Use of ceramic part in G-M refrigerator

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Engineering ceramics has good property of wear resistance. In this paper, the application of toughening ZrO_2 ceramics for wear part in G-M refrigerator is presented. In order to increase life span and reliability of refrigerator, ZrO_2 ceramics has been applied to fabricate rotary unit, which is a wear part of G-M refrigerator. We also have studied the wear particles formed in Teflon-metal sliding and ZrO_2-ZrO_2 sliding respectively. The thickness of wear particles is estimated from analyses based on a model. The results show ZrO_2 ceramics has the highest application potential for wear part in G-M refrigerator.

INTRODUCTION

Engineering ceramics

Various industrial processes require the use of wear-resistance materials to prevent or decrease wear loss and to reduce downtime of the equipment running in contact with abrasive environment, and also to increase the performance and quality of the processes. Traditionally used hard irons and steels and some polymers are quickly destroyed. Engineering ceramics with their high hardness and high resistance offer substantial advantages over metallic or polymeric materials. They have a growing application potential for the wear parts. Ceramics used most for wear-protection are dense or low-porous ZrO_2 ceramics, and some other oxide-based ceramics. Among the ceramics used in industry at the present time, ZrO_2 ceramics, and silicon carbide-based ceramics have the highest application potential. They demonstrate excellent wear-resistance and high mechanical properties. ZrO_2-based materials are well documented for low thermal-conductivity, high fracture toughness, as well as offering excellent wear resistance in adverse environments. Toughening ZrO_2 ceramics with its enhanced toughness appears to be ideal wear-resistance materials in a variety of engineering applications.

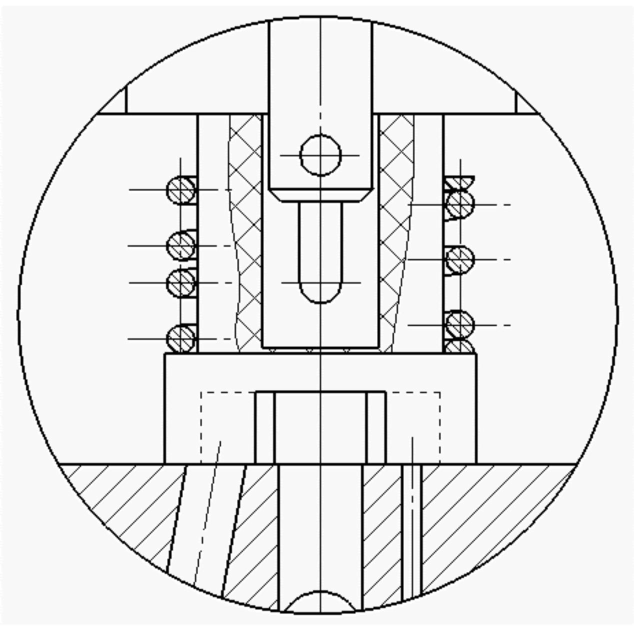

Figure 1 Schematic diagram of the rotary unit

Rotary unit of G-M refrigerator

Rotary unit is a key part of G-M refrigerator. Its running reliability directly affects the performance and life of refrigerator. As Figure1 shown, the rotary valve fits onto the square shaft on the motor and rides on the face of the valve plate. The rotary valve controls the cycling of high and low pressure gas for the expansion process as well as for driving the displacer. For every half revolution of the rotary valve, the cold head cycles once. Originally rotary valve and rotary plate are made of Teflon and metal material respectively. After running for a long time, serious abrasion will happen between two parts. The performance and life of the refrigerator will be affected seriously. The application of toughening ZrO_2 ceramics for wear part in G-M refrigerator is presented in this paper.

THE STUDY OF TOUGHENING ZrO_2 CERAMICS FOR THE USE IN VALVE UNIT

Properties of ceramics

We compared properties of ZrO_2 ceramics with other materials commonly used in cryogenic engineering. Hardness of ZrO_2 ceramics is far larger than that of other materials, also ZrO_2 ceramics with a lubricant action is appreciated. ZrO_2 ceramics with their high mechanical properties and wear resistance offer notable advantages over metallic or polymeric materials[1,2,3].

Considerations of design

Designing reliable engineering component with ceramics is considerably more difficult and unquestionably different than designing with metal materials. In order to avoid failures, ceramics component must be stressed very low and ceramics of good quality and strength must be used[4]. We have attempted to design rotary unit because ZrO_2 ceramics provide necessary wear resistance and strength properties. Ceramic materials are not able to dissipate stress concentrations by plastic deformation due to their brittle behavior. So the engineering design differs from that of metal material. To avoid stress concentration on the ceramic component, the ceramic part is embedded into metal containment (see Figure2).

Figure 2 Hybrid rotary unit with metal and ZrO_2 ceramics

Estimation of wear particle thickness

We estimate the wear particles thickness formed in Teflon-metal sliding and ZrO_2-ZrO_2 sliding respectively by an analytical approach, which used a model for the formation of such a particle. The model considers an adhesive junction formed as a result of contact between asperities on the sliding surface and subjected to a compressive stress due to normal load and a sheer stress because of the relative motion. It produces reversal of stresses in the substrate and after a large number of such occurrences may result in the formation of a wear particle resembling a flattened ellipsoid. In order that a wear particle can be formed the elastic strain energy due to recovery in the loaded condition must be equal to or greater than the surface energy of the particle.

$$Ee \geq Es \tag{1}$$

Where Ee and Es denote the elastic strain energy of the junction and the surface energy of the particle material respectively. The elastic strain energy for an ellipsoid is given by

$$Ee = P_0^2 V_p / 2E \tag{2}$$

Where P_0 is the normal stress acting on the junction, E is Young's modulus of elasticity of the particle material and $V_p = \pi ABC/6$ is the volume of the ellipsoidal wear particle. A and B are the major and minor axes of the elliptical particle surface and C is the thickness of the wear particle. The normal stress and shear stress acting on the junction raise to the junction growth phenomenon so that

$$P_0^{\ 2} + aS^2 = \sigma_y^{\ 2} \qquad\qquad S = \mu P_0$$

Where σ_y is the yield strength of particle material, S is the shear stress acting at the junction and a a constant. Combining above two equations the normal stress can be expressed as $P_0 = \sigma_y / \left(1 + a\mu^2\right)^{1/2}$.

$$Ee = \frac{\pi}{12} \cdot \frac{\sigma_y^{\ 2}}{(1 + a\mu^2)E} \cdot ABC \tag{3}$$

The fracture surface area As which results in the formation of a flattened ellipsoidal wear particle can be expressed as $As = \pi\left(\frac{AB}{4} + \left(\frac{A^2 + B^2}{2}\right)^{\frac{1}{2}} \frac{1}{2} \times \frac{2}{3} C\right)$. Where the perimeter of an ellipse is $\pi\left(\frac{A^2 + B^2}{2}\right)^{\frac{1}{2}}$.

Also, the thickness of a flattened ellipsoid is about two-thirds the thickness of an ellipsoid because the volume of the ellipsoids should be equal, i.e.

$$\left(\frac{\pi}{4}\right)ABC' = \left(\frac{\pi}{6}\right)ABC \qquad\qquad C' = \frac{2}{3}C$$

The total surface energy required is therefore given by

$$Es = 2\gamma\pi\left(\frac{AB}{4} + \left(\frac{A^2 + B^2}{2}\right)^{\frac{1}{2}} \frac{1}{3} C\right) \tag{4}$$

Thus the thickness of wear particle can be expressed as

$$C \geq \frac{\gamma AB}{\left\{\frac{\sigma^2{}_y}{6(1 + a\mu^2)E}\right\} AB - \frac{4}{3}\gamma\left\{\frac{\left(A^2 + B^2\right)}{2}\right\}^{\frac{1}{2}}} \tag{5}$$

Where γ is the surface energy of the particle material. The constant a, a value of 3 is assumed.

The wear particles formed in the manner described above may either escape from the interface or be trapped between the high points of the sliding surfaces. What actually happens to the particle depends on the location of the particle in the contact zone at the instant it is formed. If the wear particle is trapped another strong bond is likely to be formed between the steel surface and the loose wear particle because of the much higher surface energy of the steel material compared with that of the polymers. This results in the formation of a transfer film on the steel surface. Afterwards the bond will therefore be established between the newly formed polymer wear particle and the polymer-sliding surface or the polymer layer deposited on the steel surface. This particle will be liberated from the surface only if the elastic strain energy stored in it becomes greater than or equal to the adhesion energy acting on the interface, i.e.

$$Ee \geq Ea \tag{6}$$

Where Ea is the adhesion energy. When this particle is relieved from the normal and shear stresses acting at the interface due to sliding motion the adhesion at the interface will prevent the particle from contracting and there will be a residual stress of magnitude $\varepsilon\sigma_y / (1 + a\mu^2)^{1/2}$ where ε is Poisson's ratio for the particle material. Therefore

$$Ee = \frac{1}{2}\frac{\varepsilon^2\sigma_y{}^2}{(1 + a\mu^2)E} \cdot \frac{\pi}{6} ABC_1 \tag{7}$$

$$Ea = W_{ab} \cdot A_{adh} = W_{ab} \cdot \pi\left(\frac{AB}{4} + \left(\frac{A^2 + B^2}{2}\right)^{1/2} \frac{1}{3} C_1\right) \tag{8}$$

Where A_{adh} is the area over which adhesion occurs and W_{ab} is the specific energy of adhesion, i.e. the energy required to separate 1cm^2 of the interface between materials a and b involved in adhesion, which is equal to 2γ for identical materials and equal to the arithmetic average of the surface energies for incompatible materials. Thus from eqns. (6), (7) and (8) we obtain

$$C_1 \geq \frac{W_{ab} AB}{\left\{\dfrac{\sigma_y{}^2\varepsilon^2}{3(1 + a\mu^2)E}\right\} AB - \dfrac{4}{3} W_{ab} \left\{\dfrac{(A^2 + B^2)}{2}\right\}^{\frac{1}{2}}} \tag{9}$$

The two kinds of material have different wear properties, so the thickness of a wear particle of Teflon was calculated from eqns. (5) and equaled to 9.04 μm, the thickness of a wear particle for ZrO_2 ceramics was also calculated using eqns. (9) and equaled to 1.62 μm. The results show the thickness of wear particle from ZrO_2 material is far less than that of the traditional material. Wear rate of materials increases with the size of wear particle. So toughening ZrO_2 ceramics has distinct advantage of wear resistance for wear part in G-M refrigerator.

CONCLUSIONS

Engineering ceramics with their high hardness and wear resistance offer substantial advantages over metallic or polymeric materials. Toughening ZrO_2 ceramics with its enhanced toughness appears to be ideal wear-resistance materials for wear part in G-M refrigerator. It can improve the lifetime and reliability of the refrigerator.

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