DEVELOPMENT OF SUPERALLOYS FOR NEXT GENERATION COAL-FIRED POWER SYSTEMS: CHALLENGES AND OPPORTUNITIES

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ABSTRACT

The Federal Government's 7-point agenda has as high priority, power generation to provide stable electricity supply for all sectors of the Nigerian community. Inability to manage properly the oil and gas sector, problems in the Niger delta and vagaries in the oil and gas industry are serious signs of domestic energy crisis which if not well managed will spill into very deep social crisis in the near future. There is the mooted option of nuclear powered electricity generation which probably might be the best and cheapest for the country if issues like waste disposal and security are solved. This option though feasible needs long term planning because a huge chunk of our nuclear scientists and engineers have migrated to foreign lands. With this scenario, it is expedient for the country to look at combinations of power generation using fossil fuels, coal, and renewable energies. An important area which has not experienced any growth is coal powered electricity generation partly because of the mess from coal combustion, the obnoxious effluents, inefficiency of operation and the new found oil fields. While not oblivious of the effect of coal- powered plants contribution to global warming and acid rain, the US coal- fired power plants currently supply more than half that country's energy needs while the Directorate of Energy (DOE) is pursuing clean coal initiative (CCPI), Future Gen and Vision 21 which are all programmes aimed at getting to near zero the carbon emissions in coal power generation. Nigeria needs to tap into this area of clean coal initiative. One of the major challenges in development of clean coal technology is in the area of materials technology for the development of boiler/steam turbine and Integrated Gasification Combined Cycle (IGCC) systems. For example, as the most critical component in the construction of boiler systems, the superheater tubes have to undergo the most severe service conditions and must meet stringent requirements with respect to fireside *coal-ash corrosion/erosion*, steamside *oxidation and spallation*, along with *creep strength*, *thermal fatigue strength,* and *weldability.* This paper presents the challenges of developing novel superalloys for these systems and the methods being advanced to overcome the problems.

Keywords: clean -coal -technology; superalloys-development; challenges;opportunities

INTRODUCTION

The use of coal for power generation has been totally abandoned after the discovery of oil in Nigeria but interestingly in the United States of America which has one of the largest reserves of oil in the world, coal is an important resource for electric power production and serves as a foundation of the nation's power supply. Coal currently fuels power plants that supply ***more than half*** the nation's electricity, with about 90 percent of all coal consumed being used for electricity production! A primary reason the power supply in the U.S. is so affordable is because of the availability of low-cost coal as a fuel source. The strength and security of the U.S. economy is closely linked to the availability, reliability, and cost of electric power and that can be said of any nation. Since 1970, real gross domestic product in the U.S. and electricity generation have been clearly linked[1]. Since economic growth is linked to reliable and affordable electric power, the importance of finding a steady energy source for power generation cannot be overflogged especially with the Vision 20:2020 in mind. A renewed use of domestic coal resources, albeit following after CCPI will play a significant role in satisfying the energy needs of Nigeria also gaining from cheaper overheads. While we keep working towards a NZE in the use of coal for power generation, it is important not to close shop especially as we can work towards reduction in obnoxious effluents.

Superalloys play an important part in the coal powered electricity generating plants as they ensure fluid transport within the boiler/turbine systems. A *superalloy* is a metallic alloy which can be used at high temperatures, often in excess of 0.7 of the absolute melting temperature[2]. Creep and oxidation resistance are the prime design criteria. Nickel based superalloys have solutes with a total concentration which is typically less than 10 atomic percent. The vital test comes in how to further increase the strength using other solutes to create a two-phase equilibrium structure to enable high temperature performance. This paper presents the challenges and opportunities in the making of new generation superalloys.

OPPORTUNITIES

Three ways coal can be used to produce electricity are coal-fired boiler/turbine, Integrated Gasification Combined Cycle (IGCC) systems, and fuel cells using hydrogen from coal, or coal syngas, as fuel stock. Although fuel cells have received lots of attention, from long-term and short-term points of view, boiler/turbine system and IGCC are still the most important and viable solutions to produce electricity from coal. Increasing the temperature and pressure in a boiler/steam turbine and IGCC systems will increase the efficiency in power generation, and also reduce the amount of fossil fuel consumed and the emissions generated. As an example, some technical targets of Clean Coal Power Initiative (CCPI) are shown in Table 1.

Table 1: Performance Targets of CCPI[3]

	Reference Plant*	**2010**	**2020**
Plant Efficiency (HHV)	40%	45-50%	50-60%
Steam Pressure (MPa)	30	34.5	38.5
Steam Temperature (°C)	593	675	760

*Reference plant has performance typical of today's technology

A major challenge in the development of boiler/steam turbine and IGCC systems has been in the area of materials technology. For example, as the most critical component in the construction of boiler systems, the superheater tubes have to undergo the most severe service conditions and must meet stringent requirements with respect to fireside ***coal-ash***

corrosion/erosion, steamside ***oxidation and spallation***, along with ***creep strength***, ***thermal fatigue strength,*** and ***weldability.***

Since 2001 and as part of DOE's Coal Power Program (CCP), National Energy Technology Laboratory (NETL) has launched a research program of "Development of Advanced Materials for Ultrasupercritical (USC) Boiler Systems", to identify and develop the materials for next generation ultrasupercritical plants. During phase I of the program, Inconel 740, a Ni-Cr-Co superalloy developed by Special Metals Corp. (SMC), Huntington, WV,USA was identified as the best candidate of superheater tubing materials. In addition Inconel 740 can also be used in IGCC systems as tubing materials. Current Inconel 740 is able to provide guaranteed 100,000 hrs life at 700°C in coal-ash corrosion environment. However, since the long-term goal of CCP is to increase steam temperature to 760°C by 2020, it is necessary to increase the temperature capability of Inconel 740 to meet the requirements of next generation USC and IGCC systems. This is the current research going on in this area of superalloys for boiler tubings.

The essential solutes in nickel-Al-Ti based superalloys are aluminium and titanium, with a total concentration which is typically less than 10 atomic percent. This generates a two-phase equilibrium microstructure, consisting of gamma (γ) and gamma-prime (γ'). It is the γ' which is largely responsible for the elevated-temperature strength of the material and its incredible resistance to creep deformation. The amount of γ' depends on the chemical composition and temperature, as illustrated in the ternary phase diagrams(Fig.1).

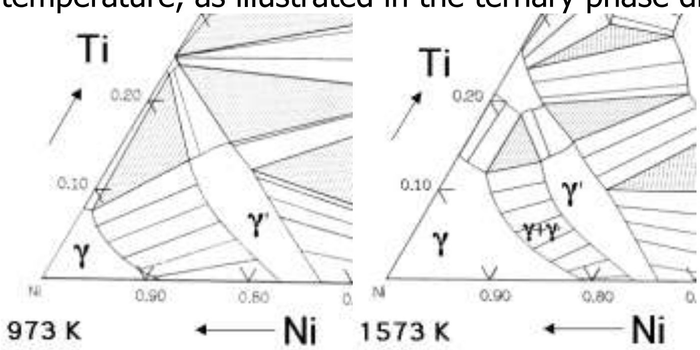


Fig.1: Ternary Phase diagrams for Ni-Al-Ti phase diagram[2]

The Ni-Al-Ti ternary phase diagrams show the γ and γ' phase field. For a given chemical composition, the fraction of γ' decreases as the temperature is increased. This phenomenon is used in order to dissolve the γ' at a sufficiently high temperature (*a solution treatment*) followed by ageing at a lower temperature in order to generate a uniform and fine dispersion of strengthening precipitates.

Fig.2 shows how the strength is at first insensitive to temperature but at higher temperatures, strength decreases. When greater strength is required at lower temperatures, alloys can be strengthened using another phase known as γ''. This phase occurs in nickel superalloys with significant additions of niobium (Inconel 718) or vanadium; the composition of the γ'' is then Ni_3Nb or Ni_3V.

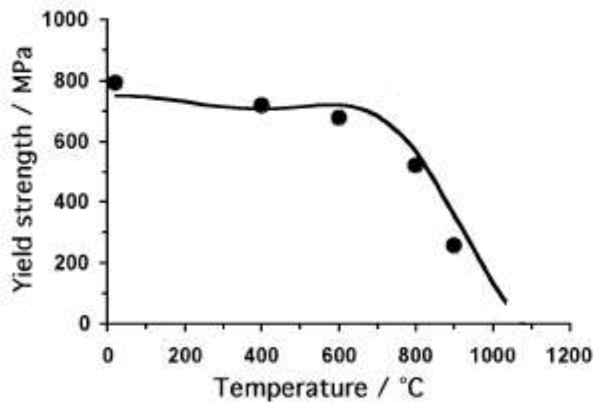
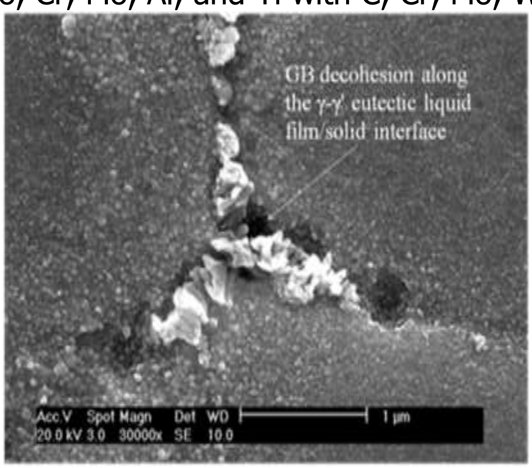


Fig.2: Yield strength response to temperature for most Ni-Al-Ti super alloys[2]

Inconel 718 however has been replaced by Inconel 740 which has an additional carbide former Cobalt. New generation of Nickel based superalloys have compositions consisting of Co, Cr, Mo, Al, and Ti with C, Cr, Mo, W, C, Nb, Ta, Ti and Hf being carbide formers.



a

Fig.3: **Micrographs showing microfissures in (a) as weld condition PM RR1000 alloy (30000x** [4]

With the aim of developing new alloys emphasis need to be laid on controlling the γ' phase and maintaining high creep strength at high temperatures.

Inconel 740, a Ni-Cr-Co superalloy has been utilized for superheater tubing materials in boiler/turbine systems and as tubing materials in IGCC systems. Current Inconel 740 is able to provide guaranteed 100,000 hrs life at 700°C in coal-ash corrosion environment.

However, to increase the temperature capability of Inconel 740 to meet the requirements of next generation USC and IGCC systems, it is important to design for creep resistant at 760^0C. New alloys need to be developed based on thermodynamic and kinetic modeling of other metallurgical factors[3]. The balancing act has to be made in:

1. modifying of the gamma prime formation elements; aluminum, titanium, and niobium to achieve 15% or slightly higher gamma prime contents at 760°C in order to improve the creep resistance is necessary;

2. elimination of eta phase formation and retarding detrimental G-phase formation at 760°C through modification of niobium and silicon contents to improve alloy structural stability;
3. modification of the aluminum/titanium ratio to reduce the growth rate of gamma prime; and
4. keeping chromium contents the same in order to achieve same or improved corrosion resistance. [3]

CHALLENGES

However, it has been observed that at high temperatures, γ' constitutional liquation causes a deleterious effect on strength at thermomechanical affected zone(TMAZ) in many superalloys[5]Precipitation hardened nickel base superalloys that contain substantial amount of Al and Ti (>3wt.%), have been considered very difficult to weld due to its high susceptibility to (Heat affected zone(HAZ) cracking during welding and post weld heat treatment by strain age cracking [6]. Cracking during welding of nickel base super alloys has been attributed mostly to large shrinkage stress occurring as a result of rapid precipitation of γ' particles during cooling from welding temperature [7].

However, it is known generally that weld cracking results from competition between mechanical driving force for cracking (stress/strain generation) and the material's intrinsic resistance to cracking. It has been discovered that liquation which could occur by different mechanisms, is the primary cause of low heat affected zone (HAZ) crack resistance in most austenitic alloys including precipitation hardened Ni base superalloys [8]. The combined effect of thermally induced welding strain and very low ductility in the alloy due to localized melting at grain boundaries results in HAZ liquation cracking. HAZ or TMAZ liquation is known to occur either by non-equilibrium interface melting below an alloy's solidus or by equilibrium supersolidus melting. Subsolidus HAZ liquation which commonly occurs by constitutional liquation of second phase particles is generally considered more detrimental to crack resistance in that it extends the effective melting range of an alloy and also influences the nature of supersolidus melting by pre-establishing non-equilibrium film at a lower temperature which changes the reaction kinetics during subsequent heating [4].

This phenomenon which was first proposed by Pepe and Savage [9] and has been observed by different investigators in various alloy system [10–12], occurs by a eutectic-type reaction between a second phase particle and the matrix producing a nonequilibrium solute rich film at the particle/matrix interface. Research work has also shown that fully austenitic alloys that contain Nb and/or Ti can be highly susceptible to HAZ/TMAZ liquation cracking due to the formation of Nb and/or Ti rich low melting intergranular liquids [20]. It has also been reported recently by Qian and Lippold [13] that degradation in weldability due to grain boundary liquation in IN 718 resulting primarily from dissolution of Ni_3Nb δ-phase and the associated Nb enrichment of grain boundary has occurred. Constitutional liquation of carbides, borides and sulfides has been reasonably well discussed in other superalloy weldments [8,9,12].

Constitutional liquation of MC carbides, and coarse γ' precipitate was observed to have contributed to the TMAZ liquation and its attendant microfissuring in RR1000 superalloy system a recently PM developed superalloy towards the drive in improving gas turbine engine efficiency in modern aircraft engines and power generation system through the increase of Turbine Inlet Temperature (TIT)[3,4].

The above results, alongside with the fact that Al and Ti (especially Ti, which also segregate into liquid in nickel base alloy) are melting point depressants, suggest that apart from the rapid precipitation effect of γ' phase on TMAZ microfissuring, these γ' elements could also be contributing to high TMAZ microfissuring susceptibility in γ' precipitation-hardened alloys like RR1000 in other ways.

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