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SUPERALLOYS, THE MOST SUCCESSFUL ALLOY SYSTEM OF MODERN TIMES - PAST, PRESENT AND FUTURE

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Abstract

The deep roots of superalloys go back to 1907, although the term ‘super-alloy’ is believed to have first been used in the mid 1940s to refer to cobalt-base alloys such as Vitallium and nickel-base Waspaloy®. During the past 50 years, much alloy, hot working, heat treating and process development has occurred, enabling many of the end use technologies we know today.

This presentation will discuss some of the history of the superalloy industry related to the superalloys 718, Waspaloy and their derivatives, including ATI 718Plus® alloy. The presentation will then describe the wide range of manufacturing techniques used for the production of superalloys, available product forms and end-use applications. Concluding the presentation will be a discussion on what advancements we are likely to see in the future.

Introduction

Superalloys are successful today because they have solved pressing demands for durability and strength in machines and systems that were barely imaginable a hundred years ago. Superalloys have helped us conquer air and space, plumb the depths of the earth and ocean, and address many other challenges of modern life.

As such, they deserve to have their story told. The nature of this industry, however, makes the telling a challenging task. Its history is one of many small events and inventions that took place across the boundaries of nations, industries and countries. Many individuals contributed to the state of the art today, and only a few left their names in the scattered records.

This paper is an attempt by one of those individuals who has been witness to many of the industry’s milestones to combine eyewitness history with industry research and begin to set the story down in print. It is hoped that we can begin the dialog needed to create a complete history, and set the stage for a view of the superalloy industry’s bright and exciting future.

Because it is, to some extent, a first person account, I would like to state that this paper has a bias. It is written by an engineer who spent his career working for a superalloy mill; furthermore a mill that was a pioneer in the industry. With full disclosure out of the way let me close this introduction with the following: Alloy 718, Waspaloy and their derivatives are the most successful alloy systems of our time. Their success is due to a combination of factors that include the properties and performance of superalloys in service, the added value provided by vacuum melting, the success of gas turbines and the continuous development of superalloys and the products made from them. This success was and is driven by the dedicated professional engineers who work in the industry, to whom we owe a debt of gratitude and recognition.

A Working Definition

Superalloys have been defined many times by metallurgists for books and conferences, with reasonable consistency. A few of the most comprehensive definitions follow:

1. A superalloy, or high-performance alloy, is an alloy usually based on Group VIII A elements that exhibits excellent long-time strength, creep resistance, corrosion and erosion at temperatures above 1200^{o}F, good surface stability, and corrosion and oxidation resistance. Superalloys typically have a matrix with an austenitic face-centered cubic crystal structure. A superalloy's base alloying element is usually nickel, cobalt, or iron. Superalloy development has relied heavily on both chemical and process innovations and has been driven primarily by the aerospace and power industries.
2. Superalloys were originally iron-based and cold wrought prior to the 1940s. In the 1940s investment casting of cobalt base alloys significantly raised operating temperatures. The development of vacuum melting in the 1950s allowed for very fine control of the chemical composition of superalloys and reduction in contamination and in turn led to a revolution in processing techniques such as directional solidification of alloys and single crystal superalloys.
3. A *superalloy* is a metallic alloy which can be used at high temperatures, often in excess of 0.7 of the absolute melting temperature. Creep and oxidation resistance are the prime design criteria. Superalloys can be based on iron, cobalt or nickel, the latter being best suited for aeroengine applications. The essential solutes in nickel based superalloys are aluminum and/or 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.

A good working definition, although less technically precise, is: superalloys are the nickel-, cobalt- and iron-based alloys used in the hottest, most demanding components in gas turbines and oil and gas equipment. Superalloys facilitate improved operating efficiency and reduce environmental emissions.

Why are Superalloys the Most Successful Alloy System of Modern Times?

This statement may be difficult to prove but it shouldn't be too controversial, considering that no one has or will likely try to disprove it. That being said I will make the case based upon the attributes of superalloys, where they are used, and the impact of those components.

Summary of Superalloy Properties

Superalloys are all of the following, and more:

- Suitable for applications at the highest fraction of their melting point of mechanically superior alloys
- Strong and ductile at cryogenic temperatures
- Excellent oxidation resistance

- Good corrosion and erosion resistance across a wide range temperature and environments
- Able to achieve elevated mechanical properties across thick sections
- Most cost effective metal solution where the above are required for the component to be successful in service

What is it about superalloys that allow them to be successful in torturous environments?
The following is a list of attributes that, although long and comprehensive, are by no means exhaustive:

Attributes of Superalloys
- Tight chemistry control
- Gamma prime and double prime
- The ability to be hot worked to have consistent and desirable grain structure
- Excellent mechanical properties
- Responds well to heat treating
- Able to achieve elevated mechanical properties across thick cross sections
- Weldability
- Cost effective
- Performs (strength and toughness) at elevated temperatures
- Oxidation and corrosion resistance
- Vacuum melted
- Multiple vacuum melted
- Electro-slag remelted
- Triple melted
- Cleanliness facilitated by raw material selection and vacuum melting
- Hot form- and forge-ability
- Able to be coated
- Enable products of significant value to society

Technologies Enabled by Superalloys
The above attributes provide design engineers great flexibility to customize superalloys, making them suitable for diverse applications, including:
- Jet engines to power commercial and military aircraft
- Gas and steam turbines for electrical power generation
- Hot spots on aircraft where strength is required
- Space exploration applications such as Space Shuttle components
- Oil and gas exploration and production at depth and in environments too severe for steels and other metals
- Cryogenic applications.
- Biomedical implants (cobalt-based alloys)
- Fasteners for many of the above applications
- Automotive turbochargers

Our lives are touched and the quality of life improved by these technologies, which are possible in part because of superalloys, that:

- Transport us across long distances
- Secure our National Defense
- Produce electricity that power our factories, businesses and homes
- Heat our homes
- Provide fuel to power our vehicles
- Improve our mobility as we age

If growth in demand of an alloy system is a measure of success, superalloys qualify. Superalloy demand has grown from essentially zero in the early 1950's to 120M pounds in 2008, the last market peak. Growth is cyclical due to the nature of the aircraft markets, the largest consumer of superalloys. But, with few exceptions, each new market peak is higher than previous.

If increasing technology of an alloy system is a measure of success, superalloys qualify. New alloys, finer and cleaner microstructures, improved processes and expanded sizes have been the rule. Demand from its end use applications pushes superalloy technology, and expanding superalloy technology further enables end use applications to reach new levels of performance and efficiency while often lowering its environmentally impact.

If being irreplaceable is a measure of success, superalloys qualify. Since their earliest use, the predominant replacement for a superalloy is another superalloy. The replacement is more highly alloyed, alloyed with a preferred blend of elements, or processed differently to outperform the original alloy in the specific application.

If you add it all up, there is no reason to dispute the claim that superalloys are the most successful alloy system of modern times. With that case made, let me proceed and talk about other interesting aspects of superalloys.

Where Did the Name Come From?

The term "superalloy" was first used in the mid-1940s to describe high temperature alloys that could not only be used at elevated temperatures but maintained their strength and toughness at elevated temperatures. The applications were the developing gas turbine engines for defense jet aircraft. Another alternative is that the nickel- and cobalt-alloys invented for aircraft engine turbochargers or superchargers was the origin of the name superalloys.

One speculation as to the origin of the name was that "super-alloys" of a stainless variety led to improved iron-based alloys, whose name became superalloys with the hyphen dropped. This explanation has merit but leaves unexplained why the word 'super' was used or where it came from. A metallurgical origin of the name superalloy is the alloys' special blend of elements and the resulting phases created alloys not believed to be possible therefore beyond our expectations or "super."

While the specific origin of the name is not definitively known, each of the alternatives is possible. It is the writer's view that the name is a combination of all possibilities. The logic is, nickel- and cobalt- based alloys have special or super properties (maintaining strength nearly to its melting point), and a target application for these alloys was superchargers for aircraft engines. When the name was first used it stuck in the culture, perhaps because of the popularity of the comic book character Superman.

Whatever the origin, by 1960 the name was here to stay. It is interesting to note this is before most of the advancements in composition, structure, and heat treating that make superalloys the metals they are today were invented.

If the name became part of the language in the late 50s, is that also when the era of superalloys began? How far back do the roots go? The answer is that there is not one path, but several.

For me, the era began with ATI Allvac, my employer since 1980. ATI Allvac was founded in 1957 as the 'Allvac Metals Company' by James D. Nisbet. Mr. Nisbet was also a published writer. His historical autobiography, The Entrepreneur, documents his starting of Allvac and his career. Along with the personal files of Jim's brother Oliver Nisbet, Allvac's long time Vice President, this narrative forms a good starting point.

A History of the Superalloy Industry

Where does the history of superalloys begin?

The story of superalloys is a tale of four technologies: alloy composition, vacuum melting, forging, and gas turbines for jet engines and power turbines. Which one was most important? Although the technologies are entangled, the driving force was gas turbines – or, more correctly, the aircraft they powered. Without aircraft, many of the superalloys' metallurgical developments would not have been needed.

The need for temperature resistant steels was driven by the industrial revolution and its outgrowth of products. Ni, Cr and Co were added to iron before becoming its substitute. These alloys were generally called high-temperature alloys. The high-temperature name was used into the 1940s before the term superalloys emerged. For a half-century, engineers and scientists in the U.S. and Europe invented various high-temperature alloys to meet existing and envisioned needs.

Around the same time (circa 1905), vacuum melting was invented to improve the reliability of the steels of the day. Vacuum melting permitted closer control of elemental chemistries. It also prevented the unintended alloying of nitrogen and oxygen from the air into the alloy and removed gases trapped in the metals. Vacuum melting also allowed the addition of refractory elementals such as niobium as well the ability to increase and control the amounts of aluminum and tantalum.

Vacuum melting was the breakthrough that tied it all together. Complex alloys of nickel, cobalt, chrome, molybdenum, aluminum and other elements could now be merged into an alloy with tightly controlled chemistries free of non-metallic impurities. High-temperature alloys stayed stagnant, and superalloys were born with a platform for their growth: vacuum melting, vacuum induction and vacuum arc remelting.

Before this topic is left it is important to name the third ingredient resulting in the birth of superalloys. On December 17, 1903 the Wright brothers made the first successful flight of a heavier-than-air craft. The race began to create machines that could fly higher and faster. It was fueled by both commercial and defense demand, and it eventually led to development of the jet engine. Jet engine construction required metals with a balance of strength and toughness. Alloys with extreme temperature resistance that were vacuum melted – superalloys – would become the answer.

To summarize, high-temperature steels gave way to nickel- and cobalt-based high-temperature alloys that were improved by vacuum melting, creating superalloys. Demand was driven by the application of gas turbine engines to power airplanes, advancing and expanding superalloy technology.

Early Years – Pre 1950

Early Alloy Development Leading to Superalloys

The seeds that grew into superalloys were planted in 1907 by Elwood Haynes and A.L. Marsh. Haynes was an automotive entrepreneur who also tinkered with alloy development. The alloys he experimented with were attempts to meet the emerging need to lower the cost of machining auto engine components. The growing problem was that as machining rates were increased, the cutting tools of the day would wear rapidly. What was needed was an alloy that would maintain its strength and hardness at elevated temperatures. Haynes found the answer in cobalt-chrome alloys which, through future development, would evolve into Vitallium. Vitallium has been said by some to be the first superalloy.

At the same time A.L Marsh was experimenting with nickel-chrome alloys for electrical resistance applications. Ni-Cr alloys have also been said to be the forerunner of superalloys.

The following list of patents is a small representation of early alloys that led to the development of superalloys. The selections show the evolution of alloy composition as applications changed. The driving forces for development were the automotive engine, followed by the steam turbine for electrical power generation.

Alloys, Patents and Applications Leading to Superalloys

- 1906 Ni-Cr binary alloy for electrical apparatus, Patent # 811,859 by Marsh
- 1907 Co-Cr binary alloy for cutting tools used to machining automotive engine components, Patent # 873,745 by Elwood Haynes
- 1907 Ni-Cr binary alloy for cutting tools used to machining automotive engine components, Patent # 873,746 by Haynes
- 1917 Fe (47%), Cr (23%), Ni (30%, Co may be substituted for Ni) alloy for heating elements. Patent # 1,211,943 by Hunter.
- 1924 Fe (bal), Ni (3.75 – 4.75%), Al (5.75 – 6.25%), Si (1.75 – 2.25%), C 2.4 – 2.8%) alloy for internal combustion engine parts, valve head and such. Patent # 1,680,007 by Boegehold.
- 1924 Fe (bal), Cr (10-15%), Ni (25 - 40%), Co (<10%), W (2 – 5%), Nb (1 – 3%), Ti (.1 - .2%), Mn (.5 – 1%), B (.2 – 1%), C (.3 – 1.0%) alloy for blades for steam turbines. Patent # 1,489,243 by Girin
- 1924 Fe (bal), Cr (5-9%), Ni (5%), W (.25 – 1%), Si (1 – 5%), C (.05 – .6%) alloy for turbine blades and electrical heating elements. Patent # 1,555,395 by Armstrong & De Vries.

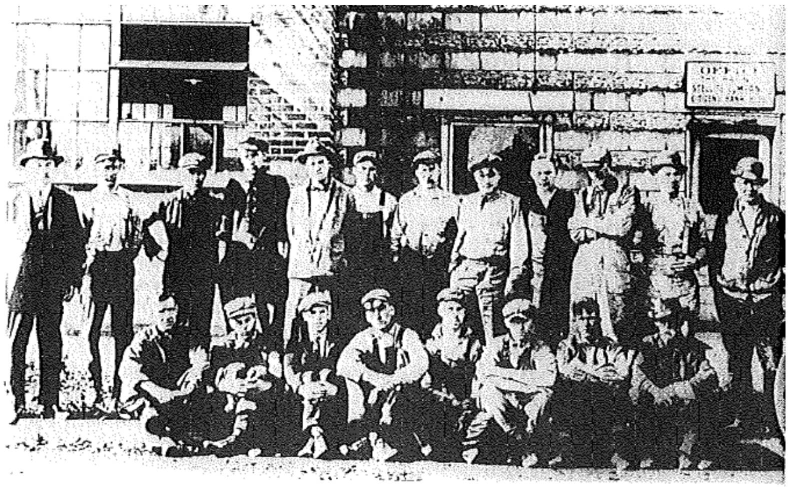
- 1925 Fe (bal), B (.75 – 4%) alloy for pistons, piston rings and valves for internal combustion engines. Patent #1,562,043 by Pacz.
- 1925 Fe (bal), Cr (2.8 – 7%), Co (.2 – 5%), W (.2 – 7%), Si (<3%), C (.2 – 5%) alloy for forgeable engine valves. Motor parts and such. Patent # 1,545,095 by Giles.
- 1930 Fe (bal), Ni (33 – 48%) alloy for internal combustion engine valves. Patent #1,759,477 by Armstrong.
- 1931 Fe (bal), Cr (1 – 20%), Al (1.5 – 4.5%), Si (<4%) alloy for engine valves. Patent # 1,850,953 by Armstrong.

Breakthrough Events in Superalloy Processing

- 1905: W. von Bolton consumable electrode arc melted tantalum in a cooled copper crucible under a low pressure of argon.
- 1917: W. Rohn first melted nickel alloy in a vacuum resistance heated furnace.
- 1923: Heraeus Vacuumschmelze A.G. founded to operate vacuum furnaces.
- 1926: Two VIM furnaces in operation melting 80 Ni 20 Cr and 65 Ni 15Fe 20 Cr for thermocouples and denture alloys.
- 1950: Dr. Mohling melts first large heat, ten tons, vacuum induction melt of aluminum and titanium containing strengthened superalloy at Allegheny Ludlum Steel laboratory in Watervliet, NY.
- 1952: Special Metals Co., New Hartford, N.Y. produces the first production heat of Waspaloy in a 6-lb furnace for Pratt & Whitney J48 turbine engine blades
- 1953: First production vacuum arc remelting of superalloys by Allegheny Ludlum Steel in their Watervliet, NY laboratory.
- 1957: First vacuum melting conference was held in New York University
- Circa 1960: Allvac Metals Co., Monroe, N.C. exclusively produces double vacuum melt (VIM/VAR) superalloys
- 1962: World's largest vacuum induction furnace (12,000 lb) installed by Allvac Metals Co. in anticipation of market acceptance and growth of vacuum melted superalloys.

Early Cobalt Alloy Development

When was the first cobalt alloy developed? An answer to this question may not exist, but what is known is a U.S. patent was awarded for a cobalt alloy in 1907. The patent, No. 873,745, was for a cobalt-chrome binary alloy, awarded to Elwood Haynes. Haynes was the founder and namesake of The Haynes Stellite Company in Kokomo, Indiana, now called Haynes International Inc. Another patent was also awarded Mr. Haynes in 1907 for a nickel-chrome alloy for electrical resistance applications. Haynes choose not to develop nickel-chrome alloys however, leaving that task to A. L. Marsh, who owned U.S. patent No. 811, 859 for nickel-chrome alloys for electrical resistance applications.



Elwood Haynes Museum

Employees of the Haynes Stellite Company, 1916, Elwood Haynes at far left

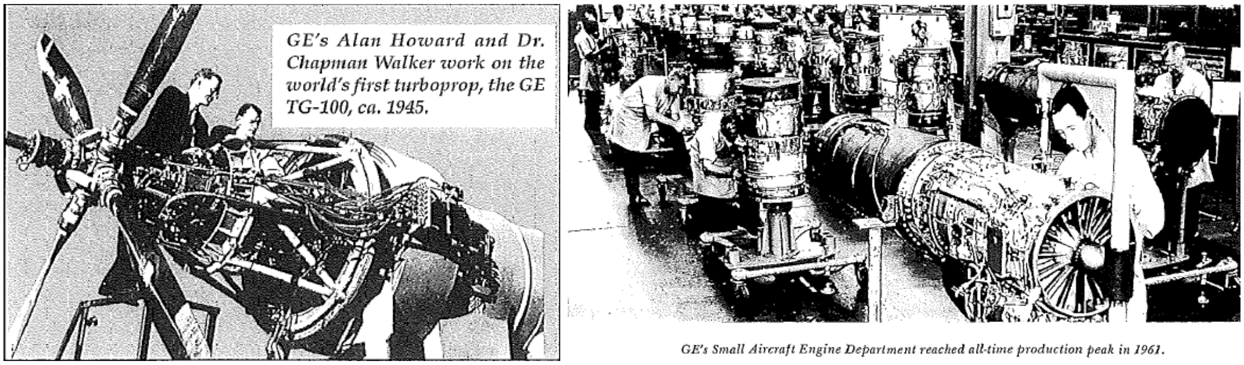
Figure 1. 1916 Photo of Haynes Stellite Employees

The first use for this cobalt-chrome alloy was knives that maintained their cutting edge and appearance because of the hardness and high luster the cobalt-chrome alloy provided, although this was not the intended application. The aim of the alloy development work, which was being done in the basement of Mr. Haynes's home, was to find an alloy suitable for contact points on spark plugs for the emerging automobile.

Automobile development was driving metalworking and machining. As automobile production volume grew and cost became a concern, improved cutting tools were needed that cut steel faster and lasted longer. Haynes' cobalt-chrome alloy proved to be the answer, and demand for it grew. The cobalt-chrome alloy's successes led to the construction of a dedicated melting plant. This plant was the first mini-mill, with a total size of 50 square feet. The business grew and in 1915 the Haynes Stellite Company was incorporated.

The success of cobalt alloys in improving the productivity of machining operations benefited many industries, including the infant aircraft industry. With the beginning of World War I, the demand for aircraft engines grew rapidly, and the demand for tooling made from Haynes's alloys grew along with it. But the leap from cobalt-alloy tooling to superalloy aircraft engine components would come later, as the aircraft industry sought to surpass the limits of the piston engine and adapt the gas turbine to powered flight.

Gas turbine development for jet aircraft in the U.S. began in 1941 when the U.S. learned that turbojet powered aircraft was being developed in England by Frank Whittle and in Germany by Hans von Ohain. A 'super-secret' facility was constructed on the site of General Electric Supercharger Division in West Lynn, MA. The facility had long worked on turbine technology to utilize the waste gases from turbochargers.


GE's Alan Howard and Dr. Chapman Walker work on the world's first turboprop, the GE TG-100, ca. 1945.

GE's Small Aircraft Engine Department reached all-time production peak in 1961.

Figure 2. Early GE Jet Engine and Production facility

Meanwhile in Europe, England and Germany were flying experimental turbojet aircraft. England was reluctant to share their technology with the U.S. until the advent of war with Germany compelled them. In 1943 a British turbojet engine named W1X was delivered to the NACA laboratory in Cleveland, Ohio along with the plans for the improved W2X. The work being done in England was led by Air Commodore Frank Whittle, who became an important asset in advancing U.S. development.

The work that followed was downgraded from 'super-secret' to top secret. A modest test facility was built at the Cleveland laboratory where "spin pits" lined with wood to protect the workers from the dangers of blades flying off in all directions when engine compressors reached their limits during endurance testing.

Bell Aircraft, Buffalo, NY was tasked with concurrent development of a fighter aircraft. Prototypes failed, but development continued.

As it turned out, turbine engine performance favored flight. The low temperatures and forward motion of the aircraft created a ram effect that increased efficiency, and therefore energy, to power flight. It was also learned that a portion of the energy released by the turbine could be used for propulsive thrust in addition to powering the compressor.

German engineering prevailed and in 1944 Germany was mass-producing the Jumo 004, a turbojet with an axial-flow compressor, for the Messerschmitt 262. U.S. General Arnold was quoted as saying "The jet propelled airplane has one idea and mission in life and that is to get at the bombers, and he is going by our fighters so fast that they will barely see him, much less throw out a sky hook and slow him up." This aircraft provided super speed but came too late to change the outcome of the war.

It can be concluded from a review of historical events that the dawn of jet engines occurred between 1941 and 1943. Jet engines required better materials leading to the development of superalloys beginning around the same time, which required better chemistry and cleanliness control that led to rise of vacuum melting in the mid 1950s. It took three emerging technologies for the superalloy industry to become what it is today.

The Foundation is Laid

The products that the industrial revolution gave the world continued to be refined. Performance improvements led to the never-ending demand for metal solutions. And of course cost reduction was critical to grow market demand for the emerging products.

Electrical appliances, automobiles, more electricity to power the new appliances and higher performance engines for better performing automobiles provided an ever increasing spiral upward in demand for metal solutions and mass production. Mass production made improvements more important because they were leverages across big volumes of components and products.

History of Age Hardening

In November of 1919 at the International Nickel Company's research laboratory in Bayonne, NJ, as the story goes, a memo was placed on the desk of Paul Merica requesting development of a higher strength Monel® 400 alloy. The target application was steam turbine blades. The practice of the time was to melt a series of heats with differing chemistries to determine which had the desired effect. Aluminum levels were increased up to 5%. This work was the first of its kind on a nickel alloy to identify and take advantage of age hardening. U.S. Patent 1,572,744 was issued on February 9, 1926 for an alloy that became known as Monel K-500® alloy.

Other metallurgists, learning of the finding, began work to exploit this new technology. On April 2, 1930 U.S. Patent 1,755,554 was issued to the International Nickel Company protecting age hardening. Concurrent work in Europe was being done in Germany and France. Heraeus Vacuumscmelze of Germany patented a nickel-chrome alloy with a 6% aluminum addition in 1926 (UK Patent 286,376) and Society Anon. de Commentry of France received a patent in 1929 (UK 371,334).

The Stage is Set

The invention of turbojet engines for military aircraft in Germany by Hans von Ohain, (He-178) and Frank Whittle (W1X) in England led to the development of new age hardening alloys Tinidur (Fe-30Ni-15Cr-1.8Ti-0.08C) by Friedrich Krupp AG Hoesch-Krupp company in 1936 and Nimonic® 80 alloy by Mond Nickel Company, Ltd. in 1946 (UK Patent 583,162, December 11, 1946 respectively) Tinidur proved to not be weldable and was replaced with Cromadur (Fe-12Cr-18Mn) in circa 1944. Alloy 80 remains in use today.

High Temperature Alloys Become Superalloys in the 1940s

The automobile's internal combustion engine was adapted to power the airplane, adding demands for the alloys used for aeroengine parts. The power produced by engines grew, quickly increasing operating temperatures. New parts were also invented, such as the turbocharger and the supercharger. Flight added the aspects of risk, reliability, and strength to weight ratio to the performance of the internal combustion engine. In a car, if the engine failed, you were forced to walk. If an aircraft engine failed you would be lucky to be able to walk.

During the same time period the technology that had been developed for steam turbines began transforming, as gas turbines were developed. The need for alloys that performed at higher temperatures was similar to what was occurring in aircraft engines. These applications together provided the platforms for new high performance alloys.

The complexity of alloy composition advanced and we began to see the names of engineers we recognized and associate with superalloys on patents.

- 1945 Fe (bal), Cr (12-22), Ni (10 - 31%), Co (9 – 50%, W (2 – 6%), Mo (2 – 6%), Nb (2 – 6), C (.1 – .7%) alloy for gas turbines parts and such. Patent # 2,397,034 by Gunther Mohling.
- 1945 Fe (bal), Cr (18-23), Ni (8 - 20%), W (.75 – 2%), Mo (.75 – 2%), Nb (.15 – 1.5), Ti (.1 – 1%), Si (.4 – 2%), Mn (.4 – 3%), C (.2 – .35%), S (<.04%), P (<.04%) alloy for gas turbines and alike. Patent # 2,416,515 by Evans.
- 1945 Fe (bal), Cr (15 – 25%), Ni (2 - 25%), Co (10 – 40%), W (.5 – 15%), Mo (.5 – 5%), Al (>.5), Si (.<1%), B (<2%), C (<.35%), N (.25%), Total of .5 – 3% of one or more of Cb, Ta, Al, B alloy for gas turbines and such. Patent # 2,432,619 by Franks & Binder.
- 1946 Fe (bal), Ni (~55%), Co (5 – 15%), W (4 – 6%), Mo (13 – 18%), Al (2.5 – 3.5%), Si (.2 - 1%), Mn (.3 - 2%), C (<.15%) alloy for turbines, supercharger buckets, valves and such. Patent # 2,398,678 by Rudolf H. Thielemann.
- 1946 Fe (bal), Ni (50 - 70%), Mo (15 – 20%), Al (.5 – 5%), Mn (.5 - 4%), Si (.1 - .5%) alloy for superchargers, gas turbines and such; forgeable, machinable. Patent # 2,404,247 by Parker.
- 1947 Fe (bal), Ni (24-26%), Cr (14 – 16%), Mo (4 – 6%), Nb (1.5 – 2.5%), Si (.4 - .6%), Mn (.40 - .60%), C (.3 - .4%) forgeable, machinable, high temperature, high strength alloy exposed to airplane exhaust gases. Patent # 2,423,738 by Rudolf H. Thielemann

<u>Exploratory High-Temperature Alloy Research, 1946 – 1950</u>

In 1946 James D. Nisbet, a high temperature R&D engineer with GE Research Laboratory, Schenectady, NY, began a research project that would take four years to complete. This work, published in June 1946, proved to be more important than realized at the time in that it planted the idea in Mr. Nisbet that led to the founding of the company now known as ATI Allvac.

The foreword to *Exploratory High-Temperature Research*, written by W.E. Ruder of The Research Lab – The Knolls, does a good job of describing the environment in the gas turbine and high temperature alloy industries in 1950:

> "Early in World War II, with planes flying higher and faster, we were faced with the job of producing, quickly, alloys with high strength in a temperature range previously not seriously considered. From experience we knew that such alloys should probably contain chromium or aluminum, or both, for oxidation resistance; nickel or cobalt, or both, as bases: with wolfram or molybdenum, or both added to strengthen the matrix. We also hoped that metallic compounds, stable at high temperatures, might be found which would give us increased strength by a precipitation hardening treatment. By concentrating effort on the part of many laboratories and many trial and error experiments, some very good alloys were developed. During this period it was my constantly growing wish that someday, when we had time, a more logical and basic study of the effects of alloying might be undertaken. Early in 1946, Mr. Nisbet undertook to carry out just such a program. It was an ambitious and laborious project, involving most careful and detailed planning and close control of the many variables

encountered in melting, refining, casting, and testing. The field to be explored was almost limitless and had to be carefully surveyed before it was entered, if any new facts with broad applications were to be gleaned.

Physical metallurgy has made important advances during the past 40 years in its progress towards becoming an exact science. The effect of heat treatment and alloying on the structures of steels and in turn the effect of these structures on physical properties is now fairly well defined. Phase diagrams of the multitude of alloy combinations have been accurately determined. The mechanism of precipitation hardening is fairly well understood. The effect on physical properties of alloying pure metals except in certain limited fields, such as copper and aluminum alloys, has never been very thoroughly investigated. Our knowledge in this field is still quite empirical, and while many useful alloys have been produced, few basic principles of alloying have as yet emerged.

In the present work Mr. Nisbet and his associates have made a noteworthy contribution to the science of alloying and its effect on physical properties – broad conceived, carefully executed, and thoroughly analyzed in the light of existing knowledge. They have, through a basically experimental approach, evolved some interesting new concepts of alloying effects on physical properties, particularly in relation to temperature. Some 2000 alloys have been carefully prepared and tested for hardness, tensile strength, rupture strength at various temperatures allotropic changes, magnetic properties, and metallographic structure. The results are correlated and graphically presented. In the chapter on "Alloy Design" broad generalizations are presented - - admittedly too broad in some cases for the experimental evidence presented - - but challenging, nevertheless, and worthy of serious consideration by all who would prepare new alloys to meet new needs."

The experiment vacuum melted and centrifugal cast 6 pound heats at under 10 microns pressure and tested upward of a thousand compositions over the four years. Vacuum melting was chosen because it permitted tight control of chemistries and eliminated the random effect the atmosphere had on air melted compositions. The compositions tested were divided into four categories:

- Ternary: Fe-Cr-Co
- Quaternary: Fe-Cr-Co/Ni
- Quinary: Fe-Co/Ni-Mo/W
- Sextary: Fe-Cr-Co/Ni- Mo/W

A schematic and picture of the vacuum furnace used in the experiment are shown in Figure 3.

The results were separated and reported in two major categories. The first "Solid solutions and the effect of composition on the properties of solid solutions;" and the second, "Supersaturated solid solutions and the effect of precipitation on their properties."

The purpose of the work was to characterize alloys and the impact of alloying elements. No alloys were recommended to be put into service or patents applied for as a direct outcome of the research project. Raw materials of the highest purity were selected for the preparation of alloys and the vessel materials that would come into contact with the molten alloy were restricted to those which would not react and add impurities into the alloys.

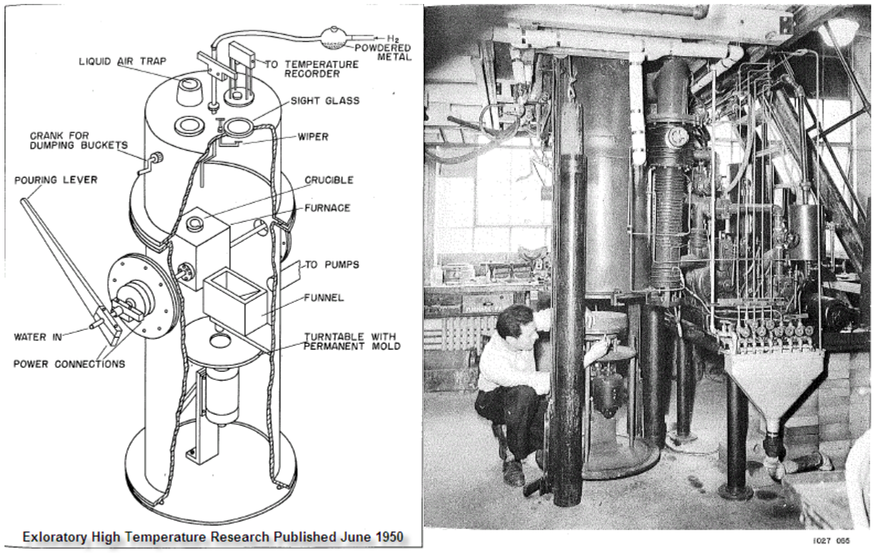


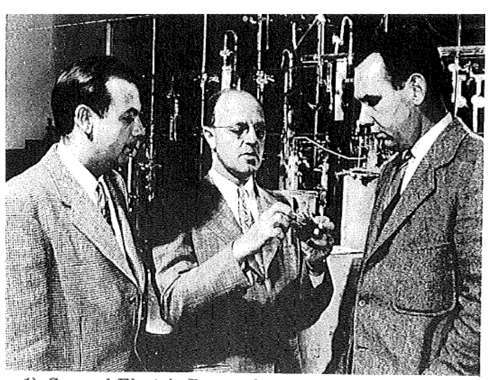
FIG. 6 VACUUM MELTING AND CASTING MACHINE

FIG. 11 VACUUM MELTING AND CASTING MACHINE - OPERATOR REMOVING CASTING FROM CENTRIFUGAL TABLE

Figure 3. 1950 VIM Schematic and Furnace

Mr. Nisbet made an interesting comment about the organization of the report, which can only be correctly stated in his original words. “Because engineers are primarily interested in the specific facts concerning specific materials, all of the data obtained on alloys tested are included in the appendix, tabulated in such a way that they may be quickly reviewed in a search for a material that will have certain desired characteristics. Because metallurgists are primarily interested in generalizations, these data are correlated and interpreted in the main body of the report.” I wonder if this comment is believed true today or has the study of metallurgy advanced in the past 60 years to where metallurgists and engineers have a more common character?

The vacuum furnace and melting techniques were experimental and therefore many refinements were necessary. One of the more significant challenges was “carbon boil.” Carbon was added as an aid in the removal of oxygen. The resultant “evolution of carbon monoxide from the molten metal caused during the carbon-oxygen reaction is enormous.” Work to improve the process had limited success. Carbon boil caused the molten metal to splatter and therefore loss of metal was common. In addition, carbon could not be fully removed and became a variable in the experiment.



1) General Electric Research
Dr. Holloman, Dr. Suits and Nisbet

Figure 4. Drs. Holloman and Suits, GE with James Nisbet, founder of Allvac Metals Company

Superalloys in the 1950s – Emergence of Vacuum Melting

A Brief History of Vacuum Melting

Vacuum melting was first performed in 1916 in Hanau, Germany by Dr. Wilhelm Rohn and W. C. Heraeus in a vacuum induction furnace of their design. Their work, focused on steels, led to the development of clean steels that enabled aircraft engine technology including the development of turbine engines for military aircraft used in WWII Ref.22. "

In 1945 a small vacuum furnace was built at NACA to melt high temperature alloy samples for evaluation. The furnace was built using two Curtiss-Wright air-cooled engine cylinder barrels welded end to end as the shell. Crucibles with a capacity of about 150 grams were slip cast from beryllium oxide and resistance heated by a wound coil of molybdenum wire. There was no way to pour the melt into a mold, and after a heat was made, it was frozen in the crucible, which had to be destroyed to reclaim the solidified casting.

The engineer on the program, Dr. Darmara, left NACA in 1946 to return to his former employer Utica Drop Forge and Tool Company as Chief Metallurgist. The work performed at NACA was the foundation that resulted in the development of vacuum induction melting in 1952. The Metal Division of UDF later became Special Metals.

In 1946 a designed experiment was started in Schenectady by James D. Nisbet "to satisfy the basic need for a systematic study of high-temperature alloy properties to obtain fundamental relationships, It was anticipated that this would result in principles which would form the basis for design of high-temperature properties and for the empirical design of high-temperature alloys." To reduce the variability of the results, melting in a vacuum was chosen. This work was not intended to prove the benefits of vacuum melting but to simply minimize the "effects of such impurities as oxygen, nitrogen, and carbon."

The result, however, was to plant a seed in the mind of a metallurgical researcher that the future of high-temperature alloys, not yet widely known as superalloys, depended upon the benefits only vacuum melting could provide. This seed was evident by a comment in the report saying "These vacuum melting techniques have been highly successful in permitting consistent production of high-purity materials, even those containing high percentages of chromium and titanium. It should not be difficult to adapt these techniques to full-scale commercial processes where high purity is required." Based upon this body of work investigating alloy compositions and vacuum melting that conclude in 1950, the stage was set for the development of superalloys, including alloy 718 and its derivatives, to meet the demands of rotating components in jet engines and eventually land-based turbines and oil and gas production.

Benefits of Vacuum Melting

The benefits of vacuum melting can be stated as follows: "There are several excellent reasons for the adoption of vacuum melting and casting procedures. The removal of atmospheric gases from the furnace prevents contamination of the melt by those gases and minimizes oxidation. The maintenance of a high vacuum, together with the introduction of the reducing agent into the system, permits removal of oxygen already in chemical composition with the metal. As a matter of fact, hydrogen tends to reduce nitrides as well as oxides. Gases already in solution tend to come out of solution as the pressure decreases. Finally, the combination of vacuum melting and degassing techniques permits the use of such highly active additions as titanium. It must be reiterated that even though these techniques are the best available and permit clean melting of materials far richer in active elements (such as chromium and titanium) than is possible with ordinary commercial methods, absolute purity was not attained."

"By 1950 – 1951 the demands of the jet engine age and the newer high thrust engine strained the possibilities of conventional air-melting method to the limit. Vacuum induction melting was tried again to resolve the difficulties in melting requirements. This time the seed fell on fertile ground."

"While many of these titanium- and aluminum-containing alloys were developed by the more conventional air-melting techniques, it was vacuum melting which served to accelerate alloy development and gave alloys creep-strength heretofore regarded as practically unattainable. The advantages of vacuum induction melting – the prevention of contamination of the metal bath and the hardening of elements by the interstitials, the precision with which chemistry could be controlled, the distilling off of "tramp" or low melting elements, and the overall cleanliness, gave to the aircraft engine consistency and strength that were critically needed. Vacuum induction melting became such a popular solution that there was a concentrated effort to put everything in a vacuum furnace."

The following comment made by Rudolph Thielemann in 1967 in a presentation to the European Investment Casters Federation is a testimonial to the role vacuum melting played in the success of superalloys and their role in gas turbines. "Since the early work on the exhaust gas driven turbosuperchargers, a great deal of progress has been made in developing high temperature alloys for critical gas turbine applications. In this effort, the development of new processes and techniques for melting, consolidating and casting the alloys has been very important. The introduction of the (vacuum) melting furnace has furthered the metallurgical progress in the alloy development more than any other single factor."

<u>Superalloy Producers and Trademark Names of the 1950s</u>

Allvac Metals Company, Monroe, NC

Allvac used two trade names. When the alloy was double vacuum melted (VIM/VAR) it was called "Allvac," as in "Allvac 718." When the alloy did not require VIM as its primary melt practice but was remelted using either a VAR or electro-slag remelt (ESR) practice, the trade name used was "Nickelvac," as in "Nickelvac X".

Other industry trade names are:

Hastelloy and Stellite – Haynes Stellite Company, Kokomo, IN
Inconel and Incoloy – Huntington Alloys, division of International Nickel Company
Nimonic – Mond Nickel Company, Ltd
Unitemp and Udimet – Special Metals Company, division of Utica Drop Forge

Trademarked names of alloys of the era still used today are:

Astroloy – Pratt and Whitney
René– General Electric Company Waspaloy – Pratt and Whitney

In the 1950s, superalloys comprised approximately 10% of a jet engine. This proportion grew to 50% by 1990 and has maintained this position in spite of the growth of competitive materials such as titanium, steels, ceramics and composites. The following is a list of producers of gas turbine, the engine model number and aircraft that were in production in 1959. Evolution and revolution occur in an industry over fifty years. This list shows some of the changes.

<u>Gas Turbines for Aircraft in 1959</u>

- Allison Division of General Motors, Indianapolis, IN
    - 501 turboprop, 726-740 lbs. thrust, for the C130
- Armstrong Siddeley Motors Ltd., Parkside, Coventry, England
    - Sapphire turbojet, 11,000 lbs. thrust, for the Hunter and Javelin
- Bristol Aero-Engines Ltd., Filton House, Bristol England
    - MK200 turbojet, 16,000 lbs. thrust, for the Vulcan
- Continental Aviation & Engineering, Detroit, MI
    - 356 turbojet, thrust not determined at the time
- Fairchild Engine Division, Deer Park, NY
    - J83 turbojet, 2,000 lbs. thrust, for a classified aircraft
- Pratt & Whitney Division of United Aircraft, East Hartford, CT
    - JT 3 and J57 turbojets, 9,700-16,900 lbs. thrust, for the B-52, F-100 (in 1959??), KC-135, DC-8, B707, B720
- SNECMA, Paris, FR
    - Atar 9 turbojet, 13,227 lbs. thrust, for the Mirage
- Westinghouse Electric Corp., Aviation Gas Turbines, Kansas City, MO
    - J34-WE46 turbojet, 3,400 lbs. thrust, for the T2J
- GE Aviation
    - J47, J79, J85, J93 turbojets

<u>ATI Allvac's Beginning Years</u>

James D. Nisbet, after working in research for GE, joined Universal Cyclops. His role was to build a research center for vacuum melting. Mr. Nisbet's interest was in high temperature metals. However, the work in the facility was by no means restricted to cobalt- and nickel-based alloys. As was the case in the industry at the time most vacuum melting was done on specialty steels. Jim became restless before long and asked for the resources to build a greenfield production plant for vacuum melting. Universal's leadership at the time is said to have believed vacuum induction melting to be a good laboratory process, but would not make a profitable business venture. As was often the case, Jim's convictions were strong. He left Universal Cyclops and went on the road, literally driving to visit his friends in the industry to sell shares in his future company, the Allvac Metals Company (short for "All Vacuum Melted.")

Jim chose Monroe, NC as the site for his company. Why Monroe? Monroe was certainly not a metals center. In fact it was the opposite: a small southern agricultural community. But Monroe had a train station so visitors could get there and natural gas was available to power the planned heating furnaces. It was close to Charlotte so it could be found on a map. And it was close to Jim's home, a farm just across the state line in Van Wyck, SC. Finally, the location was close to the home of Jim's brother Oliver, who would be a significant source of funding for the new company and its initial sales executive.

To raise money, additional shares were sold to the public. The underwriter was Interstate Securities Corporation, Charlotte, NC. The purchases of shares were over-subscribed. The capital was used to "set up a budget to include the purchase of equipment, inventory and to reserve sufficient working capital for initial production." Comments from Allvac's early employees say this may have been the last time that the Allvac Metals Company had excess working capital considering the rapid growth that followed.

In September 1957 Allvac began business with groundbreaking for the installation of a 500 lb. vacuum induction melting furnace. On September 16, 1958 the first VIM heat, Waspaloy, was melted. While this was being accomplished the company's rolling mills were being installed and plans were in place to ship its first order by year end. Market conditions were changing, with stretch-outs in defense aircraft build rates, but the emerging market for commercial aircraft helped buoy the market for superalloys. It is interesting to note that at this time another market was exploring the use of gas turbine…the automotive industry. This led to a handful of cars powered by turbine engines but of course this application for superalloys never materialized.

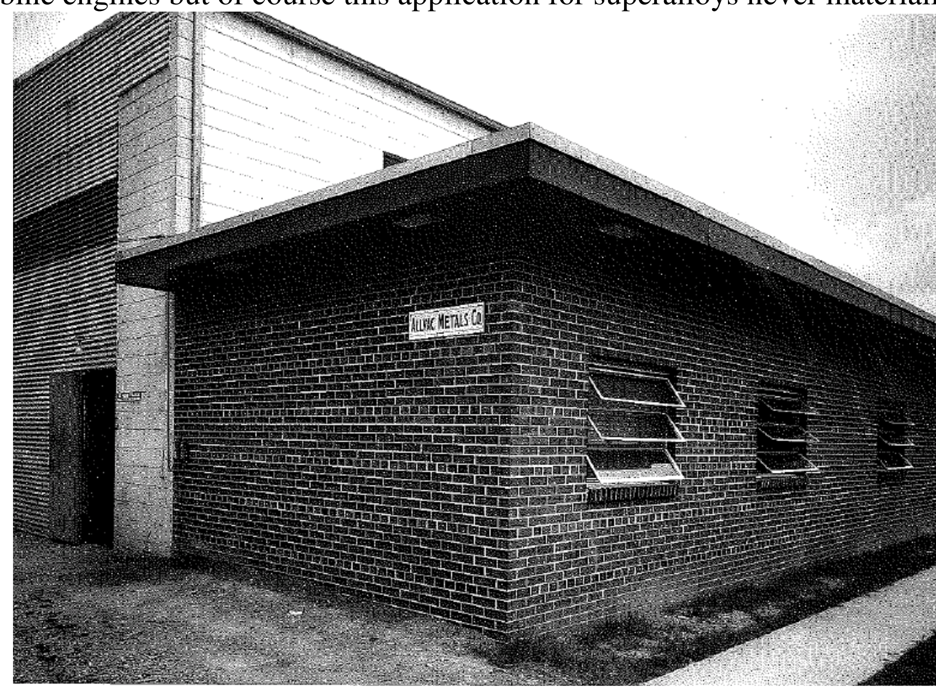


Figure 5. Allvac Metals Company, Monroe NC, 1958

Figure 6. Boeing 707 Maiden Flight December 20, 1957, powered by 4 – P&W JT4s or Rolls-Royce Conway Turbojets. First Passenger Flight October 26, 1958 by Pan American World Airways

In 1958 the company's primary alloys were Waspaloy and René41. The products produced were: ingots from 150 lbs. to 1500 lb, billets from 3″– 8″ diameter weighing up to 1000 lb, bars from .5″– 3″ diameter, plate .187″– 2″ thick x 20″ wide, and strip .060″ x 12″ wide. These products were made internally using the following equipment: 17″ x 35″ breakdown mill, 10″ x 20″ bar mill, centerless grinding and lathes for bar finishing, and swing grinders for conditioning

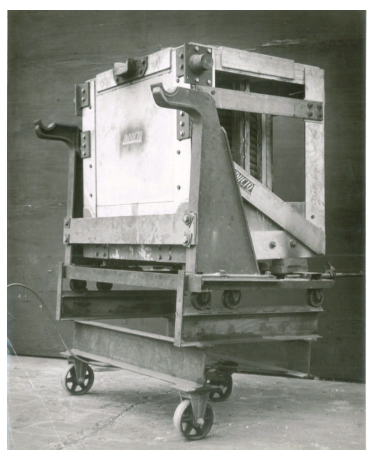
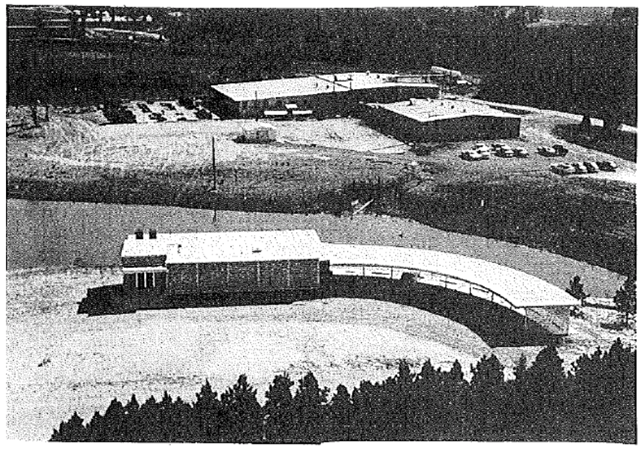


Figure 7. Allvac's 500-lb VIM Furnace

1959 was Allvac's second full year of operations and its first year of profitability, with total net income of $55. The story goes that this was a surprise to Jim so he went to discuss the issue with his finance executive. When asked what he had to do to show a profit, the financial chief simply said "that's the way it worked out." This level of integrity was a core characteristic of the company that still exists today.

VIM capacity was expanded to 3500 pounds and billet capability increased to include 12″ – 14″ billet weighing up to 2500 lb. By September 30, 1960, year-to date sales for three quarters were $493.393.53. This was respectable growth, considering the value of money in 1960 and that the company was just three years old.

Around 1961 Allvac took the position that it would only make and sell double vacuum alloys, regardless of specification. This position separated the company in the marketplace from other producers and set the stage for the consumers of superalloys to see the benefits of vacuum melting. The difference was, and still is, improved cleanliness that resulted in improved forgeability and superior properties for the end user.



The new laboratory office building containing 5,600 square feet was completed and occupied in September, 1961.

Figure 8. Allvac Metals Company 1961

In 1962 a 16,000-lb VIM furnace was added, giving Allvac the world's largest VIM furnace. VIM furnaces were also being operated by Universal Cyclops (2000 lb.), GE (500 lb.), Carpenter Steel, Allegheny Ludlum, Firth Sterling and Special Metals. By comparison ATI Allvac today operates many VIM furnaces in three facilities, with the largest pouring 50,000-lb ingots. Internal ingot breakdown capability was also added with the addition of a 2200 hp reversing blooming mill began rolling superalloys in 1963. To make ends meet, Allvac also melted and produced magnets. With the growing success of superalloy sales the Allvac Magnet Co. was discontinued.

By 1963 the superalloy industry, still referred to as high temperature alloys by many, was in a full growth mode. Pilot plant production methods were replaced by high volume production operations. Allvac operated its new 16,000-lb VIM feeding two VARs, one 12″ and the other 24″ in diameter. Vacuum melting had taken hold in a big way. The Allvac Metals Company's 1963 Annual Report described the state of the industry:

> "The plan is an optimistic one in which management has confidence. Like in all projected plans, "ifs" are important factors. If our share of the market is obtained; if prices become stable; if manufacturing costs continue to improve; if technical can meet the rigid specification requirements; and, if needed operating funds can be obtained, the plan can be achieved. Innovation is the answer to these "ifs" and in this department, Allvac leads the industry."

This statement is still true today at companies across the gas turbine and superalloy industries.

As of 2010, the Allvac Metals Company, now named ATI Allvac continuously produced superalloys for 53 years.

The 1960s and Beyond – Growth of the Superalloy Industry

By 1960 the melters of superalloys were a mixture of steel companies, forging companies with their own melt shops and one entrepreneurial company established in 1957 to specialize in superalloys. Between 1960 and 1965, vacuum induction melting became the standard for producing high temperature alloys, with the specialty steel companies, who were slow to accept the technology, being the large customers. Firth Sterling and Carpenter Steel soon installed VIMs.

The size of VIM furnaces expanded significantly as 'steel' mentality was superimposed on the emerging vacuum melting industry. In a 1963 AMM press release it was announced that a 60,000-pound vacuum furnace called Therm-I-Vac would be installed in Latrobe, PA. The company president was paraphrased as saying "Sooner or later all quality steels will be produced by vacuum melting techniques to eliminate gases and other impurities from the molten metal."

The Therm-I-Vac process was not a VIM but instead "steel made in electric furnaces, in the usual way, is poured from a ladle into an electric induction furnace housed inside a vacuum chamber. As the molten metal enters the vacuum, it literally explodes into thousands of tiny droplets as the vacuum sucks undesirable gases out of the steel." This furnace along with consumable vacuum remelt furnaces started production in 1964. It is concluded that the Therm-I-Vac furnace later was converted into a 30,000 pound VIM furnace still operated today.

This technological wave was unstoppable. Steel companies and steel forgings companies entered the vacuum melting business. The race was on to see which companies could capitalize on the trend to vacuum melt and who would operate the best, largest vacuum furnace.

The trend peaked in 1968 when Cameron Iron Works in Katy, Texas installed what was then the world's largest VIM furnace, at 120,000 lb capacity. It was built in a 120,000 square-feet facility housing the VIM furnace, a 50-ton 18,000 KVA electric arc furnace, a degassing chamber, and associated equipment. An article announcing the expansion quoted CIW as saying:

> "At the present aerospace is the biggest consumer, but oceanography may be just as big in the future. As man advances into space, metal requirements become more complicated because of heat and pressure, and the same is true in the ocean. As man presses his search for minerals and oil on the ocean floor, our research will have to keep pace."

CIW's strategy appeared to be based on a belief that the melting of specialty steels was moving from air melting to VIM. This transition didn't fully materialize, however; and in the early through the mid-1980s this furnace was melting 60,000-lb VIM heats, primarily of superalloys, and was dismantled in the late 1980s. CIW's comment, made over 40 years ago, has been proven nevertheless to be largely correct, although it did not anticipate the dramatic growth of commercial aerospace, keeping the aerospace industry the largest consumer of superalloys.

Alloy 718: The Most Widely Used Superalloy

In the world of superalloys, Alloy 718 is considered by many as the most successful and versatile nickel-based alloy ever invented. It is used extensively in the aerospace, power generation and oil & gas markets for highly engineered critical components in hot corrosive environments.

Additionally, its derivatives, such as alloys 706, 925 and ATI 718Plus® are also used in substantial quantities.

Alloy 718 was patented on July 24, 1962 by Herb Eiselstein to meet the demands of emerging jet engine technology. The patent was applied for in 1958. After nearly four years and two amendments, the patent was issued. Alloy 718 replaced highly alloyed steels and nickel-based superalloys.

The versatility of Alloy 718 is seen in the number of individual chemistries, melt regimes and forging (billetizing) practices. The permutations of these characteristics are greater than 2000! While every discrete permutation is not used, the number that are used is substantial. It is easy to conclude that Alloy 718 is versatile.

- Over 20 different chemistries of Alloy 718 are melted.
- 7 melt schemes are employed to melt Alloy 718 with many having multiple practices. (i.e. different melt rates)
- The hot working practices using presses, radial forges and large and small rolling mills, to meet end use mechanical and structural requirements, are too numerous to accurately estimate.

In addition to mill products, Alloy 718 and its derivatives are cast into parts. Some of the alloys such as Alloy 720 are vacuum atomized into powder that are HIPed into mill products and near net shape components for critical applications.

Alloy 718 has been in use for nearly 50 years. Will it be King forever? It is securing its place on the newest commercial engines (GEnX, Trents 1000 & XWB) for next generation aircraft (Boeing 787, Airbus XWB) as well as the latest gas turbine engine derivatives (F136) for the next generation of defense fighter aircraft (JSF).

The 718 family of alloys will have a dominant place in gas turbine engines for commercial and defense aircraft, gas turbine engines for municipal, industrial and marine power generation and downhole and above ground control devices for oil & gas exploration and production for many years to come. It is safe to say that its life span could approach 100 years.

<u>The Early Growth Years</u>

Brochures from companies producing superalloy in 1960 advertised the grades shown below. The predominant practice for melting ingots, air melt, was followed by remelt in a vacuum arc remelting furnace (VAR). The least used but the fastest growing approach was double vacuum melted ingots produced using vacuum induction melted (VIM) electrodes followed by VAR.

Grades produced in 1960 included:

- Astroloy
- Alloys B, C, D, N, W, X
- Nimonic 75, 80, 80A, 90, 95, 100, 105
- Alloy M-252
- Inconel 713C
- Alloy 700

- Alloy 718
- Waspaloy (trademark of Pratt & Whitney Aircraft, 1946)
- Rene 41
- Udimet 500ZB
- Alloy 901
- IN-100
- Vitallium
- Alloy L-605
- Alloy A 286 (iron-based superalloy)

<u>Trade Names</u>

A practice in 1960 was for mill producers to modify the chemistry of an existing nickel-base alloy and give it their own trade name. Often the alloy's number was not changed. The confusion this entered into the marketplace was significant considering the substantial difference in competing alloys of the same name except for the trade name. Examples of this include:

Hastelloy W	Ni 60%, Mo 25%, Cr 5%, Co 1%, V .3%, C .08%
Inconel W	Ni 74%, Mo 0%, Cr 15%, Co 0%, V 0%, C .04%, Ti 2.4%, Al .6%
Inconel 700	Ni 44%, Mo 3%, Cr 14%, Co 29.5%, C .1%, Ti 2.5%, Al 3.0%
Udimet 700	Ni 53%, Mo 5%, Cr 15%, Co 18.5%, C .12%,Ti 3.5%, Al 4.25, B .08%

<u>Key Events</u>

The following excerpts were taken from articles, press releases and company annual reports from their respective years. The size of VIMs built is surprising. Some of the actual period information contradicts what was operated in the 1980's and beyond.

<u>1963</u>

- Latrobe Steel Company "…installation of the most complete and flexible vacuum melting facility in the industry…" VIM "Therm-I-Vac and VAR
  - "After steel is made in an electric furnace in the usual way, it is poured from a ladle into an electric induction furnace housed inside a vacuum chamber. As the molten metal enters the vacuum, it literally explodes into thousands of tiny droplets as the vacuum sucks undesirable gases out of the steel." J.E. Workman, President Latrobe Steel Co. in a Metal Market Article in 1963.
- The Vanadium Alloy Steel Company or VASCO operated CVM, consumable vacuum melting, furnaces producing from 3,000 to 26,000 lbs. heats. The ingots were for research and production.

<u>1964</u>

- Superalloy market reported to be $20M
- Union Carbide's Stellite Division, Kokomo, IN producing vacuum melted alloys (VAR) went into full production
  - "Improved ingot surface"
  - "Carbide segregation and "freckling" (undesirable intermetallic compounds) have been eliminated."
  - 30″ dia. 15-ton ingots

- Eastern Stainless Steel Corp., Baltimore MD, formed Kastalloy Metals Co. to produce and distribute remelted alloys for the casting industry.
    - 718 cryogenic fuel lines for the Saturn C booster rocket, Waspaloy engine components for the new A11 supersonic fighter, A286, Rene 41, Astroloy, N-155, L605, and Hastelloy all for jet engines.
  - Special Metals, Inc. (recently separated from Kelsey-Hayes and prior to being purchased by Allegheny Ludlum) begins operating an 11,000-lb VIM.
  - Mill product pricing by the piece instead of by the pound is encouraged by the aerospace industry. An executive of the time was said to have found piece pricing a new concept and was quoted as saying he "would have to sleep on it." The change was considered another way of negotiating lower pricing.
- <u>1965</u>
  - Allvac was purchased by Vanadium Alloy Steel Company Cameron Iron Works, Houston, TX is world's largest vacuum melter
    - Integrated company operating VIM and VAR (34″diameter), billetizing and forging.
    - Operated a 10ton VIM in Livingston, Scotland and two VARs
    - "Vacuum melted high density nickel based alloys in billets, bars, slabs, sheet and plate."
    - Discs, engine shafts, turbine wheels of 901, Waspaloy, Astroloy, 718, A286
  - Universal-Cyclops Steel Corp. renamed to Cyclops Corp.
- <u>1966</u>
  - Special Metals Corporation, New Hartford, NY, a subsidiary of Allegheny Ludlum, began construction of a 30,000-lb VIM. Operation began in 1967
    - Doubled VAR capacity by adding 2 additional VARs
  - Latrobe Steel Company, Latrobe PA, operates VARs
- <u>1967</u>
  - Cameron Iron Works installs a 60ton VIM at its new facility In Cypress, TX. Also installed were hot and cold rolling mills roll gauges down to .008″. This expansion targeted superalloys for rotating parts for the growing aerospace industry.
  - Superalloy Capacity (believed to be VIM capacity not mill product capacity)
    - 1957: 750 tons
    - 1967: 90,000tons
- <u>1968</u>
  - U.S. produced 80% of jet engines for the "free world market."
  - The buildup of engine production due to the Vietnam War was projected to end by 1971.
  - The military accounted for 80% of turbine and turboprop engines through the middle of the 1960s. Production peaked at over 14,000 engines.
  - Commercial engine production was forecast to reach 5000 engines annually by the end of 1970
  - Key military programs included F-111, A-7, Air Force FX and Navy VFAX

<u>Alloys and Applications</u>

The following charts were presented by Rudolph Thielemann, at the European Investment Cast Federation Conference in 1967, showing primary alloys used for turbine components of the day.

High Temperature Alloys Used For Turbosupercharger Blades and Discs

17W alloy wrought blades/discs Ni 19%, Cr 12%, W 2.2%, Mo 1%, C .5%, Fe bal
16-26-6 wrought discs Ni 25%, Cr 16%, Mo 6%, C .1%, Fe bal
Vitallium cast blades Cr 27%, Mo 6%, Ni 2%, C .25%, Fr bal
6059 cast blades Ni 32%, Cr 23%, Mo 6%, C .4%, Fe bal

Air Melted Cobalt Base Alloys for Turbine Blades and Vanes
X-40 cast turbine blades/vanes Cr 25%, Ni 10%, W 8%, C .4%, Co bal
WI-52 cast turbine vanes Cr 20%, Ni 3%, W 11%, Nb 1.5%, C .4%, Co bal
S-590 wrought turbine blades Cr 20.5%, Ni 20%, W 4%, Mo 4%, Nb 4%, Co bal
S-816 wrought turbine blades Cr 20 %, Ni 20%, W 4%, Mo 4%, Nb 4%, Co bal

Gas Turbine Disc Alloys
Discaloy wrought turbine disc Cr 13.5%, Ni 26%, Mo 2.7%, Ti 1.7%, B .005%, Fe bal
A-286 wrought turbine disc Cr 15%, Ni 26%, Ti 1.7%, B .005%, Fe bal
Rene 41 Cr 19%, Mo 10%, Co 10%, Ti 3.1%, Al 1.5%, B .005%, Ni bal
Waspaloy Cr 19.5%, Mo 4.3%, Co 13.5%, Ti 3%, Al 1.3%, B .006%, Zr .06%, Ni bal
U-500 Cr 18%, Mo 4%, Co 18.5%, Ti 2.9%, Al 2.9%, B .006%, Zr .05%, Ni bal
U-700 Cr 15%, Mo 5.2%, Co 18.5%, Ti 3.5%, Al 4.3%, B .03%, Ni bal

Vacuum Melted Wrought Nickel Base Alloys
Alloy 901 wrought turbine disc Cr 12.5%, Ni 42%, Mo 6%, Ti 2%, B .005%, Fe bal

Was there ever an 'Inconel' alloy?

Today, the term 'inconel' is improperly used to describe alloys 600, 718, X750 and their derivatives. This common mistake is made in discussions, formal papers and patents by technical and non-technical people employed by companies ranging from independently owned machine shops to multinational engine primes worldwide.

The original Inconel was a trademarked alloy family developed and marketed by Huntington Alloys in the formative years of the superalloy industry. The original Inconel's chemistry was Ni 78%, Cr 14.5%, Fe 7%, C .05%, and closely resembles alloy 600☹ Ni 72%, Cr 15.5%, Fe 8%, C .075%). Huntington's development was funded by the International Nickel Company as an outlet for the nickel they mined. The alloys developed include alloy 718 and its derivatives, the namesake of the conference for which this paper was written. Early success and strong marketing helped transform the Inconel brand into the industry ubiquity that it is today, similar to Kleenex, Jell-o and other trademarks that have become generic through common misuse.

The Story of Boron

Boron plays an important role in helping refine the structure of superalloys. Did the innovation of boron control come from research or chance? Here is what happened.

All-prime raw materials were used to make superalloy heats until volume grew. When volume grew, so did the need to cut costs. One step taken to reduce cost was to use scrap as part of the charge design. Before long, it was noticed that heats melted using scrap had improved properties. The investigation that followed found the significant difference in heats with and without scrap was the boron level. Studies confirmed this, and boron's role in alloy 718 and other superalloys was solidified forever.

Where did the boron come from? Boron was a residual in scrap from ingots that were air melted only by companies whose primary products were specialty steels. The revert (internal scrap) streams in these companies contained boron passed on from prior heats. Therefore, when revert was used in the charge makeup, boron was inadvertently added though not specified.

A Brief History of Superalloy Powder

Powder Metallurgy (PM) superalloys have been used in aircraft turbines for approximately 40 years. They originated from the contributions of many scientists and engineers in both government and private industry. The first commercial development began with vacuum induction atomization at the Federal-Mogul laboratory in Ann Arbor, Michigan. Although a request for quotation for high purity superalloy powder was released by Wright-Patterson Air Force base in 1965, subsequently produced by Hoganaes, early development was primarily driven by Pratt & Whitney Aircraft. They believed that powder metallurgy would be an improved method for making superalloys for highest temperature, highly stressed parts for a new generation of fighter aircraft engines. The time frame was the late 1960s.

The earliest development involved PM Astroloy, an alloy similar to cast/wrought 700. Pratt & Whitney then selected a vanadium bearing, higher cobalt, lower molybdenum alloy named IN-100, originally developed as a cast/wrought alloy by the International Nickel Corporation. Pratt & Whitney experimented with as-HIP compacts that were isothermally forged, but chose to move to HIP and extrude, or direct extrusion. Full scale consolidation was performed by hot extrusion at Cameron Iron Works in Texas who had been using hot extrusion for manufacture of oil field equipment. The superalloy extrusions were cut into sections and isothermally forged into disc preforms for high pressure turbine disks for the F-100 engine to power the F-15 fighter.

During the early 1970s, General Electric was developing Rene 95 using cast/wrought methods before cross rolling to heavy plate. This proved to be a difficult task. GE approached the Crucible Steel Company, Pittsburgh, PA, owned by Colt Industries, to manufacture Rene 95 in their 600 pound atomizer. Under construction was a new facility in Oakdale, PA which would house a 5000-pound vacuum induction atomization unit and a 45″ diameter HIP unit purchased from Battelle Laboratories. This facility is now ATI Powder Metals.

The first Rene 95 qualification heats were produced in the 600 pound research unit and the powder transferred to the Oakdale facility for screening, canning, evacuation, and hot isostatic pressing. Rene 95 was initially applied in the T-700 engine for the U.S. Army's Blackhawk helicopter. GE also used the alloy in the as-HIP and heat treated condition for the turbine spool of the F-404 engine for the F-18, the F-110 engine for the F-16 and eventually the B-1 bomber.

Federal-Mogul was acquired by Special Metals Corporation and became qualified for Rene 95. Rene 95 powder was also purchased from Carpenter Steel.

In 1980, at the Farnborough Air Show, an F-18 experienced engine failure attributed to an as-HIP René95 turbine disc. GE Aircraft elected to remove PM superalloys from all parts where it was not absolutely necessary and inserted direct age 718 alloy process by cast/wrought methods. The remaining PM parts were processed using extrusion and isoforging. As-Hip material remained in military versions of the T-700 Blackhawk engine until 1987 and is still used today as an alternative for high pressure turbine blade retainers where fatigue was a secondary failure mechanism. René88 DT eventually replaced almost all Rene 95 extrude and isoforged material.

During the early 1980s Snecma, the French turbine manufacturer, began utilizing as-HIP low carbon Astroloy for military fighter engines and eventually developed N-18, a lower cobalt, higher molybdenum alloy similar to IN-100 without vanadium but with a small hafnium addition.

By the mid-1980s the aircraft turbine industry had moved to a unified philosophy of one alloy in finer powder forms, extruded to full density and isothermally forged into near-net preforms or mults from which individual parts were produced. At the same time Garrett AiResearch, who became Allied Signal Inc. before becoming Honeywell, adopted the as-HIP philosophy for auxiliary power unit turbine discs. While propulsion engines, particularly fighter jet engines, experience many throttle changes during flight, requiring extended low cycle fatigue life as engine loads rise and fall, auxiliary power units run more like diesel engines, rising to full load after startup and running steadily in this range for nearly entire flights. This design philosophy must recognize creep and high temperature strength as primary failure modes with low cycle fatigue as a secondary failure mode, much like the role of a high pressure turbine blade retainer ring in a propulsion engine. As-HIP material filled this role very well. In addition to costing less than an extruded + isothermally forged part, as-HIP material could still withstand a higher sensitivity and more rigorous non-destructive ultrasonic inspection than cast and wrought materials, and was typically easier to machine. The nearly isotropic properties enjoyed in an as-HIP disc also simplified design criteria across the hub, web, and outer rim of a small disc. Garrett utilized PM low carbon Astroloy, a slightly lower carbon variant of the original material created in Ann Arbor Michigan at Federal Mogul. Special Metals Corporation and Crucible Compaction Metals became qualified sources. It is still in widespread use today along with PM alloy 720, chemically similar to the original cast and wrought Udimet 720.

While the large engine manufacturers in the United States were developing their PM superalloy processes, Rolls-Royce engineers utilized cast and wrought alloys including 718 and 720 alloys as their disc materials. Rolls-Royce recently introduced RR1000, a superalloy containing tantalum and hafnium, in the Trent 1000.

This brief history of the development, primarily in United States, of PM superalloys, cannot give proper credit to the many engineers at industry laboratories and government installations, including NASA and the US Air Force. It is merely an attempt to provide an overview of the timeline that moved superalloy powder from a laboratory experiment to a core technology of military and commercial aircraft turbines.

Specification Evolution

Alloy 718 Specifications

The first issue of AMS 5662 was dated 9-1-65. It has been revised a dozen times with the current revision being ‘M’. Through the years and specification revisions the properties of metal produced to the specification is essentially unchanged. Major element percentages and their ranges have not changed although a few additional elements are now controlled that were not listed in 1965. Tensile and yield strength, heat treat parameters and grain size requirements are the same with only transverse elongation and reduction of area properties having been reduced.

The first end user specification identified for alloy 718 was issued on 3/20/62. Revisions have exceeded AMS revisions up to three times. Chemistry percentages and ranges of major elements are largely unchanged but most minor elements are more tightly controlled. As with the AMS 5662, elements are now controlled that were not initially specified. In 1962 single vacuum melting (VIM) was permitted where double melting is now required (VIM + consumable remelt). Grain size, not specified, in 1962, is typically controlled to requirement finer than the AMS specification. The 1962 four page specification has grown to as many as nine pages.

Waspaloy Specifications

The new issue of AMS 5708 was dated 7-15-63. It has been revised ten times and has grown from three to ten pages. Single melting in a VIM or double melting with the second melt being a consumable remelt is unchanged over the forty-six years that have passed since the initial specification was issued. While the specification is unchanged, industry melt practice is changed to VIM followed by a consumable remelt. Like alloy 718, the major element percentages and their ranges have not changed although the same few additional elements are now controlled that were not listed in 1963. Stress rupture requirements and heat treat parameters are the same.

The first end user specification for Waspaloy was issued on 7/15/60. Specification changes are similar to those described above for AMS Waspaloy and end user alloy 718. Chemistry percentages and ranges of major elements are largely unchanged but most minor elements are more tightly controlled. As with the AMS 5708, elements are now controlled that were not initially specified. In 1960 single vacuum melting (VIM) was permitted where double melting is now required (VIM + consumable remelt). Mechanical properties are unchanged.

To summarize the evolution of specifications for alloy 718 and Waspaloy, the changes in the specification, and the quality of the metal produced, reflect changes that vacuum induction melting and remelting brought to the superalloy industry. Among vacuum induction melting's value-added benefits, are dramatically improved chemistry control and cleanliness and the ability to control minor elements to tighter limits.

Superalloys Today

Over the years superalloy producers have come and gone. Today there are three major U.S. based producers and a similar number based outside the U.S.

Available Product Forms

Superalloys are available in every mill product form including:

- Ingots and billet for open and closed die forgings and extrusions
- Slabs for rolling into plate and sheet
- Forged round and rectangular billet and bar
- Forged cylindrical, tapered and stepped shafts
- Rolled round, rectangular, shaped bar and coil
- Hot rolled plate and sheet

- Cold drawn bar, rod, coil and wire
- Cold rolled sheet and strip in standard and precision gauge tolerance
- Hot extruded and cold pilgered tubing

Ingot and mill products are produced using a variety of single, double and triple melt techniques including the following.

- Electric arc furnace (EAF)
- EAF and argon oxygen refined (AOD)
- EAF or EAF/AOD followed by electro-slag (ESR) or vacuum arc (VAR) remelted
- EAF/VAR/VAR
- Vacuum induction (VIM) followed by ESR or VAR
- VIM/ESR/VAR

Mechanical properties and grain structures differ based upon needs of downstream processing and end use applications. Alloy 718 and superalloys have excellent versatility as seen in the applications and components they enable.

<u>Applications</u>

- Commercial and military jet engines
- Rocket motor components
- Auxiliary power units (APUs)
- Power turbines for municipal, industrial and marine applications
- Oil and gas exploration, production and flow lines
- Defense systems
- Locomotive engines
- Heavy vehicles and selective light vehicles
- Tooling for extrusion and forging

<u>Components</u>

- Components in jet engines, APUs, industrial and marine gas turbines include rotating and static parts such as turbine and compressor cases, disks, shafts, blades and vanes, and fasteners.
- Components in municipal gas turbines include turbine wheels, spacers, stub shafts, compressor rotor bolts and fasteners.
- Oil and gas industry in downhole, subsea and above ground components including pup joints, safety valves, side pocket mandrills, packers, gate and ball valve parts and blowout preventers.
- Diesel engine valves and other engine parts
- Extrusion and forging dies where temperatures exceed the limits for tool steels.
- Superalloys facilitate commercial applications essential and irreplaceable in defense systems such as aircraft and weapon systems for national security.

<u>The Superalloy Committee of The Specialty Steel Industry of North America</u>

In 1988 the U.S. producers of superalloys formed an association to represent the industry's interests in Washington D.C. and develop statistics on the size of the superalloy market. The

Superalloy Committee (SAC) formed within an existing association for specialty steel companies. The organization is currently called SSINA, the Specialty Steel Industry of North America. Looking back at the history of the superalloy industry it is not surprising that the industry leveraged its relationship with specialty steel to form its industry association. It's also interesting to note that the symbiotic relation between superalloys and specialty steel is as important today as it was in the dawning and during the growth of the superalloy industry.

The SAC's impact on the superalloy industry has been, and continues to be significant, thanks to the works of industry executives from the superalloy companies and the team of attorneys and economists who helped manage the SAC. A topic addressed earlier in this paper is "What's the definition of a Superalloy?" The development history is complex and sometimes unclear. One of the early tasks of the SAC was to clearly define which nickel-, cobalt- and iron-based alloys are superalloys. The Committee categorized these alloys, removing the confusion. The categories are:

1. Heat Resisting Alloys
2. Corrosion Resistant Alloys
3. Nickel-base Superalloys
4. Electrical Alloys
5. Iron-based Superalloys
6. Cobalt-based Superalloys

This categorization accomplished two important distinctions. First it recognizes the differences in nickel-, cobalt- and iron-based superalloys, and secondly it recognizes the importance of other nickel alloys without confusing them with superalloys. If you would like to learn more about the Superalloy Committee please visit the Committee's website at www.ussuperalloys.com.

The Superalloy Committee is active today, carrying out the mission set forth by its founders, appraises the needs of the industry to determine how the SAC can aid in the growth of the Superalloy Industry and works closely with Congress and governmental agencies to assure the interest of National Security are met by the superalloy industry.

Superalloys Tomorrow

<u>What does the Future of the Superalloy Industry Look Like?</u>

Three factors gave life to and nurtured the superalloy industry: new alloys enabling performance at higher temperature; vacuum melting, providing consistent repeatable processing for cleanliness; and the growing jet engine market, driving superalloy technology.

The invention of new alloys led to the need for vacuum melting to provide cleanliness required for consistent performance demanded by jet engines. Single vacuum induction melting led to double vacuum melting with vacuum arc remelting following the vacuum induction primary melt. To move alloy cleanliness to new levels, a third melt, electro slag remelting, was added between VIM primary melting and the VAR final melt.

But technology demands continued to evolve requiring powder technology and isothermal forging to producing hardware from alloy chemistries too segregation-prone for VIM/VAR melting. While new and improved chemistry was being developed and alloy cleanliness was improving, hot working of the ingots became the next area of focus. Billetizing techniques became highly engineered processes providing fine grained, equi-axed superalloy billet to the closed-die and ring rolled forgings operations that followed. These refined structures' finer, more consistent grain size allowed jet engine design engineers to raise the bar for component performance and design to tighter standards without lowering safety margins. So a fourth element: highly engineered billet was added to the three cornerstones supporting the superalloy industry.

In summary, today's superalloy industry is the product of elements:

- Alloy development
- Vacuum melting
- Engineered billetizing
- Deformation Processing
- The technological demands of jet engines.

What comes next? The future cannot be seen with certainty, but there is a way to look ahead. If recent trends are carefully appraised and designers of products made from superalloy are consulted as to their needs, the future starts to clarify. Today superalloys are an enabling technology for highly efficient gas turbines for aircraft and municipal electrical power generation and the safe recovery of oil and natural gas buried miles beneath the earth's surface and sea beds. The needs of these end uses critical to our way of life will push superalloys to new levels of quality, reliability and in-service performance.

Forecast for Cast/Wrought Processed Superalloy Products

<u>More powder alloys converted to cast/wrought</u>

Reasons for this trend:

1. pressure to reduce the cost of making the ingot.
2. cost advantage of hot working ingot to billet using press and radial forging techniques compared to extrusion
3. forging offers greater flexibility in billet diameter without adding the cost of extrusion tooling
4. cost-effective forging campaigns require fewer ingots to be forged at one time than extrusion.
5. lack of powder and isothermal forge capacity to fulfill industry needs

<u>New alloys</u>

The need for cost-effective alloy alternatives that offer improved performance at elevated temperatures is a constant. A recent example is ATI 718Plus® alloy.

<u>Existing alloys improved through chemistry refinements and tighter elemental control</u>

Little changes can have big returns in the performance of a superalloy during forging as well as in the final part.

<u>Cleaner microstructures</u>

The superalloy industry exists today because cleanliness delivers better performance in the end product. The future will likely include breakthroughs in this area.

Ingot diameter increases

36-inch 718 alloy triple melted premium quality ingots are available today for use in industrial turbines. Approval of 24-inch 718 ingots for jet engine applications cannot be far behind.

Billet diameter increases

A barrier to larger diameter superalloy billet has been removed: a 10,000 ton billetizing press coupled with a 700mm radial forge began operating in late 2009 at ATI Allvac. The facility is approved to produce premium rotating quality billet including alloys 718, 720 and Waspaloy. Fine grain billet up to 16-inch diameter will be developed. Larger diameters may follow as the capabilities of the facility are fully developed.

Forged billet and bar with engineered structures availability

Finer grain will be available, offering closed-die forgers greater flexibility in processing, and engine designers an additional parameter to consider if desirable in their application. Binary grain structures: i.e., coarser or finer grain in the center of the billet and finer or coarser grain from mid-radius to surface in a predetermined, predictable, engineered pattern will become available. This forecast is undoubtedly further in the future than others discussed. It will also require significant development as well as a compelling business case.

Engineered mechanical properties

The new forging capability discussed above changes the game in superalloy forging. Superalloy strength at elevated temperatures often makes the billetizing press subservient to the alloy being forged. With the 10,000 ton press, this is no longer the case. Superalloy billet forged on the 10,000 ton press will be subservient to the press. Since this process is highly automated, variability is reduced and repeatability increased. Such precision control opens the door to developing forging billet and bar with optimized properties and structures specifically matched to the component design.

Forecast for Superalloy Powder Products

Heat size increases

Significantly larger heat sizes for powder atomization will become approved for premium rotating quality applications.

New alloys

Higher turbine operating temperature gave birth to and nurtured the superalloy industry. This need will continue to drive the development of new powder superalloys. ATI Powder Metals, located near Pittsburgh, operates an R&D laboratory with extensive sub-scale capabilities that will be a platform for new alloys that solve today’s problems and remove barriers to the next generation of gas turbines.

Multi-alloy compacts and billets

If one superalloy is good, two may be better. Powder compacts will be designed with multiple chemistries of a single alloy or multiple alloys. Processing will be engineered to create preforms that can be closed-die forged and heat treated into components with highly engineered multiple properties.

Multi-alloy cast–wrought/powder billets
Improved efficiency, low emissions and cost effectiveness will drive development of disks made from hybrid billets comprised of cast–wrought/powder superalloys. These highly engineered superalloys components will enable dramatically advanced future generation gas turbines.

Some Things Change with Time, Some Things Don't

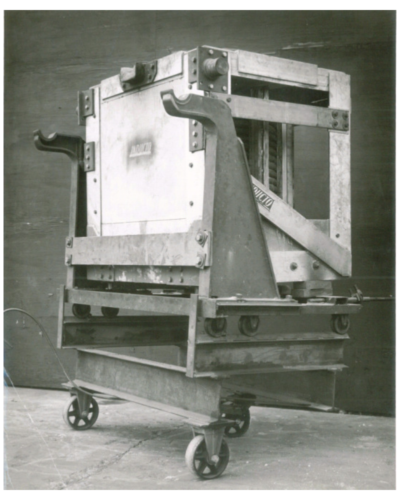
This paper addresses the past, present and future of the Superalloy industry. The following collection of contemporary references shows that while some things change with time, some things remain the same. These are presented for your perspective and entertainment. Many of these words will ring with irony in the ears of today's engineers.

Some Things Change with Time
Throughout the 1940s and well into the 1950s it was said that the qualification of a new superalloy for gas turbine applications, jet and municipal power took one to two years. Today that time is extended often a decade or more. The reasons for this is the existing materials are working; therefore advancements can be made in a slow, conservative, risk averse manner emphasizing reliability.

"As the alloy has high strength at very high temperatures, it is somewhat difficult to forge. The most satisfactory results are obtained with small ingots having a cross section not greater than about four inches square" Rudolf H. Thielemann, Ni-Mo-co-W-Ti alloy patent #2,398,678, March 1, 1941 (predecessor to Waspaloy)

Process Capabilities Have Changed

- The typical VIM heat size was 500 pounds in 1957. Today 45,000 pounds is common.




Products Have Changed

- In the early days of superalloys mill products were offered as rounds from .25″ up to 4″ diameters and rectangles with up to a 4″ cross section. Today mill products are produced as rounds from fine wire to 14″ diameter and larger.

Superalloys Produced Have Changed

- In the 1960s approximately 15 to 20 high-temperature alloys were melted. Today there are more than 20 alloy 718 chemistries melted with most meeting the ASTM B 637 specification.
- New alloys have been invented but only a few have found sizable applications. Included in the list of successful new alloys are alloy 720, alloy 925, RR1000, and ATI 718Plus® alloy.
- In the nickel chapter of the 1948 Metals Handbook nickel alloys such as alloy 600 were typically melted in 6000-lb coreless induction furnaces or 10,000-lb electric-arc furnaces. The charge, typically about 4650 lb and 9200 lb respectively, produced an 18″ x 18″ x 40″ ingot. Air melting was the production process of the day. Today nickel alloys such as alloy 600 are melted in electric furnaces, typically 20 to 30 tons, and then refined in AOD vessels. The product of this melt could be an ingot or an electrode. Electrodes are remelted using ESR or VAR techniques into ingots up to 40″ diameter. More complex precipitation hardening nickel alloys such as alloy 718 receive primary melting in VIM furnaces up to 45,000 pounds, where one or more electrodes are poured, before remelting once or twice in ESR and VAR furnaces.

Some Things Don't Change With Time

"*Since the inception of Allvac Metals Company some months ago*, the market for high temperature metals has changed from a "seller's" market to a "buyer's" market. Many of the potential customers are associated with the defense business. Recent economy measures in Congress and drastic cut-backs in the Defense Department have caused the customers to adjust their plans and inventories accordingly." January 1958

"Cermets and ceramics continue to be prime hopes for overcoming high temperature problems. The feeling in the industry is that a breakthrough in ductility isn't too many years away." *Aviation Age* 1958-1959

"Machining the 'UNMACHINABLE' is perhaps the number one problem …nickel-base and cobalt-base alloys…this could mean an increase in machining cost …" *Aviation Age* 1958-1959

"The *new engine* boosts the speed of a conventional jet by 40 miles an hour, increases thrust by at least 25 per cent and yet offers from 20 to 25 per cent less fuel consumption at cruise level."
JT3D engine in 1962 (4 engines powered the Boeing 707 at 640 miles per hour)

"The plan is an optimistic one in which management has confidence. Like in all projected plans, 'ifs' are important factors. If our share of the market is obtained; if prices become stable; if manufacturing cost continue to improve; if technical can meet the rigid specification requirements; and, if needed operating funds can be obtained, the plan can be achieved. Innovation is the answer to these 'ifs' and in this department, Allvac leads the industry." 1963 Allvac Annual Report

"…the routine metal manufacturers were skeptical of the future economics of vacuum melting; whereas, the technical people closely associated with the process were making a strong technical case for its value used in melting nickel-based superalloys." 1967 -- Jim Nisbet, International Vacuum Metallurgy Conference

"…the insatiable demands of the turbine engines that power our high performance military and commercial engines, as well as our industrial turbines, have motivated a search for new materials. These materials are for use at high temperatures in one of the most complex and difficult environments ever encountered. During this entire period, the materials technologists have met these demands with ever-improving superalloys, which, in addition to their increased use in engines as temperatures are pushed further upward, have become important to many other applications." G. Mervin Ault, Director of Space Technology and Materials, NASA Lewis Research Center. 1972 Foreword in the book The Superalloys.

A Few of the Pioneers of the Superalloy Industry

The Hall of Frame of superalloy pioneers in alloy development and processing and the many iconic engineers who have and continue to grace the industry exists only in the Conference proceedings and papers written on the subject and the minds of those in the industry. The information is widely disbursed and forgotten as time passes. The list below, admittedly incomplete, is an attempt to list some of the people who helped form the Superalloy industry and describes their contributions.

<u>Rudolf Thielemann</u>

- Started his career with General Electric, Schenectady, NY
- First to recognize Vitallium as an alloy for gas turbine blades
- In 1945 joined Pratt & Whitney Aircraft
- Patent holder of cobalt-base alloys (1941-1966) that led to the invention of Waspaloy® in 1946, named after P&W's popular radial internal combustion engine, the Wasp engine.

<u>Dr. Gunther Mohling, Allegheny Ludlum Steel Company</u>

- The 1984 Superalloy Conference was dedicated to Dr. Mohling for his extensive body of work on superalloys starting in the late 1930's when advancements required individual creativity and were largely novel.
- First to vacuum induction melt a large heat, ten tons, of aluminum and titanium containing strengthened superalloy. This accomplishment was achieved at the laboratory he founded in Watervliet, NY in 1950. Alloys melted included Waspaloy, A-286 (co-inventor) and M252.
- Produced the first production electric vacuum arc remelting of superalloys in 1953.

<u>James D. Nisbet</u>

- Graduate Clemson University, SC in 1937 and was hired by General Electric, Schenectady, NY. He brought with him little but his ambition and a love for flying.
- After initial engineering positions he settled into the research center and began working on high-temperature alloys for power turbines.

- Performed extensive research on high temperature alloys melted in a vacuum to eliminate variation caused by the reaction of the alloys with air.
- In 1946 he embarked on a research project that lasted four years.
- In June of 1950 the project was complete and a 316-page report titled Exploratory High-temperature Alloy Research and 288-page volume of data and reference materials were published. The report's abstract describes the work well: "A high-temperature exploratory metallurgical research report covering four years of experimental work and the evaluation and interpretation of test results on several hundred alloys involving combinations of seventeen different elements."
- Hired by Universal-Cyclops in 1954 to build a research facility to perfect vacuum melting as a production process.
- Founder of Allvac Metals Company, Monroe, NC in 1957, dedicated to the production of superalloys.
- First to exclusively produce superalloy using double vacuum melting (VIM/VAR)
- Holder of several patents on processing and control of vacuum induction melting.
- The Allvac Metals Company merged with the Vanadium Alloy Steel Company that later merged with Teledyne, Inc., which merged with the Allegheny Ludlum Steel Company in 1998, later becoming Allegheny Technologies Inc. (ATI) and giving the name ATI Allvac to the company Mr. Nisbet founded.

Clarence G. Bieber, International Nickel Company

- Inventor of numerous nickel-base alloys
- Credited with doing the research that led to the development of numerous nickel-base alloys including Inconel and Maraging steels
- Holder of numerous superalloy patents

Dr. Falih N. "Doc" Darmara, Specials Metals, division of Utica Drop Forge & Tool Corp

- Born in Izmir, Turkey, received his Ph.D. from Harvard in 1938 and did advanced study at MIT in the late 1930s.
- Hired as chief metallurgist at Utica Drop Forge & Tool Co. in 1941
- Joined The Lewis Flight Propulsion Laboratory of NACA (The National Advisory Committee for Aeronautics – now NASA) in 1944 to perform alloy development.
- Designed and built the first commercially successful small (6 lb) vacuum induction furnace, leading to the birth of a new industry.
- Became the first President of Special Metals Corporation in 1961.
- Patented several vacuum melting processing techniques and a process for making superalloy powder in August 1974 (US Patent 3829538).
- Dr. Darmara retired from Special Metals in 1976 and passed away on July 15, 2009 at the age of 98

Elwood Haynes

- Automotive entrepreneur in Kokomo, Indiana, whose first love was tinkering with alloys in his basement.

- 1907 patent for a binary cobalt-chrome alloy to improve the productivity of metal cutting tools in automotive applications. The alloy could be considered the father of Vitallium, identified by some to be the first superalloy.
- 1907 patent for a binary nickel-chrome alloy for emerging electrical resistance applications such as toasters.
- 1915 founded The Haynes Stellite Company in a 50 square foot cement block building.

<u>Herbert L. Eiselstein</u>

- Inventor and patent holder of Alloy 718 in filed in 1959 and awarded in 1962.
  - Licenses were given royalty free
- Native of Huntington, WV
- VP of Technology and R&D, Inco Alloys International

Conclusion

The story of superalloys, their development, and of the engineers who made innovation happen, parallels the story of the great industrial force of the last century: power by internal combustion. It enabled great leaps in transportation and power systems to improve the quality of life for billions of people on earth. Superalloy technology was one of the catalysts that transformed this evolving force, giving it speed and power, wings and thrust, enabling us to reach for new worlds of possibility. Superalloy technology has been one of the definitive innovations of recent history, literally doing more while costing less.

Today, as we contemplate the limits and impact of many of our technologies, we are looking to many sources for ways to gain more value at less cost, to mitigate and minimize, to remedy and repair. Superalloys are among the solutions that will open new doors, delivering more efficiency to existing systems and enabling new solutions that haven't yet been imagined.

Innovation created the superalloy industry. Innovation has kept it vital and relevant. Innovation will be its future.

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A debt of gratitude is owed to all authors and presenters at conferences for the past four decades who discussed the history of high-temperature/superalloys and vacuum melting within their company or the industry. The information allowed me to weave the story of our industry more

accurately and in greater depth. It is to these same individuals I certainly owe apologies for having certainly missed one or more footnotes.

Lastly, my thanks go out to Phil Morton and Brad Fisher for their help in reviewing and editing this paper. Without their assistance this work would not have proceeded beyond a rough draft.

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