GOOD MORNING YOUNG MINDS

WROUGHT ALLOYS AND STAINLESS STEEL

Specific learning objectives

❑At the end of this presentation, the participant should be able to

✓1. Enumerate wrought alloys

✓2. Describe the objectives of ANNEALING

✓3. Describe the stages of annealing

✓4. Describe the types and properties of stainless steel

✓5. Enumerate the Heat treatment process

❑ WROUGHT ALLOYS

✓DEFINITION:

"Wrought metal can be defined as the cold-worked metal that has been plastically deformed to alter the shape of the structure and certain mechanical properties."

Cast alloy → Cold worked → Wrought alloy

An **ingot** is formed by melting the component metals together and then the alloy is solidified.

↓

Once solidified, the alloys have a polycrystalline structure. This cast alloy is the starting point which is called an ingot.

↓

The alloy is then subjected to series of thermomechanical process and drawn into **different shapes** to produce the **wrought alloy**.

In other words, the cast alloy is cold worked to produce the wrought alloy.

❖Examples for wrought alloys:

- ❑Stainless steel
- ❑Elgiloy(cobalt–chromium–nickel)
- ❑β-Ti
- ❑Nitinol.

- A wrought alloy properties and microstructure that are not associated with the same alloy when cast.
- Substantial permanent deformation by cold working causes lot of dislocations within the metals.
- The increased stress required to produce further dislocation to achieve permanent deformation provides, what is called ***strain hardening.*** Strain hardening is otherwise called ***work hardening.***
- Cold working alters the shapes of grains and usually in an orthodontic wire the **GRAINS GET ELONGATED PARALLEL TO THE WIRE AXIS**.
- The effects associated with cold-working apart from strain hardening include distorted grains and decreased ductility.

CLINICAL IMPLICATIONS

- Cold Working/Strain Hardening/Work Hardening– Main methods to harden SS alloy.
- The metal is stressed beyond its proportional limit , Hardness and Strngth of the metal increases at the area of deformation.
- Ductility of the metal decreases.
- As the dislocations move and pile up at the grain boundaries , further plastic deformation becomes difficult.
- Due to this, repeated plastic deformation of the metal , which occurs while bending of ortho wires → Lead to brittleness of the wire

↓

FRACTURE

ANNEALING/HEAT TREATMENT OF ORTHODONTIC ALLOYS

❖ *“Controlled heating and cooling process designed to produce desired properties in a metal.”*

- The annealing process usually is intended to soften metals, to increase their plastic deformation potential, to stabilize shape and to increase machinability.

❑Drawbacks of cold-working a cast metal into a wrought metal:

1. Strain hardening
2. Lowered ductility (⬇)
3. Distorted grains
4. Increased tensile strength (⬆)

- These effects can be eliminated simply by **heating the metal** to an appropriate elevated temperature. This procedure is termed as ***annealing*.**

❑*Annealing takes place in three successive stages :*

1. Recovery
2. Recrystallization
3. Grain growth

- ✓ Rule of thumb during annealing is to use a temperature that is approximately half the melting point of the metal or fusion temperature of the alloy.

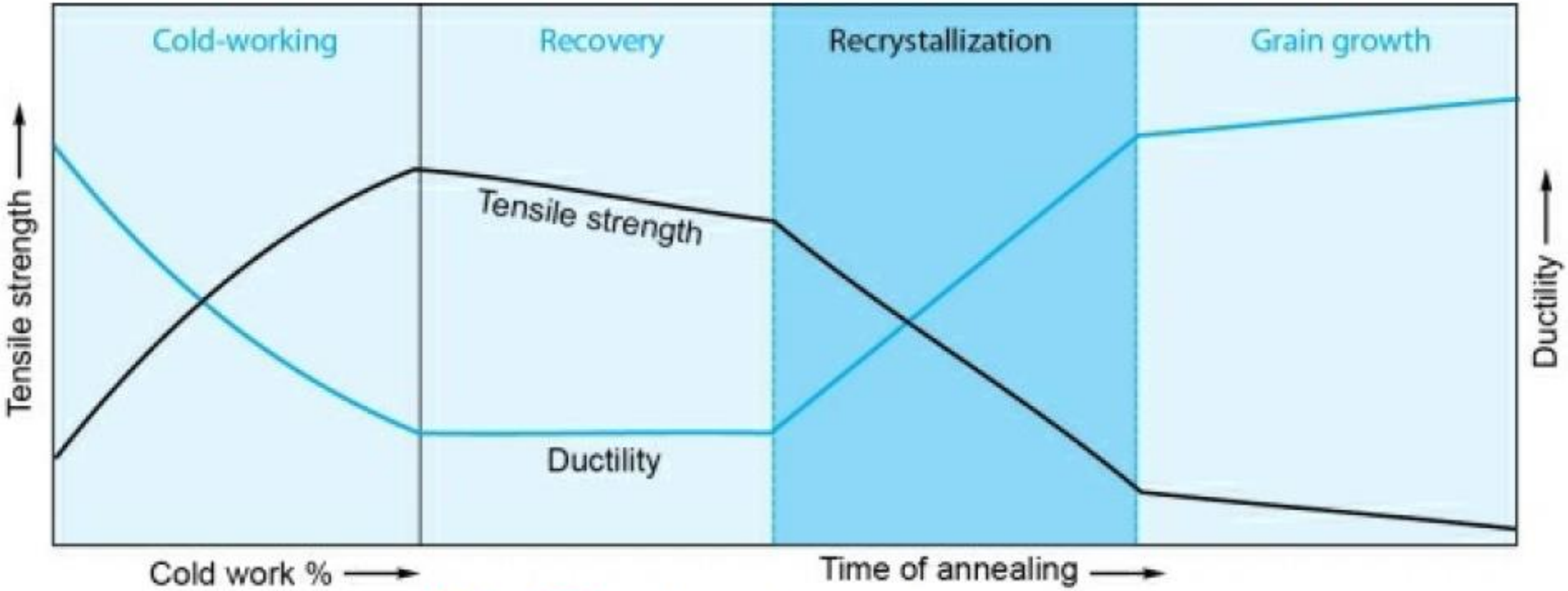


FIG. 17.1. Annealing–stages.

STAGE-I: RECOVERY

-Maximum stress relief occurs

- ✓No visible changes are seen in the structure under microscopic view.
- ✓Cold-work properties begin to disappear.
- ✓Tensile strength is decreased slightly
- ✓Negligible change in ductility.
- ✓The residual stresses are eliminated in this stage. Elimination of residual stresses reduces the tendency of warping.
- ✓Pronounced decrease in electrical resistivity.
- ✓Decrease in dislocation density.

- Subjecting the orthodontic appliances to heat to relieve the stress, stabilizes the configuration of the appliance and allows for perfect determination of the force, the appliance can deliver.

- This kind of heat treatment where only the recovery stage is reached is called ***‘stress relief annealing’.***

- For stainless steel, it is usually heated to a temperature of **370–380°C for 11 min.**

STAGE-II: RECRYSTALLIZATION

- Metal loses its property of Resiliency.

- Changes are observed in the microstructure.
- Distorted old grains start disappearing and are **replaced by fresh strain-free grains.**
- These new grains nucleate in the worst coldworked areas in the metal, and their grain boundary migration consumes the original cold-worked structure.
- **Ductility and softness** increase to the original state.
- That is why recrystallization has to be avoided during stress relief heat treatment of orthodontic appliances.
- **Resilience** also is decreased substantially.

- After Recrystallization metal attains its original soft and ductile condition.

STAGE - III: GRAIN GROWTH

- After recrystallization, the alloy/metal structure has got a certain grain size depending upon the number of nuclei.
- More severe the cold-working, greater the number of nuclei.
- The grain size can be fine or coarse at the end of recrystallization.
- If these grains are further annealed, the grain size increases. Large grains start consuming small grains. Grain growth ceases after a certain point.

❖ Clinical applications

- The properties of the wires can be altered by varying the amount of cold working and annealing.
- **Steel gets hardened by cold-working and is softened with annealing.**
- Fully annealed wires are soft and highly formable.

  Example - **soft ligature wires** used for tying archwires into brackets.
- Partially annealed wires have got more strength but reduced formability.
- 'Super grade' stainless steel wires are brittle and will break when bent acutely.
- Regular grade can be bent without breaking.

STAINLESS STEEL

Harry Brearley. Source: Copyright. Sheffield Industrial Museums Trust.

HISTORY

- **FIRST DEVELOPMENTS:**

- The first true SS was melted on 13th august 1913 by **Harry Bearley**. (associated with BROWN FIRTH LAB)

- **Ernest Stuart**, the cutlery manager of Mosley first referred to this material as ‘**stainless**’.

- Other claims have been made .One of these claims is based on an article in a 1913 Swedish hunting and fishing magazine about a steel that was used for gun barrels. (Stainless Steel World, April 2002, Pg no. 52-53)

Harry Brearley. Source: Copyright. Sheffield Industrial Museums Trust.

- **GERMAN DEVELOPMENTS:**

- With a year of Brearley’s discovery, **Krupp** in Germany was experimenting by adding nickel to the melt.

- From these two inventions, just before first world war, the 400 series of martensitic and 300 series of austenitic SS were developed.

- Brearley’s successor at Brown Firth Laboratories, **Dr. W.H. Hatfield** is credited with the invention of **18/8 SS** in 1924.

- **OTHER GRADES:**

- Most of the standard grades still in use today were invented in the period 1913 to 1935 in Britain, Germany, America and France.

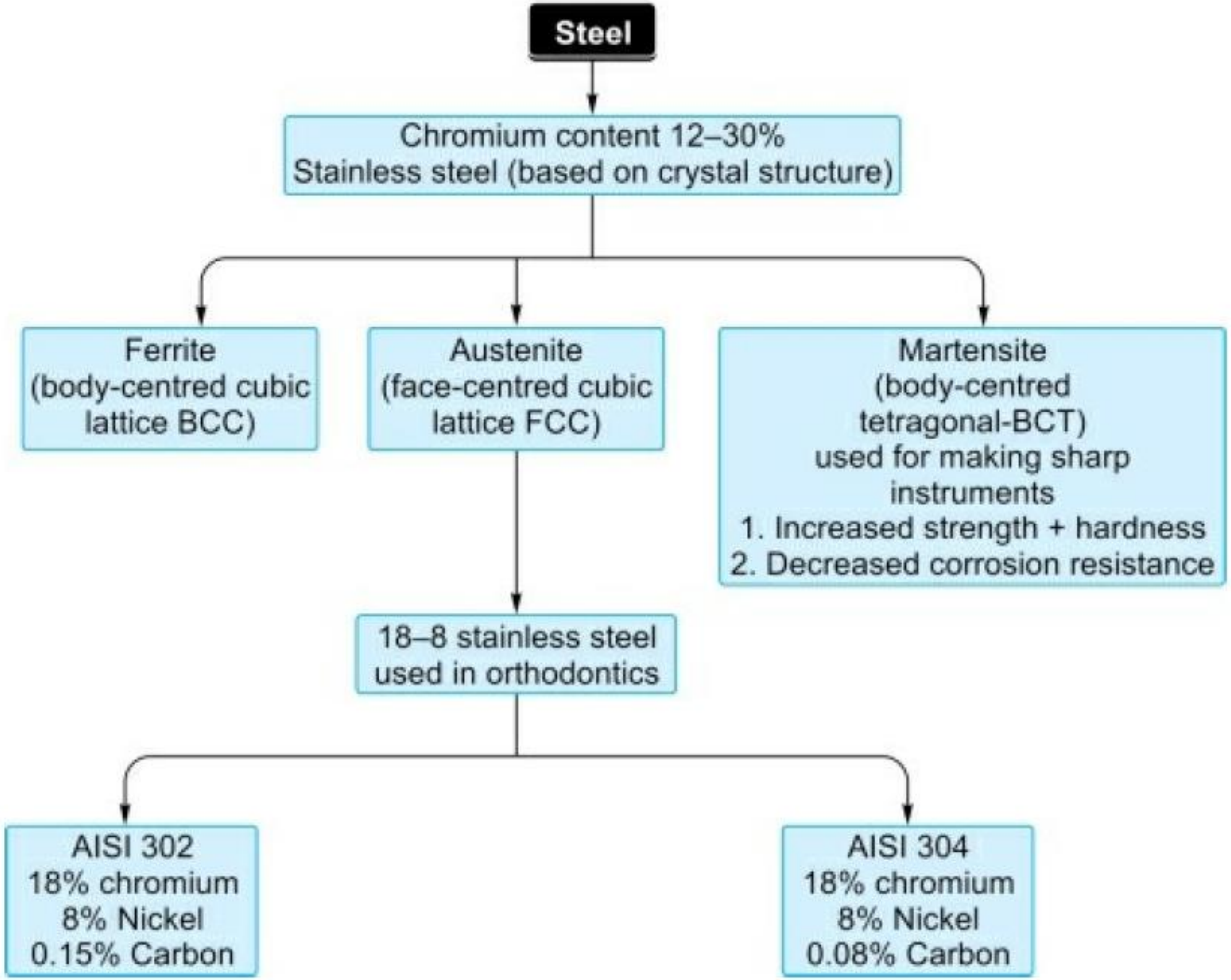
WHAT IS STAINLESS STEEL ?

- Steel is an alloy of iron containing less than 1.2% carbon.
- Stainless steel is a family of iron based alloys that must contain **atleast 10.5% chromium** by weight. (Anusavice, approx 12-30%)
- The corrosion resistance and other useful properties of steel are enhanced by increased **Cr** content and addition of other elements such as Mo, Ni and Nitrogen.
- Stainless steel - **low cost** and **excellent formability**, along with good mechanical properties

COMPOSITION

- **ALLOYING ELEMENTS IN SS:**
- There are more than 60 grades of SS.
- It can be divided into 5 classes.

CLASS OF STEEL	CARBON CONTENT	CHROMIUM CONTENT	NICKEL CONTENT
AUSTENITIC SS Fe-Cr-Ni (Mo)	0.25%	16-26%	7-22%
FERRITIC SS Fe-Cr (Mo)	0.20%	11.5-27%	
MARTENSITIC SS Fe-Cr-C (Ni-Mo)	0.15-1.2%	11.5-17%	0-2.5%
DUPLEX SS Fe-Cr-Ni (Mo)-N	0.03%	21-26%	3.5-8%
PRECIPITATION HARDENING STEELS Fe-Cr-Ni(Mo-Cu-Al-Nb)-N	0.09%	12.25-18%	3-8.5%



Steel

Chromium content 12–30%
Stainless steel (based on crystal structure)

Ferrite
(body-centred cubic
lattice BCC)

Austenite
(face-centred cubic
lattice FCC)

Martensite
(body-centred
tetragonal-BCT)
used for making sharp
instruments
1. Increased strength + hardness
2. Decreased corrosion resistance

18–8 stainless steel
used in orthodontics

AISI 302
18% chromium
8% Nickel
0.15% Carbon

AISI 304
18% chromium
8% Nickel
0.08% Carbon

FIG. 17.2. Stainless steel–composition and types.

ROLE OF ALLOYING ELEMENTS

- **CARBON:**
- The amount of carbon is the key
- In all the categories except martensitic SS, the level is quite low.
- In martensitic SS, the level is deliberately increased to obtain high strength and hardness.
- Effects corrosion resistance

- **CHROMIUM:**
- Addition of atleast **10.5%** chromium can significantly alter the corrosion properties.

- At and above this level, an extremely thin surface layer is instantaneously formed (as long as oxygen is present) that prevents diffusion of oxygen atom through this layer and protects iron from rusting.

↓

PASSIVATION.

- **NICKEL:**

- Results in formation of austenitic structure.(300 series SS grades)

- Gives strength, ductility and toughness even at cryptogenic temperatures.

- Non-magnetic

- Resistance to acid attack particularly sulfuric acid

- **MOLYBDENUM:**
- Helps to resist detrimental effect of chlorides.

- **NITROGEN:**
- Increases resistance to localized pitting attack and intergranular corrosion.

- Helps to increase yield strength.

- **MANGANESE:**
- Assist in deoxidation during melting
- Prevents formation of iron sulfides inclusions
- Austenitic stabiliser
- Can replace Ni in 200series SS grades at higher level

- **SILICON AND COPPER:**
- Improves corrosion resistance to sulfuric acid.
- Ferrite stabiliser
- In austenitic SS, high silicon contents improve resistance to oxidation and also prevents carburizing at elevated temperatures.
- **SULFUR:**
- Generally kept to low levels as it can form sulfide inclusions
- Used to improve machinability where these inclusions act as chip breakers.

- **TITANIUM:**
- Main element used to stabilise SS before the use of AOD (Argon-oxygen-decarburization) vessels.
- React with carbon to form titanium carbides
- **NIOBIUM:**
- Prevents intergranular corrosion particularly in the heat effected zone after welding.
- Also prevents formation of chrome carbides.

BENEFITS OF SS:

- Corrosion resistance
- Fire and heat resistance
- Hygienic
- Pleasing appearance
- Strength to weight advantage
- Ease of fabrication
- Impact resistance
- Long term value

ALLOY CLASSIFICATION WITH GENERAL PROPERTIES

AMERICAN IRON AND STEEL INSTITUTE

1) AISI 200 SERIES AUSTENITIC:

- Alloys *201 202 203 204 205*
- High strength in the annealed.
- Non-magnetic, not heat transferable.
- Excellent formability.

2) AISI 300 SERIES AUSTENITIC:

- Alloys 301 302 303 304 305 308 309 310 314 316 317 321 330 347 384
- High strength by cold working
- Non-magnetic, not heat transferable
- Good formability
- Excellent corrosion resistance
- Good high and low temperature mechanical properties

3) AISI 400 SERIES FERRITIC:

- Alloys 405 409 429 430 434 436 442 446
- Non-hardenable 400 series
- Magnetic but not heat transferable
- Good corrosion resistance
- Limited temperature use

4) AISI 400 SERIES MARTENSITIC:

- Hardenable 400 series
- Magnetic but can be hardened by heat treatment
- Adequate corrosion resistance
- Limited temperature use

5)PRECIPITATION HARDENING:

- Alloys 13-8,15-5,15-7,17-4,17-7
- Develops strength by precipitation hardening reaction due to heat treatment.

6)DUPLEX:

- Alloys 329,2205,2304,2507,3RE60
- More resistant to stress corrosion cracking than austenitic yet tougher than ferritic alloys.

PHYSICAL PROPERTIES OF SS

PROPERTIES	304 AUSTENITIC	430 FERRITIC	410 MARTENSITIC
TENSILE STRENGTH IN MPa	579	517	483
YIELD STRENGTH IN MPa	290	345	310
ELONGATION IN %	55	25	25
HARDNESS	B80	B85	B80
MODULUS OF ELASTICITY IN TENSION IN GPA	193	200	200
DENSITY IN KG/M^3	8060	7780	7780
MELTING POINT IN CELSIUS	1400-1455	1425-1510	1485-1535

Properties of stainless steel

- *Passivating effect:* Resistance to tarnish and corrosion of the stainless steel is because of the passivating effect of the chromium.
- The chromium in the stainless steel forms a thin adherent transparent but tough and impervious oxide layer on the surface of the alloy when it is subjected to an oxidizing atmosphere as mild as clean air.
- This protective layer prevents further tarnish and corrosion by blocking the diffusion of oxygen to the underlying bulk alloy. This is called ***'passivating effect'.***
- For this effect to take place, a minimum of 12% of chromium is required.
- If the oxide layer is ruptured by mechanical or chemical means, a loss of protection against corrosion results.

HIGH TEMPERATURE PROPERTIES

- With time and temperature, changes in metallurgical structure can be expected with any metal.
- In SS, the changes can be softening, carbide precipitation or embrittlement.

- When exposed to a temperature of 700-950°F over an extended period of time hardenable and non hardenable 400 series and duplex SS are subject to embrittlement.

- 885°F is called embrittlement temperature because at this temperature process is most rapid.

CORROSION:GALVANIC CORROSION

When two different metals are immersed in a corrosive solution, each will develop a corrosion potential. If corrosion potential of two metals is significantly different, and they are in direct contact and immersed in an electrolyte the more noble metals will become cathode and more active metal will become anode.

The increased corrosion of anode is referred as galvanic corrosion

- The greater the corrosion potential of each metal the greater the potential for corrosion.

GENERAL CAUSES OF CORROSION

- Surface inhomogeneity in surface of SS
- Incorporation of bits of carbon steel or a similar metal in its surface
- Brazed and soldered joints

SENSITIZATION

- Austenitic SS may loose its resistance to corrosion if it is heated between approx 400°C. and 900°C. The decrease in corrosion resistance is caused by the precipitation of chromium iron carbide at the grain boundaries at these high temperatures. The chromium level is depleted below that necessary for protection (approx 12%)

- The SS becomes susceptible to intergranular corrosion and partial disintegration of weakened alloy may result.

Heating stainless steel to 400–900°C

↓

Reaction of chromium and carbon at grain boundaries

↓

Formation of chromium carbide in grain boundaries

↓

Loss of chromium from matrix of SS less than 12%

↓

Loss of passivating effect

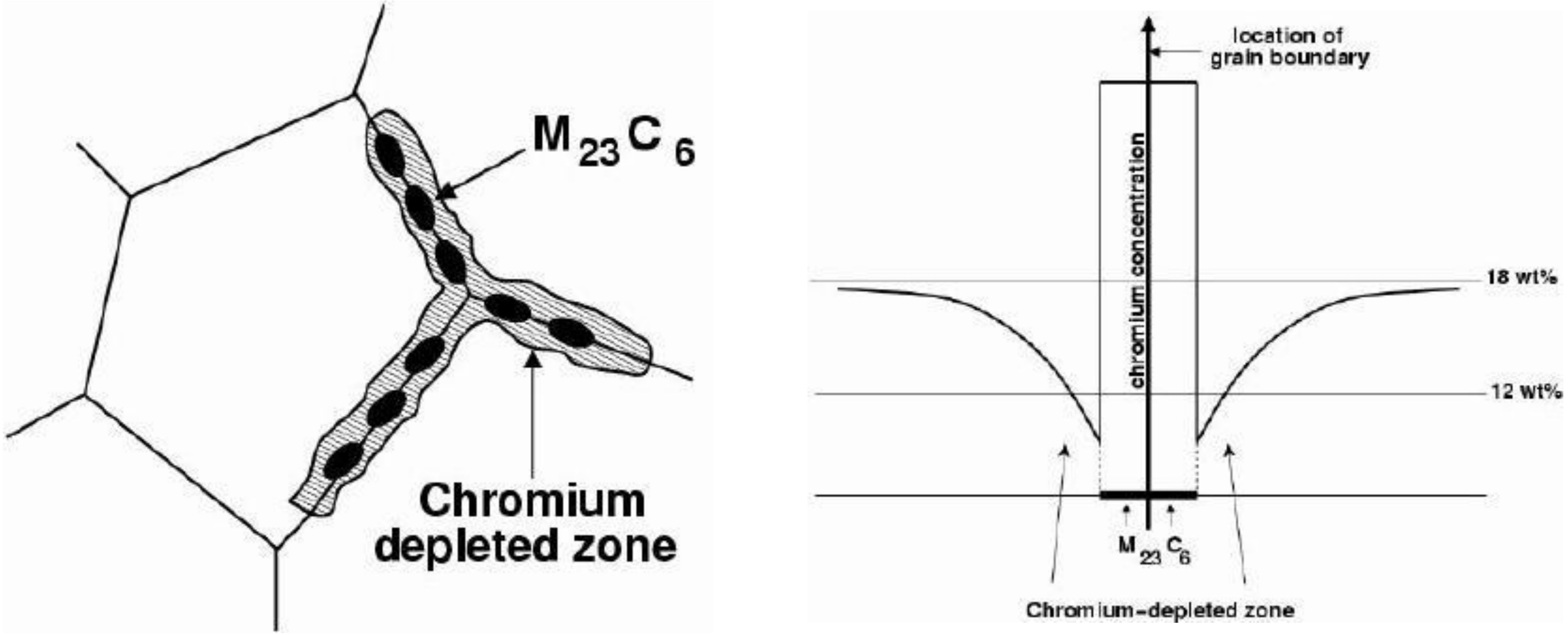
↓

Reduction in corrosion resistance

↓

Weakening of the metal

Schematic illustration of grain boundary, carbide precipitation and corresponding chromium profile



- Various methods can be used to minimize sensitization when austenitic SS is heated into this problematic elevated temperature range:

1. **Reduce carbon content of the steel** to an extent that such carbide precipitation cannot occur.
2. If SS is **severely cold worked** and heated within sensitization temperature range, chromium carbide instead precipitate at dislocations, which are located on slip planes within bulk grains.
3. ***Stabilization:*** Most successful method employed to eliminate chromium carbide precipitation is introduction of some other element which will react with carbon. Titanium is most often used and added 6 times that of carbon. Formation of chromium carbide can be prevented in this manner. Stainless steel that has been modified in this manner is said to be 'stabilized'.

APPPLIED ASPECTS

- 1) Orthodontic wires
- 2) Bands
- 3) Brackets
- 4) Screws
- 5) Instruments
- 6) Equipments
- 7) Implants

PROPERTIES

- **STRESS**
- Stress is the internal distribution of the load, defined as force per unit area
- *It is the internal distribution of a load applied to* a material.

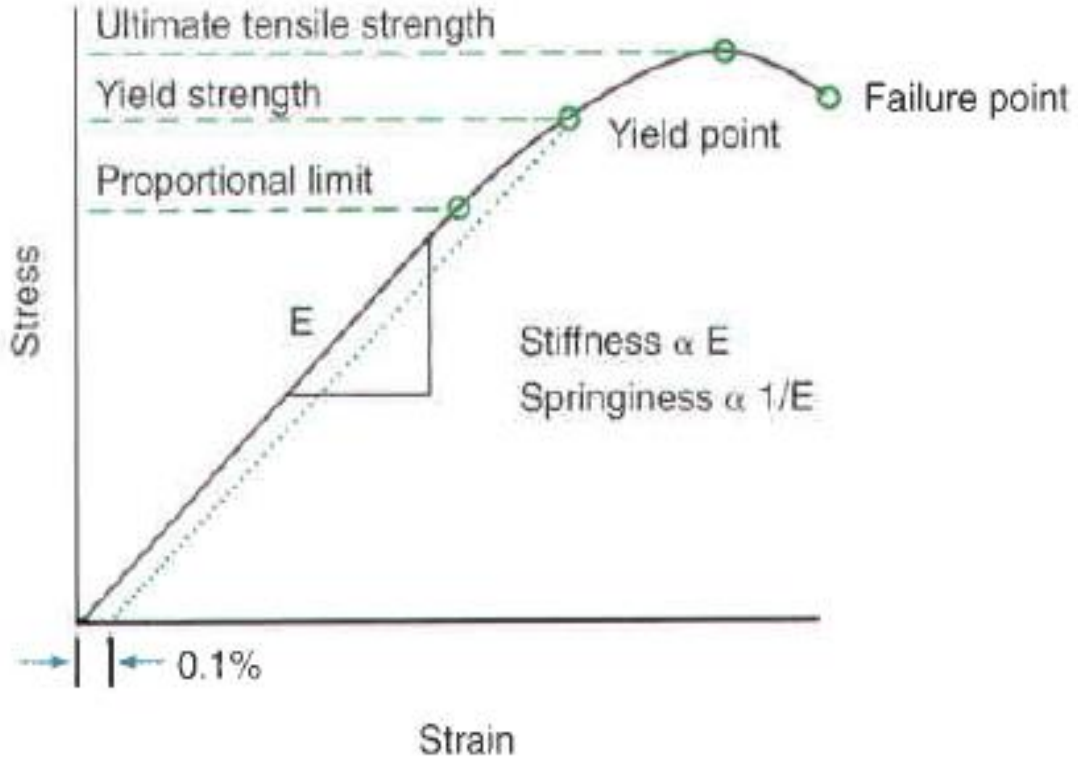
$$\text{STRESS} = \frac{\text{INTERNAL FORCE}}{\text{AREA OF ACTION}}$$

- ***STRAIN***
- *It is the internal distortion produced by the load.*
- It is defined as deflection per unit length.

$$\text{STRAIN} = \frac{\text{CHANGE IN LENGTH}}{\text{ORIGINAL LENGTH}}$$

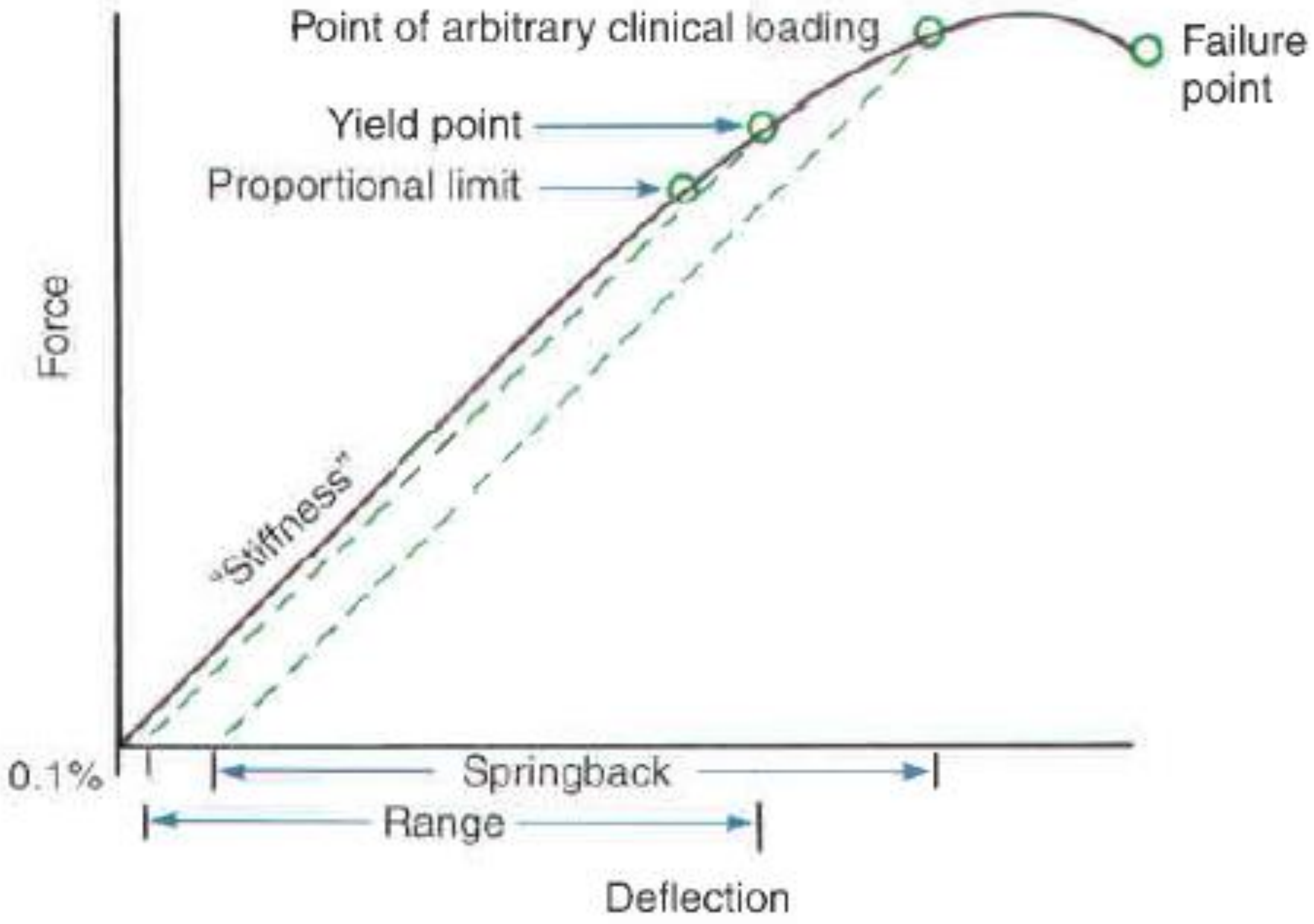
Proffit W, Fields H, Sarver D.Contemporary Orthodontics.5th Ed.St Louis:Mosby;2013

- ***MODULUS OF ELASTICITY***:
- *According to the Hooke's law,* stress and the strain are directly proportional to each other in the elastic portion of the graph.
- The ratio of the stretch in the spring and applied force (stress) (but only within its proportional limit) is called '*Modulus of elasticity*'
- Is a constant for a given material



- ***PROPORTIONAL LIMIT****:*
- *It is the point on the graph at which* a permanent deformation is first observed.
- Although the definitions differ, the elastic limit and proportional limit, for all practical purposes, represent the same point.

- ***ELASTIC LIMIT****:*
- *It describes the greatest load, to which the* wire can be subjected, such that it returns to its original form
- After this point, when the load on the wire is removed, it does not return back to its original length.


Point of arbitrary clinical loading
Failure point
Yield point
Proportional limit
Force
"Stiffness"
0.1%
Springback
Range
Deflection

- ***YIELD STRENGTH***
- This denotes the amount of stress on the stress-strain graph which causes a certain amount of permanent deformation (usually 0.1%) is calculated. This is called the *yield strength*

- ***ULTIMATE TENSILE STRENGTH***
- The maximum force that a wire can withstand, before it fractures, is denoted as the *ultimate tensile strength.*
- *This is always higher than the* yield strength, and clinically, it is usually the indicator of the maximum force that the wire can deliver

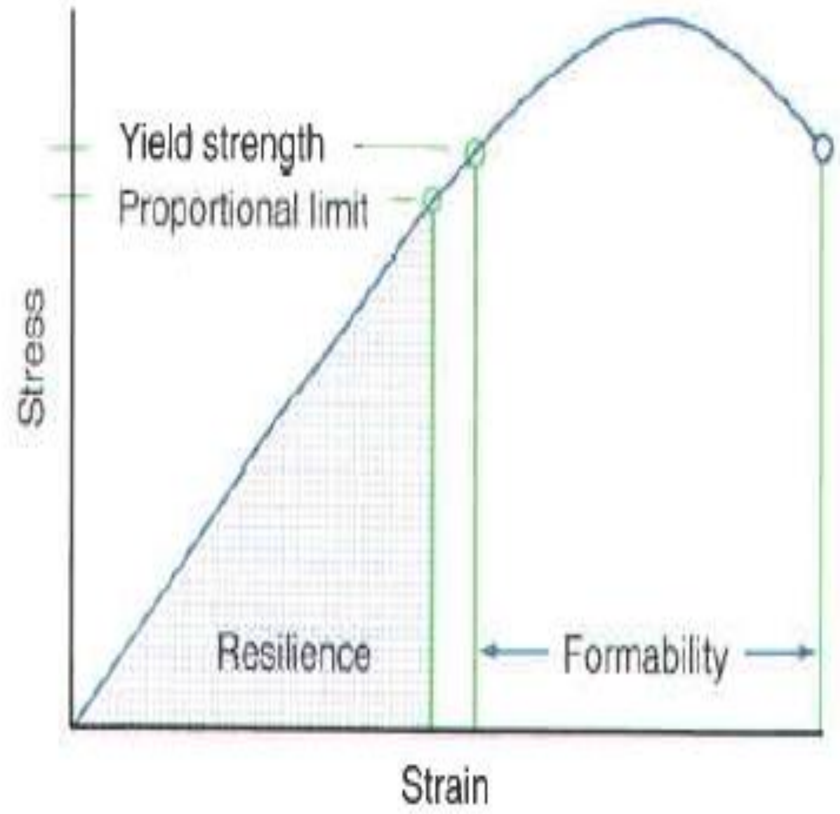
- ***STIFFNESS*:**
- It basically refers to the resistance of the wire to deformation. Stiffness also the measures the force the wire is capable of delivering for a particular amount of deflection.
- Burstone believes that the stiffness of a wire is related to both the material and cross-section.
- Stiffness and ***SPRINGINESS*** are reciprocal properties:
- Springiness= 1/Stiffness
- Each is proportional to the slope of the elastic portion of the force-deflection curve
- The more horizontal the slope, the springier the wire; the more vertical the slope, the stiffer the wire.

- ***SPRINGBACK*:**
- Springback refers to clinically applicable term for maximum elastic deflection, maximum flexibility, range of activation, range of deflection, or working range.
- It is the extent to which a wire recovers its shape after deactivation.

- ***RANGE***:
- The distance that the wire bends elastically, before permanent deformation occurs.
- Clinically, this means the distance to which an archwire can be activated without exceeding the limits of the material

- **TOUGHNESS:**
- Toughness is defined as the force required fracturing a material. It can be measured as the total area under the stress - strain graph.

- ***BRITTLENESS****:*
- *This is considered being the opposite of* toughness. A brittle material cannot undergo plastic deformation



- ***RESILIENCE*** is the area under the stress-strain curve out to the proportional limit. It represents the energy storage capacity of the wire, which is a combination of strength and springiness
- ***FORMABILITY*** is the amount of permanent deformation that a wire can withstand before failing. It represents the amount of permanent bending the wire will tolerate (while being formed into a clinically useful spring, for instance) before it breaks

STAINLESS STEEL

Stiffness	High
Springback	Low
Load Deflection rate	Highest
Biocompatibility	Good
Resiliency	Low
Friction	Very low
Formability	Good
Cost	Lowest

Hardness of stainless steel wires has been shown to vary within the 235 to 300 range

Stainless steel wire presented modulus around 170 Gpa

Ultimate tensile strength reported was 2100 Mpa

- ***BAUSCHINGER EFFECT:***
- *This denotes the phenomena when* the material is strained beyond its yield point in one direction, and then strained in the reverse direction, its yield strength in the reverse direction is reduced

- ***STRAIN OR WORK HARDENING OR COLD WORKING:***
- *It is the* process of plastically deforming a metal at a temperature lower than at which it recrystallizes new grains.
- This temperature is usually one-third to one-half of its absolute melting point. Cold working disrupts the normal atomic arrangement and incorporates strain across the grain boundaries.

- ***HEAT TREATMENT:***
- *It refers to a general process of using* thermal energy to change the characteristics of metallic alloys as in tempering, precipitation hardening or annealing.
- In a clinical setting different wires are heat treated according to manufacturer’s recommendations. A wire is considered heat treated when it appears straw coloured.

- ***ANNEALING:***
- *It is the process of reversing the effects of* cold working such as strain hardening, distorted grains, etc. by simply heating the metal. In clinical setting a wire is considered annealed when it appears red hot

HEAT TREATMENT OF STAINLESS STEEL WIRE

- Cold working contribute to the high yield strength and modulus of elasticity of stainless steel.
- Residual stresses present in a wire subsequent to bending can markedly affect the elastic properties of the wire.
- **Heat treatment is therefore used in stress-relieving** stainless steel after bending the wire into an arch, loops, or coils. This helps to enhance the elastic properties of the wire.

- The recommended temperature-time schedule for stress-relieving stainless steel is **750” F (399” C) for 10-11 minutes**.

- *Funk* recommends the use of a color index to determine when adequate heat treatment is achieved. He suggests that a **straw-colored wire** indicates that optimum heat treatment has been attained.

Heat treatment of SS wires at temp of 700*C (1300*F) or higher causes rapid softening and loss of wrought microstructure as a result of RECRYSTALLIZATION.

OPTIMUM HEAT TREATMENT WILL INVOLVE ONLY RECOVERY STAGE OF ANNEALING

Clinicians perform heat treatment using electrical resistance (spot) welding apparatus

❑ Heat treatment of SS will decrease Modulus of Elasticity and Modulus of Resilience.

❑ There is substantial increase in elastic limit after heat treatment.

❑ Main clinical purpose of HT is to minimize breakage rather than to achieve significant increase in resilience.

- HEAT TREATMENT OF TMA AT 480*C FOR 7-12 MIN.
- INCREASES IN RESILIENCE AND ELASTIC MODULUS IN TENSION.