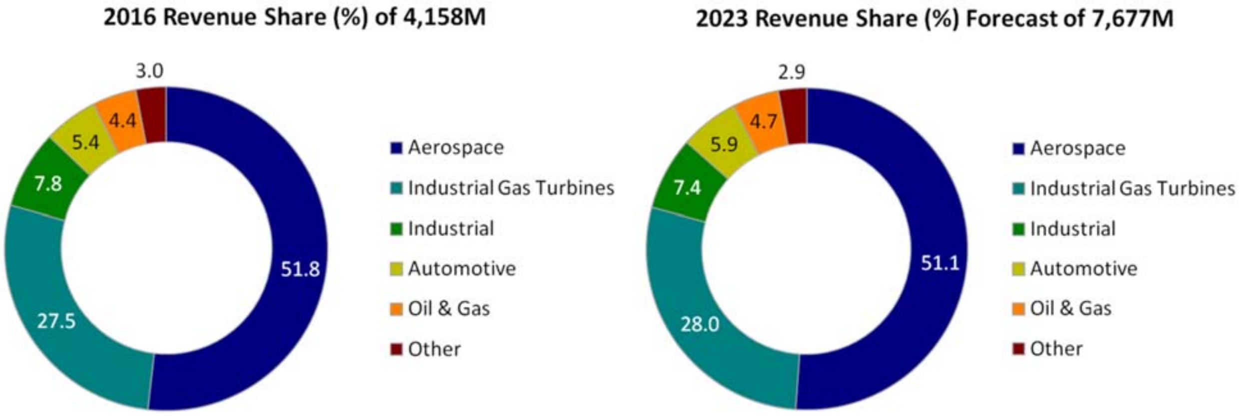
2 ADJACENT MARKETS FOR HIGH PERFORMANCE ALLOYS

2.1 CURRENT AND FUTURE MARKETS FOR HIGH PERFORMANCE ALLOYS

A review of market reports and forecasts for HPAs identified relevant alloy categories and non-FE industrial applications. The global HPA market had $4,158 million (M) revenue in 2016 and is forecast to reach $7,677M by 2023, according to a recent in-depth market research report by Allied Market Research. [1]

Exhibit 2-1 shows the 2016 market revenue share for HPAs and the 2023 market revenue share forecast by application industry segment.

Exhibit 2-1. Global market share for HPA, 2016 and 2023 (forecast) [1]



Aerospace applications represent the majority of demand with 51.8 percent of the total market in 2016 and a projected 51.1 percent of the total market in 2023. The four largest application segments of aerospace, industrial gas turbines (IGTs), industrial and chemical processing and automotive make up 92.5 percent of the current HPA market, and are forecasted to make up 92.4 percent of the 2023 market. [1]

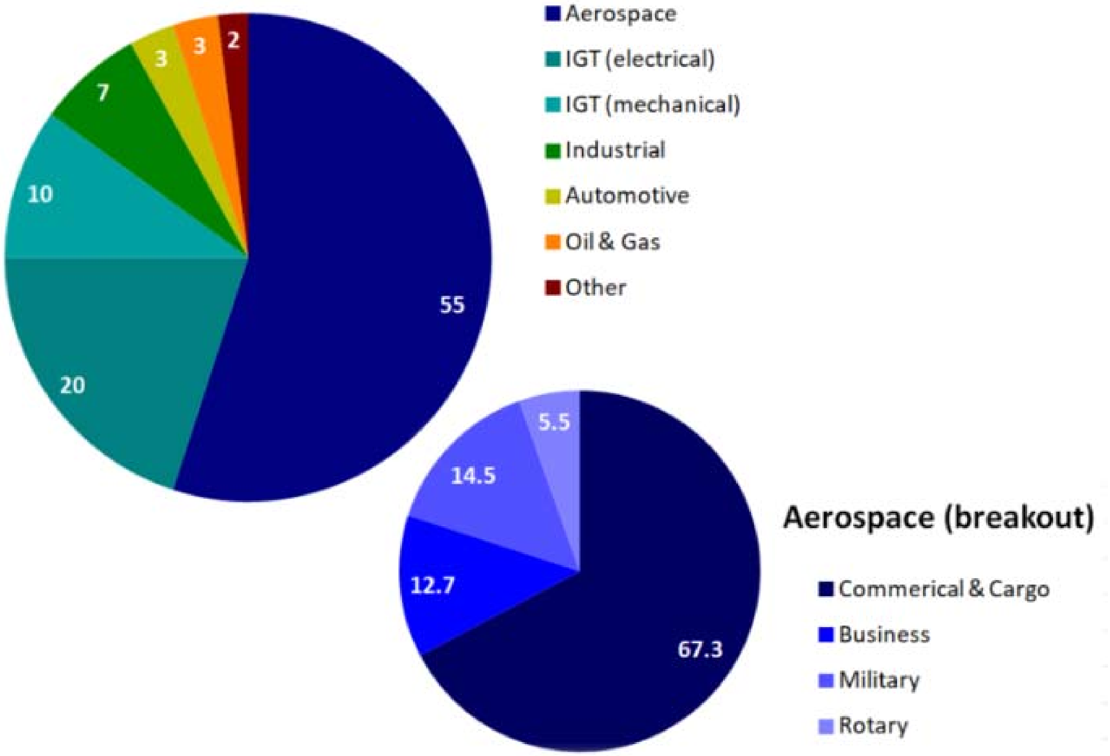
Each of these industry segments has specialized and highly nuanced needs. Material properties are tailored precisely to meet these performance specifications, and go through stringent qualification processes. This application review targets the determination of whether current NETL-relevant alloys have the potential to provide a performance advantage over traditional HPAs used in these industries, or whether certain applications could utilize less expensive alloys with minor compromises on performance parameters to achieve cost savings.

2.2 HIGH PERFORMANCE ALLOYS IN ADJACENT INDUSTRIES

2.2.1 Aerospace

Aerospace applications account for over half of the current and projected global market for HPAs. Exhibit 2-2 shows the estimated HPA use in the commercial and cargo, business, military, and rotary aerospace market subcategories [2]. Turbofan engines account for the vast majority of aerospace HPA applications.

Exhibit 2-2. Superalloy market share by application, 2013



A small portion of HPAs is used for fuselage structural and fastener components, as these applications require lightweight, high strength alloys such as aluminum, titanium, and magnesium. Turbine blades require alloys with high strength at high temperature and under thermal cycling. Resistance to abrasion, erosion, and corrosion under operating conditions is a critical performance parameter for fan blades, turbine blades, and vanes, as well for combustor components.

The aerospace industry uses high strength titanium alloys such as Ti-6Al-4V for intake fan blades or blade edge liners. High strength, creep- and fatigue-resistant nickel-based cast superalloys such as Waspalloy, Hastelloy X, and Nimonic 263 are used for blades and vanes in the aft portion of the high pressure compressor, which have environments that exceed the operating temperature of titanium alloys.

The outer combustor casings are manufactured from Alloy 718 or Waspalloy. The inner combustion liner protects the case from the combustion flame and is usually made from cobalt sheet material such as HS188 or nickel-based superalloy such as Hastelloy X. Recent improvements in the manufacturing process make silicon carbide (SiC)/SiC ceramic matrix composite (CMC) liners an attractive alternative to costly alloy liners.

The high pressure turbine (HPT) has the highest gas temperature in its first stage, approximately 1350–1500°C in modern engines. These temperatures are close to the melting point of nickel superalloys, thus requiring active cooling using internal air channels and thermal barrier coatings (TBC), typically yttrium-stabilized zirconia. The TBC coating is applied over an oxidation protection layer, such as MCrAlY (M: one or more of the elements iron, nickel, and cobalt), a nickel aluminide coating, or a platinum aluminide coating.

The airfoils are cast either as a directional solidified microstructure (with grains alignment parallel to the blade longitudinal axis) or as single crystals, to reduce stress rupture.

The first-stage disk in the HPT is typically made from a powder nickel-based superalloy, isothermally forged to provide optimum strength at the operating temperature.

The blades of the low pressure turbine (LPT) are typically nickel-based superalloy castings (Alloy 718, Waspalloy). The new GEnx and LEAP engines employ lightweight cast γ-titanium aluminide, Ti-48Al-2Nb-2Cr. Exhibit 2-3 outlines the most commonly used alloys in aerospace applications.

Exhibit 2-3. HPAs commonly found in aerospace applications

Alloy	Base Metal	Main Alloying Elements	Unique Properties
Ti alloys	Ti	Al, V, W	High strength, lightweight
Ti-6Al-4V	Ti	Al, V	
403/403Cb	Fe	Cr, Mn, Si	Martensitic 12% Cr steel Higher rupture strength
GTD-450	Fe	Cr, Ni, Mo	Martensitic, precipitation hardened, high Cr, Mo
A286	Fe	Ni, Cr, Ti, Mn	Austenitic, high strength
Hastelloy X **Nimonic 263,618,230**	Ni	Cr, Co, Mo, Ti	High strength, high temperature
Nimonic 105	Ni	Co, Cr, Mo, Al	High strength, 750°C service temperature
Alloy 718	Ni	Cr, Fe, Mo, Nb, Ti	High temperature to 1300°C Most common SA, ingots up to 750mm
Alloy 706	Ni	Fe, Cr, Nb	Less segregation
LC Astroloy **IN 100** **MERL76** **Rene 88 DT** **Rene 95** **Udimet720/ 720 LI**	Ni	Cr, Co, Al, Mo, Nb, W, Ti	Powder metallurgy
IN-713 **IN 100/Rene 100** **Rene 125 Hf**	Ni	Cr, Mo, Al, Ta+Nb, Ti	Cast superalloys Strengthened with W, Mo Improved ductility with >2% Hf

Alloy	Base Metal	Main Alloying Elements	Unique Properties
Rene 41 **Rene 77** **Rene 80** **Rene 80+Hf**	Ni	Cr, Co, Mo, W, Ta, Al	High Cr for corrosion resistance, but lower high temperature strength
IN 738 **GTD-111**	Ni	Cr, Co, Ti, Al	Cast Ni-based superalloys Directionally solidified castings Single crystal, internal cooling
GTD-222	Ni	Cr, Co, Ti, W	Improved creep strength
FSX 414	Co	Cr, Ni, W	Hot corrosion resistance
HA188	Co	Ni, Cr, W, Fe	Oxidation-, hot corrosion-resistance up to 2000°C

2.2.2 Industrial Gas Turbines

The operation principle of IGTs is similar to aerospace turbofan engines, but the energy output is used to drive electrical generators or provide mechanical energy. Aerospace engine companies drove in-house alloy development since the late 1940s, and are also involved in IGT and FE turbine technologies. Though the technology is fundamentally similar to the aerospace segment, system weight considerations are not as critical. Corrosion and erosion properties gain importance due to the variety of fuel sources with more corrosive composition. IGTs are deployed in a variety of land-based and maritime applications, the latter requiring additional protection against corrosion.

IGTs are manufactured in a broad range of sizes, with small IGTs comparable to small aerospace turbines and large IGTs with meter-sized blades and vanes. Stress and fatigue resilience considerations gain importance in large IGTs, and combustor technology requires modifications to allow operation with IGT fuel sources. Material requirements for IGT components mirror those used in aerospace turbines. IGTs compressors and turbines generally have more stages than aerospace engines, and have airfoils, blades, vanes, disks, rotors, shafts, and casings of significantly larger size. The material property considerations are almost identical to the aerospace applications.

Since many IGT original equipment manufacturers also manufacture aerospace turbine engines, the historical alloy developments have proved beneficial to both market segments. TBCs and oxidation/chemical corrosion protection for components in high temperature sections of the turbine and ceramic matrix composites for combustor and HPT liners push properties further for use in IGTs. Corrosion resistance and protective coatings play an important role in maritime IGT use. Exhibit 2-4 outlines commonly used alloys and their properties.

Exhibit 2-4. HPAs commonly used in IGT applications

Alloy	Base Metal	Main Alloying Elements	Microstructure	Unique Properties
Ti alloys	Ti	Al, V, W		High strength, lightweight
Ti-6Al-4V	Ti	Al, V		
403/403Cb	Fe	Cr, Mn, Si		Martensitic 12% Cr steel Higher rupture strength
GTD-450	Fe	Cr, Ni, Mo		Martensitic, precipitation hardened, high Cr, Mo
A286	Fe	Ni, Cr, Ti, Mn		Austenitic, high strength
Hastelloy X **Nimonic 263, 618, 230**	Ni	Cr, Co, Mo, Ti		High strength, high temperature
Nimonic 105	Ni	Co, Cr, Mo, Al		High strength, 750°C service temperature
Alloy 718	Ni	Cr, Fe, Mo, Nb, Ti	Gamma prime	High temperature to 1300°C Most common SA, ingots up to 750mm
Alloy 706	Ni	Fe, Cr, Nb		Less segregation
LC Astroloy **IN 100** **MERL76** **Rene 88 DT** **Rene 95** **Udimet720 / 720 LI**	Ni	Cr, Co, Al, Mo, Nb, W, Ti		Powder metallurgy
IN-713 **IN 100 / Rene 100** **Rene 125 Hf**	Ni	Cr, Mo, Al, Ta+Nb, Ti		Cast superalloys Strengthened with W, Mo Improved ductility with >2% Hf
Rene 41 **Rene 77** **Rene 80** **Rene 80+Hf**	Ni	Cr, Co, Mo, W, Ta, Al	Cast, directional solidification, single crystal	High Cr for corrosion resistance, but lower high temperature strength
IN 738 **GTD-111**	Ni	Cr, Co, Ti, Al	Gamma prime	Cast Ni-based superalloys Directionally solidified castings Single crystal, internal cooling
GTD-222	Ni	Cr, Co, Ti, W	Gamma prime	Improved creep strength
FSX 414	Co	Cr, Ni, W		Hot corrosion resistance
HA188	Co	Ni, Cr, W, Fe	Solution heat treated	Oxidation-, hot corrosion-resistance up to 2000°C

2.2.3 Industrial and Chemical Processing

Industrial applications include gas compressors, chemical and pharmaceutical processing equipment, thermal processing equipment, chemical processing equipment, water and wastewater processing, and food processing. Chemical processing includes a broad range of products such as insecticides and pharmaceuticals, as well as industrial chemical and petrochemical manufacturing. These applications are typically faced with highly corrosive environments, and components can be prone to pitting. A primary application for HPAs in chemical processing is in fracturing tubes of petrochemical plants. Specialty alloys are selected for high temperature, high pressure and, corrosive ambient environments such as oxidation, sulfidization, carburization.

Potential opportunities derive from high temperature, high alloy stainless steels with superior corrosion resistance. High chromium, molybdenum, and nitrogen contents in steels react with oxygen in the atmosphere to form a protective scale at the surface. The efficacy of this process is influenced by amount of the alloying element, temperature and fluctuations, and time in service. [3] Nickel as an alloying element controls thermal expansion and contraction during temperature fluctuations to reduce spalling of the protective scale. Other atmosphere conditions such as CO_2, water vapor, and chlorides must be considered in chemical processing applications. These conditions will change the formation and stability of the protective scale.

Weldability and methods for joining are also especially important for industrial processing applications such as wastewater removal. These production processes affect surface quality, which will have a direct impact on performance. Any non-uniformity in the surface can exacerbate pitting and other corrosive effects. [4] Similar alloys will perform differently under these extreme conditions. For example, stainless steel alloy 304 has three different classes—304, 304H, and 304L. 304L is ideal for welding applications because its comparatively low carbon content performs better against pitting and corrosion in the heat-affected zones associated with welding. [5]

High performance steels are sufficient for many industrial processing applications, but in some cases, nickel-based superalloys are also necessary. Commonly used nickel alloys are Monel 400, Inconel 625, Incoloy 825, and Hastelloy X. Exhibit 2-5 shows the unique properties of alloys commonly used in industrial processing applications.

Exhibit 2-5. Alloys commonly used in industrial and chemical processing applications

Alloy	Base Metal	Main Alloying Elements	Unique Properties
304L	Fe	Cr, Ni, Mn	Resistant to atmospheric corrosion, reducing and oxidizing, as well as acidic conditions Excellent strength and weldability Low cost option
316L	Fe	Cr, Ni, Mn	Resistant to atmospheric corrosion, reducing and oxidizing, as well as acidic conditions Excellent strength and weldability
Duplex Alloy 2205	Fe	Cr, Ni, Mn, N	High strength High impact toughness Resistant to corrosion and pitting at high chloride levels
Monel 400	Ni	Co, Cu, Mn, Fe	High strength and toughness over wide temperature range Excellent corrosion resistance

Alloy	Base Metal	Main Alloying Elements	Unique Properties
Inconel 625	Ni	Cr, Mo, Fe, Nb	High strength Excellent fabricability including joining Corrosion resistance
Incoloy 825	Ni	Fe, Cr, Mo	Exceptional corrosion resistance Resistance to cracking
Hastelloy X	Ni	Cr, Fe, Mo, Co	Strong oxidation resistance in prolonged service temperatures up to 870°C Exceptional forming and welding High ductility

2.2.4 Automotive

Automotive applications mirror the alloy performance requirements in the aerospace industry, such as high temperature reliability, high strength, and corrosion resistance. Cost considerations limit the use of HPAs to small volume applications like turbochargers, performance disk brakes, turbine housings, and combustion area liners. A major driver for the use of advanced alloys in the automotive industry is weight reduction using aluminum and titanium alloys.

Potential opportunities for alloys in the automotive industry are process improvements for hot-forgeable nickel-based superalloys and wrought large volume parts and nickel alloys for electric vehicle batteries and supercapacitors. Rare earth elements find applications in next generation magnets for electric motors and high frequency inductors. Exhibit 2-6 outlines alloys commonly used in automotive applications.

Exhibit 2-6. Alloys commonly used in automotive applications

Alloy	Base Metal	Main Alloying Elements	Unique Properties
Nitronic 50	Fe	Cr, Ni, Mn, Mo	Superior corrosion resistance for price
Haynes 282	Ni	Cr, Co, Mo, Ti, Al, Fe	High temperature strength Easily fabricated

2.3 CURRENT INDUSTRIAL RESEARCH

A review of recent patents and publications from top companies in each industry is useful to gauge the level of interest and needs within the aerospace, IGT, chemical processing and automotive markets. These searches indicated that there is not a high demand for even higher performance alloys. Companies in these markets have optimized their materials and processes to meet their unique needs. Primary focuses now include composite materials, coatings, and lightweight alternatives such as titanium and magnesium.

While private industry may not be focusing resources on the development of HPAs, they are still widely used, and are forecasted to be a growing market. Research performed at NETL as well as other national research laboratories can support life prediction of parts in service, process modeling, and advance repair techniques. These types of research activities are especially time-consuming, costly, and require advanced technical skill, but they provide invaluable data for any entity using HPAs.

3 CROSSCUTTING RESEARCH

The current Crosscutting High Performance Alloy portfolio focuses on three families of alloys (nickel-based superalloys, high performance austenitic stainless steels, and ferritic steels), and can be grouped into four primary research themes (IGT, aerospace, chemical processing, and automotive). Certain projects within the portfolio focus on specific alloys that are already in use in adjacent markets, and could have direct application to those industries. A review of the current and recently completed projects provides understanding of where this research may be applied outside of FE.

3.1 NICKEL-BASED SUPERALLOYS

Nickel-based HPAs have been specifically developed for the most demanding applications in aerospace, IGT, and FE systems. Designed for superior strength in extreme temperature operation, creep, fatigue, and corrosion resistance, these alloys withstand process environments that cause less sophisticated alloys to degrade rapidly.

Nickel superalloys have a face-centered cubic (FCC) nickel matrix, with chromium or aluminum alloying elements for surface stabilization. [6] Extensive developmental efforts address the understanding and optimization of microstructure evolution in the alloy and component manufacturing processes and the impact of exposure of such components to extreme temperature, pressure, oxidizing, corrosive, and abrasive operating conditions encountered in turbofan engines, IGTs, and FE combustion environments.

Despite the property and performance advantages that nickel-based superalloys offer, their limited joinability and weldability poses a barrier to widespread implementation in FE systems and adjacent industries. The expensive alloying elements and difficult, proprietary manufacturing processes (powder metallurgy, casting, directional solidification, single crystal investment casting, thermal post-processing, hot isostatic processing, etc.) currently restrict the use of these specialty alloys to applications that grant unique operational benefits. For example, AUSC operating conditions, enabled by the use of superalloys, yield 47.5 percent net efficiency, as compared to 34 percent net efficiency achieved by traditional coal fired power plants. [7]

Crosscutting research at NETL of nickel-based superalloys primarily focuses on generating databases of mechanical behavior over prolonged periods at high temperature and pressure, and modeling additive manufacturing process parameters' influence over resulting microstructure. Exhibit 3-1 outlines the research projects currently funded under the Crosscutting portfolio, and their application to adjacent markets.

Exhibit 3-1. FE High Performance Materials program research relating to nickel-based superalloys

Alloy	Research Objective	IGT	Aerospace	Chemical Processing	Automotive
Hastelloy X	Optimized AM process on microstructure, mechanical properties	high strength, medium temperature	high strength, medium temperature	petrochemical cracking	
263 **Ni-20Cr-20Co-5Mo-Al-Ti**	Understanding of microstructural underpinnings of creep strength and failure, predict life with confidence, data to feed model	high strength, medium temperature	high strength, medium temperature		
Haynes 282 **Ni-20Cr-10Co-8Mo-Al-Ti**	Process parameter influence on microstructure, mechanical behavior	gas turbine applications in combustion turbine and exhaust, nozzle components	gas turbine engine		turbochargers, seals, high temperature springs
	Model of degradation during cyclic use over time				
	Process parameter influence on microstructure, mechanical behavior				
	Microstructure and properties of parts used in service				
	Improved weld of high gamma prime superalloy with stainless steels				
	Forging, casting, characterization				
	Understanding of mechanical behavior under service conditions				
	Microstructural characterization of large cast valve body, large forging, effects of grain size				
	Understanding of microstructural underpinnings of creep strength and failure, predict life with confidence, data to feed model				
	Design guidelines for dynamic operation of the boiler that result in better material fatigue conditions				
Alloy 617 **Ni-22Cr-9Mo-10Co**	Long-term mechanical behavior of weldment	high temperature strength and oxidation resistance			
Inconel 718	Understanding of mechanical behavior under service conditions	high temperature, high strength and oxidation resistance	high temperature, high strength and oxidation resistance		

These projects will yield valuable understanding of microstructural properties of nickel-based superalloys, and create direct links between microstructure and performance. These data sets can be used to inform process modeling, and develop more efficient manufacturing processes, such as large cast parts and additive manufacturing (AM). Because nickel-based superalloys are particularly difficult and expensive to forge and machine, improved processes are critically important to FE, as well as aerospace and IGT markets.

In general, HPAs within the NETL High Performance Materials portfolio have potential applications in adjacent industries, although no immediate insertion or replacement opportunities have percolated from the analysis of the adjacent market needs. The main translational benefits emerge in application areas that reach beyond specific alloys.

3.2 HIGH PERFORMANCE AUSTENITIC STAINLESS STEELS

Austenitic stainless steels are iron-based alloys that are known for their corrosion resistance and formability and typically contain high amounts of chromium and nickel. Though the overwhelming majority of austenitic steels are not considered superalloys, advanced stainless steel alloys such as the Super 304H, 316H, and Sanicro 25 alloys are designed to enhance their mechanical properties and strengthen creep- and fatigue resistance compared to traditional stainless steels. Austenitic-based superalloys rely on an FCC microstructure with solid solution hardening, and precipitates tailored according to desired properties. [3] These alloys benefit either from a series of hot and cold working, or by precipitation hardening.

The High Performance Materials program at NETL continues to push the properties of these materials and assess their performance, because they are significantly less expensive than traditional superalloys. Joining and welding of these alloys enables cost-effective system construction by selective use of HPAs in regions with extreme operational conditions while using less expensive alloys for system components with moderate temperature and pressure conditions. Exhibit 3-2 outlines the current and recent research projects addressing austenitic steels in the Crosscutting program at NETL.

Exhibit 3-2. FE High Performance Materials program research relating to austenitic stainless steels

Alloy	Research Objective	IGT	Aerospace	Chemical Processing	Automotive
Super 304H Fe-18Cr-8Ni-Nb-N-Cu	Understanding of mechanical behavior under service conditions	low temperature components, piping, fittings, flanges	low temperature components	chemical and petchem processing, pressure vessels, tanks, heat exchangers, piping systems, flanges, fittings, valves	
	Database to link microstructural features to long term behaviors of secondary phases, inclusions, decompositions/evolution, service performance TTP				
	Understanding of microstructural underpinnings of creep strength and failure, predict life with confidence, data to feed model				
316H	Database to link microstructural features to long-term behaviors of secondary phases, inclusions, decompositions/evolution, service performance TTP	low temperature components, piping, fittings, flanges	low temperature components	chemical and petchem processing	
Sanicro 25 Fe-22Cr-25Ni-Nb-N-Cu	Understanding of mechanical behavior under service conditions	close to HA188			
	Understanding of microstructural underpinnings of creep strength and failure, predict life with confidence, data to feed model				

Upon completion, these projects will build understanding of alloy behavior under specific extreme applications, as well as provide linkages of specific microstructures with long-term behaviors. These data sets can be used to train models, and support life prediction of components, based on real service conditions. Because these alloys are widely used in adjacent markets, broader understanding of component behavior and life prediction would be valuable to those industries as well.

3.3 FERRITIC STEELS

Ferritic steels generally do not fall into category of superalloys. They have good corrosion resistance, but do not maintain adequate strength at high temperatures over prolonged periods. [3] However, they remain an important part of current research, especially relating to extending properties, and as part of dissimilar weld joints. They are considerably less expensive than other steels, because they do not require expensive alloying elements. Improvements in the mechanical behavior of weld joints under extreme temperature and pressure can dramatically reduce the cost of parts, as well as repairs. Testing of the mechanical property evolution of ferritic steels under exposure to FE operating conditions revealed the potential of using these alloys in FE applications. Ferritics allow reliable joining and welding to other alloys, which enables selective use in demanding service environments, both in FE applications as well as adjacent industries. By improving processes and modeling behaviors, NETL research can be directly applicable to adjacent industries that are already using these materials, such as in IGT and aerospace. Exhibit 3-3 outlines current research in ferritic steels in the NETL portfolio.

Exhibit 3-3. FE High Performance Materials program research relating to ferritic steels

Alloy	Research Objective	IGT	Aerospace	Chemical Processing	Automotive
9-12%Cr Ferritics	Lowered cost of critical components by strategic use of superalloy	Turbine discs			
	Impurities effect on degradation				
	Understanding corrosion behavior as a result of shot peening, supporting model of boiler conditions				
Grade 91/92	Understanding of mechanical behavior under service conditions	piping, tubing, flanges	piping, tubing, flanges		
	Database to link microstructural features to long-term behaviors of secondary phases, inclusions, decompositions/evolution, service performance TTP				
	Creep fatigue data, enabling accurate lifetime prediction of components subjected to flexible operation				
	Solid state joining alternative to welding, enabling enhanced creep strength of ferritic steels				
	Functionally graded weld joint				
	Model for variability of creep strength as a function of microstructure and service conditions				
	Understanding corrosion behavior as a result of shot peening, supporting model of boiler conditions				
SAVE12AD	Understanding of mechanical behavior under service conditions	piping, tubing, flanges	piping, tubing, flanges		

These research objectives contribute primarily to lowering the cost of components and repairs. By improving the performance of dissimilar welds under extreme conditions, the most costly alloys can be used only where they are the most critical. Similarly, the ability to predict quality and performance of parts made by AM will increase adoption of manufacturing and fabrication using this advanced technique.

4 HPA OPPORTUNITIES FROM CURRENT PORTFOLIO

The current Crosscutting High Performance Alloy project portfolio addresses needs specific to FE applications using alloys that are in use in adjacent markets. Opportunities to support the adjacent markets based on NETL competencies are within process modeling, welding, characterization, and AM.

4.1 PROCESS MODELING

Reliability of key components of the power plant made from advanced alloys is of prime importance. Many utilities are motivated to extend the life of turbine-generator components and reduce costs while maintaining safe operating conditions. The methods used to manufacture and assemble components can have significant impact on their performance over use in service. HPAs are particularly difficult and expensive to forge and machine, improved processes are critically important to FE, as well as aerospace and IGT markets. During operation, these materials undergo different metallurgical degradation processes due to complex thermomechanical loadings and corrosion in aggressive environments. Life assessment of these components is essential beginning from their initial manufacture, through repair work, and replacement of the degraded parts. Validated software tools can be used by power plant engineers and component designers to increase the accuracy of predicting the life of high temperature components in long-term service subject to significant cycling operation, and improve the designs of new high temperature components for either new power plants or for use in existing power plants.

Computational materials, and process and systems modeling are widely employed by HPA manufacturers and users to build understanding of the relationship between process parameters and resulting material or component properties. However, these models are extremely costly and time-consuming to develop and train. Characterizing the microstructure and properties of parts exposed in the field for significant amounts of time helps to determine the evolution of key lifetime damage parameters, and validate lifetime prediction models based on operation parameters. These models are especially valuable in designing materials and components for creep resistance. A creep modeling toolkit, developed to predict the long-term creep performance of materials for base alloys and weldments in FE systems could be applied for use in adjacent markets, in any application that may see a wide range of thermal and mechanical conditions. Precipitation modeling using thermodynamic databases will provide fundamental quantities that will be used as inputs for upscaling strategies/methods. Models that are sensitive to the unique microstructure of each alloy can capture the different creep mechanisms and predict the variability of the creep strength as a function of the microstructure and service conditions.

One benefit of process modeling could be accelerated alloy development, particularly to enhance the properties of ferritic and stainless steels to approximate HPA performance properties at significantly lower cost. For example, prediction of creep life near 100,000 hours for P91 ferritic steels with microstructure inputs is used in the design and validation of AUSC boilers, resulting in components with increased reliability using fewer resources for development. This work can continue to include a wider range of operating conditions, applied stresses and longer time spent in service. The models developed can provide guidelines to designing a microstructure with improved creep properties.

4.2 WELDING

Welded components and repairs enable fossil-fired power plants to be more economical and technically viable and thus to play their necessary and important role in maintaining the balance of the United States energy portfolio. For example, the manufacturing of mixed material rotors for steam turbines for AUSC applications requires the welding of Haynes 282 to steel, resulting in modular construction of rotors using smaller forgings of superalloys only in locations where needed. By optimizing the use of superalloys in selective areas of the rotor, the rotor will withstand significantly higher temperatures, while conserving costly materials.

However, standard welding of components often results in compromised mechanical properties of materials used, limiting performance of the weld joint. Specifically, this can mean alteration of carefully designed microstructures, resulting in significant reduction of creep strength in the weld region, and reversing the design intent of creep resistant alloys. Additionally, a lack of reliable predictive modeling capabilities limits applications to effectively innovate welding technologies for creep resistance in design and service.

Integrating materials welding science with advanced experimental and characterization techniques and computational materials modeling will advance the development of usable solutions to these issues. Mechanical data and measured properties collected over long periods in service conditions can validate and refine models of weld performance. Improved welding techniques will enable advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency, operational flexibility, and lower capital and operating costs.

4.3 CHARACTERIZATION

Designing and evaluating accelerated tests to determine the relationship between microstructure and performance of HPA components under service conditions is a critically important element of advanced material development. Novel process metrology systems can generate large sets of data to monitor system and component performance, improve component reliability, and predict maintenance cycles. These datasets can be used to train and validate models and life assessment tools, which can dramatically reduce the time and expense associated with material innovation, as well as aids in predictive and scheduled maintenance. A traditional development cycle can typically take up to two decades to complete, whereas model-aided improvements can be achieved in as little as two to five years. However, the databases are expensive and time consuming to build, and material properties and sample history must be carefully tracked over long periods. Links between microstructural changes and accumulation of damage can establish in-service performance, and predictable behavior within operational environments.

Carefully designed experiments can also be used to collect data describing compounding mechanisms.

Detailed characterization of component chemistry, mechanical properties, microstructural features, and oxide scale thickness measurements provide essential data and information required to develop and/or validate existing life assessment tools used for predicting component remaining life. These are important in FE applications, considering the average age of existing coal-fired power plants is over 40 years old, but are also vital to ensuring the long-term safety and reliability of other applications, especially those that operate under cyclic conditions such as aerospace and automotive.

4.4 ADDITIVE MANUFACTURING

AM technologies are an important part of advanced manufacturing, design and flexibility. However, there are several key challenges currently relating to AM processes for HPAs. The internal microstructures, part-level physical properties, and performance under load are all dependent on the manufacturing process, including variation within different AM technologies. The large number of AM processing parameters available means that AM manufacturing R&D can be very slow and expensive, if done without the support of process and materials modeling tools. Conceptual knowledge of the effects of feedstock properties, deposition rates, thermal history, cooling rates, phase transformation, defect formation, and residual stress is still in an early phase, and the framework to accurately predict the part properties is not well established. Moreover, understanding microstructural and performance differences of components produced using different additive technologies, such as electron beam melting, laser metal deposition, and selective laser melting. AM modeling will enable the various interactions and parameter sensitivities to be investigated independently from each other; however, extensive microstructure characterization and mechanical testing must be performed to determine the relationships among the deposition process, microstructure, and mechanical properties. A machine learning approach can also support rapid qualification of high temperature structural alloys with increased AM process reliability, enabling design flexibility for full utilization of AM.

Correlating the process parameters used during a given AM process, with bulk material properties of the components produced is critical to the development of predictive tools for design of AM components. Physics-based models describing all steps of the AM process allow the determination of the alloy microstructure and mechanical properties based on the AM process parameters. Developing quantitative technical understanding of the process-microstructure relationships for AM technologies helps to determine the optimum AM technology for scaling, and demonstrates the capability of AM technology to produce components with certain morphologies and compositions where needed, to increase structural life in severe service conditions. Integrated physics-based material and damage modeling into an AM control system to produce and test materials engineered for an aggressive environment, extreme high temperature and very long operation time regimes.

Using AM to create alloy composition gradients can also improve component functionality, reliability, thermal-mechanical fatigue resistance, and overall weld integrity. Graded materials produced by AM reduce the coefficient of thermal expansion mismatch and sharp compositional transition associated with dissimilar metal welds. This is not only a key technology advancement toward the development of next generation AUSC plants, but also the life extension of current fleets that have been through frequent cycling.

5 CONCLUSIONS

5.1 APPROACHES TO GROW THE HPA MARKET

The High Performance Materials program at NETL has enabled the development of specifically tailored alloys that uniquely suit the needs of AUSC applications. These demanding applications are extremely high temperature and pressure, and can involve large fluctuations in environments. However, there remain high barriers to expansion into the aerospace, IGT, chemical processing and automotive markets, because those markets have independently developed alloys to suit their own needs.

The opportunity for NETL to expand its research program into the aerospace, IGT, chemical processing, or automotive markets lies in cost reduction, property enhancements, and fabrication flexibility of existing alloys. Cost reduction of components requiring HPAs is likely to come primarily from computational modeling, especially process modeling, and dissimilar welded component parts. Effective modeling will require the extensive mechanical testing and characterization, especially under service conditions for prolonged periods of time. Property enhancements can be pursued using modeling as well, in addition to expanded research in the use of coatings for thermal and corrosion protection. Fabrication flexibility will include expanded use of AM, as well as improved welding techniques. All of these research areas will yield results that are directly applicable to the adjacent markets reviewed.

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