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Semester: 7TH **Subject: Mechanical Working of Materials**

Department: Metallurgical & Materials Engineering

LECTURE IST

METAL WORKING PROCESSES

1.0 INTRODUCTION

The benefits of civilisation which we enjoy today are due to the better quality of products available to us. The manufacturing process plays an important role in ensuring the quality of the product. Proper design that takes in to account the functional requirement of the product and also its manufacturing aspects will help in achieving better quality & longer service life of any product and or engineering component. The service performance of any product depends to a large extent on its properties. An ideal design process should provide a suitable manufacturing process that would ensure to produce a better quality product at an economical cost.

In simple terms, manufacturing involves converting basic raw material into a finished product having the desired quality & properties. To be viable in the modern industrial competitive environment it is necessary for the engineer to consider various aspects of manufacturing. A detailed understanding of the manufacturing processes is very essential for every engineer in order to appreciate the capabilities, advantages and also the limitations of the different manufacturing processes.

1.1 MANUFACTURING PROCESSES

There are different processes available to manufacture different products and these processes can be broadly classified as:

i) Metal removal or Machining processes

ii) Metal casting or Foundry processes

iii) Fabrication or Joining and assembly processes

iv) Metal working or Forming processes

Metal removal processes

These processes are usually referred to as the secondary manufacturing processes where in the additional unwanted material is removed in the form of chips from the basic raw material (called as the blank material) by using a harder tool in order to get the desired shape and size. These processes involving material removal is also called machining processes. These manufacturing processes have design & size limitations of their own besides being expensive and time consuming. Still these processes are being used as they give better dimensional accuracy and good surface finish. Various processes belonging to this category are milling, grinding, shaping & planing, turning, and sawing, etc. The active use of computers in most of these manufacturing processes has positively contributed in automation and designing the process.

Metal casting processes

Metal casting processes involve pouring molten metal into a prepared mould having the desired shaped cavity and allowing it to cool & solidify. The object after solidification is removed from the mould and then subjected to finishing operations. The process of casting a product is one of the oldest known manufacturing processes and dates from antiquity. A wide variety of products of different shapes and sizes are manufactured by the process of casting. There are different casting processes available today to produce different products and these include sand casting, plaster mould casting, precision investment casting, permanent mould casting, die casting, centrifugal casting, and special casting processes. To select the best & suitable one to manufacture a particular object depends on many factors, such as size, shape, finish, dimensional tolerance, design intricacy, cost, and physical & mechanical properties, etc.

Fabrication processes

These processes are considered secondary manufacturing processes and it necessarily involves joining different pieces either permanently or temporarily so that they would perform the intended job. The joining can be done by heat and pressure. This category of the fabrication processes comprises joining processes such as soldering, brazing, gas welding, electric arc welding, and electric resistance welding, etc.

Metal working processes

These are solid state manufacturing processes where in initial metal may be first heated to a temperature which is slightly below the solidus temperature and then an appropriate force is applied so that the material flows and attains the desired shape. The shape of the product is controlled by means of a set of tools called dies which may be of open or closed type. These processes are suitable for large scale production rates.

Following are some of the metal working processes:

i) Rolling

ii) Extrusion

iii) Forging

iv) Drawing

v) Sheet metal forming

2.0 METAL WORKING PROCESSES

Mechanical working processes are used to achieve optimum mechanical properties in the metal by reducing internal cavities or voids, if any, present in the material and thereby make the metal dense. Further, the impurity present in the metal also gets elongated with the grains and in the process they get fragmented and dispersed throughout the metal matrix. This reduces the ill effects of the impurities and thereby improve the mechanical properties especially the strength.

2.1 PLASTIC DEFORMATION AND ITS NATURE

When the solid metallic material is subjected to the external load of sufficient magnitude it under goes deformation. Depending on the magnitude of the imposed load, the deformation may be either elastic or plastic. Metals are more often worked by plastic deformation because of its beneficial effect on the mechanical properties. At low temperatures, the necessary deformation in a metal can be obtained by applying very large amount of mechanical load to the metal. However, at elevated temperatures the necessary deformation in a metal can be achieved by applying only a small load.

The deformation of metals which is caused by the displacement of the atoms is achieved by the process of slip, and or twinning. On the macroscopic level, when plastic deformation occurs, the metal appears to flow in the solid state along specific directions which are dependent on the type of processing and the direction of externally applied load. The grains or crystals of the metal get elongated in the direction of metal flow and this metal flow can be observed in the form of 'fibre flow lines' under microscope after polishing and appropriate etching of the metal surface. As the grains are elongated in the direction of flow, they offer greater resistance to stresses acting across them. The metal would be weak along the flow lines. In general, the mechanically worked metals referred to as 'wrought products' would be able to achieve improved mechanical strength in specific orientation than that of the flow direction. By careful manipulation of the applied load, it is possible to control the fibre flow lines in any specific direction and achieve optimum mechanical properties.

In metal working processes, the wastage of material is either negligible or very limited, and the production rate is very high. In general, metal working processes have great economy in production.

2.2 HOT WORKING AND COLD WORKING

On the basis of the amount of heat applied to the basic metal prior to applying the mechanical load, the metal working processes are broadly divided into hot working and cold working processes.

All those processes which work above the recrystallisation temperature are called as 'hot working' processes whereas those processes which work below the recrystallisation temperature are called as 'cold working' processes.

Recrystallisation

It is the process of forming new crystals when the atoms reach a certain higher energy level under the action of heat and the force. The old grain structure of the metal which is deformed by the mechanical working is destroyed during recrystallisation, and entirely new crystals which are strain free are formed. The new grains start nucleating at the location of severest deformation. The American Society of Metals (A.S.M.) defines recrystallisation temperature as "the approximate minimum temperature at which complete recrystallisation of a cold worked metal occurs within a specified time". The recrystallisation temperature depends on the amount of cold work a material has been subjected to. As such, higher the cold work, lower would be the recrystallisation temperature and for most of the metals, it is generally between one third to half the melting point.

Hot working and its advantages & disadvantages

As indicated above, the hot working process is carried out above the recrystallisation temperature. The temperature at which the metal working is completed is important in view of the fact that any extra heat left after working will help in the grain growth, thus giving poor mechanical properties. In general, hot working has its own advantages and disadvantages.

Advantages

A few of the advantages of hot working processes are as under:

1. As the material is above the recrystallisation temperature, any amount of working can be done on it since there no strain hardening taking place.
2. At a high temperature, the ductility of the material would be higher and

as such large amount of hot working can be carried out on the material.

3. Brittle materials can be subjected to hot working.

3. At higher temperature, the magnitude of the shear stress required to induce deformation gets reduced. Therefore, during hot working very less force is needed to achieve the desired deformation.

4. If the temperature and rate of metal working is properly controlled, it is possible to achieve favourable grain size and there by better mechanical properties.

Disadvantages

Some of the disadvantages of hot working processes are:

1. The surface finish of the hot worked metal is poor because at elevated temperatures scaling of the surface takes place. Further, at higher temperatures there is every possibility of the decarburisation of skin in steels.

2. The dimensional accuracy in hot working is difficult to achieve because of the thermal expansion of metals taking place at higher temperatures since it is difficult to control the temperature of work piece.

3. It is difficult to handle and maintain hot metal during hot working processes.

Cold working and its advantages & disadvantages

In cold working, metal working process is carried out at the temperature which is below its recrystallisation.

Advantages

1. At lower temperatures strain hardening takes place and as such in cold working operations strength and hardness of the material increases.

2. In cold working as the working temperatures are low, no decarburisation of the metal surface takes place.

3. Since the metal working is done in cold state, the formation of oxide on the surface does not take place and consequently, very good surface finish is obtained.

4. In cold working better dimensional accuracy is obtained.

Disadvantages

1. Since the material possesses higher yield strength at lower temperatures, the amount of deformation that can be induced in the material is limited.

2. The amount of deformation that can be given to the material during cold working is limited by the strain hardening that takes place at lower temperatures. Any further deformation can be induced in the material only after annealing.

3. The materials that are brittle cannot be cold worked.

To be Continued ....

REVIEW QUESTIONS

1. What are the properties that are associated with metallic materials?
2. What is strain hardening or work hardening? How is it relevant in manufacturing?
3. What is plastic deformation?
4. Why are fine grained materials preferred for room temperature applications & coarse grained materials for high temperature applications?
5. What is the major distinguishing feature between hot & cold working?

In Continuation to Lecture 1st ....

LECTURE 2nd

In order to make the **understanding** of the subsequent topics **easier**, it will be appropriate to take **note** of the following **facts**:

1. The most basic relationship for plastic deformation is the constant volume relationship (i.e. $V_0 = V_1 = V_2 = V_3$) and the

CONSTANT-VOLUME RELATIONSHIP

is expressed as:

$$\in 1 + \in 2 + \in 3 = 0 \text{ ....} (1)$$

where $\in$ *is the strain.*
(Strain is expressed as **True Strain or Natural Strain** because of **large deformation)**

2. In metal working processes, **compressive stresses and strains** often predominate.

If a Block of initial height $h_t = h_0$ is compressed to h_i

Then, Axial Compression OR Axial Compressive Strain (using the usual sign convention) will be :

True Strain $\in = \int_{h0}^{h1} dh/h = \ln h1/h0 = -\ln h1/h0$ ...(i)

(Where $h0 > h1$)

Conventional Strain $e = (h1 - h0) / h0$

$$= \frac{h1}{h0} - 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(ii)}$$

The calculated Strain will be negative indicating **COMPRESSIVE STRAINS.**

However, in metal working problems, it is a common practice to **reverse** the **convention** so that compressive Stresses and Strains are defined as **'POSITIVE'.**

When using this convention and also using the subscript 'C', the

True Strain $\in_C = \ln h0/h1$, *and*

Conventional Strain $e_C = (h0 - h1) / h0$

$$= 1 - (h1 / h0)$$

3. The Metal Working Deformations are expressed as Reduction in Crossectional Area.

4. The **Fractional Reduction** is given by $r = (A_0 - A_1) / A_0$

From **Volume Relation** $A_1 L_1 = A_0 L_0 = L_1/L_0 = A_0/A_1$

Therefore, **Fractional Reduction** $r = [(A_0 - A_1) / A_0]$

OR $\mathrm{r} = 1 - (A_1 / A_0)$

OR $A_1 / A_0 = (1 - \mathrm{r})$ OR $1/(1 - \mathrm{r}) = A_0/A_1$

Therefore $\in \;= \ln A_0 / A_1 = \ln[1/(1 - \mathrm{r})]$……(iii)

5. The requirement of **Metal Working Process** is the ability to **make** an **accurate** prediction of the **Stresses**, **Strains**, and **Velocities** at **every** point in the **deformation region** of the WORK PIECE.

There are various approaches to do this and the main approach involves THREE SETS of Equations:

1. The Static Equilibrium of Force Equations
2. The Levy-Mises equations expressing a relationship between Stress and Strain Rate

   Here, in elastic region, the Strains are determined by the Stresses through Hooke's without regard to how the Stress state was achieved. However, for Plastic deformation Stresses depend on the entire history of loading. Therefore, in PLASTICITY it is necessary to determine the differentials or increments of Plastic Strain throughout the loading path and then obtain the total Strain by integration or summation.

3. The Yield Criterion

The methods of **Analysis** are:

a) The Slab method
b) Uniform deformation method
c) Slip line field theory, and
d) Upper and lower bound solutions

6. There are two general categories of Plastic Stress-Strain Relationships as given under:
    1. Incremental or Flow Theories; relate the stress to the Plastic Strain increments
    2. Deformation or Total Strain Theories; relate the Stresses to the total Plastic Strain

7. Temperatures in Metal Working

    Forming processes comprise **Hot Working Operations** and **Cold Working Operations.**

A) Hot Working

It is the deformation that is carried out under the conditions of :

- Temperature, and
- Strain Rate

such that the Recovery processes take place simultaneously with the deformation. As such, Strain Hardening and the distorted grain structure produced by deformation are rapidly eliminated by the formation of new Strain-Free grains as a result of Recrystallization. Further, very large deformations are possible in HOT WORKING because the recovery processes keep pace with the deformation.

Hot Working occurs at a constant Flow Stress and because the Flow Stress decreases with the temperature, the **Energy** required for the deformation is **much less** than Cold Working.

B) Cold Working

It is the deformation that is carried out under the conditions where Recovery Processes are not effective. Here, the flow Stress increases with the deformation. Therefore, the total deformation **possible** in cold work **without fracture** is **less.**

8. **Hot Working** is the initial step in the mechanical working of most metals and alloys. It results in:
   - ➢ decrease in Energy required to deform the metal and
   - ➢ increase in the ability of the metal to flow without cracking.

- The rapid Diffusion that takes place at hot working temperatures aids in decreasing the **chemical inhomogeneity's** of the cast ingot-structure. Defects like blow holes and porosity are eliminated by the welding together of these cavities. Further, the coarse columnar grain structure of the casting is broken down and is refined into a smaller equiaxed recrystallized grain structure.
- These changes in the structure due to the hot working results in increase in Ductility and Toughness over the cast state.
- However, there are certain disadvantages associated with hot working because of the fact that high temperatures are involved with it. The **maximum** hot working temperature is limited to about 40^0C (100^0F) below the melting point of the metal.

- Due to the high temperatures, the surface reactions between the metal and the furnace atmosphere become a problem. Ordinarily, hot working is carried out in Air and as such the oxidation takes place due to which a considerable amount of metal may be lost.
- The reactive metals such as Titanium are embrittled by oxygen, therefore, are hot worked in an inert atmosphere.
- Surface decarburization of hot worked Steel results in surface deterioration. Therefore, extensive surface finish is needed.
- In hot working, the dimensional tolerances are greater.
- The structure and properties of hot worked metals are not so uniform over the cross-section as in cold worked metals.
- Since the deformation is always greater in the surface layers, metal will have a finer recrystallized grain size I this region.
- The core of the metal will be at higher temperature for a longer time during cooling; grain growth can occur in the interior of a large metal piece.
- Greater the amount of deformation, lower the recrystallization temperature.
- Rapid deformation and rapid cooling will require a higher hot working temperature for the same degree of deformation

9. Cold Working

It results in **increase** in hardness and strength, and **decrease** in ductility. Therefore, when cold working is **excessive** the metal will **fracture** before reaching the desired shape and size. In view of this fact, cold working operations are carried out in **several steps** with intermediate **Annealing** operations to **soften** the cold worked metal and **restore ductility**. This sequence of repeated cold working and aneealing is called the Cold-Work-Anneal cycle.

10. **Strain Rates** or Deformation **Velocity** has three principle **effects** in metal working as given below:

    1. The Flow Stress of the metal **increases** with the Strain Rate
    2. The temperature of the work piece is **increased** with the Adiabatic heating, and
    3. There is improved lubrication at the Tool-Metal interface, so long as the lubricant film can be maintained.

To be continued ....

NOTE

1. The contents given above in the lecture note is compiled from various sources and is only for the study purpose of the students. The students are advised to refer the relevant books as listed at the end of the syllabus in the course curriculum for further understanding of the topic/subtopics covered in this lecture note.

2. In case of any doubt/difficulty the students are free to contact me in person or through E-mail on my E-mail ID: rajinderambardar@gmail.com