NIGERIAN INSTITUTE OF INDUSTRIAL ENGINEERS

2011 INTERNATIONAL CONFERENCE

THEME: Infrastructural Development for Industrialization: Challenges and Prospects

DATE: August 4 - 6, 2011.

VENUE**:** CONFERENCE CENTRE, UNIVERSITY OF IBADAN, IBADAN, NIGERIA.

N.I.I.E. 2011 Conference Proceedings

PREFACE

The theme of this year's Conference; Infrastructural Development for Industrialization: Challenges and Prospects is apt. We are all witnesses to the weakening and bleeding of the economy due to lack of supporting infrastructure. Added to this is low productivity. Improved productivity is necessary to establish a "comfortable" STANDARD OF LIVING for ALL. There is also no doubt that Industrialization would remain a pipe dream in our circumstances; except we begin to do 'things differently'.

The response to the Call for Papers for the Conference was fairly good. Several papers (30) were received and referred. A good number of submitted papers needed changes which could be classified as "major". Only the accepted papers and corrected papers (21) were selected for the Conference Proceedings. As part of the review process, papers were reviewed by at least two referees.

During preparations for the Conference, the Interim President, Professor A. F Akinbinu was called to eternal rest. We appreciate and applaud his leadership. May his gentle soul rest in peace. Amen.

We would like to thank various persons who have contributed to the preparation of this proceeding, book of abstracts as well as organization of the Conference. Professor D. E Osifo deserves special mention; being the engine that propelled the organization of the conference through several advisories.

We also thank all authors, and wish everyone a successful Conference.

Professor A. E Oluleye
Chairman, Technical Committee

Dr. O. G Akanbi
Secretary, Interim EXCO

August 4, 2011

NIIE 2011 INTERNATIONAL CONFERENCE PROGRAMME

Date: Friday 05 August 2011

Time: 11.30 AM – 1.00 PM

Co-Chairs: Professor Nick Damachi / Professor Godwin Ovuworie

Session 1

Date: Friday 05 August 2011
Time: 2.00 – 4.00 PM

Co-Chairs: Professor Festus Olorunniwo / Engr. Sunny Etok

Session 2

Friday 05 August 2011 2.00 – 4.00 PM

Co-Chairs: Dr. Christian Bolu / Dr. Sociis Okolie

Session 3

COAL-FIRED POWER SYSTEMS: OPPORTUNITIES AND CHALLENGES IN THE DEVELOPMENT OF SUPERALLOYS FOR BOILER SYSTEMS

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ABSTRACT

Coal fired power systems are still integral part of energy generation in many countries. The fact that this scenario will remain for quite sometime has accentuated the pursuit of clean coal initiatives (CCPI) aimed at getting to near zero(NZE)the carbon emissions in coal power generation.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. 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; opportunities; challenges, micro fissuring

I. INTRODUCTION

The use of coal for power generation has been totally abandoned for gas powered systems and nuclear generation in some countries. However, it is still an important source of power generation in many countries including China, USA,Germany, Russia, United Kingdom and Canada[1-5]. Taking the USA as an example, it has one of the largest reserves of oil in the world and coal currently fuels power plants that supply more than half the nation's electricity, with about 90percent of all coal consumed being used for electricity production[6]! Russia presently uses coal powered plants that supply more than 29% of all its power needs[7]. The primary reason for the attractiveness 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[6]. Since economic growth is linked to reliable and affordable electric power, the importance of finding a steady energy source for power generation cannot be overemphasised. A renewed use of domestic coal resources, following after CCPI will play a significant role in satisfying energy needs 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 high 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[8]. 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.

II. 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 longterm 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. This option is being pursued in different countries [6,7]. Though the Russian pursuit is slow because of financial constraints, the USA effort is in full steam. Combining this with electrostatic precipitators and DeNOx and DeSOx systems will result in high reduction of obnoxious effluents and higher performance efficiency[7]. As an example, some technical targets of Clean Coal Power Initiative (CCPI) based on increasing steam temperature and pressure are shown in Table 1.

Table 1: Performance Targets of CCPI [7,9]

	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 super heater tubes have to undergo the most severe service conditions and must meet stringent requirements with respect to fireside coal-ash corrosion/erosion, steamside oxidation anspallation, 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 longterm 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).

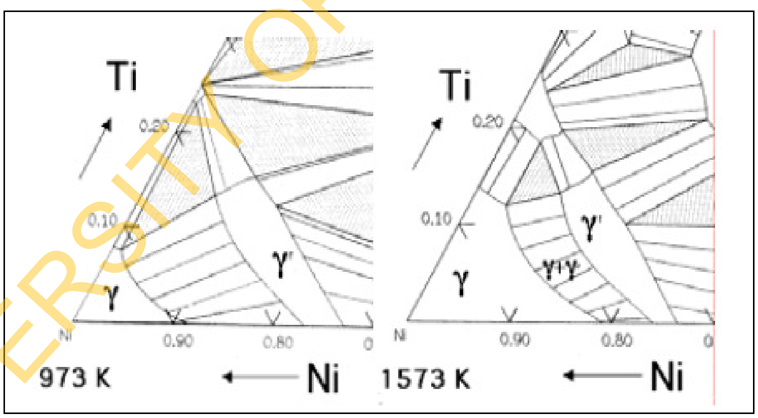

Fig.1: Ternary Phase diagrams for Ni-Al-Ti phase diagram [8]

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.

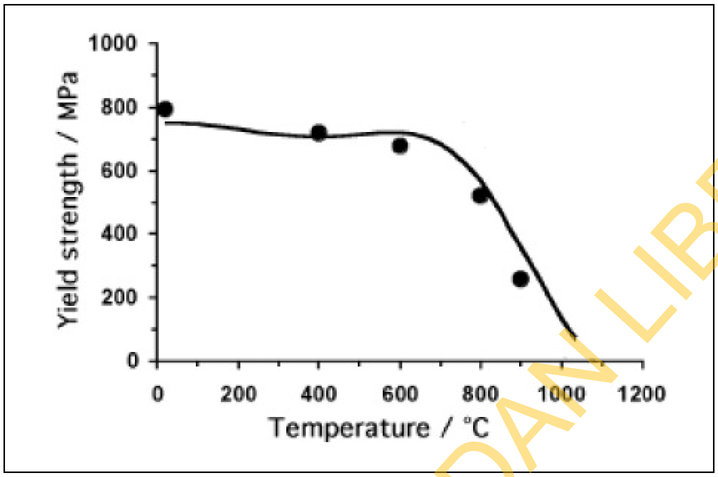

Fig.2: Yield strength response to temperature for most Ni-Al-Ti super alloys[8]

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, Nb, Ta, Ti and Hf being carbide formers.

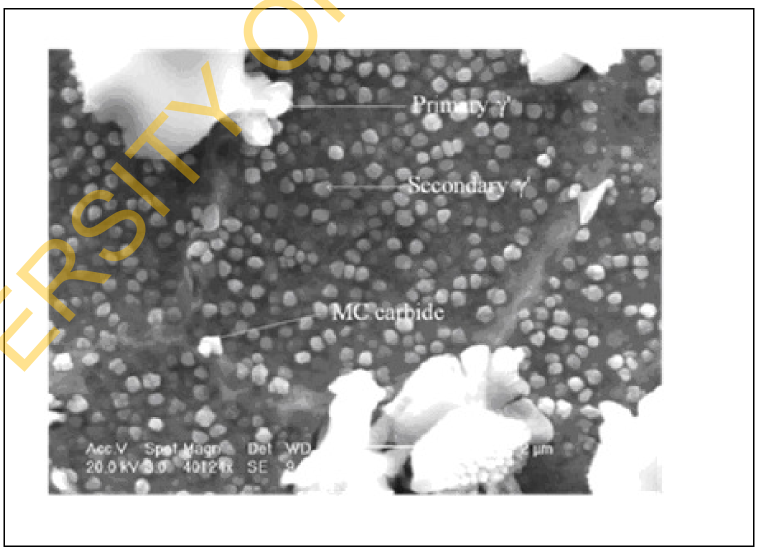

Fig.3: SEM micrograph of γ' and MC carbide in solution heat treated PM RR1000[10]

With the aim of developing new alloys, emphasis need 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 resistance at 760C. New alloys need to be developed based on thermodynamic and kinetic modeling of other metallurgical factors [9]. A balancing act has to be made in:

1. Modifying of the gamma prime formation elements; aluminum, titanium, and niobium to achieve higher gamma prime contents at 760°C in order to improve the creep resistance;
2. Elimination of eta phase formation and retarding detrimental γ-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 which will be useful for weldability; and
4. Keeping chromium contents the same in order to maintain the good corrosion resistance.[9]

III. 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[11]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 [12]. Cracking during welding of nickel based 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 [13]. 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 [14]. 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 [15]. This phenomenon which was first proposed by Pepe and Savage [15] and has been observed by different investigators in various alloy system [16–18], 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 [18]. It has also been reported by Qian and Lippold [19] that degradation in weldability due to grain boundary liquation in Inconel 718 resulting primarily from dissolution of Ni3Nb 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 [14,15,18]. Constitutional liquation of metal arbides(MC), and coarse γ' precipitate was observed to have contributed to the TMAZ liquation and its attendant microfissuring in Rolls Royce(RR)1000 superalloy system, a recently Powder Metallurgy(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)[10,11]. Fig.3 shows the microstructure of the RR1000 alloy showing the primary and secondary γ' phases and metal carbide constituents. 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.

IV. PROBABLE SOLUTION TO TMAZ MICROFISSURING

It is well known that imposed strain on metastable solids can thermodynamically drive the system towards equilibrium [20]. Fundamentally, this occurs through the atomic diffusion and this is affected by the magnitude and direction of the externally imposed strain[21, 22]. In a study of vacancy assisted atomic diffusion, Cowern et al [22] developed a relationship between activation energy per unit strain, Q, and diffusion coefficients under strain, D(strain), and without strain, D(relax), expressed in equation 1, where s is the strain (negative for compression, positive for tension), k is a constant and T the absolute temperature. This equation implies a direct dependence of the activation energy. Thus, the higher the straining, the more the activation energy and the faster the diffusion.

$$D(strained) = D(relaxed)\exp\left(\frac{-Qs}{kT}\right) \qquad (1)$$

Barker and Purdy [23] also developed an equation for the initial migration velocity required for a metastable liquid to rapidly solidify prior to cooling (equation 2), where D_L is the solute diffusivity in the liquid phase, ΔC is the concentration difference across the liquid film at the start of the migration process, $C_{L,T}$ and $C_{S,T}$ are the equilibrium solute concentrations in the liquid and solid phases respectively, at the solidifying interface

$$v = \frac{D_L\,(\Delta C)}{(C_{L,T} - C_{S,T})\delta} \qquad (2)$$

Rapid isothermal re-solidification of metastable liquid prior to cooling at high temperature has been reported variously by these researchers[21,22,23] to occur in fusion welds of various alloy systems due to (i) back diffusion of solute atoms from the liquid phase, and (ii) liquid film migration (LFM) [23, 24]. Resistance to liquation cracking through LFM has also been observed in various fusion welded nickel alloys based on other rapid solidification criteria [14,15,16]. However, the migration extent is still small, thus the production of crack free weld is limited in fusion welding. However, one thing is gained here that rapid isothermal solidification can be enhanced by application of sufficient amount of strain to bypass liquation in the superalloys. This is the focus of many researches now[25].

IV. CONCLUSION

While the challenges of production of alloys capable of withstanding supercritical (SP) temperatures are being surmounted by new nickel based superalloy designs, there remains the challenge of integrity of weldments at high temperatures due to susceptibility to TMAZ microfissuring. This is not insurmountable because the ability to suppress formation of liquation of the γ' precipitates and metal carbides which lead to microffisuring can be done by application of strain immediately after welding to induce a rapid isothermal solidification that does not give chance for liquation of MC's and γ' precipitates.

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