COATINGS FOR HIGH TEMPERATURE APPLICATIONS

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OUTLINE

Reasons for Surface damage

Need for Surface Modification

Classification of wear & Corrosion

Surface modification processes:
- case studies
  (i) Exhaust valves
  (ii) Boilers
  (iii) Gas turbine blades
REASONS FOR SURFACE DAMAGE

Loss of Usefulness of Material Objects

- Obsolescence (15%)
- Breakage (15%)
- Surface deterioration (70%)
  - Wear (55%)
  - Corrosion (15%)

LOSS OF USEFULNESS OF MATERIAL OBJECTS
CLASSIFICATION OF WEAR

Flow chart of various wear mechanisms.
FORMS OF CORROSION

Uniform or general corrosion
Galvanic corrosion
Pitting corrosion
Crevice corrosion
Erosion-corrosion (Cavitation erosion & Fretting corrosion)
Intergranular corrosion including sensitization and exfoliation
Dealloying
Environmentally assisted cracking (SCC, corrosion fatigue, & hydrogen damage)
MODES OF HIGH PTEMPERATURE CORROSION

Oxidation

Carburization and metal dusting

Nitridation

Halogen corrosion

Sulfidation

Ash/salt deposit corrosion

Molten salt corrosion

Molten metal corrosion

Principal modes of high –temperature corrosion in industrial environments, as well as the interaction between oxygen activity and principal corrodenet activity
APPLICATIONS

Engineering components
Gas turbines of aircraft/Marines engines
Boilers, superheaters, heat exchangers in Fossil-fired power plants
Petro-chemical processing
Fluidized-bed coal combustion

performance : materials
wear/Corrosion resistance or
high temperature mechanical properties
NEED FOR SURFACE PROTECTION

- Increasing component life and hence reducing maintenance and replacement cost
- Avoiding excessive component breakdown and thereby limiting consequential losses because of lost production
- Reducing investment costs through increased machinery life
THERMAL SPRAYING

Definition of Thermal Spraying: ASM

- A group of processes in which a finely divided material (metallic or nonmetallic) is heated rapidly in a hot gaseous medium & simultaneously projected at high velocity on to a prepared substrate surface where it builds up the desired coating.

- powder, rod, cord or wire
PRICIPLE OF TS

1 - Spraying particles transport
2 - Impact on the surface
3 - Thermal transfer from particles to substrate
4 - Particles Solidification and
5 - Mechanical bond
6 - Local Fusion
# THERMAL SPRAY METHODS

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy source</th>
<th>Other names for the process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Flame spraying</td>
<td>Oxyfuel</td>
<td>Oxyfuel gas-powder spraying</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxyfuel gas-wire spraying</td>
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<td></td>
<td></td>
<td>Metallising</td>
</tr>
<tr>
<td>b) Arc spraying</td>
<td>Electrical</td>
<td>Electrical arc spraying</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Twin arc spraying</td>
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<tr>
<td></td>
<td></td>
<td>Metallising</td>
</tr>
<tr>
<td>High energy process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Plasma spraying</td>
<td>Electrical</td>
<td>Air/Vacuum/Low pressure plasma</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) Detonation flame spraying</td>
<td>Oxyfuel</td>
<td>D - Gun</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>c) High velocity oxyfuel spraying</td>
<td>Oxyfuel</td>
<td>High velocity oxygen fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High velocity flame</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High velocity air fuel</td>
</tr>
</tbody>
</table>
Flame spraying is the oldest of the thermal spraying processes

Flame spray uses the chemical energy:

- combustion of gases to generate heat

**Oxyacetylene torches are the most common:**

- acetylene as the main fuel in combination of oxygen to generate the highest combustion temperature
FS process: Powder, wires or rods are introduced axially through the rear of the nozzle into the flame at the nozzle exit. The feedstock materials are melted and the particles/droplets accelerated toward the substrate surface by the expanding gas flow and air jets.
OXY FUEL GAS WIRE SPRAYING

Schematic diagram of Oxy-fuel gas wire spraying
MATERIALS USED

- Zn & Al $\rightarrow$ anti-corrosion cathodic coatings on steel.
- Ni/Al composite wire $\rightarrow$ bond coats, heat & oxidation resistance.
- Mo $\rightarrow$ bond coats, excellent resistance to adhesive wear.
- High Chromium steel $\rightarrow$ hard and wear resistant coating.
- SS, Ni and monel $\rightarrow$ anti-corrosion and wear.
Schematic diagram of Wire Arc Spraying
<table>
<thead>
<tr>
<th>Material</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>Reclamation and machine element work</td>
</tr>
<tr>
<td>Carbon and low-alloy steel(1)</td>
<td>Reclamation, corrosion resistance and medium wear resistance</td>
</tr>
<tr>
<td>Martensitic stainless steel</td>
<td>Corrosion and wear resistance</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>Corrosion resistance and machinability</td>
</tr>
<tr>
<td>NiCu (Monel)</td>
<td>Marine corrosion</td>
</tr>
<tr>
<td>NiCrBSi</td>
<td>Wear and corrosion resistance, hot hardness.</td>
</tr>
<tr>
<td>NiCr (80/20)</td>
<td>Corrosion and high-temperature oxidation resistance</td>
</tr>
<tr>
<td>NiCrFe</td>
<td>High-temperature corrosion resistance</td>
</tr>
<tr>
<td>NiAl</td>
<td>Intermediate layer used to improve the adhesion of ceramic coatings.</td>
</tr>
<tr>
<td>Mo</td>
<td>Wear resistance, anti-galling, arc erosion, bonding</td>
</tr>
<tr>
<td>Al(1)</td>
<td>Resistant to atmospheric and marine corrosion, resistant to oxidation after heat treatment</td>
</tr>
<tr>
<td>Zn(1)</td>
<td>Atmospheric and marine corrosion resistance</td>
</tr>
<tr>
<td>Bronze</td>
<td>Medium wear resistance, high strength, used in bearings</td>
</tr>
<tr>
<td>Aluminium bronze(1)</td>
<td>Corrosion resistance, bond coat, bearing applications</td>
</tr>
<tr>
<td>Copper</td>
<td>High electrical and heat conduction, radio frequency shielding</td>
</tr>
<tr>
<td>Babbit</td>
<td>Journal bearing applications</td>
</tr>
</tbody>
</table>

(1) Indicates material can also be deposited by arc spraying.
Detonation Thermal Spraying Process

Barrel 1-1.5m long and 20-30 mm Internal dia into which the gas mixture is injected and ignited by a spark plug

Schematic diagram of D-Gun wire spraying
ADVANTAGES

• Dense microstructure with 0.1 - 2 % porosity.
• Smooth surfaces finish (1 - 4 \( \mu \text{Ra} \)).
• Better impact wear / fretting wear / erosion / corrosion / resistance.
• Controlled residual compressive stress
• Negligible thermal degradation of powder but also to preserve bulk microstructure
Materials and Applications

• WC/Co coatings:
  - D-Gun coatings have higher degree of retained carbides
    (Due to the reducing atmosphere of the confined combustion zone in the barrel and the shorter dwell time)

  - D-Gun coatings: densest and hardest
HIGH VELOCITY OXYFUEL SPRAYING

Diagram showing the process of high velocity oxyfuel spraying:
- Oxygen and fuel enter through a Laval nozzle.
- Powder mixed with nitrogen carrier gas is fed into the nozzle.
- Compressed air helps in accelerating the mixture.
- Shock diamonds form as the mixture exits the nozzle.
- The coating is applied to the substrate.
HVOF spraying Tungsten Carbide / Cobalt Chromium Coating (WC/10Co4Cr) onto Roll for the Paper Manufacturing Industry
SURFAC MODIFICATION BY PLASMA PROCESSES
Two different arc Modes:

Non-transferred arc : Plasma spraying
- An arc is established between the electrode and the constricting orifice: working piece is essentially kept out of the electrical circuit
The heat imparted to the job is obtained from the plasma jet only

Transferred arc : PTA

The arc is struck between the cathode and the work piece (anode)
This results in greater energy transfer to the workpiece
PLASMA SPRAYING (APS)

Schematic diagram of Plasma Spraying

Characteristics
Flame Temperature:
Approximately 12,000 - 20,000°F (6,000 - 11,100°C)

Gases Used:
Ar/H₂
N₂/H₂

Particle Speed:
800 - 1,800 ft/s (240-550 m/s)

Photo Courtesy of Westaim Ambeon
PLASMA SPRAYING (APS)

Schematic diagram of Plasma Spraying
AIR PLASMA SPRAYING
**SPRAYING MATERIALS**

- **Pure metal**  
  Mo, Ni, Ta, Al, Zn.

- **Alloys**  
  NiCr, NiCrAlY, FeCrBSiC, steels, Bronzes.

- **Pseudo alloys**  
  CuW, AlMo.

- **Ceramics/Carbides**  
  Al$_2$O$_3$, Cr$_2$O$_3$, TiO$_2$, ZrO$_2$, WC.

- **Cermets**  
  Cr$_3$C$_2$/NiCr, WC/Co, ZrO$_2$/NiAl
A coating technology: in which spray particles ranging in size from 1 to 50μm in dia, in the solid state are accelerated to high velocity (above 700-1200m/s, supersonic velocity) and subsequently develop a deposit or coating on a substrate by an impaction process.

Various terms: Kinetic energy metallization, Kinetic spraying, High velocity powder deposition & Cold gas-dynamic spray method.
Temp/velocity regimes for common thermal spray processes compared to cold spray.
COLD SPRAY PROCESS

Schematic diagram of Cold spraying

Characteristics
Jet Temperature: 500 - 1250°F
Gases Used: He, N₂
Particle Velocity: 2000 - 3,300 ft/s (600-1000 m/s)
ADVANTAGES

- TS may be used to deposit non-weldable coating materials such as plastics or ceramics
- No distortion
- No post treatment
- Reduced cost
- Low Heat Input - No HAZ.
- Versatility: Almost any M, C or P.
- Thickness Range: 0.001 inch to more than 1 inch thick, depending on the material and spray system.
- Coating thickness generally range from 0.001 to 0.100 inch
### TEXTILE COMPONENTS

#### Textiles: typical applications

<table>
<thead>
<tr>
<th>Component</th>
<th>Surfacing material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread guides, overrun rollers</td>
<td>Alumina, chromium oxide</td>
</tr>
<tr>
<td>Machine cams</td>
<td>Co–Cr–W high alloy</td>
</tr>
<tr>
<td>Looper and latch needles</td>
<td>Co–Cr–W high alloy</td>
</tr>
<tr>
<td>Winding spindles</td>
<td>WC/Co</td>
</tr>
<tr>
<td>Flattening rolls</td>
<td>WC/Co</td>
</tr>
<tr>
<td>Crimper rolls</td>
<td>Co–Cr–W medium alloy</td>
</tr>
<tr>
<td>Carpet trimming knives</td>
<td>Co–Cr–W medium alloy</td>
</tr>
</tbody>
</table>

Thread overrun roller and thread guides coated with ceramic by plasma spraying to protect against frictional wear.
APPLICATION

Engine Wear

Adhesive wear (cylinder liners and piston rings)

Abrasive wear (cams, rocker arm, and tappets)

Scuffing (cylinder liners and piston rings)

Corrosive wear (piston ring, cylinder)

Fatigue wear (connecting rod & valve seat)
APPLICATION: Valves

Function:
- control the gas flowing into and out of the engine cylinder
- it must form a gastight combustion chamber seat at the valve seat ring in the cylinder head
- high-velocity reciprocating motion with low friction along valve guides
WORKING CONDITIONS

Valves: - exposed to severe loads they are lifted up to 3000 times in a minute & force back firmly on to their seats by valve spring.

The valve typically receives an acceleration of 2000 m/s² under high temperature.

Inlet valve is kept cool by regular inward flow of fresh mixture, but it can still reach a temperature as high as 500 C.
WORKING CONDITIONS

Exhaust valve is heated to between 650 – 850 C, high temp corrosion

Temperature distribution of valves during operation:
An air cooled 200cm³ engine (a) Inlet valve, (b) Exhaust valve
During operation:

The carbon soot formed by combustion can stick to the valve, hindering valve closure and consequently causing leakage.

To prevent this, the valve revolves during reciprocating motion.

The rotation rubs off the soot and prevents uneven wear of the valve face and seat.

The face is exposed to high temperature combustion gas and rubbing occurs without oil lubrication.
PROBLEMS/PROPERTIES

Problems:

- wear occurs on the stem and at its end (valve seat)
- high temperature strength and corrosion

Properties:

- the valves must be of light weight to allow reciprocating motion
- High rigidity, high hardness and good wear resistance
- high temperature fatigue strength and
- high temperature corrosion resistance
MATERIALS USED

Exhaust valves: Materials Used: Single or Bimetallic metals

1. Precipitation-hardening austenitic steel
   (0.5 C-9Mn-3.75Ni-21Cr-0.4N)
   - best properties of this alloy: Solution-treated at 1180 C, quenched and aged for 12 h at 760 C

2. Ni-base alloys: Nimonic alloys
   Nimonic 80A (wt.%): C = 0.02, Cr=19, Co=1.6, Ti = 4.42
   Al = 1.05, Fe = 2.08, Mn = 0.4%, Si =0.44, P & S = 0.005

3. Co-base heat resistant alloy (stellite No.6)
   1.2%C, 1.1%Si, 0.5%Mn, 3%Ni, 28%Cr, 1%Mo, 3%Fe

Role Cr: forms thick oxide
## Arc weld surfacing processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Abbreviations</th>
<th>Approximate deposit thickness minimum/mm</th>
<th>Deposition rate/kg h(^{-1})</th>
<th>Dilution single layer/%</th>
<th>Typical uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual metal arc</td>
<td>MMA</td>
<td>3</td>
<td>1–4</td>
<td>15–30</td>
<td>Multilayers on heavier sections</td>
</tr>
<tr>
<td>Tungsten inert gas</td>
<td>TIG, GTAW</td>
<td>1.5</td>
<td>≤2</td>
<td>5–10</td>
<td>High quality, low dilution work</td>
</tr>
<tr>
<td>Plasma transferred arc</td>
<td>PTA</td>
<td>2</td>
<td>≤10</td>
<td>2–10</td>
<td>High quality, lowest dilution work</td>
</tr>
<tr>
<td>Metal inert gas</td>
<td>MIG, GMAW</td>
<td>2</td>
<td>3–6</td>
<td>10–30</td>
<td>Faster than MMA, no stub end loss, positional work possible</td>
</tr>
<tr>
<td>Flux-cored arc</td>
<td>FCAW</td>
<td>2</td>
<td>3–6</td>
<td>15–30</td>
<td>Similar to MIG. Mainly for iron base alloys for high abrasion resistance</td>
</tr>
<tr>
<td>Submerged arc (wire)</td>
<td>SAW</td>
<td>3</td>
<td>10–30</td>
<td>15–30</td>
<td>Heavy section work: higher quality deposits than FCAW</td>
</tr>
<tr>
<td>Submerged arc (strip)</td>
<td>SAW</td>
<td>4</td>
<td>10–40</td>
<td>10–25</td>
<td>Corrosion-resistant cladding of large areas</td>
</tr>
<tr>
<td>Submerged arc (bulk welding)</td>
<td>SAW</td>
<td></td>
<td></td>
<td></td>
<td>Similar to SAW wire but other alloys possible</td>
</tr>
</tbody>
</table>
WELD DILUTION

Schematic of dilution definition

\[ d(\%) = \frac{B}{A + B} \times 100 \]
RECENT METHODS

Hardfacing Techniques:

Plasma Transferred Arc (PTA)

Laser beam hardfacing
Plasma Transferred Arc (PTA)

The PTA process is a technological evolution of GTAW welding. The main differences are:

- **Constricted arc** with columnar shape
- **Use of metallic powders** as filler material

**PTAW Constricted Arc**

**Arc Length – Arc Divergence**

**GTAW Open Arc**

Variation of Thermal cross section = 20%
PLASMA PROCESSES

PLASMA TRANSFERRED ARC WELDING (PTAW) PROCESS

The arc is struck between the cathode and the work piece (anode)

This results in greater energy transfer to the workpiece
REASONS TO CHOOSE PTA

From Metallurgical and Mechanical property standpoint

- Precise control of weld parameters
- Powder feed rates, gas flow rates,
- Current and voltage (heat input)
- Controlled heat input helps Less dilution,
- Less HAZ (otherwise, grain coarsening, martensite transformation, or strain aging)

PTA weld deposits:
- low levels of inclusion, oxides and discontinuities make good toughness and general corrosion resistance
MATERIALS FOR PTA HARDFACING

Carbide-strengthened alloys
Boride-strengthened alloys
Silicide-strengthened alloys
Intermetallic laves-phase alloys
Solid solution alloys
Cermet composites
Solution: hardfacing improves the wear resistance

The valve face is coated with melted stellite powder

Co-based heat resistant alloy:

Materials Used:

2. Co-base heat resistant alloy (stellite No.6) (57HRC)

1.2%C, 1.1%Si, 0.5%Mn, 3%Ni, 28%Cr, 1%Mo, 3%Fe

Role Cr: forms thick oxide
# MATERIALS FOR PTA HARDFACING

## A Brief Guideline for Hardface Material Selection

<table>
<thead>
<tr>
<th>Type of Wear</th>
<th>Alloy Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-to-metal, High-stress</td>
<td>Co-Cr-W Carbide type</td>
</tr>
<tr>
<td>Adhesive wear</td>
<td>Ni-Cr-Si silicide alloys</td>
</tr>
<tr>
<td>Metal to metal, High stress</td>
<td>Co-Cr-W Carbide type</td>
</tr>
<tr>
<td>Adhesive wear, Corrosion, Oxidation</td>
<td>Co-Cr-Mo-Si Laves</td>
</tr>
<tr>
<td></td>
<td>Ni-Cr-W alloys</td>
</tr>
<tr>
<td></td>
<td>Ni-Cr-Mo</td>
</tr>
<tr>
<td>Low stress abrasion</td>
<td>Ni-Cr-B-Si alloys</td>
</tr>
<tr>
<td></td>
<td>High alloy cast iron</td>
</tr>
<tr>
<td>High stress abrasion</td>
<td>Ni-Cr-B-Si-WC composites</td>
</tr>
<tr>
<td>High angle erosion</td>
<td>Co-Cr-W/Mo hypoeutectic alloy</td>
</tr>
<tr>
<td></td>
<td>Amorphous metals</td>
</tr>
<tr>
<td>Low angle erosion</td>
<td>Ni-Cr-B-Si alloys</td>
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<tr>
<td></td>
<td>High alloy cast iron</td>
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<tr>
<td></td>
<td>Ni-Cr-B-Si-WC composites</td>
</tr>
<tr>
<td></td>
<td>Co-Cr-W/Mo hypereutectic carbide</td>
</tr>
<tr>
<td>Cavitation</td>
<td>Fe-Cr-Co alloys</td>
</tr>
<tr>
<td></td>
<td>Co-Cr-W alloys</td>
</tr>
<tr>
<td>Galling</td>
<td>Co-Cr-W Carbide type</td>
</tr>
</tbody>
</table>
LASER BEAM HARDENING PROCESS

The use of a laser beam in surface treatments offers several advantages over conventional heat sources:

- **The energy supply can be well controlled;**
- **Very local treatment is possible;**
- **The total heat input is low, resulting in minimal distortion;**
- **The heating and cooling rates are high, resulting in a fine microstructure and/or metastable phases;**
- **The treatment is a non-contact process. There is no tool wear, nor act mechanical forces on the workpiece;**
- **The process depth is well defined.**
## Laser surface treatment processes

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<tr>
<th>Solid state laser treatments</th>
<th>Transformation hardening</th>
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</thead>
<tbody>
<tr>
<td>Liquid phase laser surface treatments</td>
<td>▪ Laser melting</td>
</tr>
<tr>
<td></td>
<td>▪ Laser alloying</td>
</tr>
<tr>
<td></td>
<td>▪ Laser cladding</td>
</tr>
<tr>
<td></td>
<td>▪ Laser nitriding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser treatments with partial evaporation</th>
<th>Solid state laser treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Shock hardening</td>
<td>Transformation hardening</td>
</tr>
<tr>
<td>▪ Laser engraving and marking</td>
<td></td>
</tr>
<tr>
<td>▪ Paint stripping</td>
<td></td>
</tr>
<tr>
<td>▪ Laser cleaning</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thin coating processes</th>
<th>Liquid phase laser surface treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Laser PVD</td>
<td>▪ Laser melting</td>
</tr>
<tr>
<td>▪ Laser CVD</td>
<td>▪ Laser alloying</td>
</tr>
<tr>
<td>▪ Laser assisted electroplating</td>
<td>▪ Laser cladding</td>
</tr>
<tr>
<td></td>
<td>▪ Laser nitriding</td>
</tr>
</tbody>
</table>
Processing parameters compared to other laser processes

Metal’s Handbook, vol 5
LASER CLADDING PROCESS

Cladding/Alloying: Principle

Laser cladding is a process by which a powdered/wire material is melted by use of a LASER in order to coat part of a substrate.
The powder/wire is injected into the system by either coaxial or lateral nozzles.

The interaction of the metallic powder stream and the laser causes melting to occur, and is known as the melt pool.

This is deposited onto a substrate; moving the substrate or laser beam allows the melt pool to solidify and thus produces a track of solid metal.
COATING AND WELD PATTERNS

Cross-sections and bead appearances by diode laser and TIG cladding.
## MATERIALS

Selection of alloys and principal alloying elements used for LAS ER Cladding

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>C</th>
<th>Si</th>
<th>Mo</th>
<th>Fe</th>
<th>Ni</th>
<th>Co</th>
<th>Nb</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellite SF6</td>
<td>19.0</td>
<td>0.7</td>
<td>2.3</td>
<td>3</td>
<td>13.5</td>
<td>Bal</td>
<td></td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Stellite 158</td>
<td>26.0</td>
<td>0.7</td>
<td>1.2</td>
<td></td>
<td></td>
<td>Bal</td>
<td>Bal</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Stellite 6</td>
<td>28.0</td>
<td>1.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td>Bal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel 718</td>
<td>19.0</td>
<td></td>
<td>3.0</td>
<td>18.5</td>
<td>Bal</td>
<td></td>
<td></td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>Delcrome 90</td>
<td>27.0</td>
<td>2.7</td>
<td></td>
<td>Bal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tribaloy T700</td>
<td>15.5</td>
<td>3.4</td>
<td>32.5</td>
<td>Bal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Deloro 60</td>
<td>16.0</td>
<td>0.7</td>
<td>4.2</td>
<td>4</td>
<td>Bal</td>
<td></td>
<td></td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td>Colmonoy 5</td>
<td>11.5</td>
<td>0.65</td>
<td>3.75</td>
<td>3.75</td>
<td>4.25</td>
<td>Bal</td>
<td></td>
<td></td>
<td>2.5</td>
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</table>
## Industrial applications of laser cladding

<table>
<thead>
<tr>
<th>Part/industry</th>
<th>Material</th>
</tr>
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<tbody>
<tr>
<td>high pressure gas turbine blade shroud interlock turbine blade parts of off-shore drilling heads cylinder and valve automotive parts aerospace turbine blade turbine blade, plough blade diesel engine valve extruder screw plastic machinery extruder screw plastic machinery (steel 1.4541) deep drawing tool (cast iron GGG60)</td>
<td>Triballoy on Nimonic Cr, Cr, Ni on cast iron on cast iron Stellite, Triballoy T-800 Stellite, Colmonoy Stellite 6, Stellite SF Stellite 6 Stellite 6 LC2.3B (Ni-base) Al-bronze Stellite SF6</td>
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<td>drainage plough blade leading edge steam turbine blade valve in combustion engine (X45CrSi9) aircraft engine turbine blade Z-notch leading edge turbine blade in industrial gas turbine in power plant deformation tool gas turbine airfoil thermal barrier valve seat stainless steel seal runner stainless steel gate valve leading edge steam turbine blade valves valve in combustion engine (X45CrSi9) extruder screw plastic machinery (14CrMoV6.9) moulding die (45NiCr6)</td>
<td>Stellite 6 Stellite 6 Stellite 6 Triballoy T-800 Stellite 6 Stellite 6 Inconel 625 + CrC AISI 410 Stellite 6 Stellite; induction heating Stellite 6,F Stellite 21 NiCrAlY Co-Cr-W-C</td>
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PROBLEMS

Power plant components: Pipes and coal boilers

-failures of components due to

(i) Erosion

(ii) Corrosion (oxidation/hot corrosion) &

and combination of (i) and (ii)

- If not detected early stage:
  - leading to unwanted costly shut down component replacement/repairing
Surface modification:

- enhances the life of the components

Which type of coatings???

Ex. Case-hardening:

- thin hardened surface
  
  poor corrosion resistant and lose their effectiveness at high temperatures
- Electrodeposited intermetallic coatings
- Weld Overlay coatings
- Thermal spray coatings (HVOF/HVCC)
HIGH VELOCITY OXY/FUEL SPRAYING (HVOF)

-a high velocity flame spray process,
gas velocities exceeding Mach 1, 2300 C
HIGH VELOCITY CONTINUOUS COMBUSTION (HVCC)

In an HVCC process the spray material is introduced in wire form and the wires are melted by creating a supersonic air stream with a plasma between them.

The arc also heats an air stream that is accelerated through a nozzle and removes the molten wire particles.

- 4000° C arc temperature
- Supersonic air velocities creates fine particle atomization
- 300m/s particle velocities
- Finely layered homogeneous coating structure
- Coatings exhibit negligible porosity
- Coatings can be applied with < 5% oxides
- Applies metals, hardfacing alloys and high melting temperature alloys such as tungsten and molybdenum.
**Materials Used**

(i) $\text{Cr}_3\text{C}_2$- NiCr

(ii) NiCrMo (wire process)
PROTECTIVE COATINGS FOR HIGH TEMPERATURE APPLICATIONS

- Superalloys: Designed
  - to operate at high temp
  - good high temp mechanical,
  - heat resistance, &
  - good corrosion resistance
SUPERALLOYS: APPLICATIONS

- aircraft gas turbine engines
- Industrial land-based turbines

Two general types of environmental effects:

i. Oxidation  ii. Hot corrosion

iii. Combination of these effects

The result of 2500 h low altitude sea flight service on an uncoated and NiAl coated blade turbine blade
COATING REQUIREMENTS

• Coatings must withstand hot corrosion, oxidation, and erosion when placed into a flow of gas whose parameters are similar to those of turbine gases

• It must safely withstand the static and alternate stresses applied to the blade surface;
  - to this end the coating must have the requisite combination of strength and ductility

• It must show good stability and not be destroyed by interaction with the substrate
SELECTION CRITERIA

- High melting point: less diffusion of ions
- No phase changes
- Low thermal conductivity
- Thermal expansion match with substrate
- Good adherence
- Low sintering rate
Coatings are classified into two categories:

i. **Diffusion coatings**
   - coatings that alter the substrate outer layer by their contact and interactions with certain metal species

ii. **Overlay coatings**
   - coatings that are formed by the deposition of protective metallic species onto a substrate surface, with some elements inter diffusion providing coating adhesion
DIFFUSION COATINGS

Aluminized coatings: Al diffuses into the surface of a material by diffusion

- Diffusion coatings are based on the formation of intermetallics compounds such as $\beta$NiAl and $\beta$CoAl via diffusion process

- During service, Al present in the coating reacts either oxygen at high temp forms Alumina layer on the surface of the coated alloy

Main types of coating: 1. Pack cementation  
  2. Slurry-fusion  
  3. Gas-phase (out-of-contact) process
Main types of coating:

1. Pack cementation
2. Slurry-fusion
3. Gas-phase (out-of-contact) process
PACK CEMENTATION

- it is a type of vapor deposition process

- in this process, both the component to be coated and the reactants that combine to form a vapor are contained in an airtight retort.

- reactant: consists of aluminium containing powder, a chemical activator and an inert filler $\text{Al}_2\text{O}_3$

- upon heating in an inert atmosphere, the reactant form a vapor that reacts with the component surface enriching it with Al. (750-1150°C)

$\text{Al}$ penetrates into the substrate to form a zone thickness and morphology of which are a function of the time and temperature of the process
PACK CEMENTATION

Inwards diffusion: Formation of $\delta\text{Ni}_2\text{Al}_3$ phase
- brittle phase & low melting point,
- not practical use

Heat treatment: Between 1040 – 1095 C, to convert $\beta\text{NiAl}$
- useful for service applications

In practice, inward diffusion coatings are applicable only to
-Ni-base alloys

(because the coating initially formed by the inward diffusion of Al, substrate modification of the coating is maximized as substrate elements are locked in place)
PACK CEMENTATION

Ni-base alloys: Aluminides such as $\text{Ni}_3\text{Al}$, $\text{NiAl}$ and $\text{Ni}_2\text{Al}_3$

Co-base alloys: $\text{CoAl}$, and Fe-base alloys: $\text{FeAl}$

Inwards coatings:

- produced when Al activity in the pack high, there is a preferential diffusion of the pack through the aluminide layer being formed

- Al diffuses inward faster than Ni diffuses outward through the nickel-aluminide intermetallics that initially form on the surface reaction temp: $700 – 800$ C
PACK CEMENTATION

Modified Aluminide coatings:

Major developments in diffusion coatings:

Modification of aluminide diffusion coatings with Cr, Pt, and to lesser extent of Si

Thickness of aluminide coatings: 75-100 μ

Major Problems:

- protection of thin sections of cooled blades (cooling passages)
OVERLAY COATINGS

Coatings of this type are generally called

**MCrAlY overlay coatings**

where M represents Ni, Co, Fe or some combination of these metals

- these coatings comprise a monoaluminide (MAI) component contained in a more ductile matrix of $\gamma$, in the case of CoCrAlY.

**NiCrAlY coatings**: a mixture of $\gamma$ and $\gamma'$ Ni$_3$Al

Matrix is Ni or Co
MCrAlY COATINGS

- Overlay coatings provide design flexibility
- M - Ni, Co or Fe
- Cr- provides hot corrosion resistance
- Al – (10-12 wt%) provides oxidation resistance
- Y- (1wt%) enhances the adherence of the oxide layer by combining with S.
CHARACTERISTICS

General feature of MCrAlY coatings:

(i) An oxide scale on the outer surface

(ii) Material immediately beneath the scale – modified composition and

(iii) an interdiffusion zone in compact with the substrate
Hot corrosion resistance of uncoated and coated CMSX-4 (nickel-base single-crystal superalloy) and CM186LC (nickel-base directionally solidified superalloy) test specimens. The accelerated hot corrosion tests were carried out at 900 °C (1650 °F) in fuel containing 1% sulfur and 10 ppm salt. The diffusion coatings were applied by a proprietary electrophoresis process. The NiCoCrAlY coating was applied by electron-beam physical vapor deposition. Source: Ref 12
THERMAL-BARRIER COATINGS

Top coat

- Ceramic material like stabilized Zirconia
- Generally stabilized Zirconia (6-8.7% yttria)

Why Stabilized Zirconia?

- Strain tolerant
- Resistance to Na₂SO₄ and V₂O₅
- Low thermal conductivity
- Ideal thermal expansion match
- High thermal stability
THERMAL-BARRIER COATINGS

Advantages:

- Relatively inert
- High melting point
- Low thermal conductivity
- Resistance to thermal cycling
- Hot corrosion and oxidation resistance of coated blade can be further improved
ROLE OF BOND COAT

• Provided to improve adhesion of TBC
• Forms TGO for oxidation resistance
• Intermetallic material
• Influence on structure and morphology of TGO
COATING PROCESSES

Air-plasma sprayed coating contain porosity & micro-cracks:
- help to redistribute thermal stresses but provide corrosion paths through the coating

Low-pressure plasma spray coating:
- Provide high coating purity and essentially eliminates oxides and porosity

HVOF, EBPVD

Or combinations methods oxides and porosity
THERMAL-BARRIER COATINGS

EB-PVD Coatings have a columnar grain morphology: individual grains are strongly bonded at their base.

Major advantage:

Columnar outer structure lies in the fact that it reduces stress buildup within the body of the coating.
## COATING PROCESSES

<table>
<thead>
<tr>
<th>Plasma sprayed</th>
<th>EB PVD</th>
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<tbody>
<tr>
<td>1. Either vacuum or air plasma</td>
<td>1. By vapor deposition on preheated samples</td>
</tr>
<tr>
<td>2. For hot components of combustion chamber</td>
<td>2. For more mechanically loaded parts</td>
</tr>
<tr>
<td>3. Low cost, Low thermal conductivity,</td>
<td>3. High cost</td>
</tr>
<tr>
<td>4. Compositional flexibility</td>
<td>4. Difficult to control composition,</td>
</tr>
<tr>
<td></td>
<td>5. Much superior thermal fatigue properties</td>
</tr>
<tr>
<td>5. Immediate spallation on thermal fatigue</td>
<td>6. Columnar microstructure with multi scale porosity</td>
</tr>
<tr>
<td>6. Laminar structure + splat of cracks</td>
<td>7. Small parts</td>
</tr>
<tr>
<td>7. Large parts</td>
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EB PVD: Electron Beam Physical Vapor Deposition
Typical coating thickness/depth of penetration for various coating and surface hardening processes
THANK YOU
COATING METHODS

Electron-beam physical vapor deposition
THERMAL-BARRIER COATINGS

Typical coatings for high-temperature applications involve an oxidation resistant coating and a thermal barrier coating (TBC). The oxidation resistant coating is also called bond coat because it provides a layer on which the ceramic TBC can adhere.

Thermal Barrier coating design
SEM Micrograph of EB-PVD. The turbine blade contains internal channels for air-cooling