Material performance in compressor discs and turbine blades engineering essay

Ques1. A)Explain what material properties are relevant to reliable material performance in Compressor Discs and Turbine Blades? Ans1. A) As the design of the turbomachinary components such as compressor discs, turbine blades, combustion chamber and shafts are complex and efficiency of these components are directly related to the material performance, therefore material selection is of prime importance. Gas turbine components operate under a different range of stress and temperature conditions. Compressor discs operate at relatively low temperatures, but are highly stressed, but the turbine blades operate under the extreme range of stress, corrosion and temperature. Therefore the material properties of these components reflect on the overall performance of the components. A design is therefore as efficient as the performance of the components selected. (1)

Material properties

Some of the important properties relevant to reliable material performance within the compressor disk are listed below:-

1. Creep Resistance:- Creep resistance is of prime importance in the manufacture of compressor disks. Creep resistance material are required wherever components operate at high temperature and have a short time rigidity, but are beset with long term deformation problems. Creep is the progressive deformation of a material at constant temperature. Prolonged exposure to high temperatures can result in deformation at grain boundaries. Creep manifests itself as a coalescence of voids at triple points on grain boundaries or as a collection of voids on grain boundaries. The figure below indicates the mechanisms of creep at relevant level of stresses and temperature.

Dislocation Creep

Creeep Mechanism [2] (2)

The mechanisms that contribute to creep are given below:-

Dislocation slip and climb:- These(Dislocations) are line defects which slips through a crystal lattice when a minimum shear stress is applied on it. It initially slips through the closed packed planes as it requires less energy or applied stress. As shown in the figure above Dislocation creep results from the increased number of dislocation at high level of stress and due to the increased mobility at high temperature.

Dislocation Creep (3)

Grain Boundary Sliding:- tertiary creep is usually a sign that structural damage has occurred in an alloy. Round shape voids are seen mainly at the grain boundaries, when the creep rupture occurs. This mechanism of void formation is as a result of grain boundary sliding which occurs under the action of shear stresses.

Diffusional Creep:- It is the result of the migration of atoms from grain boundaries under tension to the boundaries which are perpendicular to the direction of the maximum stress and the migration of voids in the opposite direction. This mechanism is significant at high temperature and low stress. The grain becomes longer as the stress is applied and the process works faster at higher temperatures as there are higher vacancies.

Diffusion Creep (3)

The following figure is generally accepted idealization of the three stage creep process:-

Stages of Creep (2)

The slope of the above curve is known as the creep rate. Stage I is called the primary creep and is characterized by a decreasing creep rate. In stage II the secondary creep, the creep rate is approximately constant and while in stage III (Tertiary creep) the strain rate increases rapidly until rupture (failure) occurs. For certain ranges of applied temperature and stress stage II is very short and Stage I appear to blend directly into stage III.

Stage I represents a region of primary creep in which the creep resistance of a material increases as a function of its own deformation. Stage II creep, known as secondary creep is a period where constant creep rate occurs, resulting from the balance between the competing process of strain-hardening and recovery. Stage III or tertiary creep, occurs mainly in constant load at high stress and temperature. It occurs where there is effective reduction in the cross sectional area.

In principle many material contains dislocations (discontinuities) in their crystal structure, but the influence of such dislocations would not be felt at stresses below the yield stress of the material. In fact even at relatively low temperatures there are two ongoing mechanisms, which lead to slow plastic flow of the material. These mechanisms are the grain boundary sliding and the dislocation climb and they are greatly influenced at temperatures above 0. 5Tm.

Design of Materials to resist Creep

Resistance to power law creep (Dislocation Creep)

A base material with high melting point is chosen, Creep rate will scale with T/Tm as shown in the figure above.

Maximise obstructions to dislocation motion- precipitates and alloy hardening technique can be used

Solids with large lattice resistance are chosen such as ceramics, but brittleness problem still prevails.

Resistance to Diffusional flow

Base material with high melting temperature is chosen- scale with T/Tm

Large grain size results in long diffusional distances. (3)

2. High Proof Strength

The yield strength of a material in engineering is defined as the stress at which the material starts to deform plastically. Prior to the yield point the material would deform elastically and would return to its original shape when load or stress is removed from the material. It is also the maximum stress on the stress strain curve.

Material

Yield strength

(MPa)

Ultimate strength

(MPa)

Density

(g/cm^3)

Structural steel ASTM A36 steel

250

400

7. 8

Steel, API 5L X65

448

531

7. 8

Steel, high strength alloy ASTM A514

690

760

7. 8

Steel, pre stressing strands

1, 650

1, 860

7. 8

Steel (AISI 1060 0. 6% carbon) Piano wire

2, 200-2, 482

7. 8

High density polyethylene (HDPE)

26-33

37

0. 95

Polypropylene

12-43

19. 7-80

0. 91

Stainless steel, AISI 302 – Cold-rolled

520

860

8. 19

Cast iron 4. 5% C, ASTM A-48

130

200

Titanium alloy (6% Al, 4% V)

830

900

4. 51

Beryllium, 99. 9% Be

345

448

1. 84

Aluminium alloy 2014-T6

414

483

2. 8

Copper, 99. 9% Cu

70

220

8. 92

Cupronickel 10% Ni, 1. 6% Fe, 1% Mn, balance Cu

130

350

8. 94

Brass

200+

550

5. 3

Tungsten

1, 510

19. 25

Glass

33

2. 53

High strength or hardness is therefore required for resistance to permanent deformation and wear, but it does imply fall in ductility and toughness. Therefore high strength and tough materials are difficult to achieve. Materials with high strength are also good indicator of high fatigue strength.

In a highly mechanical loaded part such as Gas turbine Compressor disks, a common titanium alloy is used. (4)

3. Low Cycle Fatigue

Fatigue strength within the compressor disk material should be high as it undergoes a lot of cycles during its use.

S/n curve (5)

Most machines and structures are subjected to non steady loads which produces different range of stresses and strain in their components. If the fluctuating stresses are large enough, even though the maximum applied stress may be considerably less than the static strength of the material and therefore failure may occur when the stress is repeated quite often. A failure induced in this manner is called a fatigue failure. Fatigue limit is the highest stress level which the material can withstand for an infinite number of load cycles without failure.

As it can be seen from the image above fatigue failures at high number of cycles (say N> 104 cycles), materials deform plastically. But at higher stresses, lower cycles, the fatigue life is progressively reduced. (6)

The process of fatigue is divided into the following three phases:-

(4)

Crack Initiation (Primary stage):- This stage usually takes place on the surface of the component, as the stress concentration would be greatest on the surface. The metal grains are also held less rigidly at the surface and therefore slip (distortion) can readily occur. The slip process is usually responsible for the crack initiation on the surface. It is considered that slip will usually occur between the crystals aligned within the direct load.

Propagation:- During the stage II process growth appears, usually with the associated change of direction, where the material becomes so rigid that slip cannot occur any further. From that point growth occurs along a plane normal to the maximum stress.

Fracture:- the next process is the fatigue failure which occurs along the complete component section. The final process is gross yielding, it can be ductile, shear or can be a fast running brittle fracture which causes a sudden failure of the component. Very simply this. The final fracture as it can be seen in the image above can occur through the crystals or between them. (6)

4. Temperature of Operation

Compressor operates relatively at low temperature as compared to the turbine blades. The compressor disks are subjected to temperature between 600 to 900K. Therefore the thermal conductivity of the material is very important. It should be high to prevent temperature build within the disk. Thermal conductivity is the property of a material to conduct heat.

5. Weight

Density of the material should be as low as possible which results in low weight of the component which in turn results in high thermal efficiency and low specific fuel consumption. Material with higher density costs more in manoeuvrability because large proportion of the time is spent at a single altitude and speed. Therefore low weight material is used which results in higher efficiency and low specific fuel consumption. (8)

A table has also been shown with the Percentage factor for the material properties for reliable material performance of the compressor disc under the working conditions. The percentage factor is assigned based on a qualitative evaluation of the merits of the properties in the manufacture of the compressor discs.

Table for properties and their percentage factors are given below:-

No.	Material Properties	Percentage Factor (%)
1.	Density	10
2.	Yield Strength	27

3.

Fatigue strength

10

4.

Creep Strength

8

5.

Thermal Conductivity

10

6.

Heat Capacity

3

7.

Hardenability

3

8.

Machinability

7

9.

Weldability

3

10.

Cost

6

11.

Availabilty

3

12.

NDT Feasibility

2

13.

Life Span in Use

5

14.

Data Reliability

2

15

Familiarity of the material

1

Yield strength above relates to high proof strength which is explained in the above section. It is one of the very important material properties within the compressor disks. Higher the yield strength higher would be the performance of the material.

Fatigue strength as explained above is also an important property because compressor disks undergo many cycles of applied stress during its use.

High creep strength also enables the compressor disk to operate under high temperature.

Thermal conductivity of the material also needs to be high to prevent the build up of temperature.

Heat capacity also provides additional resistance to temperature rise within the disk

High hardenability helps in providing better wear resistance within the component. Therefore low density material is usually the choice.

Easy machinability is also necessary to meet the design specification.

Better weldability is required for fabrication.

Cost is also an important factor for this system, as the life span depends upon the cost factor. (9)

Turbine Blades

Temperature is one of the critical aspects in the manufacturing of the turbine blades as they are subjected to high temperatures. In order to improve the efficiency weight must be shed and operating temperature should be increased. Within the last 60 years the temperature of the gas leaving the combustion chamber, i. e. is the Turbine Entry temperature (TET) and passing over the temperature blades has increased and has risen by 800OC. To accommodate the vast increase in the turbine entry temperature, changes has been made to the components design, material and structure. Therefore its very important that the material should be carefully chosen and manufactured. (8)

Material properties

Some of the important properties relevant to reliable material performance within the turbine blade are listed below:-

Temperature resistance

As explained above within the last 60 years there has been a significant improvement in the Turbine entry temperature (TET) and has risen nearly by 8000C. To accommodate this material with high melting point are required. Because of the high temperature involved within the turbine, turbine blades are manufactured from the nickel based alloys. Eventhough nickel based allows are twice as dense as titanium (about 8. 4gm/cm3), but it is the only material which retains its integrity (mechanical properties) at high temperatures. Standard titanium alloys are avoided towards the hot end of the aero engine, not only because of their diminishing properties, but also because of temperatures in excess of 6000C and also under friction they can rapidly ignite and burn. Therefore it is very important that the material should be highly temperature resistance i. e. is the material should hold its mechanical properties at high temperatures. (8)

Yield strength/Stiffness

Yield strength of a material in engineering is defined as the point at which the material starts to deform plastically. Higher yield strength of the material is required within the turbine blades as they undergo large stresses at higher temperatures.

Yield strength is a very important property, higher the yield strength of the material, higher the material performance under the given conditions.

Specific Strength v/s Temperature

Due to the rapid improvement in the turbine entry temperature in the last 60 years it is very important that the material should be able to hold its mechanical properties with the increase in temperature. As it can be seen from the table below that nickel is the only material which retains its integrity at high temperatures. The specific strength of nickel alloys remains almost constant with the increase of temperature as compared to the other material where the specific strength decreases considerably with the increase in temperature. Therefore nickel alloys are used for the manufacture of the turbine blades.

(8)

Fatigue strength

Fatigue failure is the failure when the components are subjected to non steady loads which in turn results in stresses and strains within the components and because these loads are repeated often enough. Due to this rupture occurs, the whole process is termed as fatigue failure.

As the turbine blades undergo large thermal cycles during its use, therefore material with high fatigue strength is required.

Creep Strength

As turbine blades are subjected to high temperatures, the major component failure within them is creep. Creep as explained above is the plastic deformation of a body at a constant temperature when stress is applied over it, i. e. over time at high temperatures and loads the blade will deform lengthen and rupture.

A table has also been shown with the Percentage factor for the material properties for reliable material performance of the compressor disc under the working conditions. The percentage factor is assigned based on a qualitative evaluation of the merits of the properties in the manufacture of the turbine blades.

No.	Material Properties	Percentage Factor (%)
1.	Density	10
2.	Yield Strength	27
3.	Fatigue strength	10
4.	Creep Strength	8

5.

Thermal Conductivity

10

6.

Oxidation Resistance

3

7.

High temperature Corrosion Resistance

3

8.

Hardenability

7

9.

Castability

3

10.

Weldabilty

6

11.

Cost

3

12.

NDT Feasibility

2

13.

Life Span in Use

5

14.

Data Reliability

2

15

Familiarity of the material

1

Oxidative resistance ensures retention of materials at high temperatures and oxidative atmosphere.

Thermal conductivity also needs to be high to prevent the increase of temperature within the blades. Effective cooling is possible with high thermal conductivity of the material as well.

Specific Strength is the most important property for reliable material performance, because turbine operates at high temperature. And at high temperature specific strength of metals starts decreasing and nickel alloys are the only material which maintains constant specific strength as compared to other alloys which possess same mechanical properties. (9)

B) Using the material properties identified in part(a), explain why cast components are used for turbine blades, but in compressor, discs, fans and blades wrought material tend to be used. What are the disadvantages of wrought material for turbine section applications? Give reasons for any property differences. Use real property data to provide evidence for your answer.

Ans. B) Material section is one of the most important decisions which is made in the design, application and manufacture of large structural components. It naturally influences the performance of the overall component and thus it is very important that informed decisions are made in the preliminary design stage. Many design engineers believe that forged components are better products because it is formed or worked during the manufacturing process. It is also assumed that cast components are considered inferior because they may contain porosity. But each process has its own advantages and disadvantages.

Forging Process

Wrought or forged materials are made from cast ingots, cast ingots are then mechanically worked after solidification. The raw material for all the wrought or forged products is ingot casting. There are different zones within the cast ingot structure that contains segregation and porosity.

Typical Cast Ingot Structure

When the cast ingot is solidified the ingot is hot forged into the desired shape using a hammer, or a rolling machine. As the forging is hot worked into shape, the porosity, grains and inclusion within the cast ingot are forced to flow in the direction the part is being worked. This grain flow, according to the forging industry makes forging superior to castings. However the fact is that even though the mechanical property is higher in the longitudinal direction, but they are considerably lower in the transverse direction or perpendicular to the grain flow. Thus the design engineer needs to evaluate the loading characteristic both in the longitudinal and transverse direction.

Mechanical working is limited within large forged material.

Casting Process

Most cast products are produced in expendable sand molds. The mold is produced by forming sand around a pattern. Molding sands are mixed with materials that allow to hold the desired shape after the pattern is remove. The pattern equipment also includes risers and gates which are required to produce a quality casting. The gating system allows the metal to flow into the mold in a controlled manner. Reservoirs of molten metal which helps the casting to solidify without shrinkage porosity are called Risers.

Fig. 5 Ring Gear Casting Mold (10)

Casting process is a very versatile process, as they are best suited for complex geometries that cannot be easily manufactured with the forging process.

The main difference between a casting and a forging process is that during the final stage, shape of the component is achieved when the molten metal solidifies within the mold. Since the sand mold produces the desired finished shape, the last few operations are done within the foundry. The last few steps do not alter the directionality of the casting. Therefore it means that the mechanical properties of a casting are usually the same regardless of the direction of the applied stress.

Good casting designer usually makes sure that the final part of the casting to solidify always has a supply of molten metal available which prevents the formation of shrinkage cavities. It is therefore critical that the casting user and fondry worker should work closely to produce the part to its optimum shape.

Mechanical Property Comparisons

As mentioned above that within a forged product mechanical properties are better in the longitudinal direction as compared to the perpendicular to the line of flow. But Casting is a homogeneous, which means that the mechanical properties of casting are the same regardless to direction of the applied stress on the material.

Test Bar Orientation

In order to highlight the difference between the cast and the wrought product, 5″ thick plate of rolled 4340 steel was taken. Both of the test plates where heated within the same production furnace load. The test materials were equivalent in all respects except processing as one was cast and the other was wrought.

Tensile(ksi)

Yield (ksi)

Wrought

Cast

Wrought

Longitudinal

141

147. 6

113. 5

Transverse

138

146. 5

110. 5

Thru Thick

134. 5

147. 6

108. 5

%Elongation

%Red in Area

Wrought

Cast

Wrought

Longitudinal

15. 5%

12%

46. 5%

Transverse

12. 5%

11%

33. 5%

Thru Thick

8. 5%

11%

13.%

Test results shown in the above table shows that the mechanical properties of the cast pate are more or less the same regardless of the orientation. But the mechanical properties of the wrought material are lower in both the transverse and through thickness orientation, especially the ductility (indicated by % elongation and % reduction in area) which shows a significant decrease when compared to the longitudinal direction. It can also be seen that the tensile strength, i. e. the yield strength for the cast material is considerably higher as compared to the wrought material. (10)

The same effects can be seen when comparing the fatigue strength of cast and wrought alloys.

Figure below shows that the notched fatigue properties of the test bar cast steel are actually superior to the wrought steel regardless of the orientation. Therefore from the figure below it can be seen that cast steel is less notch sensitive than wrought steel.

Fatigue Properties

Notched fatigue properties are a more accurate representation of actual service conditions because most large parts whether cast or forged would be expected to have some type of a notch.

(10)

Cast components for turbine blades

Turbine blades are associated with high Turbine Entry Temperature, which requires the incorporating of a cooling system within the blade. To build up a cooling system within the turbine blade, the turbine blades tend to have a complex geometry and therefore the casting process is used for the manufacturing of the turbine blades. Cast products are used for some applications for significant physical size.

Single crystal blades has been one of the key advancement in the turbine section which enables internal cooling sections and latterly, thermal barrier coating. Cooled air is bled through the compressors and passed through the turbine blades. Small laser holes are build which allows the cooling air to flow over the working surface. To achieve this kind of arrangement casting procedure is used, because this kind of complex geometry can’t be achieved with forging and hence cast products are used for turbine blades.

Cast components have high tensile strength, fatigue strength and creep resistance as compared to the wrought component which is critical requirement within the turbine as turbines operates under high temperature. Turbine entry temperature is a very critical parameter for the performance of the engine and higher temperature capability can only be achieved by cast products. (1)

Temperature capability of cast components for a given applied stress is higher as compared to the wrought materials for different alloys which can be seen in the table below.

(11)

Wrought Components for Compressor Discs, Fans and Blades

As material required for compressor discs, fans and blades needs to be creep resistance, have high proof strength and Low cycle fatigue strength, these material properties are provided by the forged products.

Ductility and fracture toughness of wrought alloys is better than cast alloys which is also a prime requirement of the compressor discs as they undergo a lot of stress.

As the operating temperature within the compressor, fans and blades is less as compared to the turbine, wrought components has higher rupture strength at low temperatures, which can also be seen in the table below

Why wrought components are not used for turbine blades?

Wrought components are not used for turbine blade because of Creep, as it can be seen from the table above that the temperature capability of the wrought components is considerable less than the Cast products. And as turbine entry temperature is relatively higher than the temperature capability of the wrought products, cast products are preferred for the manufacturing of the turbine blades.

Rupture strength of cast components is also higher at high temperatures as compared to wrought components. Therefore cast products are used for turbine blades.

Rupture strength of cast and wrought alloy at 100 and 1000hr (12)

Ques2. Nickel and titanium have very different mechanical properties and yet both are extensively used within gas turbine applications for the production of rotating components. Choose one system and discuss how it has been developed over time with respect to temperature and mechanical performance, also discuss how such metals can be further enhanced for use in the turbine engines.

Ans2. The Thermal efficiency of the gas turbine engine depends a lot on on the Turbine Entry Temperature. Within the last 60 years the temperature of the gas leaving the combustion chamber, i. e. is the Turbine Entry temperature (TET) and passing over the temperature blades has increased and has risen by 800OC. To accommodate the vast increase in the turbine entry temperature, changes has been made to the components design, material and structure. Nickel is the only material which holds its integrity (i. e. mechanical properties) at high temperatures. As it can be seen from the graph below that nickel alloy’s Specific strength remains constant with increase in temperature as compared to the other alloys.

(8)

The evolution of Gas turbines is linked to nickel alloy development. A typical jet engine consists of about 1. 8 tonnes of nickel alloys and other nickel based alloy for different specific needs. The life of the early gas turbine engines was limited to about 5 hours due to the usage of steel alloys as they could not withstand temperature of gas leaving through the combustion chamber of about 950-1, 1000C. For the gas turbine engines to become more efficient and reliable, improved alloys were required.

Nickel, because of its property to retain its specific strength with increase in temperature, resistant to corrosion, and ability to alloy with other metals for the development of better alloys is used for the turbine components. In 1940 and 50s Metallurgist knew that nickel chromium and nickel chromium cobalt alloys were much stronger and more resistant to oxidation and corrosion than the stainless steel alloys. The nickel based alloys extended the life of Gas turbine engines. The improved performance of early nickel alloys, such as N06600 (containing 72% nickel), encouraged metallurgists to develop more efficient alloys. With the evolution of the metallurgical industry, new alloys were developed to cope up with the increase in temperature. They were mostly nickel based alloys with the addition of elements such as chromium to enhance the specific strength and Oxidation/ Corrosion resistance at high temperatures. Alloy development, as with the gas turbine, was made in three stages.

Firstly the alloys were improved by increasing nickel and cast alloys by using vacuum melting technique to reduce harmful oxides. Creation of complex alloys was made possible due to the improvement in the vacuum melting techniques, while maintaining homogeneous microstructure and alloy cleanliness. (13)

Second development was the use of coatings, such as CoA or NiAL, which was used on the alloy parts for better resistance to corrosion or oxidation. (13)

Final stage of Development was the cast alloy components, which were used in the hot section of the turbine blades, resulting in grain boundary segregation of some elements during the solidification of the molten metal. The above problem was rectified by the use of new casting techniques for the turbine blades. Single crystal casting and directional solidification allowed gas turbines to have an increase in the Turbine Entry Temperature (TET), which results in greater efficiency of the engine. (13)

(8)

As it can be seen in the above diagram from Rolls Royce that with the development of the Gas Turbine engines, turbine entry temperature has increased with time and so is the material development.

Recently there also has been development in the manufacturing of nickel alloys for the aerospace engineering which are listed below:-

Disc Alloys: – With the trend of increasing turbine inlet temperatures, engine designers has preferred using superalloys, with increasing alloying content in it. The high alloying content has resulted in excellent temperature and creep/fatigue properties. (14)

Development of Low Expansion Alloys:- In past the use of high expan