# ME 216 – Engineering Materials II

## Chapter 13

Metallurgy of Metal Working & Fabrication

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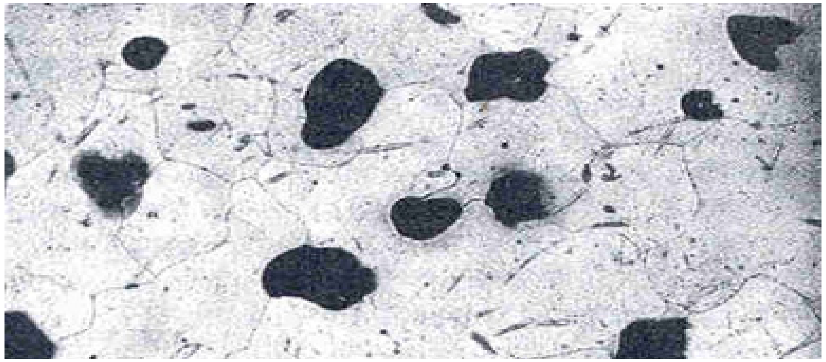
- Until now, various metallurgical aspects on understanding of the characteristics of metals and the relationship between structures and mechanical properties have been made.
- However, all those may have little practical value if not applied to form a material into desired internal structure and external shape (i.e. to fabricate the actual hardware).
- **This chapter deals with application of metallurgical knowledge to various processes for forming and fabrication of metals.**
- Discussions will be made for producing the desired structure and characteristics of materials. However, details of fabrication processes will not be given as they can be obtained from reference books.

- Casting is the oldest process known for forming materials. It consists of making a mold of desired shape and pouring liquid metal into this mold, which takes up the shape of mold upon solidification.
- There are practically no limits to shapes and sizes to be obtained by casting, and they range from tiny dental inlays of rare metals to complicated steel castings exceeding 200 tons.
- In general, casting processes are **classified according to material used for the mold**:
  - **Sand casting:** uses various types of sands and binders to make the mold.
  - **Plaster castings:** use plaster molds, providing better surface finish to cast shape, better dimensional accuracy, finer details, and more solid structure, but at a higher cost compared to sand casting.
  - **Permanent and semi-permanent mold castings:** used for a large number castings with even better surface finish is required. Metal molds are used for this purpose:
    - **Die & cold chamber pressure castings:** use metallic molds where fluid metal is solidified under sustained pressure, which gives close tolerances, sharp outlines with a fine smooth surface.
    - **Centrifugal castings:** done by pouring molten metal into a revolving mold (made of sand, clay or metal). Centrifugal action forces metal tightly against mold, which gives finer grain size, slightly increased density and uniform distribution of alloying elements.
    - **Investment (Precision or Lost Wax) casting:** used to produce complicated & small parts. A glue mold is made for desired shape, from which wax parts are produced. Special sand is placed around wax part and baked in oven, then wax melts away leaving a hard permanent mold for casting.
    - **Shell Mold casting:** uses thin shell moulds produced by mixing sand with a thermosetting resin. Sand and resin are sprinkled over the heated pattern to provide a thin shell mold, which is removed from pattern and baked to completely set the resin and produce a hard mold.

- Metal for casting may come directly from reduction of ore (e.g. from blast furnace) or from remelting and alloying. In either case, the surface is covered with slag or protective coating to avoid or minimize evaporation losses, oxidation and contamination of metal.

- Gases tend to dissolve in metals at high temp, and gas content increases with time elapsed at high temp. If remain trapped, dissolved gases cause porosity and produce unsound castings (*as seen in figure*).

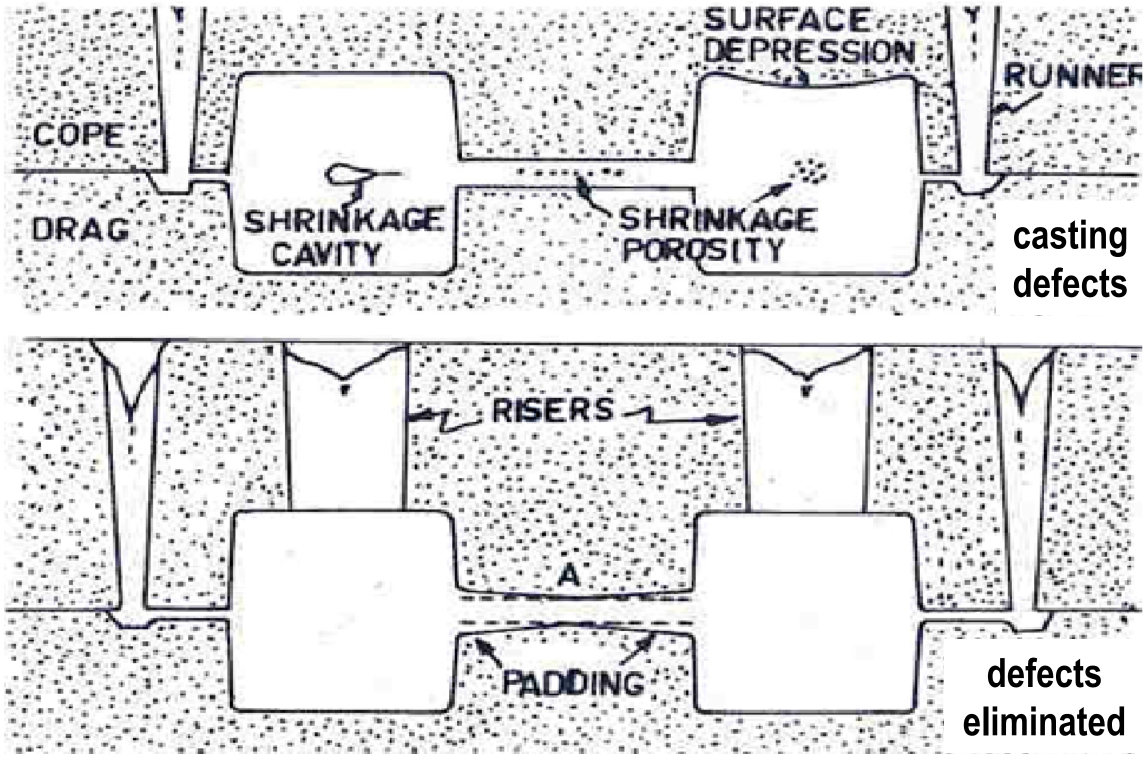
- To avoid this, casting is carried out at min. possible temp. and with least possible delay.



**Micrograph of gas holes in a cast copper**

- **Vacuum casting** makes it possible to use high casting temp which increase the fluidity of metals enabling them to completely fill the mold and low dissolved gas concentrations. However, these processes are expensive and used when no other alternative is possible.

- During solidification, a casting generally freezes on the exterior while the centre is still liquid. As metals contract on solidification, this leads to a shrinkage cavity in the centre.
- This problem can be avoided by directional solidification of casting whereby it solidifies progressively without leaving any liquid regions behind. This way, all sections of the casting will have continuous access to the liquid metal, and hence no cavity can form.
- Directional solidification can be achieved in many ways. For example, a thick section can be solidified rapidly (chilled) with a metallic mold, whereas a thin section can be cast in a pre-heated mold or a mold made of poor heat conductivity material.
- Figure shows how casting defects can be eliminated.
- In the web area, directional solidification eliminates shrinkage porosities.
- In thick sections, risers supply sufficient fresh liquid so that no cavity is formed.

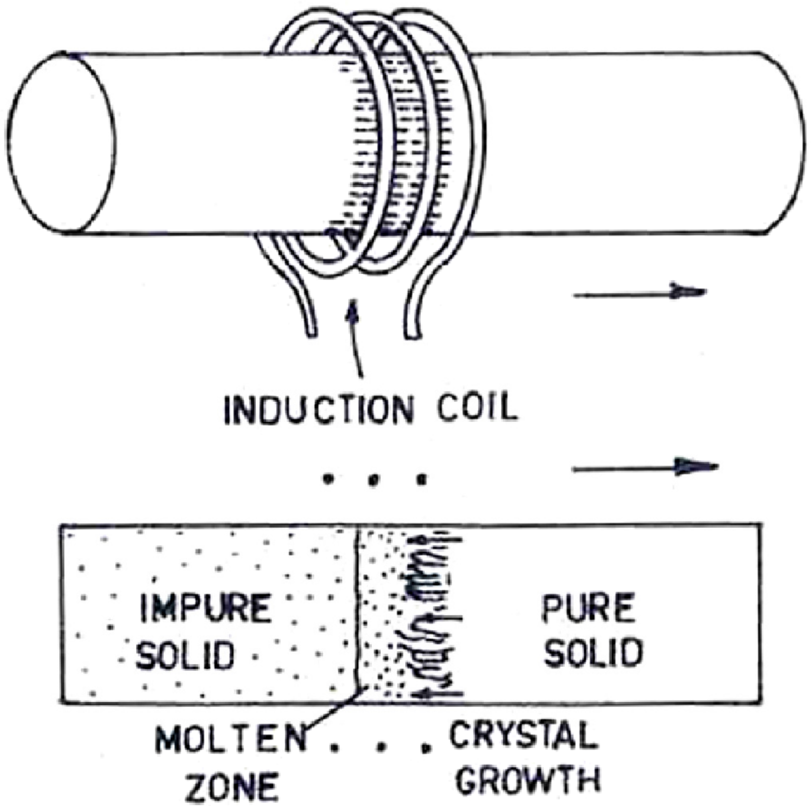


- Many impurities are soluble in liquid metal, but insoluble in solid metal. As metal freezes, such impurities are rejected by solid and remain in liquid. Thus, a difference in the impurity level between the first solidified metal and the last metal to solidify is established. This is called **ingot segregation**, which is undesirable as it gives different properties between such areas of castings. It is minimized by providing a hot dip on ingot mold or a riser on casting. This reservoir is the last to freeze and discarded as it contains most of the impurities.

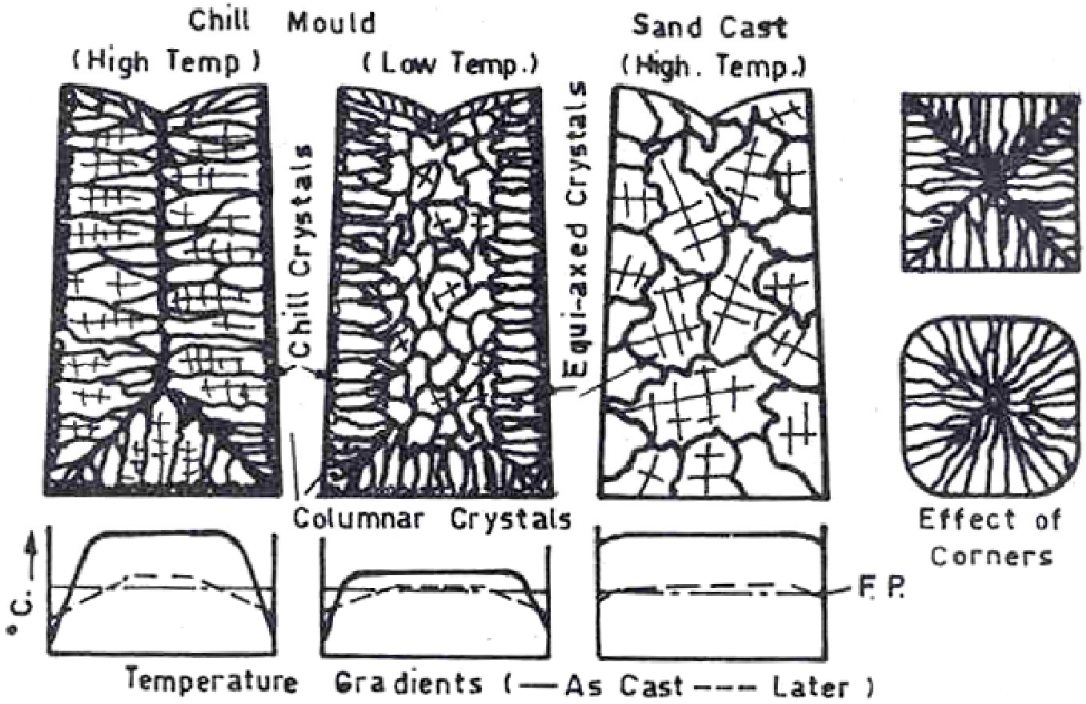
- During **grain boundary segregation**, the impurities accumulate in a film at the grain boundaries, making them brittle. For instance, **sulphur** (in excess of few hundreds of one percent in iron) produces **FeS** film on iron grain boundaries to make the metal brittle.

- In some cases, **zone refining** is applied to produce high purity material. Here, segregation is encouraged in sweeping or squeezing out impurities.

- An ingot of material is melted progressively along its length, a narrow zone at a time (*as in figure*). Molten zone moves progressively from one end to the other, and collects much of impurity that is concentrated in the last 20% of the ingot, which is cut off.

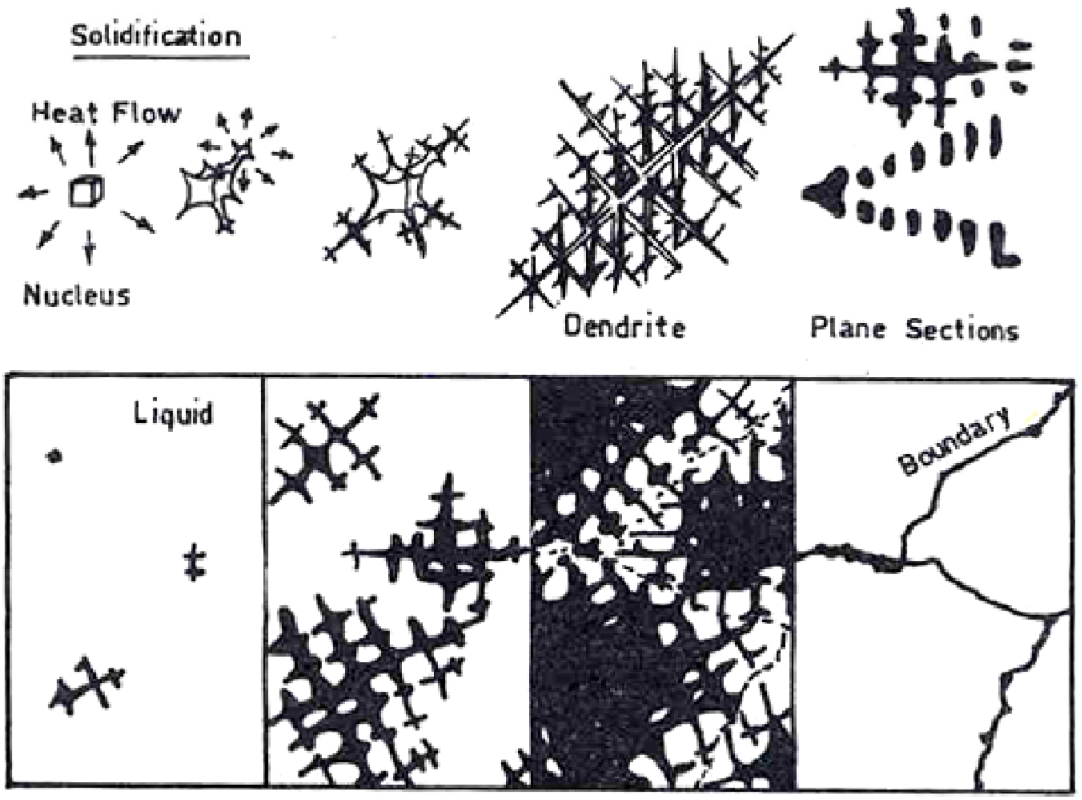


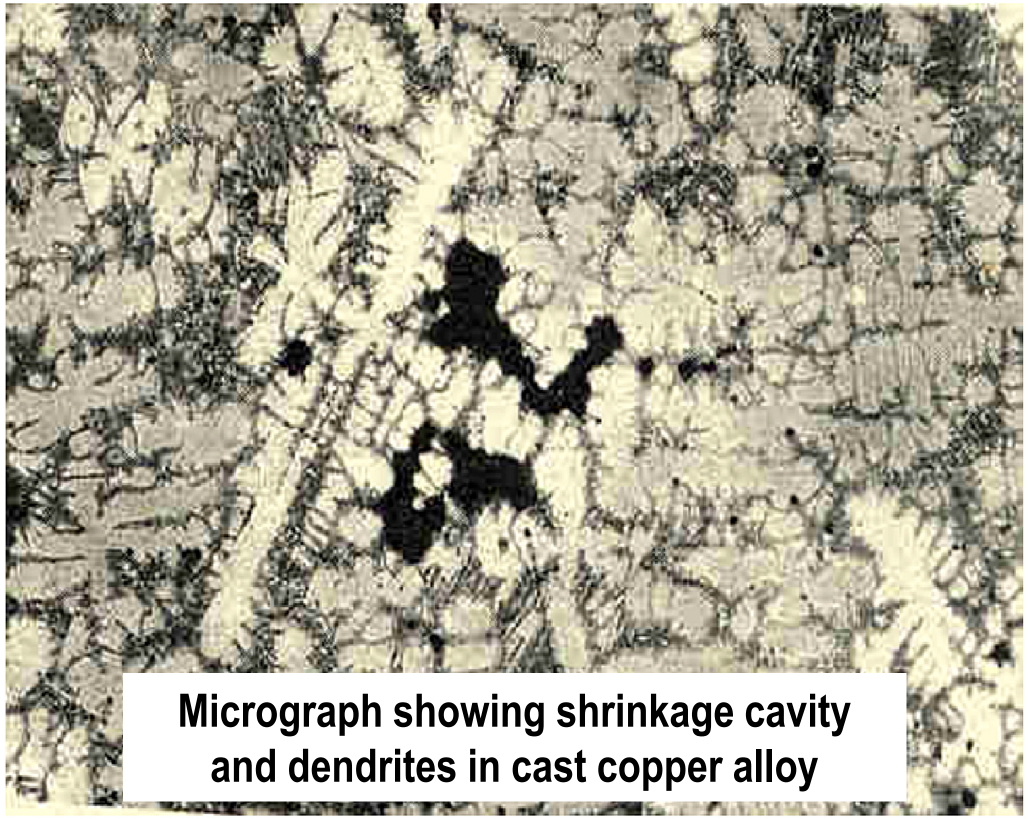
- Solidification under quasi-equilibrium conditions produces equiaxed grains, which is not true in practice.
- If molten metal is poured into relatively cold mold, metal nearest to the wall cools first and solidifies. Thus, the first crystals nucleate on the mold wall and begin to grow in all directions. Their circumferential growth is obstructed by each other, and they continue to grow inwards. The final structure is columnar on the surface with columns almost normal to surface while the inside having randomly oriented grains due to slower cooling (*see figure below*).
- Columnar structure has a preferred orientation (as in chilling), which can be reduced to min. thin "skin" area on mold surface by using sand mold, preheated metal mold, or large mold.
- Rest of interior structure is randomly oriented equiaxed grains. A plane of weakness developes at sharp corners since they contain bulk of impurities rejected by the growing columnar crystals. Such corners should be rounded.
- In sand casting (cooling slowly due to low rate of heat dissipation), a few nuclei are activated and their growth is roughly the same in all directions. The result is a coarse equiaxed grain structure with same grain size but different orientations.



- In some instances, crystals growing during solidification develop rapidly along certain crystallographic directions and slowly along others, resulting in formation of long branch-like arms or dendrites (*as shown below*).

- As these dendrites grow into grains, they must accommodate themselves to their neighbors, which makes the exterior irregular while preserving regular arrangement of atoms in interior.



**Micrograph showing shrinkage cavity and dendrites in cast copper alloy**

- In melting and casting of metals and alloys, many factors have to be considered to reduce the incidence of defects. A number of defects may arise from faults in mold construction or from poor quality sand, and experienced staff can easily avoid molding problems.

- However, in most cases, the part shape produces casting defects, which is usually decided by design engineers who know little about casting problems.

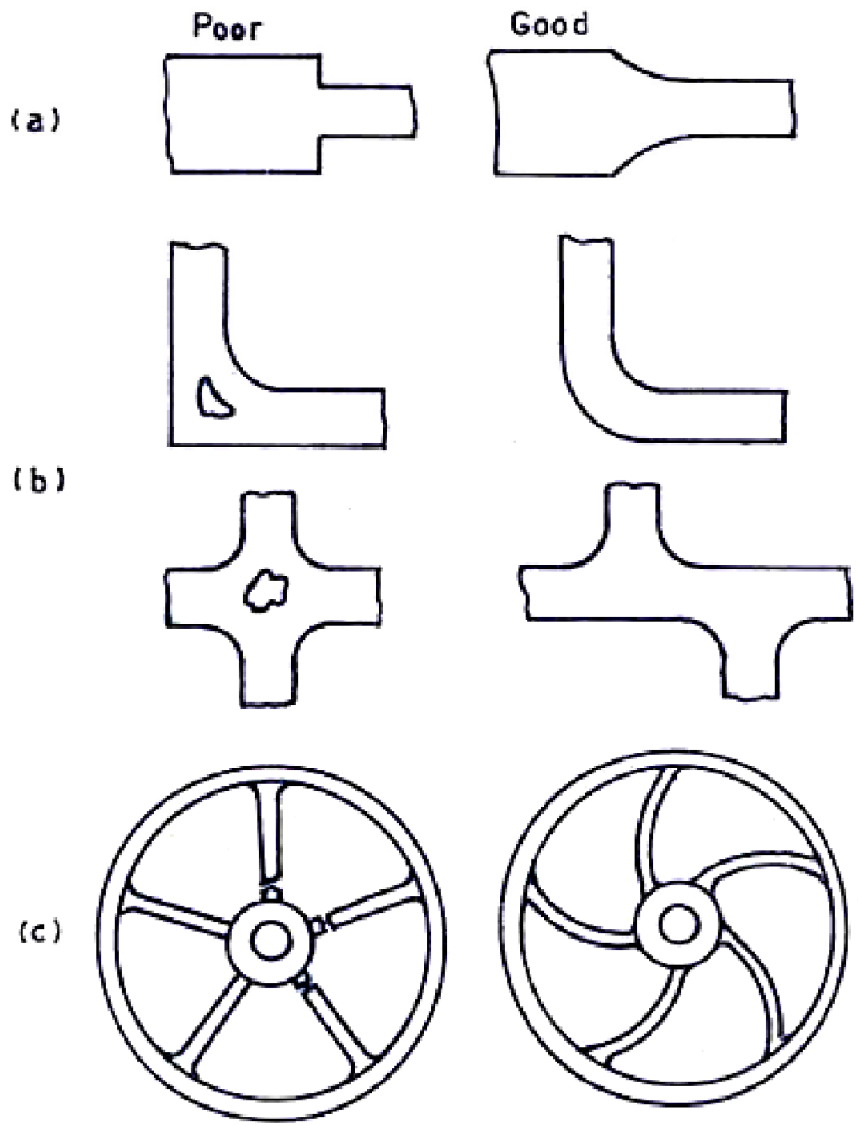
- Part shape should allow orderly solidification. In case of wall-thickness variations, transition must be made by large-enough radii. Localized heavy cross sections should also be avoided. Materials with high solidification shrinkage are susceptible to hot tear.

- Figure illustrates some design features to avoid following casting defects:

  **(a) Thickness change**

  **(b) Hot spots**

  **(c) Hot tears**



- The principals of working of metals has already been discussed in **Chapter 10**. Metals could be worked below recrystallization temperature (cold working) or above it but below melting point (hot working). Both have certain advantages and disadvantages as explained before.

- Control of mechanical properties during shaping by plastic deformation is very important.

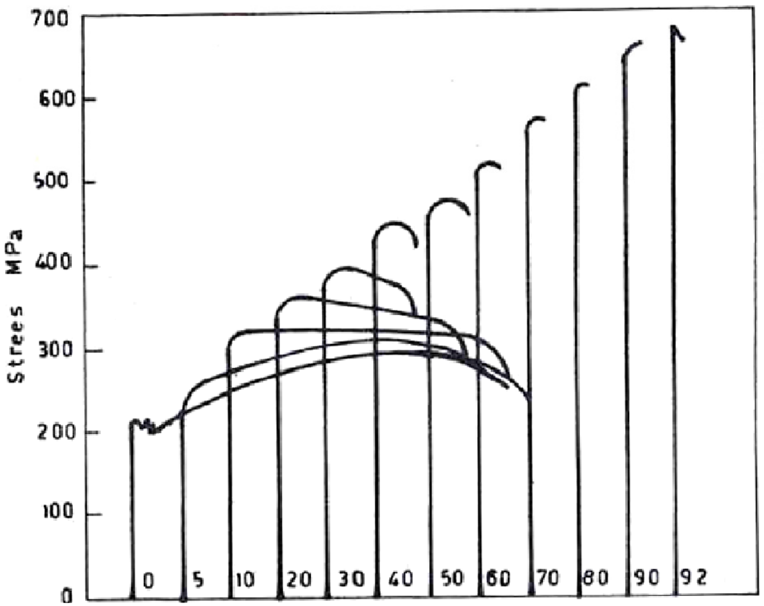
- Blow-holes and porosities produced during casting may be eliminated by hot deformation, which improves ductility and fracture toughness. In many products, mechanical properties depend upon the control of strain hardening during processing.

- On the other hand, in some cases, precise control of deformation, temperature, and strain rate during processing is required to develop the optimum structure and properties.

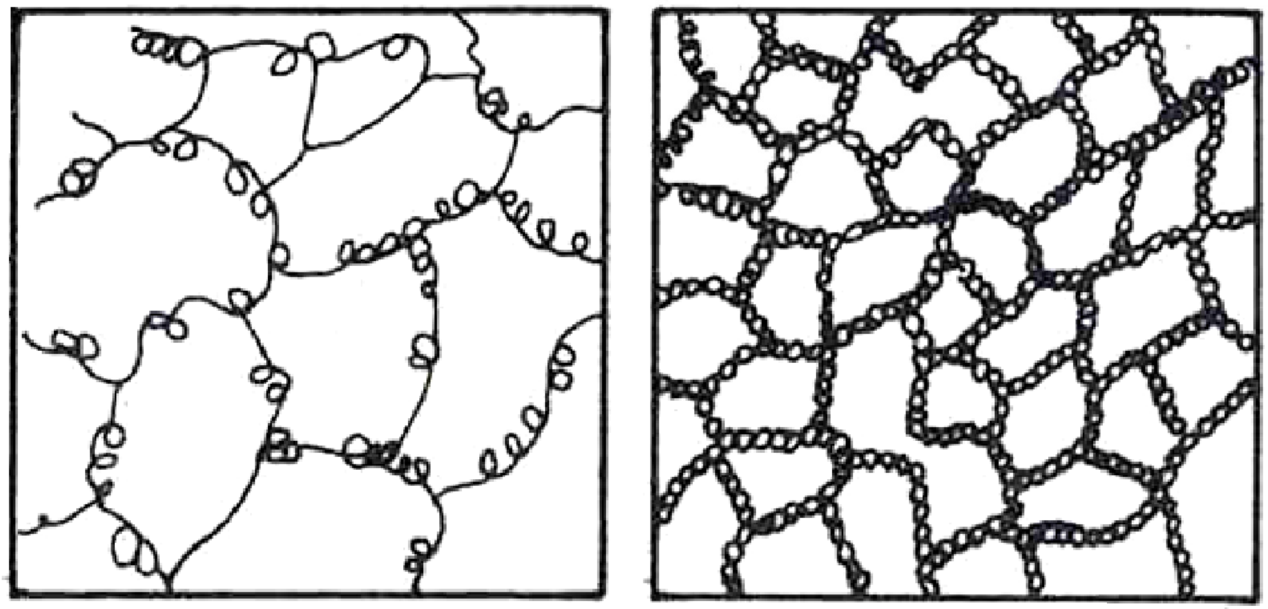
- **The effect of strengthening resulting from cold working is shown in figures below.**

- Dislocation structure of cold worked metals consists of a cellular substructure with cell walls composed of tight-packed tangles of dislocations. For large plastic strains, structures after wire drawing and rolling consist of highly elongated grains.

- On macroscopic scale, the structure of severely cold-worked metal is characterized by development of strong crystallographic texture, causing anisotropy of mechanical properties. This is of particular importance in determining the deep-drawing properties of rolled sheet.

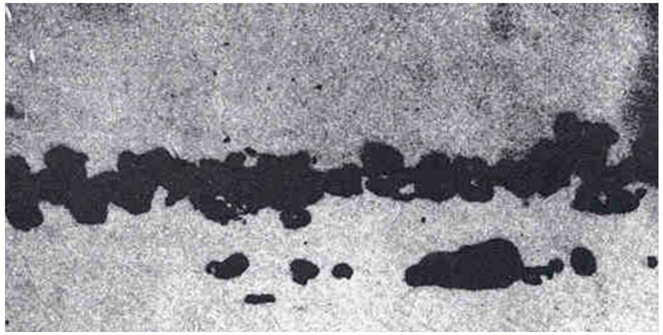



Stress-strain diagrams for low-carbon steel, cold-worked to different amounts

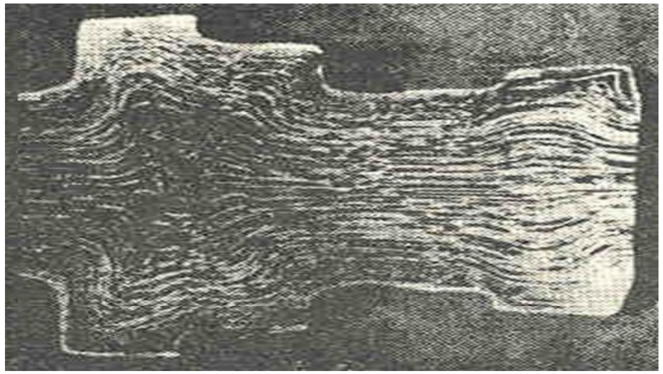


Formation of cellular dislocation structure: (left) 10% deformation (right) 50% deformation

- The predominant softening mechanism in hot working is **dynamic recovery**, which is the sole softening mechanism where climb and cross-slip of dislocations are relatively easy. This occurs in metals of high stacking-fault energy (such as Al, $\alpha$-iron and most BCC metals).
- Another mechanism intrudes at larger strains, occurring in metals with low stacking-fault energy (like Cu, Ni, $\gamma$-iron and their alloys). When misorientation between subgrains reaches high values, they act as recrystallization nuclei and dynamic recrystallization occurs as the softening mechanism.
- Hot working accelerates diffusional processes. Two examples are:
  - elimination of compositional inhomogenities (e.g. a cored structure)
  - coarsening of second-phase structure (spheroidizing pearlitic steel)
- Due to hot working, second-phase particles (inclusions) tend to have shape and distribution. Being originally spheroidal, they are distorted in the working direction into an ellipsoidal shape if they are softer and more ductile than the matrix. If they are brittle, they will be broken into fragments which will be oriented parallel to working direction.
- If they are harder and stronger than matrix, they will be undeformed but cracks around them can be initiated due to deformation. As result of mechanical deformation (both hot and cold), fibrous structure may be produced which is due to orientation of grains and second-phase particles in the working direction. Properties of ductility, fatigue, and impact will be lower in transverse direction than in longitudinal.



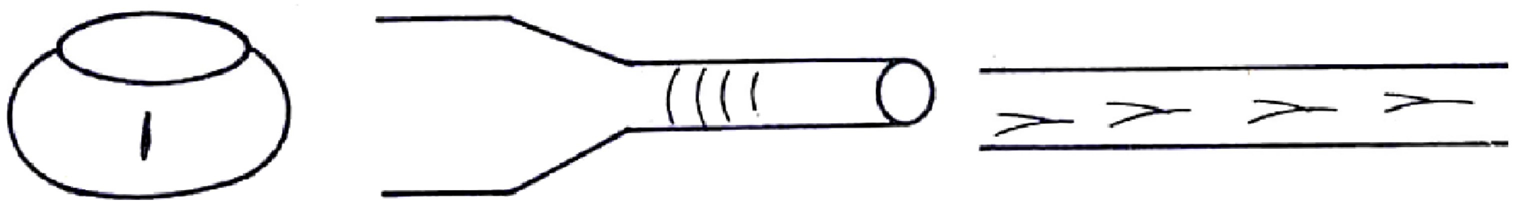
**Brittle inclusions (black) during hot rolling of a heat-resisting steel**



**Macrograph of an upset forging showing fiber structure**

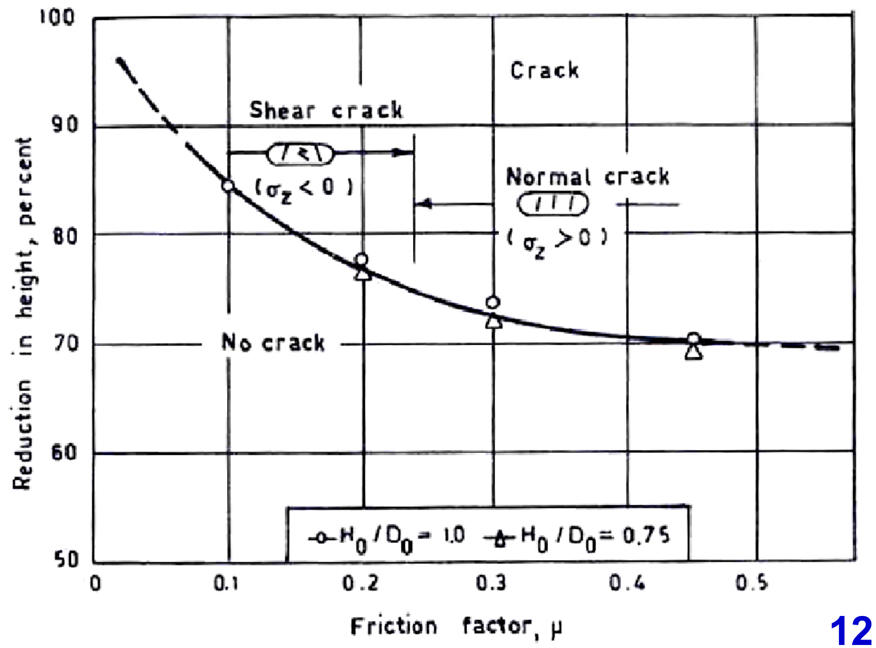
- **Workability** is concerned with extent to which a material can be deformed without formation of cracks. It is a complex technological concept, depending not only on fracture resistance of the material (i.e. ductility) but also on specific details of the process (such as thickness reduction, friction, temperature, and strain rate).

- The cracks occurring due to metal working processes can be illustrated in figure.



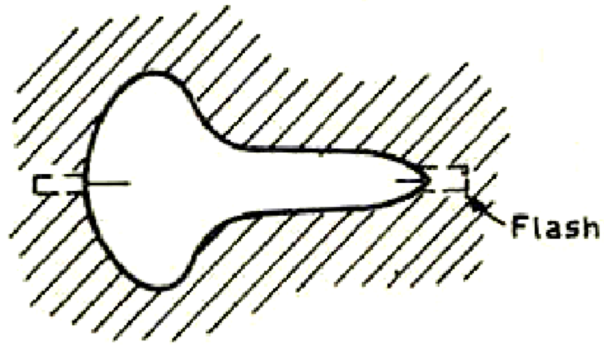
(a) Surface cracks (in upsetting or rolling)  (b) Surface cracks (in extrusion due to friction)  (c) Internal cracks (chevron cracks in drawn bars)

- There is no widely accepted workability test, but it is rated by some empirical tests used in industry.
- Such tests involve analysis of deformation mechanics (in terms of process, geometry, friction) to compute stress-strain histories at critical fracture points.
- **Kobayashi** was able to obtain workability diagram for slow-speed upsetting of steel cylinders at room temp.

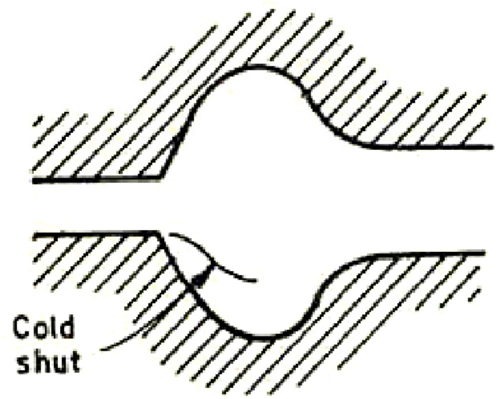


## Forging Defects

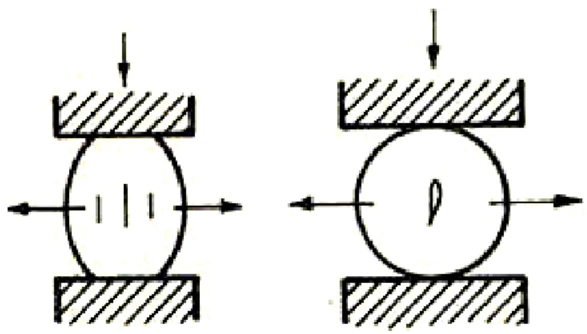
- Forging defects are illustrated in figure.
- **Surface cracks** occurs due to excessive working of surface at too low-temp or hot shortness (due to high sulfur concentration in the furnace atmosphere in steel and nickel).
- **Flash cracking** are avoided by increasing the flash thickness or by relocating the flash to a less critical region of forging.
- **Cold shut (fold)** is usually caused by poor die design.
- **Internal cracks** (due to secondary tensile stresses) develop during upsetting of cylinder or round, which can be minimized by proper die design. Internal cracking has less tendency in closed-die forging as lateral compressive stresses are developed by the reaction of work with die wall.




(a) Flash cracking

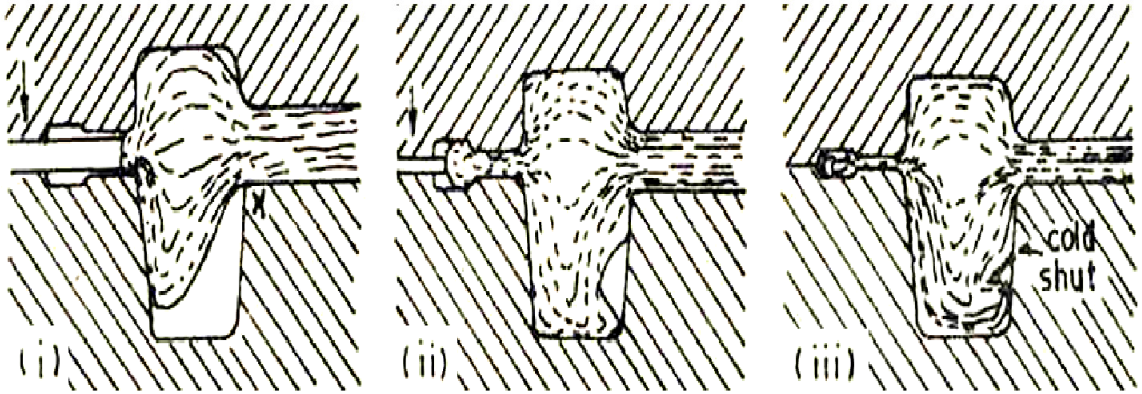



(b) Cold shut



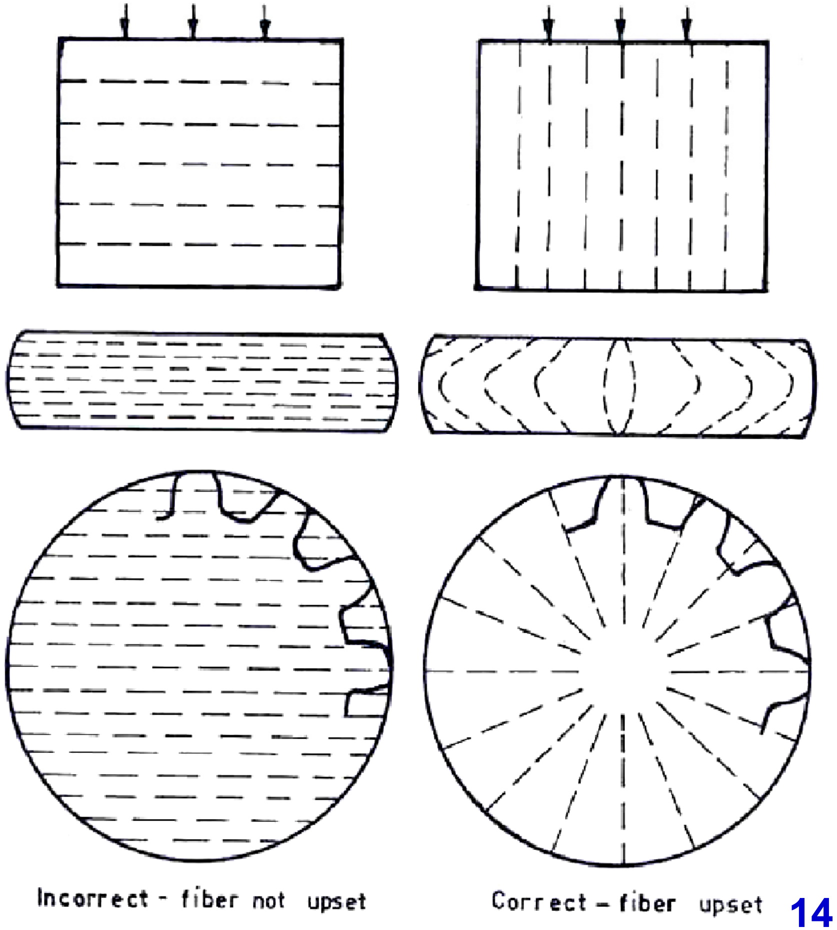
(c) Internal cracking

## Forging Defects




- Metal flows past-part of die cavity instead of following die-wall due to sharp corner. As die closes, a fold is produced in metal, giving rise to cold shut. To prevent this, generous radius should be given to every corner and intricate shapes.

- Flow lines in fiber structure is beneficial if correctly oriented. Fiber lines should not be broken in a forging.
- Forging of a gear blank is given as an example:
  - ***(left)*** *original fibers are incorrectly located*, and thus after upsetting, flow lines are not following the gear profile and they will be cut during machining.
  - ***(right)*** *proper location is illustrated*, and flow lines are correctly oriented after upsetting.



## Rolling Defects

- Various problems in rolling can arise depending on the interaction of plastically deformed workpiece with elastically deforming rolls and rolling mill.

**(a)** Roll gap must be perfectly parallel, otherwise one edge of sheet will be reduced more in thickness than the other. As volume and width remain constant, this edge of sheet elongates more. Such difference in elongation gives rise to **bows and waviness**.

**(b)** **Edge cracking** occurs due to friction hill development or inhomogenous deformation in thickness direction.

**(c)** With light reductions, only surface is deformed (i.e. **edge inward**). In later passes, it causes edge cracking.

**(d)** With heavy reductions, entire sheet is deformed and side of **sheet is barreled**, which can cause edge cracking.

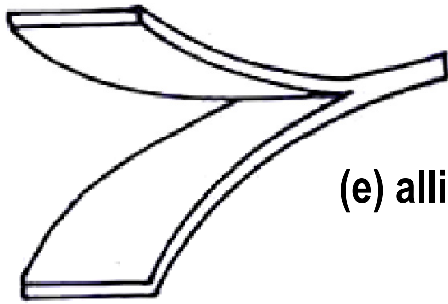
**(e)** If there is metallurgical weakness along the center line of slab, fracture will occur. This is called **alligatoring**.

(a) bowing & waviness

(b) edge cracking

(c) edge inward

(d) edge barrelling

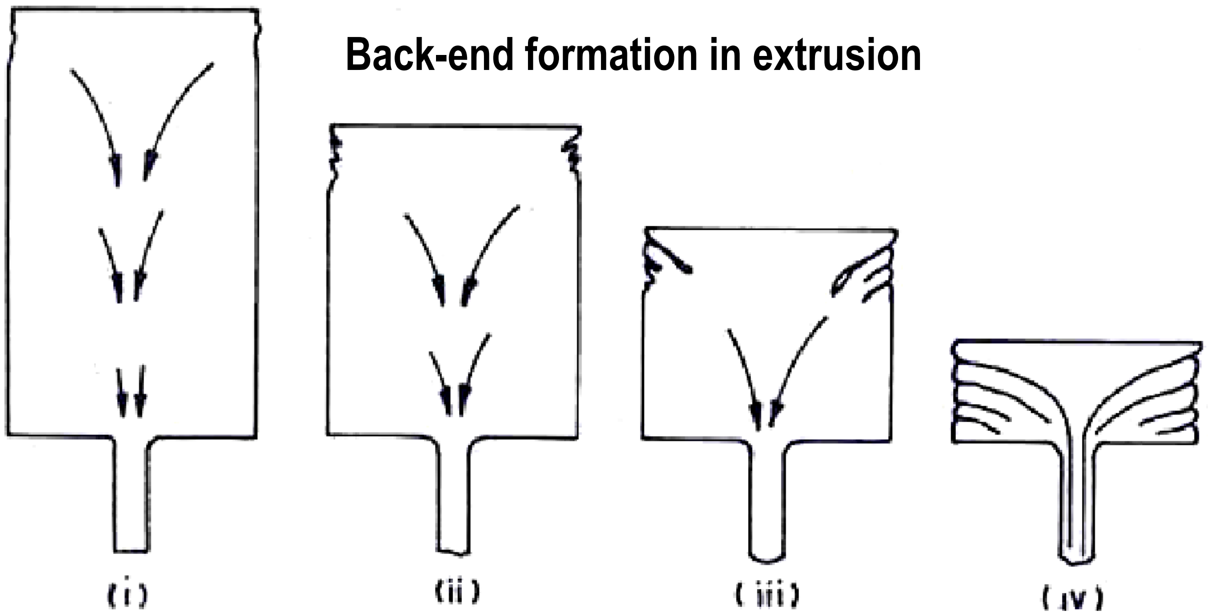


(e) alligatoring

## Extrusion Defects

- In hot extrusion, when billet is placed in the chamber, its outside skin becomes chilled and does not deform easily. Thus, the core of billet is more easily extruded as shown in figure.
- As extrusion proceeds, outer skin begins to buckle and ultimately extruded, which results in piped length. This is called **"back-end defect"**.
- To eliminate this, **10-15% of billet** (which corresponds to back-end) should be discarded.
- Transverse cracking in an extruded section is caused by frictional forces between die and workpiece. Very rapid extrusion will produce the same affect.
- There is likely to be some variation in grain size along the length of an extruded section. Leading end of rod undergoes little deformation (coarse grained) as compared to back end (suffers considerable plastic flow).

**Back-end formation in extrusion**

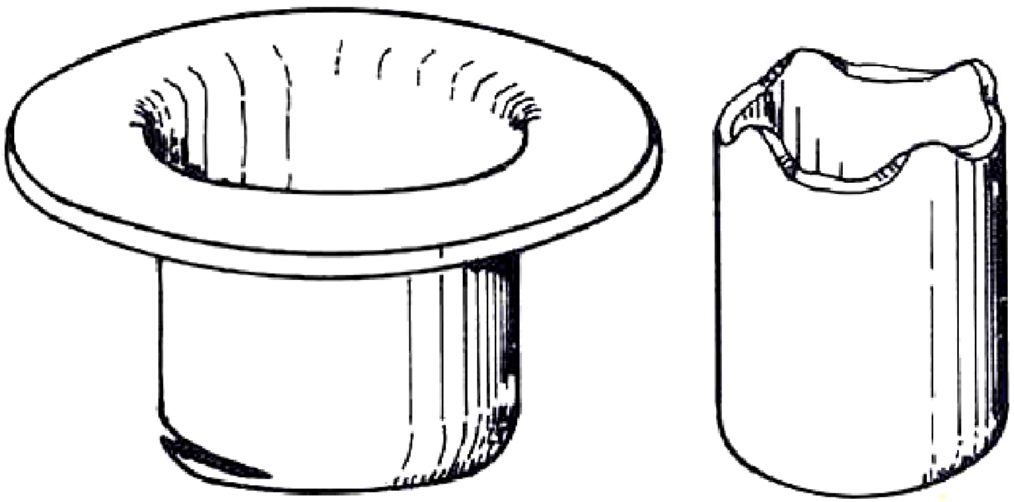


## Deep Drawing Defects

- During deep drawing, blank is held flat on die surface by pressure pad. The pressure applied must be sufficient to prevent **wrinkling**. However, there are other faults:

**(a)** This happens when wall thinning occurs to an extent that drawing force has exceeded its tensile strength. Excessive blank holding pressure, insufficient clearance between punch and die, inadequate radius of punch or die may lead to failure of this type.

**(b)** This is caused by directional properties in the sheet from which cup was drawn. This defect is minimized by avoiding excessive deformation or by locating the most suitable axes relative to sheet.



(a) Torn cup (b) Ear formation

- Suitability of metal for deep drawing is tested by **Erichsen cupping test**, in which specimen of the sheet to be drawn is clamped between a pressure pad and a die face. Load is applied to sheet by means of standard steel ball so that the sheet is drawn through die aperture until failure. The depth of cup till failure begins gives **Erichsen Number**.

- Machining is to cut a metal part to desired shape and size. Machining has a profound effect on grain structure, usefulness, and working life of part. This can be the result of **distortion and notches** produced by machining, and disturbance of the surface while metal is being cut.

- On the other hand, composition and cleanliness of the metal being cut is important in determining the quality of cut and final surface finish as well as the life of cutting tool.

- Surface finish of a machined part determines the level of surface smoothness with lack of notches and irregularities on the surface. In addition to rake of cutting tool, use of lubricants affects the surface finish. In absence of lubricants, pressure welding of chips occurs, especially for soft metals (Al and low-carbon steels). Pressure welding produces a built up edge, which makes the part surface rough and torn.

- Speed of cutting also influences surface finish and near-surface grain structure. Very slow cutting leads to formation of built up edge. At low speeds, metal structure is disturbed to a great depth and grains flow in cutting direction. Higher speeds produce better surface finish and less disturbance of grain structure.

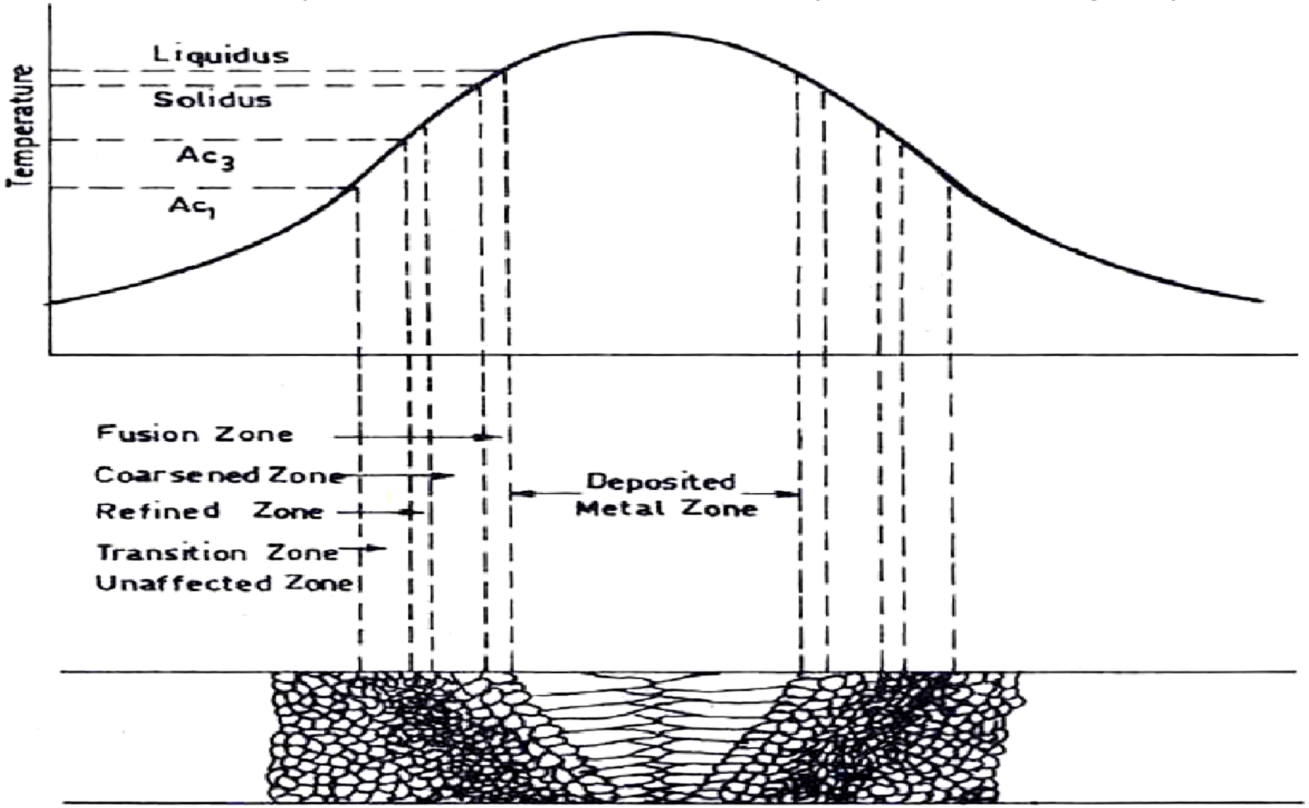
- Sulphur is usually added to improve the machinability of metals. Sulphur additions produce sulphides which are not hard enough to reduce machining. On the other hand, presence of hard inclusions or constituents not only impairs machining but also makes cutting edges of tools dull, thus reducing their working life. Annealed high-carbon steel (0.9-1.1% C) is difficult to machine due to hard, brittle carbide layers which surround the grains of metal. The problem can be overcome by spheroidising as carbides become distributed throughout the mass as tiny spherical particles.

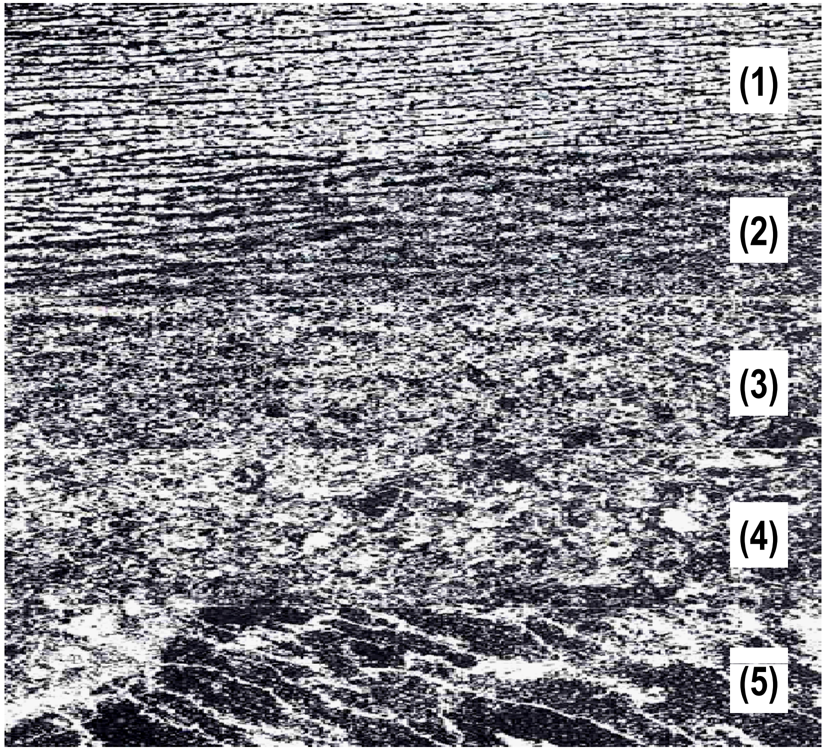
# Welding Processes

- Welding is localized union of metals (by fusion, diffusion, surface alloying) accomplished by applying heat and/or pressure with/without filler material. In welding, parts are held together by interatomic forces.
- Welding processes are **classified according to the source of heat:**
  - **Arc welding:** accomplishes heating with an electric arc with/without a filler metal.
  - **Shielded arc welding:** uses a filler as the electrode with flux providing atmosphere protection.
  - **Submerged arc welding:** uses fused/unfused flux to cover weld area.
  - **Tungsten arc welding:** uses non-consumable tungsten electrode with inert gas atmosphere.
  - **Plasma arc welding:** uses an ionized gas (plasma) to direct the flow of heat from electrode to metal, which is making this process more heat efficient.
  - **Brazing and soldering:** variants of welding in which filler metal has lower melting point than base metals (called brazing/soldering if melting temp. of filler metal is above/below 450 °C, respectively).
  - **Resistance welding:** incorporates heat generated by the electrical resistance of base metal. Welding is obtained by application of pressure onto heated material. Most common method is spot welding, but projection welding, seam welding and butt welding are also used.
  - **Oxy-fuel gas welding:** uses a fuel flame to generate heat. Oxy-acetylene is the oldest and the most common method, which uses acetylene as fuel. Hydrogen is also used in oxy-hydrogen welding.
  - **Solid state welding:** done without melting base metal. Diffusion welding relies on high-temp. diffusion between two parts to secure a joint. In friction welding, the friction between stationary part and revolving part at high speed generate heat and welding is done due to pressure between them.
  - **Beam welding:** uses high-energy electron and laser beams to melt metal locally and produce a weld with a small heat-affected zone. Such welds are sound but expensive, and used in special cases.

# Structure of Fusion Welds

- In an ideal weld, deposited and parent metals would have the same composition and structure (no discontinuity at joint). However, in practice, this is never accomplished as the weld is quickly cooled cast structure.
- **Metallographically examined weld section has following structures:**
  - Unaffected zone (1): Structure of original material (fairly fine and unaffected by heat supplied during welding).
  - Transition zone (2): Near the weld, a region exists in which metal was heated to a temp. within critical range.
  - Grain refinement zone (3): Adjacent to transition zone, metal was heated to a temp. just above critical temp.
  - Coarsened zone (3 to 4): Much nearer to weld where steel was heated to temp. much above critical range (grain size increases and becomes very coarse in adjacent to weld).
  - Fusion zone (4): Parent metal (in touch with molten metal in weld) was fused (similar properties of cast metal).
  - Deposited zone (5): Metal deposited into weld from filler rod takes a cast structure. Grains grow in direction of heat flow to yield a columnar structure (as shown in figure).



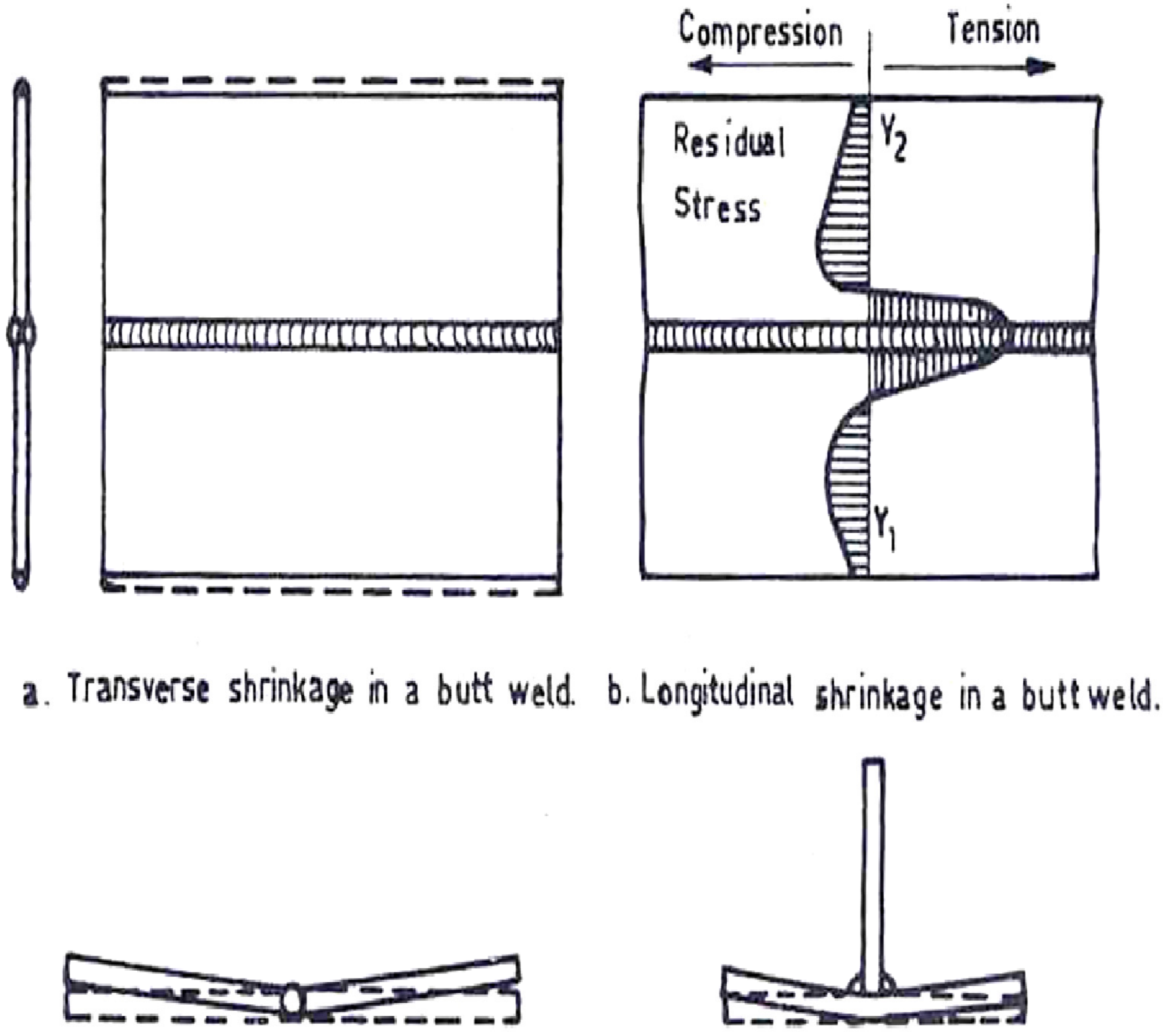

Microstructure of arc-welded low-carbon steel used in construction of penstock pipes of Ataturk Dam

- Welding process causes two thermal processes: heating and solidification. Both of them are associated with a change in volume, which causes distortion of the welded assembly due to constraints applied by cold base metal remote from weld.

- Distortion is caused by three fundamental dimensional changes during welding:
  1. **Transverse shrinkage:** which occurs perpendicular to the weld line.
  2. **Longitudinal shrinkage:** which occurs parallel to the weld line.
  3. **Angular change:** which consists of rotation around the weld line.

- Angular change is due to non-uniformity of transverse shrinkage in the thickness direction.

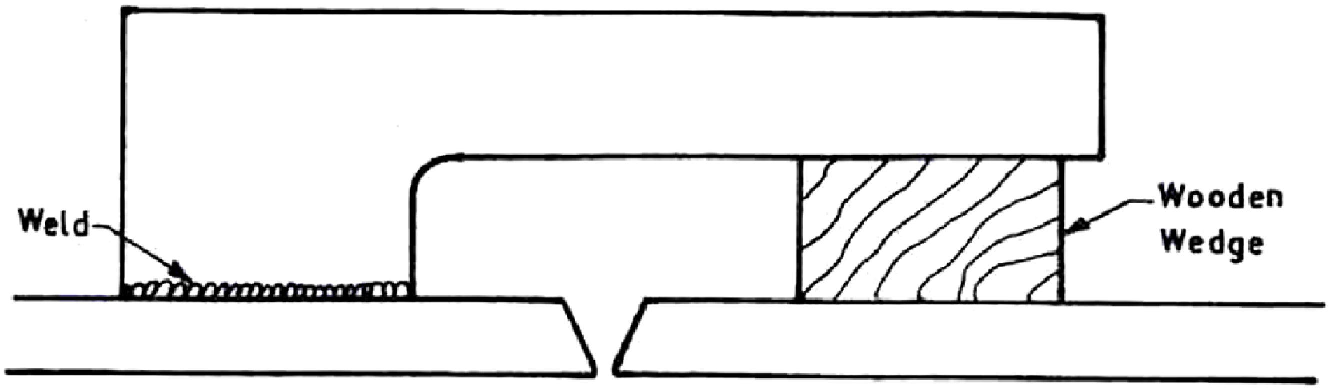
- The actual distortion phenomena are more complex than those shown in figure.



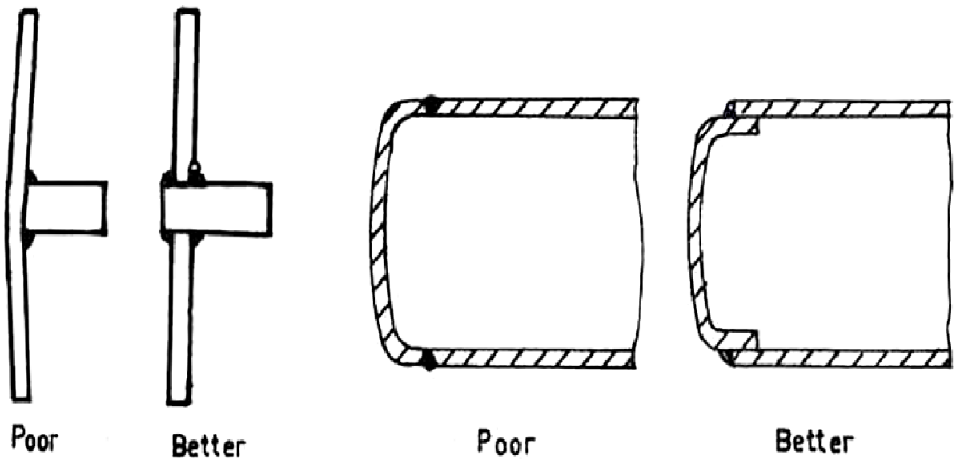

a. Transverse shrinkage in a butt weld. b. Longitudinal shrinkage in a butt weld.

c. Angular change in a butt weld. d. Angular change in a fillet weld.

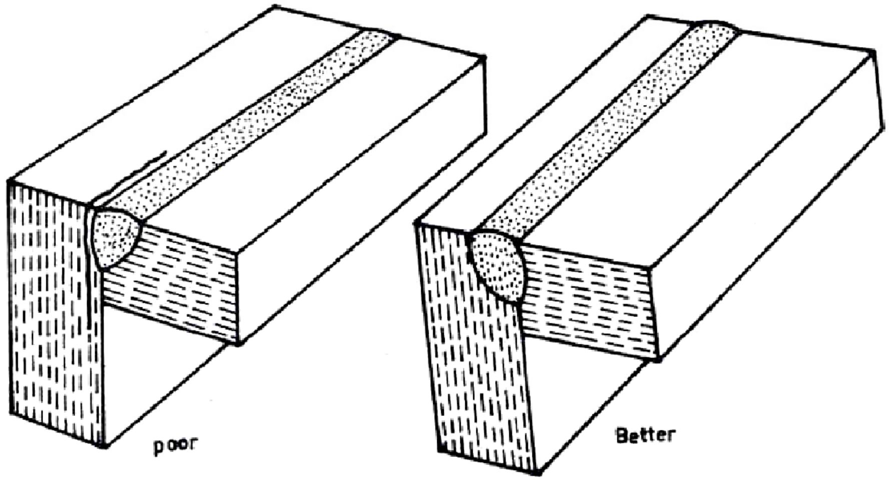
- As distortion is caused by change in volume, it can be minimized by **proper design considerations**.
- Some examples of such design features are shown in figures.




Tackling distortion by applying restraint




Design to neutralize distortion




Change in welding groove to avoid cracking