Basic Turbine Component Repair and Metallurgy

Lloyd Cooke P.Eng.

Liburdi Engineering Limited

Dundas, Ontario, Canada

www.liburdi.com

Introduction

Why Repair and Refurbish Parts?

GT Component Repairs – Why ?

- **Maintenance, after fuel, is the main operating cost over the life cycle of a GT engine**
- **Spare Part Replacements and Repairs of hot section components represent the major cost portion of all Maintenance**
- **Typically a component Repair will cost 10% - 25% of the replacement new part cost**
- **Therefore, Repairs represent the main cost savings opportunity for the operator**

LIBURDI

Component Repair Trends
Industrial Frame GTs

- Repair Shops — OEM Shops Less than 50% of Volume
  - **Estimated Annual Volume $400 million USD**
  - **18 USA (5 OEM)**
  - **10 International (4 OEM)**
- Repair Costs — 10-20% of OEM New Replacement Price
  - **Completion Times 2-8 weeks (non-OEM)**
  - **F class & Newer Technologies 3-5X more expensive than mature engine components**
- Overhaul Seasons — **Spring - February thru May**
  - **Fall - September into December**
- Replacement Parts — **Estimated New Parts Annual Sales** $4+ Billion
  - **Used and/or Refurbished Parts-$25 Million (under 1%)**
  - **New Alternate Source Parts-$150 Million (about 3%)**

LIBURDI

The Future for Industrial Frame GT Repairs

Replacement Blades for F, G, 3A Technology now Cost $1-4 million USD per Stage – increasing the incentive to source repairs

Intermediate Cycling Operation changes the operational lives of HGP components. Better algorithms for E.O.H. Equivalent Operating Hours to better predict component lives.

Repair Techniques for advance technology components are now being developed, particularly for Directional Solidified and Single Crystal materials.

Replacement Parts - Increasing Interest in Independent sources for replacement parts manufacture.

LIBURDI

Design Differences

	YEARS	TURBINE INLET TEMPS
OLDER UNITS	1950-1970	1350-1750^0 F (730-950^{0}C)
MATURE DESIGNS	1970-1985	1800-2050^0 F (980-1120^{o}C)
ADVANCE TECHNOLOGY	1985-	2300-2600^0 F (1260-1430^{0}C)

LIBURDI

Advanced Design Turbine Blades

(Industrial Frame Engines Now Using Aero Cooling, Aero Alloys)

Manufacturer/Model	1st Stage Turbine Blade/Bucket
ABB-GT24/26	**Single Crystal, Ni-Base** **Matrix Cooled** **VPS-NiCoCrAlY**
GE-7FA	**Directionally Solidified, GTD-111** **Serpentine Cooling w/Turbulators** **LPPS-CoCrAlY, Plus Internal Coatings**
Siemens V84.3A	**Single Crystal PWA-1480** **VPS-CoNiCrAlYSi Plus Internal Coatings**
West. 501F	**Directionally Solidified CM-247** **Serpentine, Film & Showerhead** **VPS-NiCoCrAlY**

LIBURDI

Inspection & Maintenance Intervals- Industrial Frame Engines

FH/YR	BASE LOAD **7000-8500**	INTERMEDIATE **3000-6500**	PEAKING **<1000**
COMBUSTION	**6 Mos-1yr**	**6 Mos-1yr**	**2 – 3 yrs**
HOT GAS PATH	**2 – 3 yrs**	**1 – 2 yrs**	**7 – 10 yrs**
MAJOR	**5 – 6 yrs**	**5 – 7 yrs**	**10 – 20 yrs**

LIBURDI

Section 1:
Determine Damage Mechanisms

- Oxidation
- Corrosion – Hot Type I, Type II, Aqueous
- Erosion
- Creep
- Fatigue (HCF, TMF, LCF)
- Detrimental Phases in Alloy

LIBURDI

Determine Root Cause of Damage

- Environment – contaminants in fuel, air
- Operating Procedures
- Plant Design – air or fuel pulsation, filtration
- Component Design Limits
  - Material or coating selection inadequate/inappropriate
  - High frequency excitation limit
  - Service interval limit
  - Ultimate life limit

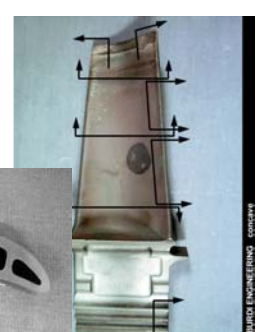
LIBURDI

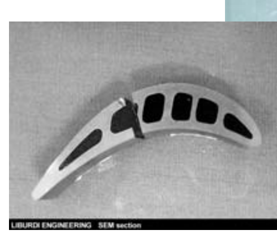
Determine Corrective/ Preventive Action

- Refurbishment processes to restore component
- Component Upgrade – coating selection, oxidation resistant or higher strength materials
- Corrective action for operations, plant design
- Adjust service interval, analysis interval

Micrographic Section Analysis

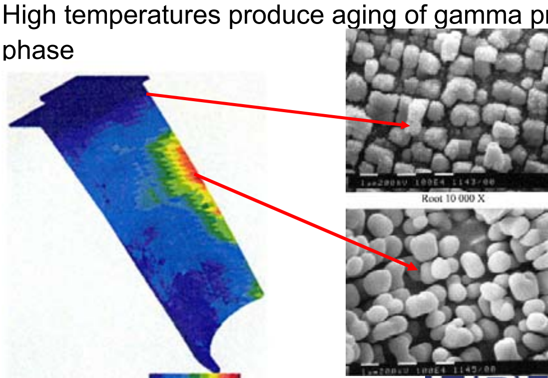
- Sectioning plan for each component type is based on experience and is very important
to determine local effects of:
  - –Temperature
  - –Stress
  - –Oxidation
  - –Corrosion





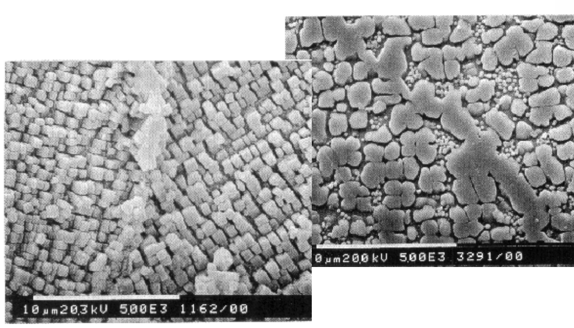
Alloy Microstructure Analysis

- Microstructure condition varies depending on temperature profile – sectioning plan is important
- High temperatures produce aging of gamma prime phase



Alloy Microstructure Analysis

- Electron Micrographs – aging of gamma prime, grain boundary carbides, other detrimental phases



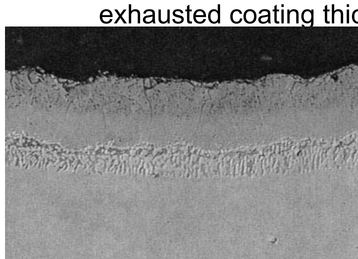
Mechanical Testing

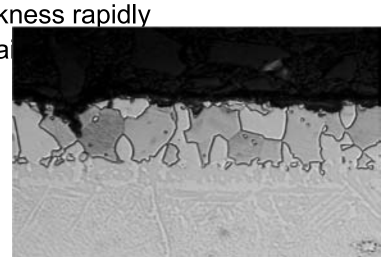
- Stress-Rupture, Creep, Tensile Test Bars
- Compare to new material specs
- eg: GTD111 Alloy after 25,233 hrs of service stage 1 blade

Min. Spec – hrs GTD 111 alloy	**Stress-Rupture Test - hrs**
23	8.3
23	11.2

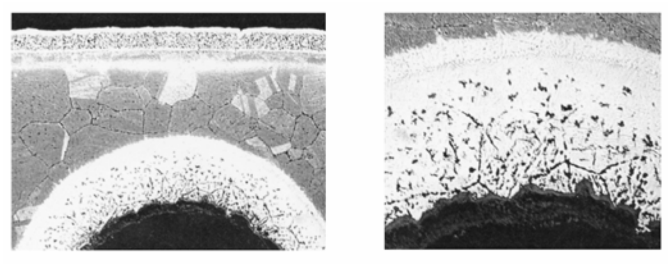
Coating Life Evaluation

- In service, beta NiAl phase diffuses to the surface to replenish surface aluminum oxide formers
- Coating life determined by remaining aluminum rich beta phase – when beta is exhausted coating thickness rapidly
fai





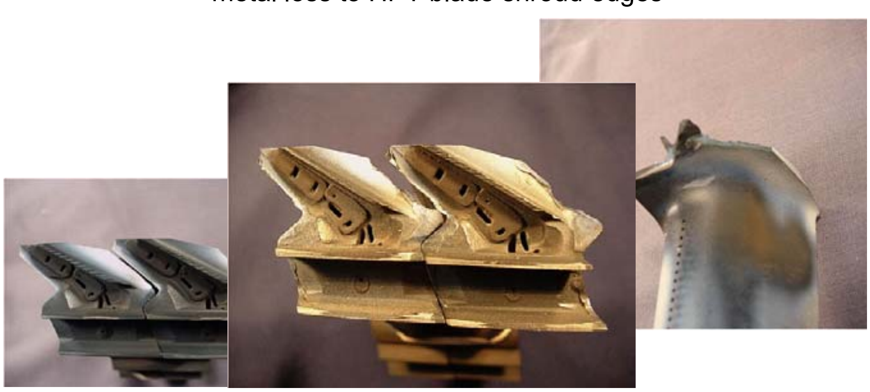
Environmental Attack - Oxidation



Internal Oxidation and Alloy Depletion in IN738

Oxidation Attack

- High temp oxidation resulting in severe metal loss to HPT blade shroud edges



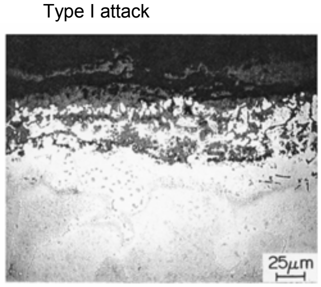
Environmental Attack - Hot Corrosion

- Hot corrosion most commonly occurs under conditions where alkali sulphate salts deposit on the component surfaces
- Sulphur is usually present as a contaminant in the fuel, while alkalies such as Na and K may be present as contaminants in fuel or air
- Oxides of V and Pb have a similar effect
- Hot corrosion is principally a function of operating hours under the corrosive conditions

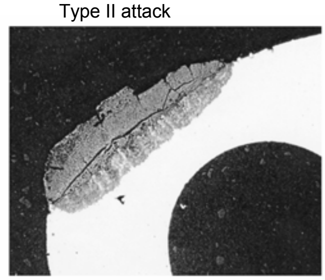
Hot Corrosion Attack

- Type I (high temp) hot corrosion occurs at approximately 875˚C (1600˚F)
- Type II (low temp) attack results in surface scale build up followed by scale/metal loss - occurs at approximately 700˚C (1300˚F) and only in high Sulphur environments

Type I attack



Type II attack

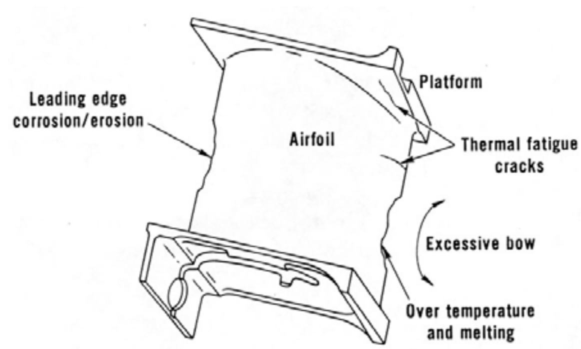


Thermal Mechanical Fatigue (TMF) Damage

- Transient thermal strains during start-up and shutdown cycles combined with the steady state thermal and centrifugal loads generate a complex low cycle fatigue load on turbine parts – thus TMF life is a function of start/stop cycles

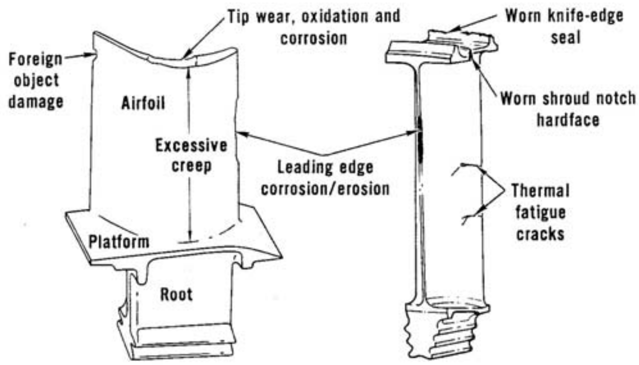
Transient Thermal Strain in a Vane Segment

Typical Service Damage – Vanes



•Fig. 6.1 Turbine vane service damage

Typical Service Damage – Blades



- Fig. 6.2 Turbine blade service damage

LIBURDI

Section 2:
Repair and Refurbishment Processes

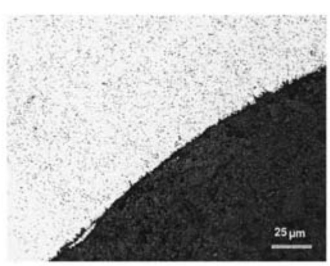
- Coating Stripping
- Repair Heat Treatments
- Rejuvenation Heat Treatments
- Superalloy Welding Processes
- Diffusion Brazing and Powder Metallurgy Processes
- Critical Dimensions

LIBURDI

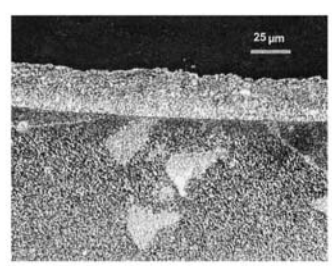
Chemical Stripping

- The repair of coated components requires that old spent coating be removed from the parts
- Coatings are typically stripped in strong, often heated mineral acid (HCl, H_2NO_3 etc.) mixtures which react with the aluminide phases in the coatings
- The acid compositions are designed and controlled to selectively remove coating without attacking the substrate alloy

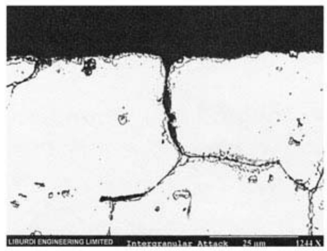
Chemical Stripping

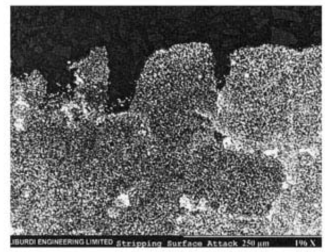


•What should happen



Chemical Stripping



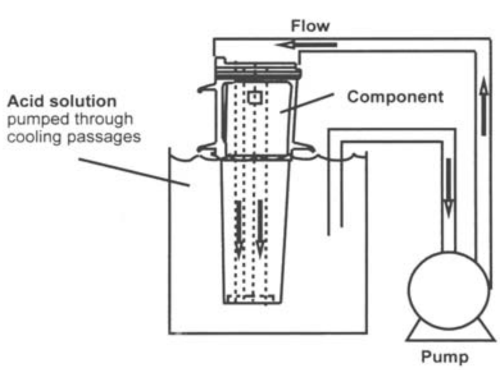


•What can happen

- Excessive exposure to the stripping solutions can lead to inter-granular attack of the base metal and so the process and handling must be designed to minimize exposure to the solutions

LIBURDI

Chemical Stripping – Dynamic Flow System



LIBURDI

Repair Heat Treatments

- Pre-weld Solution heat treatment
  - To return the material back to its "virgin- like" condition, by restoring the γ' phase, dissolve the network of carbide phases along the grain boundaries, and restore ductility
- Post-weld stress relief
  - Ensure stress induced cracking in welds does not occur in service
- Diffusion Braze heat treatment part of brazing process
- Coating Diffusion part of coating process

LIBURDI

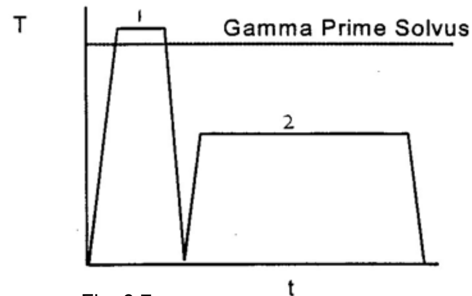
Rejuvenation Heat Treatments

- Specialized heat treatments applied to service-run parts to restore the original, as-new properties (strength, ductility, etc.) They include solution heat treatments followed by aging heat treatment cycles
- Have some similarity to the original new-part heat treatments applied during manufacture, but are different – specially tailored to restore the effects of service
- Specialized process developed and used since early 1980s to enable blade sets to achieve a 2^{nd} and 3^{rd} service life
- Rejuvenation heat treatments are different for each alloy eg: IN738, GTD111, Rene 80, MarM002, etc.

LIBURDI

Rejuvenation – Vacuum Heat Treatments

- Precipitation hardened alloys are heat treated to develop maximum properties – strength, ductility, etc.
- The Rejuvenation HT cycles consist of a solution step (1) and one or more aging cycles (2-4) depending on the all



•Fig. 6.7

LIBURDI

Hot Isostatic Pressing (HIP)

- HIP is used both in new manufacture and in repair to eliminate internal defects
- The parts are exposed to high pressure (>15ksi) inert gas atmospheres at high temperatures (>1100˚C)
- Under these conditions, the internal voids collapse and are “healed” by a creep mechanism

LIBURDI

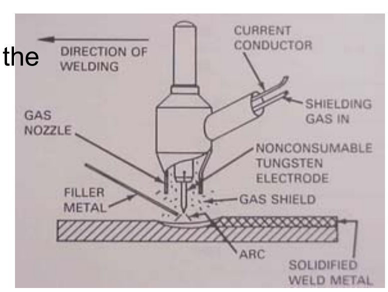
Effect of HIP – Service-run Blades

- HIP can be effectively used on used blades to eliminate any internal creep voids formed during service
- The total process of rejuvenation involves applying both the high pressure HIP heat treatments to heal internal voids, and the vacuum solution and aging heat treatments to restore the alloy micro-structure
- The effects of γ' aging are therefore also eliminated by the HIP and vacuum processing

LIBURDI

Gas Tungsten Arc Welding (GTAW) or "TIG"

- Arc established between the non consumable tungsten electrode and the workpiece.
- The process uses shielding gas (typically Argon or Helium) and filler metal.



Ref (Welding Handbook, Vol.2, 8th edition, AWS)

LIBURDI

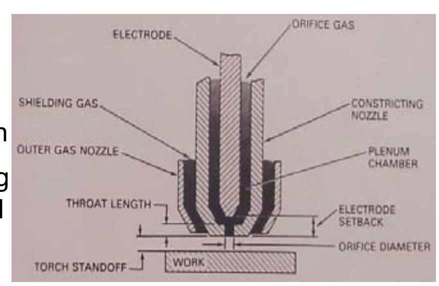
Gas Tungsten Arc Welding

Repair of hook-fit area

LIBURDI

Plasma Arc Welding (PAW)

- Constricted arc established between the non consumable tungsten electrode and the workpiece. ⇦ better penetration
- There is a plasma and shielding gas (typically Ar and Ar/H_2) and filler metal.



Ref (Welding Handbook, Vol.2, 8th edition, AWS)

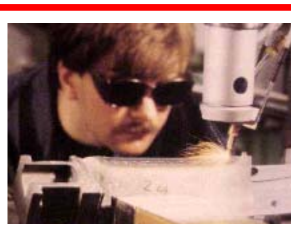
LIBURDI

Plasma Arc Welding

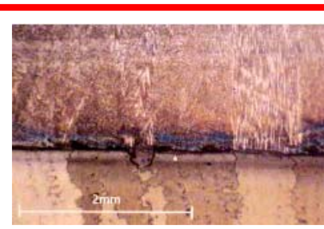

•Fig. 6.14


•Fig. 6.15

Laser Beam Welding



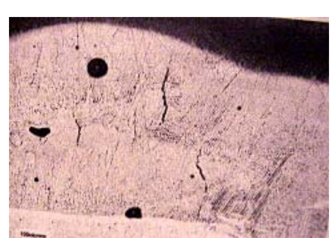
Baumann, Fritsche and Gaumann



Baumann, Fritsche and Gaumann

Robert Harrison

•Fig. 6.17



Robert Harrison

•Fig. 6.18

Weld Alloy Selection – Nickel Alloys

- Inconel 625, Inconel 617 (wire) lower strength than cast superalloys - good ductility, weldability
- Inconel 738 ,Inconel 939, MM247 are high strength similar to cast superalloys, but difficult to weld crack-free. Used for Automated welding processes.
- Waspaloy, B1900, MarM247, Haynes 214 are good for oxidation resistance – difficult to weld crack-free.

LIBURDI

Weld Alloy Selection – Cobalt Alloys

- L605, Haynes 188 cobalt (wire) for welding cobalt based alloys
- similar strength to the cobalt part (Castings are typically X40, X45, FSX-414

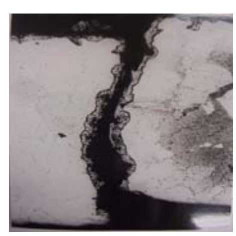
LIBURDI

Weld Alloy Selection – Wear Resistance

- Stellite 1, Stellite 6, Stellite 12, Stellite 21, Stellite 31
- PWA 694 (Coast Metal 64, CM64)
- Tribaloy 800

Diffusion Brazing:
Fluoride Ion Cleaning (FIC)

- Superalloy components containing Al + Ti severely oxidize to form oxides that penetrate deeply into cracks.
- Need to remove these oxides by HF gas (Nickel parts) or H2 gas (cobalt parts).
- Otherwise no wetting of side walls of the crack by the braze filler metal and only cosmetic repair results.
- FIC process is used to assist in the successful braze repair of nickel base Superalloy components.



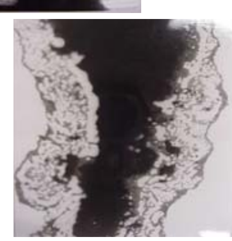
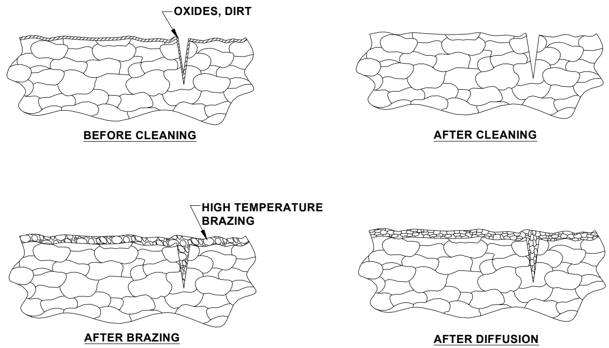


Fig. 6.21

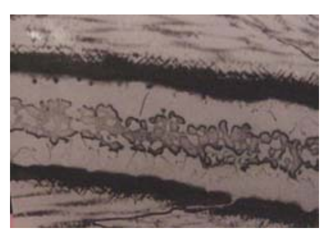
Diffusion Brazing: Process



LIBURDI

Diffusion Brazing: Process

- Diffusion Brazing:
  - The melting point depressants used in nickel base filler metals, which enable the filler metal to melt at a lower temperature than the base metal, are typically Si, B and P.
  - If the joint gap is too large, brittle intermetallic phases form in the joint, which affects its ductility.
  - Warning



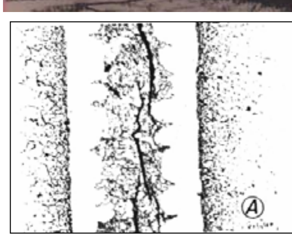


Fig.6.22

LIBURDI

Diffusion Brazing: Process

- **Liquid phase sintering:**
  - Sintering may be compared with diffusion brazing and isothermal solidification.
  - The 4 steps include: powder application, melting, diffusion sintering and homogenization.
  - Isothermal solidification occurs after the repaired area has been heated above the liquidus temp of the braze metal.

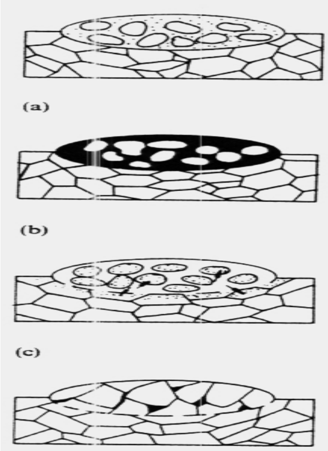


Fig. 6.29

Diffusion Braze Processes

Diffusion Brazing Processes

Abbr.	**Description**	**Company**
ADH	Active Diffusion Healing	General Electric
LPDB	Liquid Phase Diffusion Bond	Sermatech
RBD	Rechargement per Brasage Diffusion	SNECMA
SRB	Surface Reaction Braze	Chromalloy
TLP	Transient Liquid Brazing	Pratt Whitney
TPS	Transient Phase Restoration	Wood Group

Powder Metallurgy Processes

LPM	Liquid Phase Sintering	Liburdi Engineering

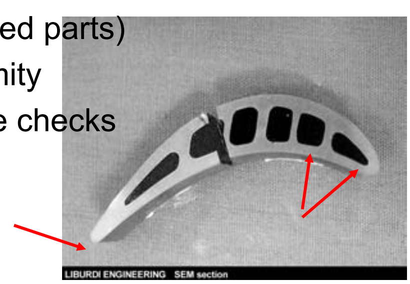
Welding – Brazing – Powder Metallurgy

Application	Weld	Braze	Powder Met
Alloy Selection	Limited	Wide range Si and/or B	Wide range Minimal Si, B
Heat Input	Local, Intense HAZ Distortion	Entire part High Temp Vacuum No distortion	Entire part High Temp Vacuum No Distortion
Crack Repair	Low strength (nickel) Manual prep No size limit	High strength – but Limited by size Chemical clean – prep	High strength Manual prep Large size limit
Surface Repair	No thickness limit Distortion	Limited thickness	Large thickness limit Applied as tape

Critical Dimensions

•Airfoil Dimensional Checks and Restoration

•Trailing edge thickness (radius)
•Wall thickness (internally cooled parts)
•Coating thickness and uniformity
•Cooling passage and exit hole checks



Critical Dimensions

•Critical machined surfaces/dimensions

•Blade tip height (unshrouded blades)

•Blade shroud Z-notch dimension and profile (shrouded blades)

•Blade shroud airseal and platform seal edges

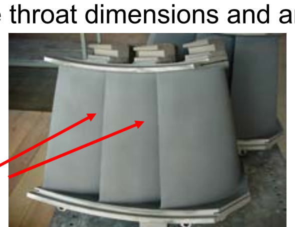
Critical Dimensions

•Critical machined surfaces/dimensions

•Vane inner shroud position (lean / twist)

•Vane fit-up hooks and rails

•Vane throat dimensions and area

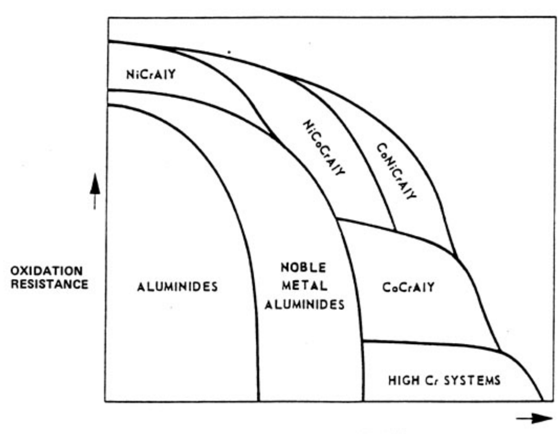


Section 3: Re-coating Selection

- Based on metallurgical evaluation of sample part from service
  - Original coating appropriate or change to new
- External and internal coating required ?
- Service environment – oxidation / corrosion resistance
  - Select coating composition
- Coating type and application method
  - Application method pack / slurry / CVD
- Thermal Barrier – required? added value?

Re-coating Selection

- Best coating to be applied after repair may be the original coating – or it may be a different coating (more appropriate for the service environment)



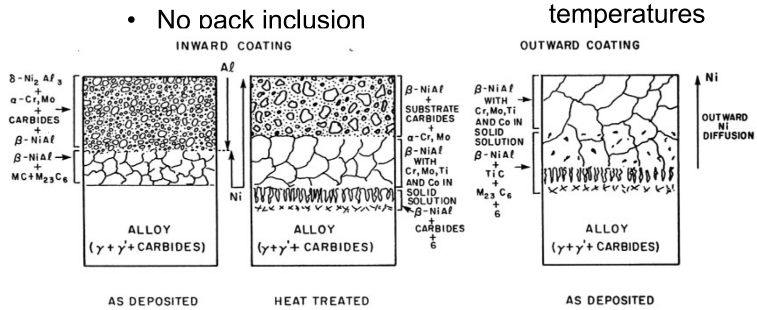
Re-coating Processes

- Diffusion Aluminide Coatings
  - Pack Aluminide
  - CVD Aluminide
  - Slurry Aluminide
- Overlay MCrAlY Coatings (Thermal Spray)
  - APS, LPPS, HVOF
- Overlay TBC Coatings (Thermal Spray)
  - APS, EB-PVD

LIBURDI

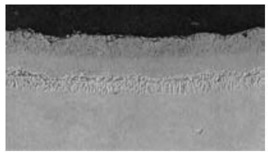
Diffusion Aluminide Coatings

- Inward Type Coating
  - High Al content
  - Low temperatures
  - No pack inclusion
- Outward Type
  - Low Al content
  - High temperatures



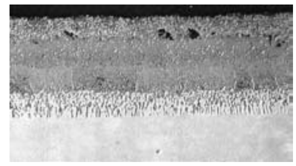
LIBURDI

Diffusion Aluminide Microstructure



Nickel Aluminide Coating
Coating

Ni - Al



Platinum Aluminide

Pt – Al - Ni

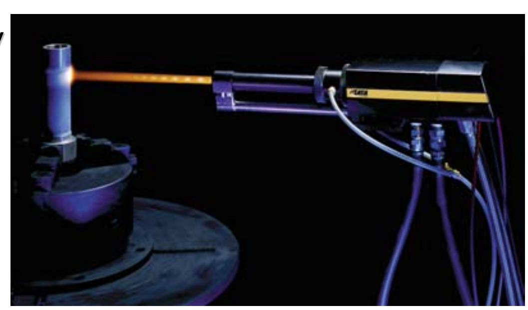
- Aluminide coatings showing beta phase aluminim rich surface layer and diffusion zone into the base metal
- Modified Aluminides use the addition of Pt, Si, Cr to enhance the coating resistance for oxidation or corrosion

LIBURDI

Thermal Spray Coatings

Characteristics Detonation (D-Gun) and HVOF Processes

- Low thermal energy
- High kinetic energy
- Short dwell time



LIBURDI

MCrAlY Composition

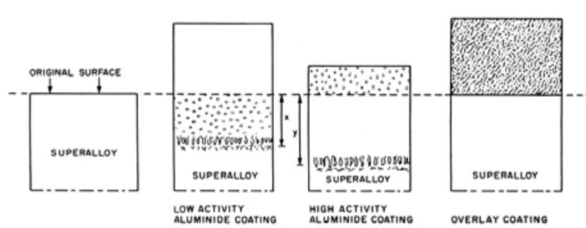
	Ni	Co	Cr	Al	Y
NiCrAlY	Bal.	Nil	15-40	5-12	0.3-1
CoCrAlY	Nil	Bal	17-35	6-10	0.3-0.6
NiCoCrAlY	Bal.	20-35	18-45	8-12	0.3-0.6

The specific alloys are tailored to the specific application:

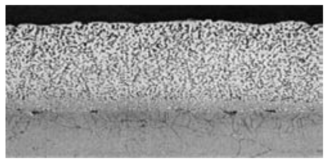
- Higher Cr and/or Co for hot corrosion applications
- Higher Al for oxidation resistance

MCrAlY Overlay Coatings

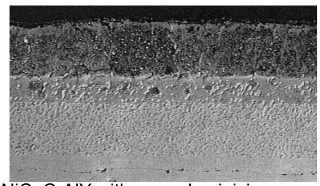
- **Overlay coatings are applied by thermal spray which results in minimal reaction with the substrate**
- **This allows greater freedom to tailor coating composition than in diffusion coatings**



MCrAlY Microstructure



NiCoCrAlY Coating

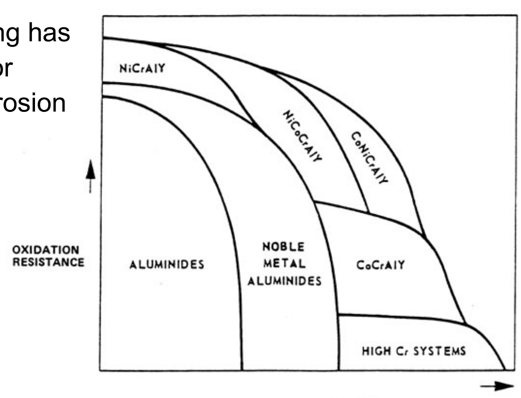


NiCoCrAlY with over-aluminizing

- **The microstructure of MCrAlY coatings consists of aluminide particles in an austenite matrix**
- **MCrAlY may be over-aluminized with diffusion aluminide to increase the aluminum content of the surface for better oxidation resistance**

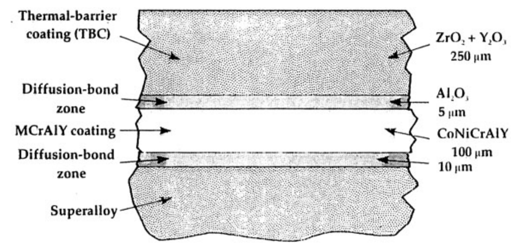
Summary of Coatings - Environmental Resistance

- Each family of coating has specific properties for oxidation and/or corrosion



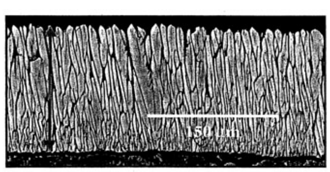
Thermal Barrier Coatings (TBC)

- **TBC's are designed to provide an insulating layer between the hot gas and the component**
- **The coatings consist of a layered structure of Y_2O_3 stabilized Zr_2O_3 over an oxidized bondcoat of MCrAlY**



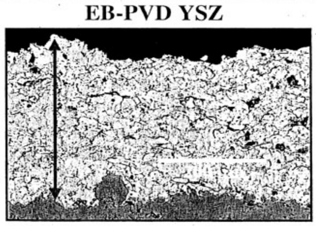
LIBURDI

Two Different TBC Microstructures



EB-PVD YSZ

- **Columnar microstructure**
- **Excellent strain tolerance**
- **Requires a flat bond coat surface for proper YSZ microstructure**
- **YSZ chemically bonds to Al_20_3 interface scale**
- **Deposited at >900˚C**



APS YSZ

- Porous, lamellar microstructure
- Good strain tolerance due to porosity and sub-critical microcracks
- Requires a rough bond coat surface for YSZ mechanical adhesion
- Deposited at <300˚C

LIBURDI

Commercial Coatings – Partial List

- **Simple Aluminides Pack – PWA 273, Codep, RT21**
- **Simple Aluminides CVD – PWA275, RT47, LOM**
- **Chrome Aluminides – RB505, PWA63**
- **Silicon Aluminides – PWA73, Sermaloy J, LSR**
- **Platinum Aluminides – LDC-2E, RT22, RT44, 1595**
- **NiCoCrAlY – GT33, PWA211, PWA286, ATD63**
- **CoNiCrAlY – GT29, ATD70**
- **Thermal Barrier Coatings – APS, EB-PVD**
- **Compressor Airfoil Coatings – Sermatel W, 5380, 5380DP**

LIBURDI