Materials and Processes
Properties of Metal

• Strength – the ability of a material to resist stress or deformation

• Hardness – the ability of material to resist abrasion, penetration, cutting action, or permanent distortion
Properties of Metal

• Brittleness – the inability of material to resist bending or deformation without shattering

• Malleability – the ability of material to tolerate deformation without failure; metals that can be hammered, rolled, or pressed into various shapes without cracking, breaking, or having some other detrimental effect
Properties of Metal

• Ductility – the ability of material to be drawn, bent, or twisted without breaking

• Toughness - withstands tearing or shearing and may be stretched or otherwise deformed without breaking; hard but malleable/non-brittle
Properties of Metal

• Elasticity – the property that enables a material to return to its original shape when the force which causes the change in shape is removed

• Density - specified weight of a material per cubic inch
Properties of Metal

• Fusibility – the ability of a metal to become liquid by the application of heat

• Conductivity – the property which enables a material to conduct heat or electricity
Properties of Metal

- Selection factors for aircraft metals
  - Strength – High
  - Weight – Low
  - Reliability - High
Properties of Metal

• Other properties

  – Crystalline structure

  – High thermal and electrical conductivity

  – Ability to deform plastically

  – High reflectivity
Forces Acting on a Material

• Tensile – stretching, pulling apart

• Compression – pushing together

• Shear – cutting force

• Torsion – twisting, opposing rotational stress
Forces Acting on a Material

- Bending – tension on the outer surface, compression on the inner
- Penetration - impact
- Fatigue – repetitive stress
- Corrosion – chemical degradation
Metal Makeup

- All elements are formed from various combinations of atoms
Metal Makeup

• When a metal solidifies, the atoms arrange themselves into a space lattice or crystal

• Smallest unit is called a unit cell
Metal Makeup

• Atoms are added in an orderly fashion to grow into a large crystal

• Most metals used in aircraft form either a cubic or hexagonal lattice
Unit-Cell Types for Metals

FACE-CENTERED CUBIC
IRON
VANADIUM
LITHIUM
CHROMIUM
MOLYBDENUM

BODY-CENTERED CUBIC
ALUMINUM
COPPER
GOLD
NICKEL
SILVER
LEAD

CLOSED-PACKED HEXAGONAL
BERYLLIUM
ZINC
COBALT
MAGNESIUM
TITANIUM
CADMIUM
Metal Makeup

• Crystals align themselves along **slip planes**

  – With an external force applied, atoms move along the slip planes

  – Below the elastic limit, they return to original after the force is removed; above, plastic deformation occurs
Metal Makeup

• Grain size - Formed during cooling of molten metal

• Fine grain – usually tougher and stronger than coarse
Metal Makeup

- Slow cooling – small number of large grains
- Fast cooling – large number of small grains
Alloys

• Alloy – a mixture of two or more metals

• Solid solution alloys
  – Solvent – base metal
  – Solute – alloying element
Alloys

• Substitutional solid solution alloy

  – Solute atoms are close in size to the solvent atoms

  – Solute atom substitutes for a solvent atom
Alloys

• Interstitial solid solution alloy

  – Solute atom is much smaller than the solvent atom

  – Solute atom fits in between the solvent atoms
Alloys of Steel

• Silicon
  – Improves ductility and hardness

• Phosphorous
  – Improves yield strength and corrosion resistance

• Nickel
  – Improves hardness, yield strength, and provides a fine grain steel
Alloys of steel

• **Chromium**
  – Provides high strength, hardness, and wear resistance

• **Molybdenum**
  – Provides high strength, hardness, grain uniformity, and improves heat treatment

• **Vanadium**
  – Increases hardness, yield strength, and impact resistance
Alloys of Steel

- **Tungsten**
  - Maintains strength and hardness at red-hot temperatures
- **Titanium**
  - Similar to tungsten but reduces brittleness at high temperatures
- **Manganese**
  - Used to remove impurities, oxides, and sulfur
Three Methods of Metalworking

Hot Working
Three Methods of Metal Working

Cold Working
Three Methods of Metal Working

Extrusion
Ferrous Metals

• Carbon Steel

– Low Carbon - 0% to 0.29% Carbon

– Medium Carbon - 0.30% to 0.59% Carbon

– High Carbon - 0.60% to 0.84% Carbon
Ferrous metals

• Maximum hardness of steel depends almost exclusively upon carbon content, up to max of about 0.85% carbon
  – Above 0.85% steel properties become complex

• Low carbon steel cannot be appreciably hardened by heat treatment
Steel Numbering System

• 1\textsuperscript{st} number represents the general classification

• 2\textsuperscript{nd} number represents the percent of principal alloying element

• 3\textsuperscript{rd} and 4\textsuperscript{th} number represents the percent of carbon (measured in 1/100ths of 1%)
Steel Numbering System

- 1xxx Carbon
- 2xxx Nickel
- 3xxx Nickel / Chromium
- 4xxx Molybdenum
Steel Numbering System

- 5xxx  Chromium
- 6xxx  Chromium / Vanadium
- 7xxx  Tungsten
- 9xxx  Manganese / Silicon
Examples of Numbering System

1 0 4 0
Carbon Steel  No Alloy 0.40% carbon

4 1 3 0
Molybdenum 1% Molybdenum 0.30% Carbon
Heat Treatment of Steel

• **Heat Treatment** - any process involving controlled heating and cooling to develop certain desirable characteristics

• The temperatures at which this takes place are called **critical temperatures**
Heat Treatment of Steel

• Three components

  – Heat
  – Soak
  – Cool
Heat Treatment of Steel

• Heat

  – Above critical temperature (for steel, this is around 1400°F to 1600°F)

  – This erases stresses previously imparted into the metal
Heat Treatment of Steel

• Soak

  – Maintain high temp for a time period appropriate to the mass and thickness of the material

  – This permits the molecules to blend and become homogenous; rearrangement of the internal structure of the steel occurs here
Heat Treatment of Steel

• Cool

  – Fast cooling makes steel hard; slow cooling makes steel soft

  – Quenching – fast cooling by emersion in a liquid
Heat Treatment of Steel

- Quenching media
  - Brine
  - Water
  - Oil
- Slow Cooling
  - Air cooling
  - Furnace cooling
  - Sand pack
Heat Treatment of Steel

• **Hardening** – add hardness to steel
  
  – **Heat** – just above critical temperature
  
  – **Soak**
  
  – **Quench** - rapid cooling by immersion in a fluid such as brine, water, or oil; then temper to relieve internal stresses
Heat Treatment of Steel

• **Tempering** (drawing) - chiefly reduces brittleness created by hardening; removes some hardness, and relieves strain to return the part to a usable state

• **Heat** - heat to **less than** critical temperature (at least 212°F)
Heat Treatment of Steel

– lower temps - less hardness removed

– higher temps - more hardness removed

– 250°F - 450°F - tempers for hardness (strong, but brittle)

– 400°F - 550°F - tempers for toughness (strong, but not brittle)
Heat Treatment of Steel

- **Soak** – based upon the mass of the material
- **Cool** - in still air (or oil, water, or a special solution)
Heat Treatment of Steel

• **Stress Relieving** - a process to remove all hardness (extreme tempering)
  
  – **Heat** - heat to below critical temp, 900°F - 1000°F
  
  – **Soak**
  
  – **Cool** - in still air
Heat Treatment of Steel

• **Normalizing** - removing abnormal characteristics and stresses from heat treating, welding, etc.
  
  – **Heat** - at least 100°F above critical temp
  
  – **Soak**
  
  – **Cool** - in still air, at room temperature
Heat Treatment of Steel

• **Annealing** - a process to relieve internal stresses, **soften** the metal, make it more ductile, and refine the grain structure - the opposite of hardening

  – **Heat** - to above critical temp

  – **Soak** - based on mass (1 hr per 1” thickness)
Heat Treatment of Steel

• **Cool** - extremely slowly (therefore softening)
  
  – Examples: furnace cooling, or packing the part in dry sand
  
  – Brings a part back to “**below normal**” condition
Heat Treatment of Steel

• **Case Hardening** - a process to create super hard surface upon a malleable core

• Two Methods
  – Carburizing
  – Nitriding
Heat Treatment of Steel

• Carburizing
  – **Heat** - use high temperature oven (~1700°F)
  – **Soak** - for a short time (1-3 hrs), in a high carbon environment
  – **Cool**
Heat Treatment of Steel

• Advantage - hardness runs deep (~0.070”); good anti-corrosion

• Disadvantage - difficult to retain part’s tolerance after high temperature heating (part often has to be re-machined)
Heat Treatment of Steel

• Nitriding
  – Heat - low temperature (~1000°F)
  – Soak - long heat cycle (~ 30 hrs), in an ammonia gas environment
  – Cool
Heat Treatment of Steel

- Disadvantage - susceptible to corrosion, depth of hardening is less (~ 0.035”), dangerous (highly flammable)

- Advantage - close tolerances (~ ± 0.001” or 0.002”)

- typical use: crankshafts, cylinders
Heat Treatment of Steel

• **Forging** - mechanically working metal at temperatures above the critical range to shape the metal as desired; small parts hammered, large parts pressed.

  – Forging imparts stresses into the steel that may have to be removed via the normalizing process.
Heat Treatment of Steel

Drop Forging
Heat Treatment of Steel

Drop Forge
Rohr Industries
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<th>Color/Description</th>
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<tr>
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<tr>
<td>540°F</td>
<td>Dark Purple</td>
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<tr>
<td>390°F</td>
<td>Faint Straw</td>
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<td>Temperature (°F)</td>
<td>Color</td>
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<td>-----------------</td>
<td>---------------------</td>
</tr>
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<td>Dull Red</td>
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<tr>
<td>1100</td>
<td>Slight Red</td>
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</table>
Cast Iron

Higher carbon content – 2% or more

Non-ductile - cannot be welded or tempered
Cast Iron

Inexpensive compared to wrought iron

Grain structure is random
Cast Iron

Close tolerance right out of the mold

Cannot reshape; you’re stuck with the cast
Wrought Iron

• Manufactured by cold rolling (material cools as it comes out of a slot, rollers press into sheet form) or extruded; a hot and cold rolled process

• Unlike cast, wrought iron has very defined grain structure
Wrought Iron

• Low carbon content (less than 0.15%)

• Ductile

• Can be heated and welded, but cannot be hardened by heat treatment
Wrought Iron

• Forms of wrought

  – Bar - straight stock, like 3-in-one tool

  – Rod – round

  – Wire - round and flexible, such as piano wire, safety wire
Wrought Iron

– Sheet metal - thin enough that it can be rolled up

– Plate - cannot be rolled

– Foil - so thin you can crumple it
Wrought Iron

- Extrusions - forced through an opening in a die; e.g., seamless tubing; may be cold or hot process

- Powder - shape made from round pellets pressed together
Non-Ferrous Metals
Aluminum

• Properties
  – 1/3 the weight of steel
  – Corrosion resistant
  – Easy to fabricate
Aluminum

- Good electrical conductor

- Many alloy combinations

- High heat and light reflectivity

- Takes a good natural finish
Aluminum

• Forms of aluminum products
  
  – Cast
    • Accurate to within ±0.001”

  – Wrought
    • This means the aluminum has been rolled or worked after casting
Aluminum Alloys

• Old System of Identification
  – The aluminum alloy number is based on the experiment number; e.g. A17S
Aluminum Alloys

• New System of Identification – started in 1958

• A four digit numbering system
  – 1\textsuperscript{st} digit – primary alloy material
Aluminum Alloys

– 2nd digit – modification number from the old system (0 = no modification; 1, 2, etc. = modification)

– 3rd and 4th digits – experiment number from the old system

– Example: 2117 is the same as A17S
Aluminum Alloys

• Alloy Numbers

  – 1000 – pure Aluminum, 99% and above
    • Non-structural

  – 2000 – Copper
    • Structural, allows heat treatment, increases strength and hardness
Aluminum Alloys

- **3000** – Manganese
  - Improves strength and corrosion resistance

- **4000** – Silicon
  - Lower melting point, used in welding and brazing

- **5000** – Magnesium
  - Corrosion resistance, hardness, and welding ability
Aluminum Alloys

– 6000 – Magnesium / Silicon
  • Formable, weldable

– 7000 – Zinc
  • High strength, very hard

– 8000 – Experimental
Aluminum Alloys

• Exception: concerning the 1000 series, the last 2 digits indicate the percentage of aluminum purity above 99%, in 0.01%

• Examples
  – 44 in 1044 means 99.44% pure aluminum
  – 00 in 1100 means 99% pure aluminum
Heat Treatment of Aluminum Alloys

- A two-stage process

- Solution Heat Treating
  - Heat
  - Soak
  - Quench

- Aging or Precipitation Hardening
Heat Treatment of Aluminum Alloys

• Solution Heat Treatment

• Heat – from 825°F to 980°F

• Soak – from 10 minutes to 2 hours
  – Nominally 1 hour for each inch of cross-section
Heat Treatment of Aluminum Alloys

• Quench
  – Cold water - for sheet, extrusions, tubing, small forgings
    • Provides corrosion resistance
  – Hot water - for large forgings and heavy sections
    • Minimizes distortion, prevents cracking
Heat Treatment of Aluminum Alloys

– Spray quenching - for clad sheets, large sections
  • Minimizes distortion, prevents cracking, better for preventing corrosion than hot water

– Time from soak to quench may be critical (to prevent re-precipitation)
  • If alloy not quenched below 100°F within 10 sec, alloy may begin to precipitate – can lead to intergranular corrosion
Heat Treatment of Aluminum Alloys

• Aging – length of time for the material to reach full strength

• Natural aging
  – 90% of full strength is reached in the first 24 hours
  – The remaining 10% occurs in the next 4 to 5 days
Heat Treatment of Aluminum Alloys

• Artificial Aging or Precipitation Heat Treating
  – A hardening and strengthening process similar to solution heat treating
    – Heat – low temperature 250°F to 450°F
    – Soak – 6 to 30 hours
    – Cool – still air/free to cool on it’s own
Temper Codes for Wrought Aluminum and Alloys

- General Tempers – the letter follows the alloy code
  - “O” – Annealed
  - “T” - Heat Treated / Fully Aged
  - “S” - Wrought
Temper Codes for Wrought Aluminum and Alloys

– “ST” – Wrought / Heat Treated / Fully Aged

– “SRT” – Wrought / Cold Rolled / Heat Treated / Fully Aged

– “F” - As Fabricated

– “FA” - Freshly Quenched / Soft
Temper Codes for Wrought Aluminum and Alloys

– “H” - Strained Hardened

– “W” – Unstable / Artificially Aged (a transient period between solution heat treating and aging)
Cold Worked Aluminum

- **F** – as fabricated (produced from the ingot without any subsequent controlled amount of cold working or thermal treatment)

- **O** – annealed
  - Re-crystallized (wrought products only) or “soft”
  - With aluminum, annealed is basically normal
Heat Treatment of Aluminum Alloys

• Full Annealing – removes the effects of previous heat treatment
  – Heat - from 750°F-800°F
  – Soak - 2 hours or more
  – Cool - rate of 50°F per hour down to 500°F, then in still air
Heat Treatment of Aluminum Alloys

• Partial Annealing – heat treat process to remove effects of strain hardening and cold working
  – Heat – from 640°F - 670°F
  – Soak - 2 hours or less
  – Cool – rate of 50°F per hour down to 450°F, then in still air
Heat Treatment of Aluminum Alloys

- Stabilizing – a reduced process from partial annealing
  - Heat – 350°F
  - Soak – less than 1 hour
  - Cool – in still air
Heat Treatment of Aluminum Alloys

- Torch Annealing – a shop technique to partially anneal aluminum without an oven
  - basically, a way to soften aluminum a bit to continue working it
  - in aviation, emergency use only
Heat Treatment of Aluminum Alloys

• Technique

  – Use an oxy-acetylene torch with a carburizing flame (more acetylene than oxygen) to apply a coat of soot on the part

  – Then use soft neutral flame to burn soot away
Cold Worked Aluminum

• **H** – strain hardened
  
  – This designation is for alloys that are not heat treat sensitive and reach full strength through cold working, e.g. cold rolling

  – The code format is “HXYZ” where:
Cold Worked Aluminum

• **X** – method of strain hardening
  
  – **1** - strain hardened only

  – **2** - strain hardened and partially annealed

  – **3** - strain hardened and stabilized
Cold Worked Aluminum

- **Y** – degree of hardening
  - 2 – 1/4 hard
  - 4 – 1/2 hard
  - 6 – 3/4 hard
Cold Worked Aluminum

- **8** – Full hard (maximum amount of commercially practicable cold working)

- **9** - Extra hard (2000 Pascal units above 8/8)

- **Z** – some variation (usually an internal system of manufacturing)
Heat Treated Aluminum

• **W** – solution heat treated, unstable temper

• **T** – treated to produce stable tempers other than “F”, “O”, “H”
  - **T1** - cooled from hot forming aged process, extrusion
  - **T2** - annealed (cast products only)
Heat Treated Aluminum

- **T3** - solution heat treated and then cold worked (work hardened)

- **T4** - solution heat treated

- **T5** - artificially aged only

- **T6** - solution heat treated and then artificially aged
Heat Treated Aluminum

- **T7** - solution heat treated and then stabilized
- **T8** - solution heat treated, cold worked, and then artificially aged
- **T9** - solution heat treated, artificially aged, and then cold worked
- **T10** - artificially aged and then cold worked
Heat Treated Aluminum

- Additional digits past the “T” number indicate a variation in treatment that significantly alters product characteristics

- Example: T38 – solution heat treated then cold-rolled to a thickness reduction of 8%
Classes of Aluminum

• Non-Heat Treatable but Weldable
  – Good corrosion resistance
  – Easy to fabricate
  – Low strength - non structural
## Classes of Aluminum

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<td>96.2</td>
<td>95.1</td>
<td>97.0</td>
<td>96.4</td>
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Classes of Aluminum

• Heat treatable and Weldable
  – Fair corrosion resistance
  – Medium strength
  – Non structural and secondary repairs
## Classes of Aluminum

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<tr>
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<td>96.2</td>
<td>98.4</td>
<td>95.8</td>
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Classes of Aluminum

- Heat treatable and non-weldable
  - Poor corrosion resistance
  - High strength alloy
  - Primary structure
## Classes of Aluminum

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<td>7075</td>
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</table>

| % Al   | 91.45 | 95.8 | 92.0 | 87.5 | 86.1 |
Classes of Aluminum

• Alclad – an aluminum-clad alloy

• sheets of aluminum alloy core coated with a layer of pure aluminum

• total depth of pure aluminum (both sides) is about 10% of total thickness
Classes of Aluminum

• resists corrosion because aluminum forms $\text{Al}_2\text{O}_3$ (aluminum oxide) film

  – major scratch - any scratch that penetrates the cladding

  – minor scratch - not through the cladding; repaired by burnishing
Nickel Alloys

• Monel

• 68% nickel, 29% copper, 1.2% iron, 1% manganese (contains no carbon)

• Highly corrosion resistant
Nickel Alloys

• Alloy 400 is magnetic

• Alloy K-500 is non-magnetic and spark resistant
  – titanium and aluminum added for age hardening
Nickel Alloys

- Inconel
  - 80% nickel, 14% chromium, 0.05% titanium
  - Very high corrosion resistance
Nickel Alloys

• Used in high temperature areas
  – 75% of room temperature strength at 1200°F

• Used in turbine blades
Magnesium Alloys

• One of the lightest materials used in aircraft structures

• Highly corrosive, corrodes easily

• Flammable – fire hazard if heated to excessive temperature
Magnesium Alloys

• heat treated to improve tensile strength, ductility, and shock resistance

• heat treated by solution heat treatment plus precipitation hardening (natural aging has negligible effect)

  – never heat in salt bath, or it will explode
Magnesium Alloys

• Note: Because magnesium is so corrosive and an incompatibility exists between aluminum and magnesium, a combination of Zinc Chromate and tape must be used when aluminum and magnesium are riveted together
Copper Alloys

Brass - Copper and Zinc
Copper Alloys

Bronze –
Copper and Tin
Titanium

• Advantages
  – high temperature applications (up to 1100°F)
  – good strength
  – resistance to erosion and erosion-corrosion
Titanium

– very thin conductive oxide surface film

– hard, smooth surface that limits adhesion of foreign materials

– surface promotes dropwise condensation (water tends to bead up on the surface)
Titanium

• Disadvantages
  – High cost compared to Aluminum and CRES
  – Hard to machine

• Wrought alloys amount to over 70% of the market
  – Most common alloy – Ti-6Al-4V
Titanium

• Welding
  – increases strength and hardness
  – decreases tensile and bending ductility
  – must take great care not to contaminate the weld
Titanium

• Heat treating
  – reduce residual stresses developed during fabrication
  – increase strength (solution heat treating and aging)
  – produce optimal combination of ductility, machinability, and dimensional and structural stability (annealing)
Titanium

– optimize special properties such as fracture toughness, fatigue strength, and high temperature creep strength

– only titanium alloys (not pure titanium) can be hardened through heat treatment

– titanium can also be casehardened through nitriding, carburization, or carbonitriding
Stainless Steels

• Definition – a ferrous alloy with a minimum of 10.5% Chromium

• Also known as CRES (Corrosion Resistant Steel)

• Most stainless steels are low carbon steels
  – less susceptible to the formation of chromium carbide along the grain boundaries
Stainless Steels

- Other alloys added

- **Nickel** – stabilizes the austenite structure
  - non-magnetic, less brittle at low temperatures

- **Carbon** – used to control the amount of hardening
Stainless Steels

• **Manganese** – gives similar results as nickel but cheaper

• High oxidation resistance in air at ambient temperature

• Forms a passivation (hard non-reactive surface film) layer of $\text{Cr}_2\text{O}_3$
Stainless Steels

– Protects the surface from oxygen

• Susceptible to pitting when not exposed to oxygen (no film formed) or when exposed to chlorine ions

– Pitting leads to stress concentration.
Types by Crystalline Structure

• **Austenitic** – over 70% of commercial production
  – Maximum 0.15% carbon
  – Minimum 16% chromium

• Necessary amounts of nickel and manganese to retain the austenitic structure from cryogenic temperatures to melting temperatures
Types by Crystalline Structure

- Typical 18/10 (18% chromium – 10% nickel), 18/8, or 18/0

- Molybdenum added (>6%) to inhibit chlorine pitting and crevice corrosion
Types by Crystalline Structure

- **Ferritic** – High corrosion resistance, softer than austenitic

- Cannot be hardened by heat treating

- 10%-27% chromium, little nickel, traces of molybdenum, aluminum, titanium
Types by Crystalline Structure

- **Martensitic** - Extremely strong and tough; can be machined
  - Harder, more brittle, magnetic
  - Can be hardened by heat treating
Types by Crystalline Structure

- 12% to 14% chromium, 0.2%-1% Carbon
- Not as corrosion resistant as the others
Stainless Steel Grades

• As defined by the American Iron and Steel Institute (AISI)

• **200 series** – austenitic – Fe – Cr – Ni – Mn

• **300 series** – austenitic – Fe – Cr – Ni
Stainless Steel Grades

- **301** – highly ductile, hardens rapidly with cold working

- **303** – free machining version of 304 (sulfur added)

- **304** – common 18/8
Stainless Steel Grades

– **316** – molybdenum added – Marine Grade (good corrosion resistance in salt-water environment)

• **400** – ferritic / martensitic alloys

  – **408** – 11% Cr, 8% Ni - Heat resistant, poor corrosion resistance
Stainless Steel Grades

– 409 – Fe - Cr – cheapest (car exhausts)

– 410 – martensitic – high strength Fe – Cr

– 420 – martensitic – surgical steel

– 430 – ferritic – decorative (trim)
Stainless Steel Grades

- 440 – higher grade of cutlery steel – more carbon content

- 600 – Martensitic precipitation hardening alloys

- 630 – 17-4 stainless steel (17% Cr, 4% Ni)