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Porous structures of natural materials and bionic design*

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Abstract: This investigation and morphology analysis of porous structure of some kinds of natural materials such as chicken eggshell, partridge eggshell, pig bone, and seeds of mung bean, soja, ginkgo, lotus seed, as well as the epidermis of apples, with SEM (Scanning Electronic Microscope) showed that natural structures' pores can be classified into uniform pores, gradient pores and multi pores from the viewpoint of the distribution variation of pore density, size and geometry. Furthermore, an optimal design of porous bearings was for the first time developed based on the gradient configuration of natural materials. The bionic design of porous structures is predicted to be widely developed and applied in the fields of materials and mechanical engineering in the future.

Key words: Natural materials, Porous structure, Bionic design, SEM
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INTRODUCTION

After long period natural selections and evolutions, natural porous structures always integrate various functions and have many characters superior to artificial porous structures, which are mainly composed of composite and complex structures.

Natural porous structures can prevent seeds, eggs, etc. from invasion of water or cracks due to collision, exchange matters with the environment during the metabolism process, and use less material to form larger space under equivalent conditions. Natural porous materials are the same Young's modulus as steel but are much lighter (Lin *et al.*, 1995; Kemps *et al.*, 2004; Xu and Zhang, 1995). Acoustic absorption property and applications (Pugh, 1973; Koizumi *et al.*, 2004; Galland *et al.*, 2005; Danielsson and Grenestedt, 1998) and thermal stability (Lin *et al.*, 1995; Heredia *et al.*, 2002) of natural porous structures have attracted much interest in recent years. Natural porous structures show complex morphology (Kitimasak *et al.*, 2003; Cubo and Casinos, 1998; Jones *et al.*, 2004).

Natural porous materials have ordered artificial micro-pores that can reach 1 nm in diameter, and have hierarchical porous structures or porous metal-organic frameworks (Davis, 2002). The fabrication structures of porous metal can be manufactured with several methods (Zhu, 1999; Maine and Ashby, 2002; Chen and Li, 2003).

Combinations of the sizes and/or the densities of pores in natural materials have functional superiority. However, the mechanism of natural porous materials is not clear for bionic design of machines and mechanical structures.

This study is aimed at investigating the microstructures of some natural porous materials, such as seeds of some plants, eggshells of several poultries and birds, animal bones, etc., all of which adjoin the environment and can resist outside invasion. This study also aimed at the bionic design of key mechanical elements, for example, bearings, based on the porous microstructure natural materials.

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EXPERIMENTAL METHODS AND RESULTS

Samples preparation

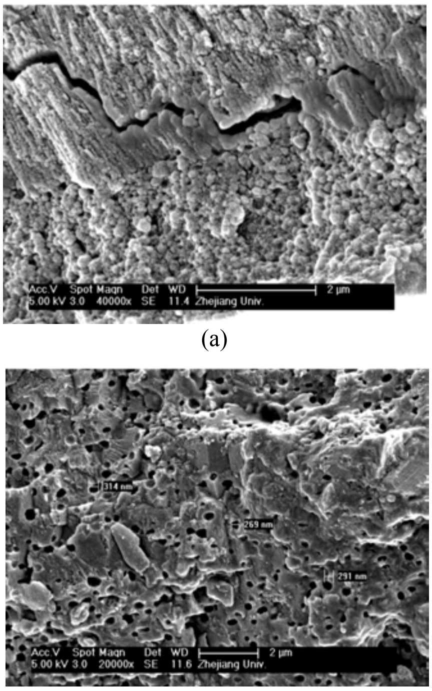
The samples used in this study were chicken eggshell, partridge eggshell, bone, and seeds of mung bean, soja, ginkgo, lotus, and the epidermis of apples, because seed-shells or egg-shells shelter embryos or fruits from the outside environment, and exchange matter with it. The microstructures of these materials were obtained with Scanning Electron Microscope (SEM).

Results

The cross sections configurations of hen eggshells have three layers: cuticle sheet, crystalline sheet and mammillary sheet. Though the borderline between cuticle sheet and crystalline sheet is faint, this classification index is still reasonable due to differences of material components and functions. Cuticle sheet, crystalline sheet and mammillary sheet which can be defined as the parts from the location of crack to mammillary tip, are respectively 2 μm (0.7%), 213 μm (77.7%) and 59 μm (21.6%). Fig.1a shows the cuticle sheet's structure. The loose and viscous-elastic porous structures provide eggshell more flexibility, and improved mechanical performance, etc. The crystalline sheet shown in Fig.1b has a typical porous structure. The diameters of round micropores range from 200 nm to 400 nm. These pores function as exchanger of matter between the outside and inside of eggshells while having enough strength to prevent crack from collision. Compared with the microstructure of sea-turtle eggshells (Kitimasak, 2003; Zhang *et al.*, 2005), hen eggshells are more compact, which suggests that moist environment influences the porous structure of eggshells.

The structure of partridge eggshells is similar to that of hen eggshells. The eggshells of birds (including poultries) and turtles are comprised of three sheets and an inner membrane. The diameter of the micro-pores is 300~500 nm, near that of hen eggshells.

The partridge eggshell membrane is composed of large numbers of fibers, which interweave and present multilayer porous form as shown in Fig.2 with observational direction normal to the membrane surface. The voids among pores are small enough to prevent leak of albumen even if the eggshell is broken.



(a)

(b)

Fig.1 Microstructure of hen's eggshell
(a) Cuticle sheet; (b) Crystalline sheet

Fig.2 Inner membrane structure of partridge eggshell

The bone, which is the mid-part of pig shank, shows obvious gradient distribution of pores. The outside part has compact pores and inside part loose pores. This type of porous structure can be explained by the need of resistance to bend and torsion mainly supported by the surface and subsurface part. The inside loose pores can absorb energy of vibration and improve shock resistance of the bones. This structure is optimal and has multipurpose functions such as load and vibration-absorption.

The microstructure in Fig.3 indicates that the whole structure is organized with fibrous and viscoelastic connections, displaying worm-like configuration. The materials are characterized by elasticity and tenacity.

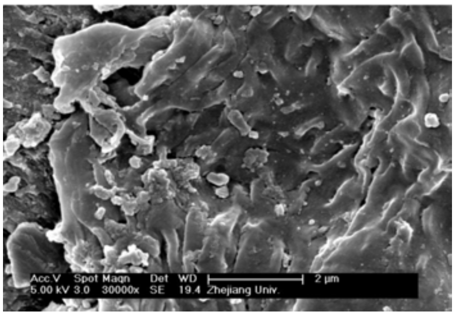


Fig.3 Microstructure of pig shank

The mung seed configuration has multi-layer-structure at the crust. Inside pores in mung seed are large but outside pores are small. At the edge of the crust, the structure showed in Fig.4 has many pits distributing on the cross section.

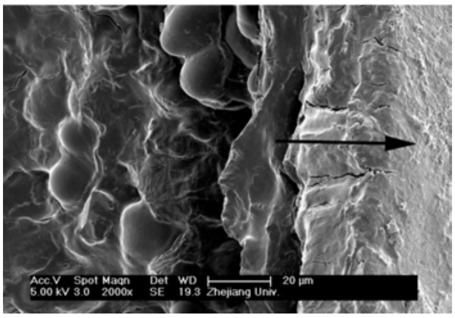


Fig.4 Microstructure of mung bean seed

Fig.5 shows that shell of dry lotus seed has a gradient distribution of porous structure. A large number of spherical grains adhere to one another. The gap among grains becomes larger from inside to outside. Considering the environment for growth of lotus seeds, the relatively large gaps in the lotus seed body make it easier for moisture to dissipate, so this kind of porous structure can provide convenient condition for the metabolism process in seeds.

Similar to lotus seed, the shell of ginkgo seeds shown in Fig.6 is composed of two semi-spheres, forming a closed space for preventing the seed from outside invasion and providing channels for materials exchange with the environment. A large number of strip-geometry grains adhering to one another form the shell, which displays two types of configurations. The inside part shows drape piece geometry cracks, and outside part short bar geometry cracks. The bar length/width ratio is 3:1~5:1, and the bars have many about 1 μm round pores, distributing on their surfaces. The long axis of the bars is parallel to the seed shell surface.

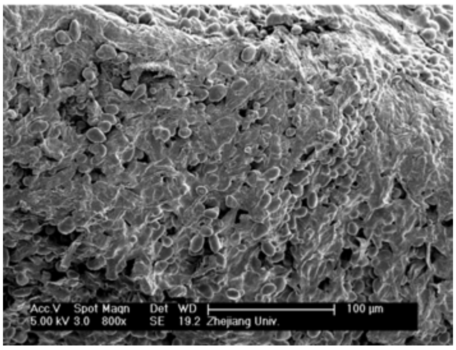


Fig.5 Micro configuration of lotus seed

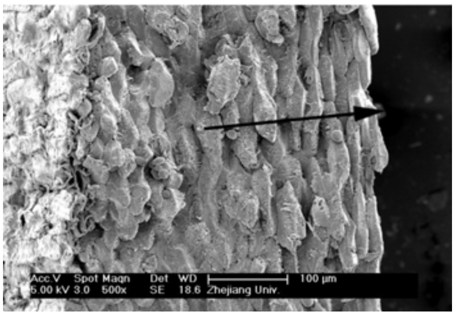


Fig.6 Microstructure of ginkgo seed epidermis

The cross section configuration of soja seed epidermis in Fig.7 displays a “sandwich” structure, which is loose in the middle part and compact at the edge. It is interesting that “hairtail” layers in the middle pile up, whose regular rank direction is normal to the surfaces of both sides of the shell. So that, we classify this kind of structure as the multi-porous type.

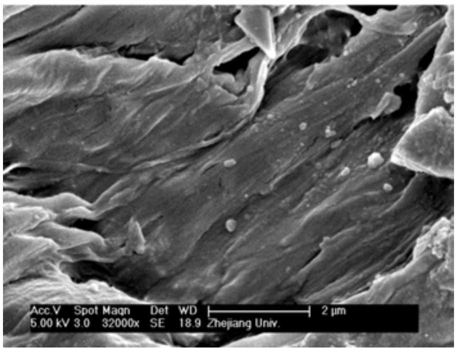


Fig.7 Microstructure of soja seed epidermis

The functions of apple epidermis are similar to that of other shells of seeds or eggs. Pieces of squama shown in Fig.8 form cascade geometry and build many closed space. These voids keep moisture, and the squamae adhering to one another in their edge reduce the dispersion of moisture into the atmosphere. Even after the outside layer dried, with the sheets of squamae mostly parallel to the epidermis surface, they would stick to the inner layer and prevent water inside from dispersing upward to the atmosphere.

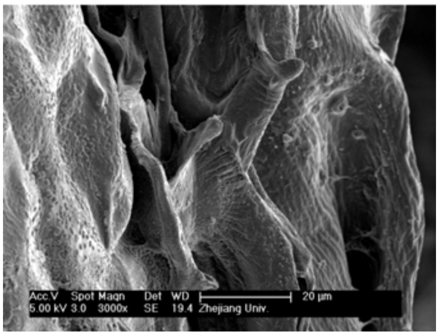


Fig.8 Microstructure of apple epidermis

The shells and epidermis of plant seeds or animal eggshells studied above have the functions of adapting to the natural environment and to ensure growth of the organism inside them. And during development of the organisms' bodies, the shells or epidermis supply the gas and water for keeping normal metabolism. Environment factors, such as temperature, humidity, oxygen concentration, etc., change along with environmental conditions which must be relatively stable, as the organism inside the shells or under epidermis, need upper stably favorable settings for growth. Thus, the epidermis of fruits and shells of organisms play a key role in their natural growth. The porous structure is an optimal choice for eggshells or epidermis of fruits, as it requires minimal material to provide necessary mechanical strength.

Discussions

The pores in porous structures of natural materials are not uniform in size and have different distribution and configuration in different parts of the materials. The structure is relatively compact near the outside surface of shells or epidermis. In the middle sheet, the configurations are complex, and include "squama" geometry such as in apple epidermis, "bar" structure of soja shell and round pores of eggshells. As the source of strength for protection against invasions and shocks from collisions, the middle layers are always thicker than other layers. The soft inner layers adhering to the body of organism have complex configurations and stable damping functions. In short, most porous configurations in shells of organisms and epidermis of fruits are the functional composite of several types of pores in their cross sections.

Density distributions of porous material pores are not uniform in the shells of organisms or epidermis of fruits in the radial direction of their cross section. In general, pores can be divided into uniform pores, gradient pores and multi pores in terms of the distribution variations of pore density, size, and geometry. Gradient distribution generally exists in many shells or epidermis due to its superiority in mechanics characteristics.

BIONIC DESIGN OF POROUS STRUCTURE

The gradient porous structure is an optimal mechanical result of the long time development of natural materials and can be applied for instruction on the structural design of mechanical elements with perfect performance.

Bearings are widely used to support shafts in rotary machines, which are key elements determining the precision and performance of mechanical systems. The porous bearing does not need oil supplement system but sacrifices a part of its mechanical strength to get oil storage space in return. The lubricants for forming the oil film come from the entrainment effect due to the rotating shaft and the thermal expansibility due to friction.

But, the disadvantage of porous bearings is the lubricant film's low load carrying capacity as a result of oil-return due to the high hydrodynamic pressure in oils, which limits its application in industry. To overcome this shortcoming, density-changeable porous bearing was developed (Capone *et al*., 1978; Quan, 1985). At the zone of oil-return, there is low density of porous materials in the bearing. This is a type of multi porous structure according to the above discussion.

More bionic optimal structures can be designed based on the superiority of gradient porous structure. The low carrying capacity of the porous bearing's lubricant film is its oil-return effect. If the pore density is less, its load capacity can be improved. On the other hand, the space for oil storage reduces. To solve this problem, the gradient porous structure is proposed (Fig.9). The pore density increases exponentially and radically inward from the outside of porous bearings. This type of porous bearing has optimal characteristics, and because of the reduction of pore density at the outside part, the oil-return effect is reduced, and entrainment effect and heat expansion squeezing effect will be enlarged due to the reduction of pore density from outside to inside. Hence, it is reasonable that this type of bionic design of porous bearing can achieve better bearing performance.

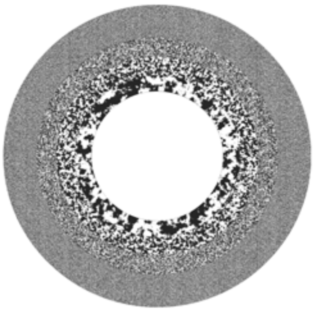


Fig.9 Bionic design of porous bearing

CONCLUSION

The investigation and morphology analysis of porous structure of various kinds of natural materials such as chicken eggshell, partridge eggshell, bone, and seeds of mung bean, soja, ginkgo, lotus seed, as well as the epidermis of apples, with SEM showed that the porous natural structures can be classified into uniform pores, gradient pores and multi pores in terms of the distribution variations of pore density, size and geometry. The gradient porous structure has obvious superiority to normal materials due to its mechanical characteristics.

Simulation of the gradient pores of natural structures led to the new bionic design for porous bearing presented in this paper. Multi-porous "sandwich" structures for integrated optimal design have considerable mechanical strength and obvious superiority over conventional materials for acoustic-absorption.

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