ALLOY 625 – IMPRESSIVE PAST/SIGNIFICANT PRESENCE/AWESOME FUTURE

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ABSTRACT

It has been close to half a century since the original research and development lead to the invention of alloy 625. Originally intended for ultra-critical steam piping, the alloy continues to find new applications and increased volume of production annually. This paper will review some of the markets where alloy 625 is the material of choice and explain the reasons for its success. Advances in material processing are noted and characterized. These advances are creating a better understanding of the uniqueness of the alloy and resulting in new uses. Welding and overlaying with alloy 625 for some developing applications will be reviewed.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

INCONEL® alloy 625 (UNS N06625) was commercially introduced by INCO ALLOYS INTERNATIONAL, INC. in the mid 1960s following a number of years of intensive research on how the varying elements of the alloy system (Ni,Cr,Mo,Nb) affected properties and fabrication. This effort resulted in the issuance of U. S. Patent #3,160,500 in December of 1964 to H. L. Eiselstein and J. Gadbut. The nominal composition for alloy 625 is listed in Table I. The composition of the other alloys mentioned in this paper are defined in Table II.

Table I. INCONEL® alloy 625 Nominal Composition (wt. %)

Ni	Cr	Mo	Nb	Fe	C	Si	Al	Ti	Mn	S
61	21.5	9	3.6	2	0.05	0.2	0.2	0.2	0.2	0.001

Alloy 625 was first introduced to this Symposium in 1991 as an invited paper presented by Tillack.[1] His paper detailed the research effort that went into developing the alloy and defined certain of its general characteristics. Other papers (22 in all) also presented in 1991 dealt with processing including casting, powder metallurgy, spray forming, weld overlaying and co-extrusion of piping, microstructure evolution, mechanical and corrosion resistant properties. Then in 1994 at the third Symposium, there were an additional 14 alloy 625 papers dealing with these subjects. Key among them was the paper by Floreen, et al., that described the effects of alloy composition and processing history on the microstructure and properties of alloy 625.[2] The paper hinted at ways to optimize various properties by tighter control of alloy composition and processing steps. In 1997, there were 15 papers at the fourth Symposium devoted in large part to the effect of aging and precipitates on mechanical and corrosion properties. This brings us to 2001 and an opportunity to view alloy 625 for its applications and to justify these applications on the basis of its characteristics.

The applications envisioned in the years following product introduction focussed principally on seawater, aerospace and the chemical processing industries.[3] Today these industries consume a significant portion of the millions of pounds produced annually by an estimated two dozen producers worldwide in virtually all product forms. The objectives in this paper are to assess the current status of the alloy as much as it is possible in terms of selected applications that have developed in the last decade or so and seek to explain the reason(s) for their development and justify their future growth. Matching alloy 625's unique properties to the ever-changing, increasingly stringent requirements of industry is the challenge faced by the metallurgists of the alloy's manufacturers if the alloy is to continue its growth. Originally intended for ultra-critical steam piping in the 1960s, it has taken until the 1990's for the

Table II. Typical Compositions of the Other Alloys Mentioned in This Paper

Material	Ni	Cr	Mo	Nb	Al	Ti	C	Si	Fe	Other
Type 316 SS	12	17	2.5	--	--	--	0.08 m	--	Bal	1 Mn m
Type 321 SS	11	18	--	--	--	5 x C	0.08 m	1 m	Bal	2 Mn m
Type 347 SS	11	18	--	--	--	--	0.08 m	1 m	Bal	2 Mn m
Alloy 800	32.5	21	--	--	0.2	0.4	0.05	1 m	Bal	1.5 Mn m
Alloy 825	42	22	3	--	--	1	0.05 m	--	Bal	--
Alloy 600	76	15	--	--	--	--	--	.5 m	--	1 Mn m
Alloy 617	52	22	9	--	1.2	0.3	0.08	0.5	Bal	--
625LCF® alloy	61	21.5	9	3.6	0.2	0.2	0.03 m	.15m	Bal	0.02 N m
Alloy 690	62	28	--	--	0.2	0.2	0.01	0.1	Bal	0.1 Mn
Alloy C-276	57	16	16	--	--	--	0.01	0.08	Bal	4 W

m = maximum

operating conditions of this application to evolve to the stage that alloy 625 has become the material of choice for waterwall overlays and superheater tubing in waste-to-energy (WTE) steam boilers. To a great extent this paper will confirm the fact that alloy 625 and its immediate derivatives are the solution to numerous environmental problems past, present and future.

Exploiting the Corrosion Resistance of Alloy 625

The alloy content of alloy 625 enables it to withstand a wide variety of corrosive environments, some of which this paper will explore in detail. In mild environments, for example, ambient atmosphere, fresh and seawater, neutral salts and alkaline media, alloy 625 is practically corrosion free. In more severe corrosive environments, chromium provides resistance to oxidizing chemicals, whereas the combined nickel and molybdenum content makes the alloy resistant to nonoxidizing environments. Because of the high molybdenum content, alloy 625 is especially resistant to pitting and crevice corrosion. Alloying with niobium has stabilized it against sensitization during welding, thereby preventing subsequent intergranular attack. Freedom from chloride-ion stress corrosion attack is imparted to the alloy by its high nickel content. This combination of corrosion resistance has made the alloy one of the most widely used materials wherever vexing corrosive environments are found. To illustrate the versatility of alloy 625, this paper will examine current and recently established uses of this alloy, where corrosion resistance has dictated alloy selection, in a typical refinery, in waste-to-energy boilers and in the automotive exhaust system. It should be pointed out that a very comprehensive characterization of the corrosion performance of alloy 625 was presented at this conference in 1991 by Ganesan et al.[4]

Petroleum Refinery Applications of Alloy 625

The recent trend towards increasing use of sour crude feedstocks and the push to "greater-than-design" production rates have resulted in an increasing inadequacy of traditional materials and process-altering solutions within the typical refinery.[5] As an example, one West Coast Refinery recently experienced excessive corrosion in their atmospheric tower, overhead condenser and transfer lines due to excessive throughput of sour crude through their desalter. This throughput lead to excessive chloride transfer down-stream which hydrolyzed to hydrogen chloride which resulted in component failure.

Alloy 625 can play a significant role within the typical refinery by inhibiting naphthenic acid corrosion, reducing polythionic acid (PTA) stress corrosion cracking (SCC), or chloride SCC, within certain temperature ranges, and by enhancing resistance to both oxidizing and reducing high temperature sulfidation.

Naphthenic acid and Hydrogen Chloride Corrosion in Distillation Towers Naphthenic acid, often in conjunction with various sulfur compounds, is a common cause of corrosion in numerous areas throughout the refinery using certain U.S. Gulf Coast, Venezuelan and Middle East crudes in plants designed for sweet crude feedstocks. Naphthenic acid corrosion is most prevalent when the process stream temperature is 220 to 400°C (430 to 750°F) and when the stream velocity is high. This is especially true in transfer lines, nozzles and return bends. Usually, the problem is most severe in vacuum and atmospheric distillation units and, to some extent, in thermal cracking units. Experience has shown that molybdenum-bearing alloys can be effective in resisting naphthenic acid corrosion with resistance increasing as the molybdenum content increases. One refinery has reported over six years of good performance for alloy 625 welding electrode overlaid on nozzles that introduce the heated crude into the vacuum tower. In the past, these nozzles experienced severe naphthenic acid corrosion due to the effect of velocity. In another refinery, alloy 625 clad steel has been used for refurbishment of an atmospheric tower. Alloy 625 filler metal and electrodes are typically used for distillation tower fabrication due to their closely matching coefficient of thermal expansion with that of the underlying steel and their ability to accept iron dilution without cracking.

Alloy 625 in Overhead Condensers While material selection for overhead condensers depends on the source of the cooling water, the amount of chloride, success of the inhibitors, maintenance of proper pH control and even water velocity, conditions can suggest the use of alloy 625. Material selection also depends on the stream side concentrations of ammonia, hydrogen chloride and hydrogen sulfide. One

Latin American refinery has refurbished a battery of condensers, tubed with 90-10 copper-nickel tubes that suffered ammonium hydrosulfide and hydrochloride corrosion of the steel shells, by overlaying the tube shell with alloy 625 filler metal approximately 3.2 mm (0.125 in) thick. Increasing chlorides escaping the crude desalter, as mentioned above, will increase the use of alloy 625 filler metal overlays in overhead condensers and their transfer lines.

Alloy 625 in Hydrotreating and Hydrocracking Units Hydrotreating uses hydrogen to remove sulfur and nitrogen from naphtha, jet fuel, diesel, gas oils and fuel oils. This process can result in hydrogen sulfide that causes high temperature corrosion and ammonia and ammonium sulfide that can result in lower temperature corrosion and erosion-corrosion. Additionally, PTA SCC can occur during shutdowns. Hydrocracking combines desulfurization with cracking to convert a full range of feedstocks into more valuable products. The corrosion problems are similar in both hydrotreating and hydrocracking units. While many alloys have good resistance to hydrogen sulfide in the normal operating temperature of hydrotreating and hydrocracking processes, not all these alloys have good resistance to PTA SCC and intergranular attack (IGA). These results for typical alloys used in hydrotreaters and hydrocrackers are presented in Table III.

One component of hydrocrackers and fluid catalytic crackers where 625LCF® alloy is frequently employed is the bellows expansion joint. Selection of alloy 625 is based on well-established corrosion resistance, strength and fatigue resistance.

Table III. PTA and Average IGA Results for Five Typical Alloys for Use in Hydrotreating and Hydrocracking Units.

Material	PTA Results		IGA Results	
	Time to First Crack (hours)	Time to Failure (hours)	Corrosion Rate (mm/yr)	Corrosion Rate (MPY)
Type 321 SS	NC*	NF**	3.5	137
Type 347 SS	NC	NF	1.1	43
Alloy 800	5	30	42.4	1668
Alloy 825	NC	NF	0.3	13
Alloy 625	NC	NF	1.4	55

IGA Tests per ASTM A263-C. *NC = No Cracking. **NF = No Failure in 72 hours.
All specimens were mill annealed plus 670°C (1250°F) for one hour and air cooled.

Table IV. Application Areas and Benefits for Alloy 625 Welding Products in the Petroleum Refinery

Refinery Application	Welding Product	Benefits
Crude Transfer Lines And Nozzles	Alloy 625 filler metal Alloy 625 welding electrode	Resistance to PTA SCC & Chloride SCC High Temperature Sulfidation & Naphthenic Acid Corrosion Resistance
Atmospheric Tower Overlays	Alloy 625 filler metal	Resistance to Hydrogen Chloride, Hydrogen Sulfide plus PTA SCC and Chloride SCC
Overhead Condensers	Alloy 625 filler metal	Resistance to Hydrogen Chloride, Hydrogen Sulfide plus PTA SCC and Chloride SCC
Hydrotreaters and Hydrocrackers	Alloy 625 filler metal Alloy 625 welding electrode	Low Coefficient of Expansion, Iron Dilution w/o Cracking PTA and Chloride SCC Resistance
Hydrotreating Air Coolers	Alloy 625 filler metal Alloy 625 welding electrode	Sulfidation, Ammonium Hydrosulfide Erosion-Corrosion Resistance PTA & Chloride SCC Resistance

Welding with Alloy 625 within the Refinery Welding and overlaying with alloy 625 filler metal and electrodes is common within the refinery for a number of reasons. These welding products closely match the coefficient of expansion of many steels, accept iron dilution without cracking, weld readily with dissimilar metals and possess the corrosion properties inherent in alloy 625. Table IV describes areas and benefits within the refinery where welding products are used.

Waste-To-Energy Boiler Tube Applications for Alloy 625

The first reference in this Symposium for the use of alloy 625 in waste-to-energy (WTE) boilers was made in 1991[6,7]. Early work by Krause[8] had shown that municipal waste can contain as high as 0.5% halides on a dry basis. Since nickel-base alloys have a long established reputation for their resistance to halogen attack dating back to the work of Brown et al.,[9] it was deemed useful to characterize alloy 625 along with other candidate alloys in laboratory simulated WTE environments. It was this work that was reported in 1991. The temperature range selected for the study was 593 to 927°C (1100 to 1700°F), this temperature range being typical of the flue gas temperature measurements in the studies of Krause[8] and Fluck.[10] Boiler internals and flue stacks, if not superheater tubes, could certainly be expected to experience thermal exposure in this temperature range. The simulated atmosphere selected for the study was N_2-10%CO_2-9%O_2-4%HCl-130ppm HBr-100ppmSO_2. No ash was used in these experiments. At the conclusion of each test, the mass change was measured. These results are presented in Table V for a selected group of alloys.

Table V. Mass Change Data in mg/cm^2 for Selected Alloys in N_2-10%CO_2-9%O_2-4%HCl-130ppm HBr-100ppm SO_2Environment after 300 Hours at Varying Temperature.

Material	593°C (1100°F)	704°C (1300°F)	816°C (1500°F)	927°C (1700°F)
Type 316 SS	-5.48	-152.08	-32.75	-45.74
Type 347 SS	-1.61	-327.80	-221.65	-68.36
Alloy 800	-0.53	-245.22	-6.63	-18.98
Alloy 825	-1.53	-127.34	-8.52	-25.89
Alloy 600	-0.32	-0.98	-6.03	-10.18
Alloy 625	-0.52	-2.06	-5.86	-5.91

In the iron-rich alloys, peak mass change appears to be associated with the formation of $FeCl_2$ [m..p. of 696°C (1285°F)]. Corrosion rates drop initially at temperatures above the melting point of $FeCl_2$ due to the volatilization of the molten phase (vapor pressure of $FeCl_2$ at 700°C (1292°F) is 0.0132 atm.) but at still higher temperatures begin to rise once again. Nickel-rich alloys appear to exhibit gradually rising metal loss rates with increasing temperature. Subsequently, the environmental parameters were altered to more closely reflect temperatures and conditions in the waterwall region of the typical WTE boiler. These results are shown in Table VI[11]. No ash was used in this test environment. The data would indicate that a wide variety of alloys may be resistant to the WTE flue gas corrosion in the region of the waterwall. Results showed a dramatic increase in corrosion rates under low or no oxygen conditions. This suggested a need to study the effect of deposits of WTE ash on corrosion rates. This work was begun at our laboratory in the mid 1990s.

Table VII shows the effect of coating test specimens with a salt mixture and exposing them at 550°C (1022°F) and 650°C (1202°F) in a simulated flue gas containing N_2-10%CO_2-10%O_2-1500ppmHCl-300ppmSO_2 after 336 hours. The flow rate was 250 cc/min. The chloride mixture consisted of 40.9%$PbCl_2$-21.9%KCl-20%$ZnCl_2$-17.2%NaCl by weight. More extensive data may be found in the reference by Baker and Farr.[12]

During the 1990s, a number of technical papers were published that documented the WTE corrosion resistance of alloy 625 in laboratory and field service.[13-18] By 1997, alloy 625 had established itself as the most widely used material for effective corrosion protection in refuse boilers. There became a broad consensus that the corrosion rate of alloy 625 was less than 0.25 mm/y (10 mpy) and that it outperformed typical steel tubing by at least a factor of 10. During this period, certain efforts to develop composite

Table VI. Mass Change Data for Selected Alloys in an N_2-10% O_2-500ppmHCl-50ppm SO_2 Environment after 1000 Hours at Varying Temperatures.

Material	427°C (800°F) µm/y	482°C(900°F) µm/y	593°C(1100°F) µm/y
Type 316 SS	-0.07	-2.54	-5.08
Type 347 SS	-0.09	-2.29	-7.11
Alloy 825	-0.02	-1.27	-2.54
Alloy 600	-0.04	-2.03	-3.05
Alloy 625	-0.02	-1.78	-2.79

Table VII. This table shows the effect on depth of attack and rate of attack of applying a salt mixture (40.9% $PbCl_2$- 21.9% KCl-20% $ZnCl_2$-17.2% NaCl by weight) on test specimens exposed at 550°C (1022°F) and 650°C (1202°F) in a simulated flue gas containing N_2-10% CO_2-10% O_2-1500ppmHCl-300ppmSO_2 after 336 hours.

	Exposure at 550°C (1022°F)		Exposure at 650°C (1202°F)	
Material	Depth of Attack (mm)	Rate of Attack (mm/y)	Depth of Attack (mm)	Rate of Attack (mm/y)
Alloy 825	0.228	5.94	0.893	23.28
Alloy 600	0.488	12.72	0.547	14.26
Alloy 690	0.413	10.77	0.354	9.23
Alloy C-276	0.076	1.98	0.143	3.73
Alloy 625	0.131	3.42	0.087	2.27

alloy 625 tubing were made. Fukuda, et al., described their efforts at this Symposium to develop a powder metallurgy co-extrusion process for a composite tube of alloy 625 on 2.25Cr-1Mo steel.[19] At this same 1991 Symposium, Wilson, et al., reported on their study to weld deposit alloy 625 on Type 304 SS.[7] The relative ease of weld overlaying alloy 625 by Gas Metal Arc Welding (GMAW), coupled with the difficulties in manufacture of composite alloy 625 on steel tubing, have tended to favor overlaying as the preferred method of manufacture of composite tubing for WTE boiler tubing. The ability to refurbish steel tubing in-situ is an additional plus for this process. Corrosion rate data are beginning to appear in the literature.[20-21] Results vary widely, suggesting the complexity of operating conditions and the variety of feedstock. Recent developments aimed largely at waterwall tubing protection include liquid atomized metal deposition (spray forming) of alloy 625[22] and plasma powder weld deposition.[23]

Alloy 625 applications in boilers is not restricted to WTE plants burning municipal waste. Montgomery and Karlsson have field tested alloy 625modified (Sanicro® alloy 63) in a straw-fired power plant[24] and Lai and Hulsizer have published their findings relative to the corrosion and erosion/corrosion of alloy 625 overlays in low NOx coal-fired boilers[25] Luer has recently published information on the corrosion fatigue of alloy 625 overlays in fossil-fired utility boilers.[26]

Other Power Applications of Alloy 625

A successful hot-salt application of alloy 625 is in the tubing of the solar central receiver of Rockwell International's Solar II power plant (rated at 10 Mwe) and soon-to-be constructed Solar III (rated at 42.2 Mwe) in Spain. The salt is the eutectic mixture of potassium and sodium nitrate. The collector is designed to heat sufficient salt to 621-635°C (1150-1175°F) to operate the electric generator throughout the night.[27]

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Automotive Applications for Alloy 625

Operating requirements for automotive power trains are rapidly becoming increasingly severe. Higher temperatures and tighter emission requirements, along with extended warranties and governmental demands for increased gas mileage, are rending traditional exhaust system materials marginally acceptable and, increasingly more common, unacceptable for a growing number of engine platforms. Within the exhaust system, alloy 625 has established a reputation as the ultimate material for the bellows portion of flexible couplings and exhaust gas recirculation (EGR) tubing. Papers describing the performance of alloy 625 in this application began appearing in the mid 1990s.[28-29]

Flexible Couplings and EGR Tubing

Flexible couplings for automotive exhaust systems are a very demanding application because they are susceptible to attack by a wide range of corrosion mechanisms encountered in everyday driving, particularly road deicing salts. Depending on the design and location in the exhaust system, potential failure mechanisms include fatigue, corrosion fatigue, oxidation, hot-salt corrosion, stress-corrosion cracking, pitting and general corrosion. Similar to the flexible coupling, the EGR tubing may also be exposed to fatigue and corrosion. It is important to recognize the potential for failure and select the most cost-effective materials. The trend towards higher temperatures and leak-free system warranties to 160,000 km (100,000 miles) or ten years makes a strong case for high-performance alloys, such as alloy 625, to replace traditional alloys for these key components.

Fabricated bellows are the heart of the flexible coupling and must resist degradation to maintain long, leak-free life. The thin walls of flexible coupling bellows can not tolerate deep corrosion penetration without significantly reducing life of the bellows. Table VIII depicts the excellent resistance of alloy 625 to hot-salt SCC and intergranular corrosion as compared to commonly used stainless steels for flexible coupling bellows.

Table VIII. Hot-Salt Stress-Corrosion Cracking Test Results for U-Bend Samples (15 min. heating/5 min. cooling, 7.5% NaCl + 2.5% $CaCl_2$, dipped daily)

Material	Depth of Cracking, mm (mils), Average of Duplicates		
	At 427°C (800°F) And 1387 Cycles	At 586°C (1050°F) And 750 Cycles	At 621°C (1150°F) And 1386 Cycles
Type 316Ti SS	0.05 (2.0)	0.05 (2.0)	0.10 (4.0)
Type 321 SS	0.025 (1.0)	0.08 (3.2)	0.25 (10.0)
Alloy 625	0	0	0.025 (1.0)

Fatigue resistance is critical to the survival of a flexible coupling bellows in automotive service. The effect of mill processing variables on tension-tension fatigue properties of alloy 625 at 593°C (1100°F) is discussed in the section of this paper on recuperators.

Aircraft Exhaust System Applications for Alloy 625

Certainly as demanding as the bellows portion of the automotive flexible coupling are the exhaust systems of aircraft gas turbines. Alloy 625 is commonly used for tailpipes, hush kits, vector nozzles and bellows. The Apache helicopter employs a complex exhaust system to exit the engine exhaust safely from the aircraft fuselage. Alloy 625 is used to make the CMX-124 tailpipe for the U. S. Navy's PROWLER aircraft. The alloy was selected on the basis of its excellent fatigue, resistance to sensitization and strength.[30] Of interest in the selection process of alloy 625 was the stability as measured by the room temperature impact results in Joules/cm^2 after thermal exposure at 593°C (1100°F) and 649°C (1200°F) for times to nearly 9,000 hours. The impact toughness for alloy 625 is compared to that of alloy 617, an alloy known for its stability, in Table IX. Reduction in impact properties in both alloys is attributed to grain boundary carbide precipitation and in the case of alloy 625 to the formation of a metastable body-centered-tetragonal niobium-rich gamma double prime (γ''), which undoubtedly converted to orthorhombic Ni3Nb during thermal exposure.

Table IX. Room Temperature Charpy V-Notch Impact Results in J/cm^2 for Alloys 625 and 617.

Temperature °C (°F)	Exposure Period (2200 Hours)	Exposure Period (4400 Hours)	Exposure Period (8800 Hours)
Room Temperature Impact Results in J/cm^2 for Alloy 625.			
593 (1100)	314	234	168
649 (1200)	86	49	31
Room Temperature Impact Results in J/cm^2 for Alloy 617.			
593 (1100)	223	181	98
649 (1200)	35	35	40

For intermediate temperature applications, it is of interest to compare the stress rupture strength of mill annealed (typically grain size less than ASTM #7) alloy 625 to that of solution annealed alloy 617 (typically grain size greater than ASTM #5). These results are shown graphically in Figure 1.

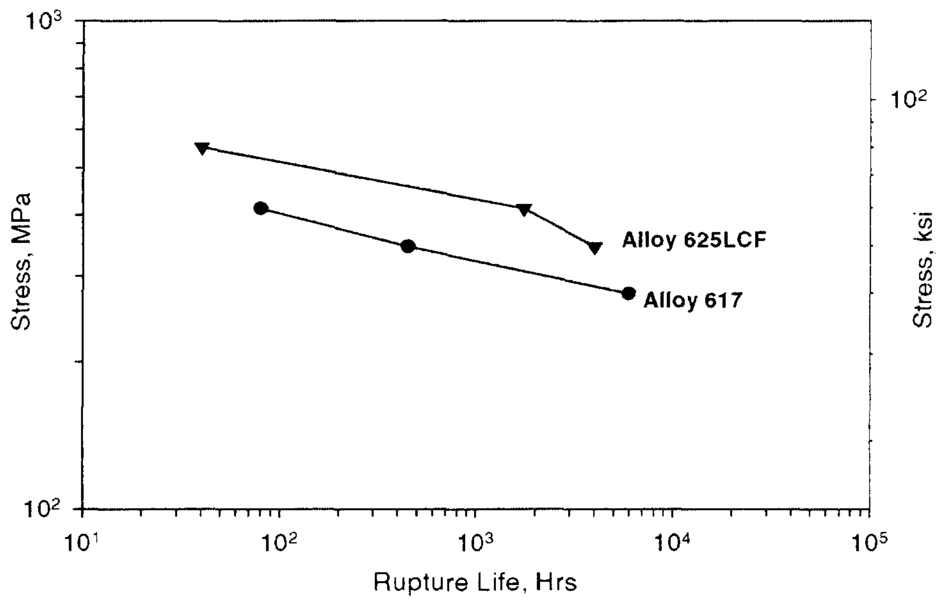

Figure 1. Stress Rupture Life Comparison of Mill Annealed Alloy 625 vs. Solution Annealed Alloy 617 at 650°C (1202°F).

Recuperator Applications for Alloy 625

The recuperator on the AGT 1500 gas turbine of the M1 Abrams tank has consumed large tonnages of alloy 625 over the past twenty years. This application is worthy of examination because General Dynamics Land Systems, then responsible for the manufacture of the tank, while seeking to explain and eliminate recuperator failures, defined certain property differences achievable by varying mill practice. Some of these differences are certainly exploitable by savvy designers to optimize component performance.[31]

The AGT 1500 recuperator heats inlet air to 538°C (1000°F) under a pressure of about 1,350 MPa (200 psi) using the engine exhaust as the heat source. Through-cracks in the recuperator plates [0.2 mm (0.008 in.)] allow pressurized inlet air to escape to the exhaust thereby reducing the amount of preheated air available for combustion. In analyzing the failures, General Dynamic engineers characterized the alloy 625 available at the time that were produced by different mill practices. It should be pointed out that because of tonnage capacity of the manufacturer's press, it was essential that solution annealed (nominally 1175°C (2150°F/0.5 min.) material be used in producing the waffled configuration on the plates. However, vacuum melted, milled annealed (nominally 1065°C (1950°F/0.5 min.) alloy 625 per AMS 5879 was also characterized by General Dynamics. The tensile data are presented in Table X and tension-tension axial fatigue data in Table XI.

These General Dynamics data show a number of distinct differences between mill practices. Notably among them is the fact that vacuum melting reduces total residue content. This in turn, aids tensile ductility as does solution annealing in contrast to lower temperature mill annealing. It also appears to enhance low cycle fatigue and stress rupture life at 593°C (1100°F) when used in conjunction with mill annealing and control of composition. Examining the fatigue lives at 593°C (1100°F) after aging at 704°C (1300°F)/300 hours suggests that the high cycle fatigue properties tend to converge as aging equalizes the strength levels of the different mill practices.

Grubb reported at the 4th Symposium that when using 0.9 mm (0.035 in.) sheet, no difference was found between material meeting the compositional limits of AMS 5599 and that of AMS 5879 when both alloys were processed to similar grain size and strength.[32] However, the jury may still be out regarding inclusion content in thin sheet and strip resulting from the mill processing differences between the two specifications, since the study of General Dynamics, which used thinner 0.2 mm (0.008 in.) sheet, varied both product inclusion content and annealing practice in their comparative test. Results reported by Smith and Yates did find a difference in 0.2 mm (0.008 in.) sheet properties when testing air or AOD + ESR melted material (up to 0.42% total inclusion content) vs. VIM + ESR (0.06% total inclusion content) sheet.[33] A literature search correlating inclusions, fatigue and nickel-base alloys found 108 citations. It remains for future research to precisely correlate mill practice variables and fatigue of alloy 625 sheet.

Table X. Tensile Properties of Alloy 625 as Defined by Mill Practice.

Room Temperature Tensile Properties			
Property	**Air Melted Solution Annealed Per AMS 5599**	**AOD + ESR Mill Annealed Per AMS 5599**	**VIM + ESR Mill Annealed Per AMS 5879**
0.2% Y.S., MPa (ksi)	339 (49.1)	507 (73.5)	467(67.8)
U.T.S., MPa (ksi)	747 (108.4)	951 (138.0)	846 (122.7)
Elongation, %	31.0	50.0	45.0
ASTM Grain Size	5	9	8.5
Total Residue Percentage	0.42	----	0.06
593°C (1100°F) Tensile Properties			
0.2% Y.S., MPa (ksi)	244 (35.4)	360 (52.2)	349 (50.6)
U.T.S., MPa (ksi)	563 (81.6)	805 (116.8)	712 (103.3)
Elongation, %	24.0	50.0	42.0

Welding of Austenitic Stainless Steels

The excellent corrosion resistance of alloy 625 is increasingly used to solve welding problems encountered in some of the austenitic stainless steels.[34] When the 3-6% molybdenum austenitic stainless steels are welded with matching filler metals, the welds often suffer from accelerated corrosion due to molybdenum segregation. During solidification, the welds cool too rapidly for the molybdenum to be distributed uniformly, resulting in dendrite cores that are considerably lower, and the interdendritic region markedly higher, in molybdenum. This often results in preferential attack of the dendritic centers, and has been a particular problem in pulp and paper manufacturing environments. The problem has been solved by using alloy 625 filler metal which raises the molybdenum content of the diluted weld metal to such a level that the pitting and crevice corrosion resistance of the weld metal is equal or better than the austenitic stainless steel base metal.

Table XI. Tension-Tension Axial Fatigue Results as Defined by Mill Practice.

Tension-Tension* Axial Fatigue at 593°C (1100°F) – Cycles to Failure			
As-Received Condition			
Maximum Stress MPa (ksi)	Air Melted Solution Annealed Per AMS 5599	AOD + ESR Mill Annealed Per AMS 5599	VIM + ESR Mill Annealed Per AMS 5879
758 (110)	----	5,455	6,939
621 (90)	Failed on Loading	10,672	14,500
552 (80)	5,924	200,000	1,900,000
483 (70)	15,966	9,950,000	>10,000,000
414 (60)	138,109	----	----
Aged at 704°C (1300°F)/300 Hours Prior to Fatigue Testing			
758 (110)	----	4592	----
690 (100)	1,314	----	69,928
621 (90)	907,078	9,919	>10,000,000
552 (80)	>10,000,000	----	>10,000,000
483 (70)	----	--	----

*Minimum Tension Stress is 34.5 MPa (5,000 psi) Test Frequency is 60 Hz

Conclusions

Seldom does an alloy become a standard material of construction in a wide variety of industrial applications. Alloy 625, however, is such an alloy. Ever since its introduction in the early 1960s, the alloy has proven to be a valuable and versatile material that is able to solve a wide variety of design and application problems. Its ability to resist low temperature aggressive corrosion environments as well as hostile high temperature environments with a high level of strength has enabled it to be specified frequently in a diverse cross section of industries. In addition to the original goal of a material for main steam-line piping, it has been used extensively in the aerospace, automobile, chemical processing, oil production, oil refining, marine, waste treatment, pulp & paper and power industries. As an indication of its versatility, slight modifications in composition and mill practice have dramatically increased the fatigue life of thin sheet, thereby increasing the design capabilities in critical turbine components. The excellent weldability of the alloy, and its ability to accommodate dilution from other compositions, has often led to the specification of alloy 625 filler metals for dissimilar welding. It seems reasonable to predict that alloy 625 as weld overlayed or co-extruded as either waterwall or superheater tubing will play a major role in the future worldwide growth of municipal WTE and refuse-derived-fuel (RDF) plants.

Thus, while alloy 625 has had an impressive past and is enjoying a significant presence, there is the promise of an even more awesome future.

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