

## 1.-

### a)

In an ideal journal bearing, with an adequate lubrication, the surfaces should not contact, and therefore produce no wear. In this study example, wear has been detected originated by the load applied to the beam, or as a result of the own weight of the shaft as discussed by Pugh, B (1970). First it is interesting to analyze which kind of wears can be detected.

Abrasive wear appears when the two surfaces in contact have different hardness. Then the hardest surface will wear the softer one. If one of the materials would be harder than the other, this softer material could be hardened by carburizing or nitriding treatments or simply applying a coating (PVD, CVD or thermal spraying) aiming to achieve the same hardness in both surfaces. In this case study is not expected this situation to appear, because shaft and bearings are made with the same material, and therefore have the same hardness.

It is also a cause of abrasive wear the evidence of a poor surface finish where asperities are present or even hard particles are free fractioning between the surfaces. These hard particles can be originated by the friction of both rough surfaces, or can be resident in the lubricant. In case of having a rough surface, a smoothing treatment like grinding or polishing could finish the problem, and reduce the amount of debris in the interface. This situation is also not likely to appear in this study, because the thickness of the lubrication film is high, compared with the surface roughness. This is due to have a hydrodynamic lubrication.

$$X = \frac{\text{ThicknessOfLubricationFilm}}{\text{Ra(SurfaceRoughness)}} \quad (1) \quad \text{For a hydrodynamic lubrication, } X > 5.$$

If the wear is still high after smoothing, could be interesting to apply a more consistent filtering to the lubricant supply to avoid the inclusion of these particles.

Oxidative wear can be given by the reaction of one of the surfaces with the oxygen in the surroundings. This surface will develop an oxide layer. The oxidation rate is given by the Arrhenius equation, and it is proportional to the wear rate, as it is detailed by Sarkar, A.D. (1976).

$$\text{RateOfWear} = A * \exp^{\frac{-Q}{R*T}} \text{ Arrhenius Equation.}$$

In this equation it can be clearly identified that the wear derived from the oxidation process is proportional to the temperature (T) achieved in the contact interface. When the journal bearing is operating, the temperature of the surfaces and the one of the lubrication increases. This leads to oxidation and the respective wear.

As it was investigated by Costa, L. et al (2001), the increase of temperature in the interface, leads to a lowering in the viscosity level of the lubrication. If we add this to the last described situations, we obtain a decrease in the thickness of the lubrication film, with the consecutive lost of efficiency against the surface roughness, *see equation (1)*, and an accelerated oxidation rate. Costa, L. et al (2001) propose for these situations an analysis in the supply pressure and supply temperature of the lubrication, an on the groove dimensions for conducting the lubricant. With these factors under control, it will be ensured that the thickness of the lubrication layer is maintained constant, despite a temperature increase.

**b)**

As it has been outlined in the statement for this study, oxidative wear is directly proportional to oxidation rate as it is justified by Sarkar, A.D. (1976).. Taking a look at the Arrhenius equation can help to deduce the parameters involved.

$$\text{OxidationRate} = A * \exp^{\frac{-Q}{R*T}} \quad \text{Arrhenius equation}$$

Where A is the Arrhenius constant

Q is the activation energy (208 kJ/mol)

T is the absolute temperature (Kelvin)

R is the gas constant (8.314 J/mol\*K)

As we are looking for the relative increase:

$$\frac{ORate2 - ORate1}{ORate1} = \frac{A * \exp^{\frac{-Q}{R*T2}} - A * \exp^{\frac{-Q}{R*T1}}}{A * \exp^{\frac{-Q}{R*T1}}} = \frac{\exp^{\frac{-Q}{R*T2}} - \exp^{\frac{-Q}{R*T1}}}{\exp^{\frac{-Q}{R*T1}}} = 32.25$$

The oxidative wear at 350°C will be **32.25 times faster** than it was at 300°C. *See Appendix, Fig 1 for a graph showing the oxidative rate vs temperature increase.*

**2.-**

The first thing to be considered is whether is helpful to have the two contact surfaces (rings and cylinder block) made of the same material. With this configuration, wear is going to attack both parts, while if the block is casted in a harder material, wear would only take part in the softer part (rings). Debris would come only from the rings, and cause wear on the rings, but not in the block. Therefore, maintenance would become easier by changing just the affected and the harder part will remain invariable, as it has been explained by Pugh, B (1970). The reinforcement with ceramic materials is spread due to their characteristic hardness and resistance to chemical wear.

The desire to reduce CO<sub>2</sub> emissions in IC engines has led to research in materials and lubricant technologies. As it is outlined by Voong, M. et al (2003), aluminium alloy components have been used for parts as pistons “due to their excellent resistance to corrosion, good thermal conductivity, low cost, and ease of fabrication by casting”. In the other hand, these materials are susceptible to wear and friction when performing under loaded and sliding conditions.

In particular, wear obtained in piston rings is originated by scuffing, and it is difficult to reduce, but adding special lubricants that adhere easily to the surfaces. It is important to mention that this lubricant must be extremely filtered, to avoid the inclusion of foreign particles that can cause wear. Once again, it is important to have a smooth surface in the rings as in the cylinder block. The presence of asperities would lead to a great wear rate. Not only this, but if the pieces have been cross honed aiming to retain lubricant (oil), the machining technique used to carry this grooves can have left residual debris. A more adequate system to carve this grooves or pits should be used, for not having residual debris, like chemical etching, laser patterning or submit the piece to an ultrasonic clearance after the carving.

Voong, M. et al (2003), suggest that chemical reactions between the aluminium surfaces and the lubricant are likely to take place, especially when temperature rises. This chemical wear, accelerate and favours other undesired situations like the apparition of debris and abrasion. Therefore, the investigation of an adequate lubricant that can maintain the thickness of the layer, and, at the same time, not producing any chemical reaction with the aluminium would be highly recommended.

### 3.-

#### a)

The objective is to achieve lightweight or a minimum weight.

$m = V * \rho = w * L * t * \rho$  Objective equation, where V=volume and  $\rho$ =density.

Clearing from the deflection equation (1)  $t = \sqrt[3]{\frac{5 * F * L^3}{32 * E * w * \delta}}$

Adding the stiffness equation for a beam in Ashby, M.F.(2005)  $\rho = \frac{\rho}{E^{\frac{1}{3}}}$

Placing the three equations together aiming to get the performance equation:

$$m = w * L * \sqrt[3]{\frac{5 * F * L^3}{32 * E * w * \delta}} * \frac{\rho}{\sqrt[3]{E}}$$

In order to get a minimum mass (weight) when the stiffness is specified, the Young's Modulus (E) has to be maximized, while the density ( $\rho$ ) has to be minimized.

The result of  $\frac{\rho}{\sqrt[3]{E}}$  has to be minimized

If the constrain is the strength, the equation for the tensile stress (2) has to be used.

$$\sigma = \frac{3 * F * L}{4 * w * t^2} \text{ Tensile stress equation}$$

Clearing to have the free variable:  $t = \sqrt{\frac{3 * F * L}{4 * w * \sigma}}$

Substituting in the objective equation:  $m = V * \rho = w * L * t * \rho = w * L * \sqrt{\frac{3 * F * L}{4 * w * \sigma}} * \rho$

Adding the strength equation for a beam in Ashby, M.F.(2005)  $\rho = \frac{\rho}{\sigma_y^{\frac{1}{2}}}$

$$m = w * L * \sqrt{\frac{3 * F * L}{4 * w * \sigma}} * \frac{\rho}{\sqrt{\sigma_y}} \text{ Performance equation}$$

In order to achieve the minimum weight, once again the density has to be minimized, while the tensile stress  $\sigma$  must be maximized. The result density/strength

$\frac{\rho}{\sqrt{\sigma}}$  has to be minimized

**b)**

By taking the stiffness equation for a beam from Ashby, M.F.(2005)  $\frac{E^{\frac{1}{2}}}{\rho} > 1.5$

It is necessary to take two random values for the density, in order to determine the limit line. E.g.  $\rho_1=0.2\text{Mg/m}^3$  and  $\rho_2=3\text{Mg/m}^3$

$$E = (1.5 * \rho)^2 \quad E_1 = (1.5 * 0.2)^2 = 0.89\text{GPa} \quad E_2 = (1.5 * 3)^2 = 20.25\text{GPa}$$

These two points give the coordinates for drawing a line in the Modulus-Density diagram. The materials above the line will have a stiffness performance over 1.5. See in the appendix, Fig 2 for the diagram.

The best choice of materials would be those of engineering composites or the engineering ceramics. If we still aim to get a low mass, those closer to the line where:

$$\left(\frac{E}{\rho}\right)^{\frac{1}{2}} = 10^4 \text{ because of their big Young's modulus and low density.}$$

**c)**

By taking the strength equation for a beam from Ashby, M.F.(2005)  $\frac{\sigma^{\frac{2}{3}}}{\rho} > 6$

Once again it is necessary to take two random values for the density, in order to determine the limit line. E.g.  $\rho_1=0.3\text{Mg/m}^3$  and  $\rho_2=10\text{Mg/m}^3$

$$\sigma = \sqrt[3]{(6 * \rho)^3} \quad \sigma = \sqrt[3]{(6 * 0.3)^3} = 2.41\text{MPa} \quad \sigma = \sqrt[3]{(6 * 10)^3} = 464.75\text{MPa}$$

These two points give the coordinates for drawing a line in the Strength-Density diagram. The materials above the line will have a stiffness performance over 1.5. See in the appendix, Fig 3 for the diagram.

The availability of materials for these constrains is greater, wood products, together with glasses, engineering composites, engineering ceramics, some engineering alloys and some engineering polymers.

**d)**

One of the constraints of this case study is that the fracture toughness of the beam materials must be greater than  $30\text{MPa}\cdot\text{m}^{1/2}$ . This condition is going to reduce the availability of materials. In the appendix in Fig 4 it has been represented the materials with an adequate fracture toughness. When the three constraints are put together, it can be identified that only certain engineering alloys and engineering composites would fit for this purpose.

Rank by Stiffness:

Ceramics > Composites = Alloys = Porous ceramics > Wood

Rank by Strength:

Ceramics > Composites = Alloys > Wood products

Rank by Density:

Alloys > Ceramics > Composites > Wood

Taking a look at the work/charts drawn by Ashby, M.F.(2005), the modulus of a material can be plotted against the relative cost per unit volume. Based on this chart:

$$C_{v,r} = \frac{\text{cost} / \text{kg} * \text{Density of Material}}{\text{cost} / \text{Kg} * \text{Density of Mild Steel Rod}} \text{ Relative cost per unit volume}$$

Therefore, Young's Modulus vs Relative cost would rank:

Ceramics > Alloys > Composites > Non technical ceramics

And Strength vs Relative cost would rank:

Alloys > Technical Ceramics > Composites > Wood

**e)**

The best selection of materials would be certain Aluminium alloys. Their stiffness is over the required 1.5, and the strength of some of these alloys is over the required. At the same time Aluminium alloys have a low density formulating it ideal for a lightweight beam. In the other hand, at the time when Ashby, M.F.(2005) collected his data in 2005, this is the most economic solution.

**4.-**

The printing rolls are subjected to free particles or debris originated by wear in the same rolls or coming from grit and dust from the environment. These particles are trapped in the sliding interface and remove material, as it is identified by Sarkar, A.D. (1976). The object to study is the relative hardness of these particles, related with the hardness of the surface (printing rolls). Chilled cast iron is a relatively soft material, with a Young's Modulus around 100 GPa extracted from Ashby, M.F. (2005). In the other hand, the granularity of this alloy is high, so it is possible self generated debris are the causes of abrasion. The configuration of the microstructure is a result of the heat treatment and the cooling applied in the manufacturing process.

The application of a harder coating, would reduce the wear, and, at the same time, provide a surface finish with a finer granularity, avoiding the self generated debris. In order to provide an adequate coating, tungsten carbide/cobalt cermets have been chosen. Cermets are ceramic-metal composites of extremely hard particles (WC) embedded in a metal matrix, that will prevent crack propagation, and therefore, the self generation of debris, apart of increasing the hardness of the surface.

To apply the coating, a thermal spray process is recommended. To choose a correct method, it is necessary to analyze the characteristics of the particles to be sprayed. Tungsten carbides melt at high temperatures, near 2867°C, but from 2200°C start a fast oxidation, therefore, the particle has to be deposited in the surface as fast as possible. There are different options:

High Velocity Oxygen Fuel (**HVOF**). This method will melt the particles, and spray them at a high speed, so the time the particles are susceptible to be oxidised is reduced. In any case, the spraying in a carburising atmosphere is recommended to reduce this process to a minimum. HVOF also provides high strength between the atoms of the coating, lowering the porosity. The disadvantage of this method is that it takes longer time to coat a certain surface, has a low efficiency and coating thickness can not be greater than 1.5 mm. In a brief, it would be the most recommended treatment, but also the most costly.

Plasma Spray (**APS**).It provides the highest temperature of all the available methods for the particles to be molten. In the other hand, this higher temperature accelerates the oxidation rate, and particles take longer to reach the surface. Therefore, a protective atmosphere should be provided, with the aim to eliminate air bubbles to be formed in the coating (air entrapment) by displacing the air at an adequate flow rate or removing the air. One again, the coating can not be greater than 1.5 mm but in this case, the efficiency is higher than the one with HVOF. This method will provide a worst result, but be more economic than the previous one.



## References:

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