INNOVATION THROUGH COLLABORATION

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Keywords: Superalloys, Gas Turbines, Collaborative R&D

Abstract

The history of superalloys and their enabling role in aircraft propulsion has been a remarkable saga of technical innovation and collaboration in a never ending quest for improved performance and economy. This has been achieved in an environment of fierce competition between Original Equipment Manufacturers (OEM's) and between their material suppliers. Through the years, notable collaborative activities have occurred involving companies, government laboratories and agencies and universities. The industrial and political environment and its influence on collaboration have evolved from the inception of the technology in WW II through the cold war era to the current era with the spread of technology throughout the world. This paper reviews this history through a modern perspective and uses examples to point to the future of collaborative innovation.

Introduction

The conception of age-hardened nickel-chromium alloys is attributed to Merica in the US and Chevenard in France in the late 1920's, but a strong commercial need for the materials did not exist at that time. The real start of the superalloy age began in the UK with the Whittle gas turbine engine. Sir Frank Whittle, shown with his demonstration WU engine in Figure 1, realized that the stainless steel blades that he initially employed were not sufficiently durable to sustain practical flight missions.

Figure 1. Sir Frank Whittle with a bench scale model of his gas turbine engine (Google Images).

In 1940 Whittle wrote to Leonard Pfeil, Research Director at the Mond Nickel Company (later Inco), requesting that he develop a superior alloy meeting 800°C tensile and creep requirements. Pfeil improved the creep strength of an existing Ni-Cr alloy by adding sufficient Al and Ti to enable γ' formation. He thereby created the first superalloy, later designated NIMONIC® alloy 80 [1, 2]. This alloy was used in Whittle's second flying engine in 1942.

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The Whittle engine and the Gloster Meteor aircraft it flew on did not win the war for the Allied Forces, but they sparked the incredible co-development of superalloys and aircraft turbine technology for military and later commercial aircraft. The early history of superalloy development is described in detail by Betteridge [3] and Sims [4].

The WW II era was a period when technology was shared freely between companies and especially between the US and UK. A duplicate of the Whittle W.1X engine was delivered to the GE plant in Lynn, Massachusetts where it was further developed into the GE I-A engine that flew on the Bell P-59 in 1942 [5]. Pioneering alloy developers such as Clarence Bieber, Gunter Moehling, Rudy Thielemann as well as Leonard Pfeil and his co-workers developed many of the iconic superalloys using largely empirical methods. In an interesting (and rare) paper, presented to the Philadelphia ASM chapter, Bieber describes his innovative alloy development techniques [6].

This open era changed in the late 1940's as the world transitioned to a Cold War mentality. Military aircraft performance continued to drive superalloy technology which developed rapidly in the US, UK, France and Russia. Much of the development in the US was sponsored or inspired by the Department of Defense (DOD) and later National Aeronautics & Space Administration (NASA), both of which built extensive research facilities. International Nickel Ltd. also built large research centers in the US at Sterling Forest, New York and in the UK in Birmingham. Inco's goal was to develop markets for nickel, and in the process, broadly shared technology. With a need to understand the basic science of superalloys, universities began to make important contributions. The work of Decker and Freeman at University of Michigan that demonstrated the value of B and Zr as grain boundary strengtheners is an example [7]. The Seven Springs conference came into being in 1968 as an industry forum to discuss phase stability in superalloys [8]. This was the "golden age" of superalloy technology innovation. All of the major alloy paradigms and process innovations germinated or were adopted between 1950 and 1970. These include vacuum melting, remelting, powder atomization, directional solidification, isothermal processing, mechanical alloying, electron beam welding, coating, internal cooling and even the additive manufacturing concept.

In this period, more formal collaborations were developed, often led by US DOD or NASA and aimed at furthering aircraft performance, but occasionally dealing with issues such as raw material shortages. In this pre-internet world, intellectual property (IP) security was primarily a matter of controlling the movement of people and paper. DOD and NASA projects had various levels of security, but control via ITAR was relatively straight forward (but not leak-proof!). Technical papers by industry technologists were common as companies endeavored to publicize their developments and government technical reports were relatively

accessible. A strong collegial environment developed among technologists in the industry despite the fact that they worked for competing companies. A large number of patents were filed during this era, and with rapid adoption of new technology at the time, there was the expectation that by the time they had expired, technology would have moved on. In this time computer technology was in its infancy and process sensing and data collection was almost non-existent. The transaction between supplier and purchaser was based entirely on testing a product to verify that it met specification.

The transition to the current state was gradual and it had many facets. Some obvious ones are the rise and eventual dominance of commercial aviation as a consumer for new engine technology. This introduced a strong cost saving mentality to an industry that previously was primarily motivated by performance. Another factor was the maturation of the technology, as the melting point of nickel defined a tangible limit. The end of the cold war and globalization of the aircraft industry and its suppliers also had an influence. Economic nationalism on the one hand and proliferation of offsets and sponsored low cost suppliers created a tension that did not exist previously. During this transition many of the corporate research labs such as Inco and Climax were down-sized or closed, thus eliminating key facilitators of collaborative efforts. Research at Air Force Research Lab (AFRL), NASA, and the Defense Advanced Research Projects Agency (DARPA) shifted from superalloys to “advanced materials” and university research dependent on NSF funding followed this trend. Chet Sims addressed this issue in his invited paper at Seven Springs in 1988 [9].

Another powerful driver of cultural change was the computer and computer enabled technology. Now, vast amounts of data could be collected, stored, analyzed and instantly transmitted to collaborators, customers or competitors anywhere in the world. Heavy investments by DARPA and DOD agencies in process modeling began to bear fruit as computer memory and speed made modeling of complex systems practical. With the maturation of technology, the focus became more and more on process control, resulting in highly controlled fixed practices that have become the foundation of Integrated Computational Materials Engineering (ICME). Concern in the US about proliferation of technology briefly relaxed with the end of the cold war only to strongly re-emerge after Sept 11, 2001 in the guise of preventing proliferation to so-called rogue states and terrorist organizations. Computer security measures implemented to combat industrial technology espionage have become a significant constraint to the flow of information and to industrial collaboration.

All of these factors, acting synergistically, have combined to change the nature of technical collaboration. The progressive decline in the number of technical papers presented by industry representatives as prime authors at this conference is a direct result of this changing environment. Whether it is because the new technical developments are considered not to be of sufficient academic value, or engineers are too busy to communicate or there is fear of internal IP leakage or ITAR violations, all have their influence. But that does not mean that collaboration has ceased, nor does it mean that it is no longer relevant to the goals of the industry. Collaborations now occur in different, more constrained, ways and the results may not be reported in the open literature. The following discussion is based on some recent examples that show how collaboration is occurring and how it can

be enhanced. The examples are by no means exhaustive; they were selected to illustrate different forms of successful collaboration.

Examples

A new supply-chain paradigm – Intra-company Collaboration

Precision Castparts Corporation (PCC) was founded in Portland in 1949 as the Oregon Saw Chain Company. Its small steel investment casting foundry was spun off as PCC in 1957. Its General Manager Ed Cooley based his business model on being able to make the largest and most complex castings in the industry. Cooley entered the aircraft casting business in 1965. He aggressively honed his capabilities for making complex nickel and titanium investment cast parts. In doing this he built a highly successful business that generated a significant return on investment [10]. In 1986 PCC began to diversify when it purchased the TRW airfoils business in Cleveland Ohio. Later PCC redefined itself as a parts supplier to the aircraft engine and then to the entire aircraft. PCC successively acquired Wyman-Gordon (forgings), SPS (fasteners), Special Metals (nickel-base alloys), Timet (titanium alloys), and Primus (airframe structural components). Wyman-Gordon and Special Metals were also participants in the oil and gas, fossil and nuclear energy markets, so this sector became a prominent part of PCC’s core businesses. To complement the capabilities of already large companies, PCC purchased several smaller, but well-known companies, such as Carlton Forge, McWilliams Forge, Rollmet and Rath-Gibson. PCC is now organized with three divisions (Castings, Aerostructures and Forged Products and Metals) with 162 separate business units and 30,500 employees. The overall structure of PCC is illustrated in Figure 2.

Figure 2. General organization of PCC businesses.

In 2016 PCC was itself purchased by the Berkshire-Hathaway Group, under whose direction it will maintain its focus on providing increasing value to its customers.

While the PCC business model does not directly foster external collaborative policy or projects, it does create an internal environment for collaborative innovation across company boundaries not previously possible. PCC does not have a corporate R&D facility or function. However, it does actively promote an internal virtual technical environment that develops and shares best practices and creates multi-function teams to work on common problems or opportunities. To this end there have been several corporate and divisional technical conferences organized around a central theme with strict presentation and format requirements. This has provided a forum for young engineers to be recognized and to develop their network among

their peers in other related companies. In addition, more technology specific meetings are held on a regular basis. These include such varied topics as vacuum melting, raw materials utilization, computer simulation and process automation. A corporation-wide technology development program also encourages peer interchange among young engineers.

Intercompany Collaboration With No Formal Agreement – Large Gas Turbine Wheels. Successful multi-company collaborations do not always require elaborate formal agreements. An example is the adaptation of INCONEL® alloy 706 for wheels, spacers and shafts for large frame gas turbines. This development was carried out entirely between the OEM (General Electric Power) and its supply chain (melters and forgers) with nothing more than simple bi-lateral non-disclosure agreements.

Alloy 706 was developed by Eiselstein and Clatworthy in 1970 as a low-cost derivative of alloy 718 [11, 12]. The inventors envisioned it as a general purpose alloy; however, they were aware that the alloy was less prone than alloy 718 to solidification segregation. This concept was further developed by Suarez et al; however, they were unable to identify process conditions that prevented both segregation and ingot cracking [13]. The possibility of using a large diameter age-hardened nickel-base alloy for a gas turbine wheel was explored by GE at that time. The properties of alloy 706 were considered attractive [14]. However, for various reasons, the time was not ripe for a transition from steel to nickel turbine rotors. Over the succeeding 20 years, the Inco patent expired without there being a significant application.

By the late 1980's GE's gas turbine designers had pushed operating temperatures to the limit of steel capability. GE then initiated work with its supply chain to develop a 706 rotor capability. Gas turbine rotors are an order of magnitude larger than aircraft turbine rotors and the high forging loads required to forge these disks could only be delivered by three 50 KT+ forging presses at Alcoa, Wyman-Gordon and at Issoire in France. Similarly, only four nickel alloy melt shops (Allvac, Aubert & Duval, Carpenter, and Inco Alloys International) had the melting and remelting capability to produce cropped and conditioned ingots as heavy as 15 T. While the basic equipment existed within these companies, there were significant differences that precluded a universal practice. Accordingly GE defined a set of product criteria and then worked with the supply chain to develop multiple process pathways. The introduction of this product was described by Schilke et al [15].

Figure 3. Wyman-Gordon 50 KT forging press in Grafton, MA.

This was not an easy scale-up of an established material. Alloy 706 is resistant but not immune to solidification segregation. The alloy also forms a significant amount of Laves phase during solidification that results in very low as-cast ductility. The high level of residual stress in large ingots makes the alloy sensitive to cracking. The initial practice was Vacuum Induction Melting (VIM) and Electro-slag Remelting (ESR) which produced suitable forged structure and properties, but was unreliable due to remelting instabilities. GE then specified triple melt (VIM-ESR-VAR) on the belief that the shallower melt pool in Vacuum Arc Remelting (VAR) and the improved stability provided by a sound electrode would minimize the possibility of a segregation anomaly that would be impossible to detect. That change did not solve the cracking problem which is illustrated by an example from Special Metals (Figure 4) and described by Minisandram [16]. Each of the melt shops developed solutions to the problem for their own unique processes using thermal stress modeling to define process windows. In this respect each melter worked independently with minimal input from GE.

Figure 4. Catastrophic longitudinal cracking of a 706 ESR Ingot.

Similar development was required for ingot conversion (billetizing) and closed die forging. Along the way composition and heat treatment criticalities and ultra-sonic inspection techniques were developed. The final result was a fixed practice specification that promoted a uniform product made by multiple suppliers with different equipment. Throughout this development there was communication between GE and its suppliers that preserved the confidential information of each supplier. For a project of this nature to succeed, there must be a clear and narrowly defined product goal with a credible revenue potential and trust that confidentiality will be maintained. The 706 development left a legacy of “big ingot” technology that provided a basis for the adaptation of superalloys for a new generation of energy systems described in the next example [17, 18].

AUSC - Industry Consortium with Very Long Term Goals.

Historically, the primary materials of construction for coal-fired steam boilers and coupled steam turbines which generate more than half of the world's electricity were heat-resisting ferritic steel grades. In the 1990's it was recognized that the operating temperatures had reached the limit where ferritic steels could no longer be used. The next generation of power plants that was designed to operate at or above 700 °C would require super-austenitic steels or possibly nickel-base alloys. Consortia were launched in Europe (1998) and the US (2001) to develop the material technology with the expectation that the first demonstration plants could be built in about 2010 [19]. This became known as Advanced- Ultrasupercritical steam technology

(AUSC). The problem of developing the technology and financing of such plants proved much more difficult than initially thought.

In the early work alloy 617, a weldable solid-solution and carbide strengthened nickel-base alloy with a prior history of use for chemical process vessels and gas turbine transition ducts, was considered a prime candidate for boiler tube and steam pipe. As a higher strength alternative, Special Metals proposed age-hardened alloy 740, that is a modification of aerospace sheet alloy 263, with improved oxidation and coal ash corrosion resistance [20].

The US AUSC Consortium is a public/private venture comprised of the US Department of Energy (DOE), Ohio Coal Development Office (OCDO), Electric Power Research Institute (EPRI), and major US boiler and turbine manufacturers. Oak Ridge National Lab (ORNL) and the National Energy Technology Lab (NETL) in Albany Oregon provided key material evaluation capabilities. The US consortium evaluated many commercial and developmental alloys for the various components in the boiler and turbine. Alloy 740 was selected for further evaluation as tube and pipe. This alloy was later modified to improve its γ' stability and heavy section weldability and renamed alloy 740H [21]. Reviews of the consortium activity were presented by Viswanathan et al. [22] and Shingledecker et al. [23].

Special Metals (and other alloy producers) were not members of the consortium, but they worked closely with members and Labs, initially to supply material for testing and later for demonstration of component manufacturing capability and to supply material for boiler test loops. Two key properties on which material selection was based were minimum creep-rupture strength in 100,000 h at 760 °C and 100 MPa, and oxidation and coal ash corrosion penetration of less than 2 mm in 200,000 h. The creep testing of base metal and weldments was done at ORNL while oxidation and hot corrosion testing was done at ORNL, NETL, Babcock & Wilcox and Foster Wheeler. The creep test data formed a key part of a data package that the consortium presented to ASME for code approval. Formal code approval of the alloy in Code Case 2702 was gained in 2011 [24]. Alloy 740H is the first age-hardened alloy to be approved by ASME for use in welded pressure pipe for creep-limited service. The design stress allowables, compared with those of solid solution strengthened boiler alloys are shown in Figure 5.

Figure 5. ASME design allowable stress for 740H compared with other widely used boiler alloys.

The materials characterization and qualification phase of the US AUSC project is complete. Recent focus has been on demonstration of capability of manufacturing components on the

scale needed for the plant. Special Metals and Wyman Gordon have been involved in a number of these activities in close collaboration with the OEMs. These include extrusion of large diameter pipe and forging of steam turbine disks of alloy 282®. Considerable work has also been done on manufacture of pipe bends and fittings with Chicago Bridge & Iron Alloy Piping Products, and Maass Flange. These activities are described in more detail in another paper in this conference [25]. (® 282 is a registered trademark of Haynes International).

Figure 6. Mock-up segment of header pipe that demonstrates technical capabilities needed for AUSC power plant such as production of large diameter ingot and pipe and welding of heavy section and complex geometry.

The AUSC consortium collaboration has been successful in a number of ways. Not only have the materials been developed and qualified to enable construction of an AUSC demonstration power plant, but it has made these materials available to the power industry throughout the world. In addition the technology is essential for other advanced power generation applications. In particular supercritical CO₂ has been identified as a highly efficient working fluid to drive compact turbines in fossil, solar and nuclear power systems. Pilot plants designed to prove these concepts are now under construction. This initiative that began rather modestly 18 years ago will make a major contribution to the world's energy future. But from an alloy developer/producer perspective, developing alloys for an application that will take a generation reach maturity is a very big risk.

Ma²JIC – Industry/University Center for Joining Technology

The National Science Foundation (NSF) has been a major supporter of basic science research in the US for many years. One of its programs, the Industry/University Collaborative Research Centers (I/UCRC), provides a framework for centers in a wide range of technologies. The Materials and Manufacturing Joining Innovation Center (Ma²JIC, formerly CIMJSEA) was launched in 2010 and is now in its second NSF award phase. This center is anchored at Ohio State University with partners at Lehigh University, Colorado School of Mines and University of Tennessee. NSF centers require company membership fees and an industrial advisory board to control selection of projects that must be collaborative and pre-competitive in nature.

Metal joining is highly diversified in both technology and the industries that utilize it. These joining processes include traditional arc, laser and electron beam welding as well as brazing, friction welding and additive manufacturing. The forty members of the Ma²JIC center include welding products suppliers, welding services companies, fabricators, users and institutions. Process modeling is a key part of this program. The center supports a wide

range of projects involving superalloys including aerospace, gas turbine, power and oil and gas applications.

One project addresses the problem of stress-relief/stress-relaxation cracking. This mode of cracking is seen in a wide range of alloys in aircraft, power generation, petro-chemical, and chemical process industries. Aircraft industry readers will appreciate the often cited weldability advantage of alloy 718 versus Waspaloy. In power and chemical plants this mode of cracking is especially insidious because it is driven by relaxation of residual welding stress in large highly restrained structures by a creep rupture mechanism. Cracking may not become evident until after years of service. For example, a stress relaxation crack in alloy 617 in a main steam pipe of a power plant experimental test loop was not seen until after 10,000 h of operation [26]. It has been shown that this kind of cracking can be prevented through joint design, welding process control and post-weld stress-relief heat-treatments.

Research at Lehigh and Ohio State Universities is focused on developing predictive tests and characterizing relative performance of commercial alloys. Many of these tests are Gleeble-based and seek to reproduce the complex thermal and stress cycles that accompany a multi-pass weld cycle. Analysis is complicated by the problem of long time microstructure stability of weldments that contain severe microstructure, composition and stress gradients. An example of a unique microstructure that has been observed in a weld in alloy 740H is shown in Figure 7 [27].

Figure 7. Grain boundary γ' denuded zone in alloy 740H cross-weld creep specimen. This feature is caused by an interaction of residual stress and a discontinuous γ' coarsening reaction [27].

A goal of this research is to develop a comprehensive model to predict life performance of a weldment in service. Such a model must consider multiple interacting forces as illustrated in Figure 8. Note that many of the processes are time dependent and non-equilibrium and must contend with steep structure and property gradients.

The development of a holistic life model will be difficult and will take several years to complete. One of the major gaps is the lack of material property data to characterize the different structural zones in a weldment such as coarse grain heat affected zone, or across a dendrite in an un-homogenized structure. An NSF funded basic research project at Ohio State University is addressing this problem using a variety of novel micro-mechanical techniques.

Development of the model for nickel-base alloys is now proceeding with DOE funding at Idaho National Lab (INL).

Figure 8. Structure for a model of weld behavior in power plant.

From an industry perspective, university based collaborative research has a number of short-comings, not least of which is the difficulty of finding common ground among participating companies for a sufficiently targeted research program. Individual membership funding tends to be limited, so external funding can be critical. The success of a center often depends on the commitment of the industrial advisory board and its understanding of the open publication needs of the university partners and a project timeline closely tied to the student graduation cycle. Nevertheless, a strong I/UCRC can be a fruitful employee recruiting mechanism as members can become familiar with the capabilities of students in a variety of settings.

Metals Affordability Initiative – Industry/DOD Partnership

The Metals Affordability Initiative (MAI) is an industry/Air Force partnership that is dedicated to development of metals technology for military aircraft. US companies representing four tiers of the supply chain (airframe and systems, engines, parts suppliers and metals producers) are members. Funding is provided through annual appropriations by the US Congress to the USAF, designated for industry led materials technology development. A significant industry cost share is required to supplement federal funding for projects. Projects are selected by a Technical Oversight Committee (TOC) where each member company, regardless of its size, has one vote. The TOC also monitors the technical progress of the projects and controls continued project funding through task gate reviews. Generally, work is done at project member companies and subcontractors that often include small businesses and universities. A wide range of projects have been completed since the MAI was started in 1999. Many of these projects have resulted in early insertion for supply chain manufacturing efficiency or products used on aircraft platforms that support enhanced mission capability or operating cost reduction. Much of the technical work is subject to ITAR restrictions and may only be reported in closed forums. Highlights of the program for 2015 have been reported [28].

One of the most successful MAI projects resulted in the adoption of digital radiography for final part acceptance of aerospace castings. Most aerospace structural castings require radiographic inspection to confirm internal quality. In the late 1990s the adoption of digital radiographic imaging transformed the medical industry. As personal and industrial photography followed suit,

film became scarce and expensive. Other reasons for interest in digital records are portability and permanence.

Although there was widespread interest in the casting industry in making the conversion from film to digital, there were major barriers that could not be overcome by one company acting independently. PCC and Howmet made an initial start under the Next Generation Manufacturing Technology Initiative (NGMTI), but funding from that source was insufficient. PCC then put together a team and proposal to MAI that was approved and got underway in 2008. The project was also supported by DoD Manufacturing Technology Program (ManTech). The PCC-led team included all of the stakeholders among the casting suppliers, OEMs and key film and equipment suppliers. Among the problems to be overcome were 1) lack of digital reference images, 2) lack of ASTM and company specifications, 3) competing commercial image systems and 4) need for NDT inspector training from shooter level all the way through Level III. In many cases this involved decades of experience with film and lack of familiarity with computers. Another barrier was the high cost of acquiring digital radiographic equipment that was sufficiently robust for foundry use.

Figure 9. X-ray radiographic image reference standards for aerospace parts.

The project was completed in 2011, culminating with the issuance of ASTM E2033 (Standard Practice for Computed Radiology). A 30 page procedure document for managing the differences between the two major systems for capturing images was agreed and implemented by each member. Training classes were developed and delivered to all levels of NDT operator. Comparative images were made of parts for each customer. After completion of the work, the project received the Defense Manufacturing Technology Achievement Award in 2011. Foundry conversion to digital radiography at PCC Structural Castings Division is well underway, with some locations having completely removed film processors. The project was reviewed by Brayshaw and Barrett [29]. The same project team is now working on the next step in digital radiography, Assisted Defect Recognition (ADR). To date several software companies have demonstrated algorithms that meet the ability of a human operator to detect discontinuities in digital x-ray images. The ability to share digital defect maps is a critical link in ICME for aerospace castings.

ICME has profound implications for the way industries collaborate. The concept involves linking process models to reduce variability of material properties, reduce rejections and improve the accuracy of life prediction. While process modeling is now strongly embedded in superalloy production technology the incentive to link models to achieve a holistic predictive ability has been lacking. The Air Force has invested heavily in ICME following a National Academy of Science Report in 2008 [30]. The ICME work builds on the long history of Air Force support for finite element modeling that accelerated the development of a robust simulation industry in the US. Many projects within the MAI portfolio now address some aspect of ICME including the one just described. Projects under the MAI mantle include prediction and measurement of residual stress caused by forging, heat treatment and joining, its effect on part distortion during final machining, and its effect on fatigue properties. More fundamental programs are considering the evolution of microstructure and its effect on the properties in forged parts. These models have been validated and the uncertainty quantified. Work is now underway to determine the sensitivity to process variables and to develop a platform, data format and security controls that will enable establishment of a digital data thread. This exposes an unresolved point of contention between oversight agencies, system owners, OEMs and parts/material suppliers regarding collection and handling of proprietary process data in a digital world.

The MAI concept has been very productive. The most recent assessment of Return on Investment (ROI) to DoD is \$1.18 billion for a government investment of \$160 million [31]. Executive and technical meetings are held quarterly with strong membership participation. This is in part the result of the required financial participation of the members, an obligation to involve a broad cross-section of the supply chain in each project and a strong business case. The active role of AFRL technical personnel is also beneficial. The principal problems have been a primary funding source subject to political uncertainties and the complexities associated with management of multi-participant government funded contracts.

SMPC – An Industrial Consortium for Remelting Research

Collaboration in process research is less common and what work is done is less well known because of the specialized nature of the technologies and a reluctance to publish results. A program that has been underway in the US for twenty-five years is the Specialty Metals Processing Consortium (SMPC). Frank Zanner, working at Sandia National Lab (SNL), approached the US specialty alloy melters with the notion of creating a consortium that would focus on advanced melting technologies. Sandia hosted a liquid metals laboratory with extensive experience in remelting of specialty alloys for the nuclear weapons industry. DOE funding for enhancing domestic manufacturing technology was available at that time. Bob Torcolini of Carpenter Technology led the difficult task of creating a consortium of highly competitive companies. Ultimately a Delaware Membership Corporation of 13 companies was founded. This corporation executed a Cooperative Research and Development Agreement (CRADA) with Sandia (and later with NETL) to create a framework for projects to be carried out by Sandia, Los Alamos and university subcontractors. Funding was by membership fees, in-kind support and Department of Energy (DoE) and later Federal Aviation Administration (FAA), United States Air Force (USAF) and United States Navy (USN). A broadly based research program in ESR, VAR and EB hearth melting processes was developed that

used the resources of the national labs with critical validation on industrial equipment. An example of this work is a unique experiment on a specially built hearth window installed in a VAR furnace shown in Figure 10. Classic images of VAR cathode spots and drip shorts were obtained that fundamentally changed the way the process was viewed [32].

Figure 10. View through hearth window of the arc in VAR. Tungsten reference post in the foreground [32].

Throughout its history, SMPC has generated many patents, publications, process tools and process understanding for its members. These include defect characterization [33], VAR process models [34], advanced controllers [35], process monitors [36], instrumentation and visualization and statistical analysis tools. Although the grand objective of commercializing new remelting processes or controllers has yet to be achieved, SMPC research has had a significant impact. There has been a progressive reduction in the number of anomalies that have been detected by ultra-sonic testing in rotor quality alloy 718 and Waspaloy bar produced in US melt shops since data collection began in 2002. Data reported on a confidential basis to FAA and provided to the Aerospace Industries Association, Rotor Integrity Sub-Committee (RISC) shows 40-75% reduction in reportable indications in each of the four product categories. This improvement is due to many factors, but the shared technology generated by SMPC is certainly one of them.

Melting process research poses difficult problems for collaboration. To begin with, process research is very costly and time consuming. Consequently, with a few notable exceptions, universities have neglected this field. Definitive validation via industrial experiments is critical, but sharing of the results is awkward and constrained. Breaking into an industrial production schedule with risk of equipment damage is always difficult. Another significant constraint is that the cost of qualifying a major process change for aero-engine bar production is almost prohibitively expensive. Hence, process data analytical tools such as the SMPC VAR process monitor can be readily applied by member companies, while more disruptive process changes such as its novel pool depth controller are difficult to justify.

HSCT – ME3, a Legacy of a NASA Project. The High Speed Civil Transport (HSCT) project was conceived as the next step in commercial supersonic flight beyond Concorde. The project that began in 1990 and ended in 1999 was managed by NASA Langley. It had truly lofty goals, a 300 passenger plane that would fly at Mach 3 at 70,000 ft. for 6000 miles. In addition the engine would be required to have low NOX emissions and be fuel efficient. The engine used standard turbofan technology and hence had to run very hot to achieve those specifications. GE and Pratt & Whitney collaborated with NASA on engine technology. While the project goal of commercial service by 2020 was not realized, critical technologies were developed that are being employed in

the current generation of sub-sonic commercial aircraft engines. This project also exemplifies many other ambitious US aerospace projects that, while not always accomplishing their platform goal, never-the-less made important contributions to superalloy technology.

Figure 11. NASA artist concept drawing of the HSCT; a plane that never was paved the way for a new generation of powder disk alloys (NASA Website).

The NASA mission requirements included a long liftoff stage to achieve cruising altitude with sustained operation at 650°C. Existing powder disk alloys could not meet the dwell-fatigue or creep properties needed for service. ME3 (Ni-20.6Co-13Cr-3.4Al-3.7Ti-2.4Ta-0.9Nb-2.1W-3.8Mo) [37] was the resultant alloy designed in the NASA/General Electric/Pratt & Whitney High Speed Research/ Enabling Propulsion Materials (HSR/EPM) [38] program for extended use up to 600°C to 700°C allowing for increased fuel efficiency, lower fuel burn and reduced emissions. The alloy was designed using statistical methods [39] and contains a high γ' content to produce balanced monotonic, cyclic and time dependent mechanical properties [40] while still able to be forged and heat treated. PCC has participated in this program from the exploration of the thermo-mechanical and microstructural properties to the development of full scale forgings. Applications for both sub-solvus and super-solvus heat treatment have been developed and are in production.

NASA has supported and published extensively on ME3. Resulting data available has also provided a platform for MAI collaboration to explore and validate ICME techniques and supports efforts to characterize how variability effects the predicative capabilities of these techniques.

Blade Cooling – A Continuing OEM/supplier Collaboration.

Modern aircraft turbine airfoils are precisely engineered to provide optimum performance in a challenging environment. In addition to an oriented single crystal structure with up to 75% γ' content, they contain intricate cooling channels and thermal barrier coatings and operate in a combustion gas well above the alloy melting point. This was not always so. The first NIMONIC alloy 80 blades were machined from solid forged bar. Wrought blade alloy technology developed rapidly: γ' content increased progressively and cobalt and refractory metals were introduced. By the time NIMONIC alloy 115 entered the market, blade alloys could no longer be clogged from ingot. Henry Wiggin Co. (Inco) introduced extruded blade bar and as a weight reduction measure produced blade forging stock with leachable iron cores as early as 1953 [3]. Rolls-Royce quickly recognized the value of using these

channels for internal air cooling and the patterns became increasingly complex. In 1970 John Benjamin at Inco's Sterling Forest Research Center developed the Mechanical Alloying process as a solid state powder processing method for making an oxide dispersion strengthened superalloy [41]. The application goal was an aircraft turbine blade where the oxide dispersion would supplement γ' to provide creep strength up to the melting point of the alloy. Over the next twenty years Inco invested heavily in this technology. A significant application developed for non-age hardened alloy MA754 in turbine vanes and bands. But the alloy never succeeded for the blade application despite steady advancements in composition, directional recrystallization and forging [42, 43]. Despite diffusion bonded wafer blade and lamilloy technologies, the cooling barrier could not be economically overcome in wrought alloys.

The early cast blades were also solid, but the foundry industry was very familiar with sacrificial metal and ceramic cores. By the time that directional and then single crystal casting processes were developed, internal cooling patterns too complex for wrought blades were already in widespread use. A relatively simple non-proprietary ceramic core is shown in Figure 12.

Figure 12. Complex, durable and removable ceramic cores are the key to success of cast blade technology.

The progression from the earliest castings with a single central cooling passage to today's complex serpentine channels with cast wall sections as thin as 0.015 in. was continuous. The impact of blade cooling on turbine inlet temperature is often overlooked by metallurgists, but Metham [44] and Goulette [45] attributed about half of the advancement to cooling. Airfoil design is a closely held technology of the OEMs while the technology to manufacture them is closely held by the suppliers. This includes alloy chemistry control, casting conditions, and ceramic shell and core design. Initially, cores were made at the foundry, but the manufacture of precision ceramic cores is a specialty in itself, so today many cores are manufactured to specification by independent suppliers.

In the 1960s airfoil designs were done as conventional engineering drawings that could be passed through the supply chain with appropriate confidentiality markings. In the modern digital world CAD dimensional drawings become integrated with data management systems at the core maker and foundry. Casting and core making processes are designed by computer simulation, dimensions are checked and recorded with white light systems and defect data collected from X-ray image recognition systems. New methods of core-making such as additive manufacturing are

adding new partners to the mix. All of this data can in principle be shared throughout the supply chain almost instantaneously. This brings us back to the question of IP integrity of the OEMs and supply chain. Several groups are working to develop data sharing technologies, but this remains a high level concern for suppliers.

Discussion

Clearly innovation and collaboration has driven the superalloy industry over the past seventy-five years. This was particularly true of the early years, when the pioneers of gas turbine technology and nickel alloy development fed off each other's successes (and failures) to innovate and challenge the status quo. The various examples cited in this paper show the importance of this symbiotic relationship between the end user and the supplier to solve critical problems of enabling technologies as well as cost reduction initiatives to take the industry forward. Of course the role of government is often vital, not only for the purposes of funding, but also to provide national mandates and a pre-competitive framework for collaboration. If we refer to the Chet Sims illustration of the key periods of Superalloy evolution shown in Figure 13, the first fifty years were, in many ways, simpler times when collaboration was often informal and exchanging ideas and data was a matter of course, and trust.

Figure 13. Update of the Chet Sims "The Major Eras" plot.

As we enter the era of predictive computer modeling and ICME to better understand our processes, improve quality, yields and lower costs even further, this is no longer the current paradigm. The early days of innovating alloys and processes just to enable engines to fly have been replaced by developing competitive advantages through tightening process controls and proprietary data which are treated as family jewels by companies. This is further complicated by an evolving supplier base which is consolidating and narrowing on the one hand in the US, but expanding on the other in terms of potential new suppliers from overseas. In the case of China and Japan, governments are leading the charge and funding massive investments and consortia to develop national capabilities in critical industries, reminiscent of post-WW II US projects. This complex landscape is encouraging a certain conservatism and in some cases, frankly, a paranoia in many companies when it comes to IP protection. This is one of the biggest barriers to successful collaborative programs in the coming years.

The pros and cons of industry consolidation can be debated, but from the perspective of an insider in the largest of these conglomerates, PCC, it is clear that the intra-collaboration throughout the supply chain from raw materials, through melting, casting, forging to final machined components is currently driving rapid innovation without the constraints of formal agreements and

IP sharing concerns. PCC's key role in the supply chain is to convert novel ideas for products and processing concepts into actual components at an acceptable cost and quality. This would be much more difficult, if not impossible, in a world where Special Metals, Timet, Wyman Gordon and Carlton, for example, were all independent companies. The dynamic of internal customers and suppliers working together to provide solutions for the external market is extremely potent.

This relationship between cost and quality is often a controversial one. On the one hand, cost reduction initiatives are critical to maintain a competitive edge for both supplier and OEM. On the other hand, too often the relentless pressures on the supply chain to reduce costs can lead to bad decisions and a direct effect on the quality of the final product. In fact, in many cases the primary collaborative programs between suppliers and OEM's are focused solely on cost reduction "pipelines", rather than innovative technology ideas. This relationship needs to be rebalanced for the ongoing technical health of the industry.

Finally, the current age of electronics and computers is enabling materials technology advancements in potentially exciting new areas, such as Additive Manufacturing. Whereas a great deal of fundamental work is already under way at research labs and Universities, ultimately the success or failure of this technology will depend on key collaborations and technology transfers between these institutes, materials companies, component manufacturers and OEM's. In that sense, whilst so much has changed since the early days of superalloy development, much remains the same.

Conclusions

Whereas the need for continued collaboration across the Superalloy world is clear, many challenges need to be faced and addressed. The issue of Intellectual Property protection is one of the most critical of them. This is a core concern of many in the industry, and it may be driving behaviors within companies. This concern is real and needs to be addressed if meaningful collaboration is to continue between competitive companies. On the other hand, supply-base consolidation has removed these barriers within companies under the same parent and so innovation is alive and well!

Acknowledgements

The authors acknowledge the contributions of Jim Barrett (PCC Structural Castings), Larry Graham (PCC Airfoils), Beth Lewis and Noshir Bhathena (Wyman-Gordon) in the planning and writing of this manuscript.

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