Effects of Technical Parameters on Properties of Wear-Resistant Triboelectric Materials

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Abstract. The influence on properties of technical parameters of hot-pressing process were optimized by using orthogonal test for wear resistant triboelectric materials, the hardness, wear and electric output properties of the materials were measured by kinds of analytical testing methods. The results shown that the friction coefficient was drastic influenced by hot-pressing temperature that the hot pressing temperature of 175 °C had higher friction coefficient. The wear rate was affected by heat treatment time that the hot-pressing temperature of 8 hours had lower wear rate. Hardness was greatest affected by the pressure that the samples using 21 MPa had greater hardness. Moreover, a vertical contact-separation triboelectric nanogenerator was fabricated based on the wear-resistant tribo-material, which the open-circuit voltage, short-circuit current and transfer charge could generates 29.85 V, 12.18 μA and 15.6 μC under frequency of nearly 2 Hz.

Keywords: tribo-material, wear-resistant, technical parameter, energy harvesting

1 Introduction
Triboelectric nanogenerators (TENGs) based on the coupling effect of contact electrification and electrostatic induction, as a invented energy harvesting technology of a new era that it can converting mechanical energy in the environment into electricity, have been applied researched due to its prominent advantage in high convert efficiency, simple process, low cost and simple structure [1-3]. The TENGs are of great advantages for capturing mechanical energy especially when the vibrational frequency is lower than 5Hz level. In recent years, the electrical properties of TENGs have been extended remarkably by means of optimizing the tribo-materials for harvesting mechanical energy, used to drive low-power electronic devices, self-powered sensors, air purification, medical rehabilitation, intelligent equipment and other fields have received extensive research [4, 5]. The continuous improvement of demand has puts forward some new higher requirements for performance of the tribo-material in industrialized applications [6]. The performance of high-quality triboelectric material should mainly include excellent wear-resistant, high stability, suitable friction coefficient and electrical output properties. In this work, the wear-resistant triboelectric materials are prepared by hot-pressing process. The composite materials will undergo three states in this process as
follows: viscous flow, gelled and hardened state. When in the state of viscous flow and gelled that the composite materials have present softening state and is essentially plastic before hardening. After the hot pressing is finished that it needs to be cured by low temperature and until the molded core of composite materials is completely hardened. Therefore, the process parameters of the hot-pressing process are key technical parameters of the wear-resistant tribo-materials [7-10]. One of the pressures, hot-pressing temperature, holding and curing time are the most important parameters of processes.

2 Results and discussion

2.1 Experimental materials

In the experiments, the composite powders of the wear-resistant tribo-materials were added to a planetary ball mill for ball milling, which contained thermosetting binders, micro-nano reinforcing fibers, regulators of friction performance, triboelectric modifiers, complex filler, and other composite materials (bal.). The design and measured composition of the wear-resistant composite materials were shown in Table 1. The results illustrate that the composition range of wear-resistant composite materials has less error, and ensure the follow-up test carries out well.

| Sample | Thermosetting binder (%) | Reinforcing fiber (%) | Performance regulator (%) | Complex filler (%) | Triboelectric modifier (%) | Other |
|--------|--------------------------|-----------------------|----------------------------|-------------------|--------------------------|-------|
| Design | 8.50                     | 27.00                 | 33.50                      | 5.50              | 25.50                    | 0     |
| Measured | 8.55                   | 27.08                 | 33.47                      | 5.12              | 25.74                    | Bal.  |

2.2 Preparation technology

According to design composition of the wear-resistant material by high-speed mixed and ball-milling method. Then the composite powders are put into the designed mold, the processing technique comprises the steps of hot-pressing, curing, polishing and cutting. The composite materials are fully stirred and mixed according to proportion by a high-speed mixer, and the composite materials were pretreated through uniformly dispersed by ball-milling treatment. The composite materials are put into the designed mold and hot-pressing, curing time with a size of 3×3×0.5 cm (length × width × height). In this paper, the hot-pressing temperature, pressure and curing time of hot-pressing process have been set, and each parameter was selected 2 level, design orthogonal test as shown in Table 2. The parameters of preparing process were as followed: milling time of 10 min, holding time of 6 min, curing temperature of 160 °C. The preparation process of the wear-resistant tribo-material was shown in Figure 1a, it’s optical photograph and microstructure of the wear-resistant triboelectric materials were shown in Figure 1b-d. From Figure 1c-d we can clearly see the micro-nano structure distributed uniformly in the composite, the grain and boundary of this composite is uniform, well-proportioned microstructure and the grain is very small.

Table 2. Orthogonal testing of the hot-pressing

| Samples | Hot-pressing temperature (°C) | Pressure (MPa) | Curing time (h) |
|---------|-------------------------------|----------------|-----------------|
| T1      | 165                           | 19             | 6               |
| T2      | 165                           | 21             | 8               |
| T3      | 175                           | 21             | 6               |
| T4      | 175                           | 19             | 8               |
Figure 1. The fabrication process of the wear-resistant triboelectric materials by hot-pressing process

2.3 The influence of technological parameters
The mechanics and friction properties of the samples with different technological parameters were tested, as shown in Figure 2, respectively. The hardness of wear-resistant tribo-material was affected obviously with the pressure, the results shown that it increases significantly with the increased of the pressure, as shown in Figure 2a. The shear strength of the wear-resistant tribo-material was affected obviously by the curing time, it increases significantly with the increase of the curing time. But at the same time, the higher pressing temperature, and it has the higher the shear strength, as shown in Figure 2b. Figure 2c show the friction properties of the wear-resistant tribo-material with the dynamic temperature range from 25 to 250 °C, and the friction coefficient of wear-resistant tribo-materials increases nonlinearly along with the increase of testing temperature. The friction coefficient of wear-resistant triboelectric materials was affected obviously by the pressing temperature, which increases significantly with the increased pressing temperature. The wear rate of wear-resistant triboelectric materials increases along with the increase of dynamic test temperature from 25~250 °C. The wear rate of wear-resistant triboelectric materials was affected obviously by the curing time, it decreases significantly with the increase of the curing time, is shown in Figure 2d.

Figure 2. Mechanical and friction properties of wear-resistant triboelectric materials with different technological parameters
3. The output performance TENG based on the material

The vertical contact-separation mode TENG was fabricated by the prepared tribo-materials serves as the triboelectric layer, and aluminum (Al) foil serves as an electrode connected with the external load, in which it is to be used for harvesting vibrational energy from the natural environment, as shown in Figure 3. The device structure and working principle of electric output including four typical steps were shown in Figure 4 a-b. The COMSOL software was employed for theoretical simulation the distribution of the electrical potential between two Al electrodes with the four states, the simulation results were shown in Figure 3c. In this cycle of the charge generation that relies on the charge transfer between two Al electrodes, due to the electric potential difference drives the electron flow in the external circuit.

**Figure 3.** The structure and working mechanism of the TENG with the wear-resistant tribo-material. The results shown that the prepared wear-resistant tribo-materials had good wear-resistant properties and high hardness under appropriate process conditions, it is can be directly used as frictional parts such as automobile's brake pads used in machines for harvesting vibrational energy, the output performance of TENG were indicated in Figure 4. The electric output of the TENG was tested in experiment (a size of 3 cm × 3 cm) by linear motor at the frequency of above 2 Hz. Figure 4a shows output short-circuit current of the TENG was measured with a peak value of ~15.6 μA, and Figure 4b shows the transfer charge quantity of ~12.1 nC in cycle under short-circuit conditions. The output open-circuit voltage of the TENG was ~29.8 V, as shown in Figure 4c. So that, the TENG have excellent performance in during vertical contact-separation process, the testing results shown that the wear-resistant tribo-material has positive effect on the TENG's output performance. The results prove that the prepared material is effectively as a wear-resistant triboelectric layer for TENG that can be used to harvesting mechanical energy from the extreme environment. In testing the stability of the TENG with the prepared wear-resistant material, the open-circuit voltage of the TENG to keep a certain level for over 50 cycles (Figure 4d).
Figure 4. The electric output of the TENG. (a) The output short-circuit current of the TENG. (b) Transferred charges quantity of the TENG. (c) The output open-circuit voltage of the TENG. (d) The stability of the TENG was represented over 50 cycles.

4. Conclusion
In summary, the technical parameters of hot-pressing process were studied for wear-resistant tribo-materials through a series of experiments. On this basis, the methods of improving comprehensive properties, especially wear-resistant of the triboelectric material were discussed, its application as vertical contact-separation mode TENG's triboelectric functional layer was researched in the process of harvesting energy. The testing results shown that the pressing temperature, pressure and curing time are three major control conditions in hot-pressing, and the pressing temperature is the most important one on the friction coefficient of the wear-resistant tribo-materials. The results also indicated that the pressure is the most important factors in hardness and shear strength, and the curing time has the greatest influence on the wear rate of the materials. In the paper that contributed to larger friction coefficient of the material treated under hot pressing temperature of 175 °C, and the lower wear rate of the material treated at curing time of 8 h. The hardness and shear strength of the material were larger under pressure of 21 MPa. The study overcame the disadvantage of conventional TENG's triboelectric materials in which non wear resistance, and the vertical contact-separation mode of TENG device was fabricated, it is demonstrated that the electrical output of 15.6 nC, 12.1 nA and 29.8 V are produced.

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References
[1]. F. R Fan, Z. Q. Tian, Z. L. Wang, Flexible triboelectric generator! Nano Energy, 2012, 1, 328-334.
[2]. Z. L. Wang, Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors. Acs Nano, 2013, 7, 9533-9557.
[3]. X. Chen, Iwamoto M., Shi Z., Zhang L., Wang Z. L. Self-powered trace memorization by conjunction of contact-electrification and ferroelectricity. Adv. Funct. Mater., 2015, 25: 739–746.
[4]. S. M. Niu, Liu Y., Zhou Y. S., Wang S. H., Lin L., Wang, Z. L. Optimization of triboelectric
nanogenerator charging systems for efficient energy harvesting and storage. IEEE Trans. Electron Devices, 2015, 62: 641–648.

[5]. S. M. Niu, Wang X. F., Yi F., Zhou Y. S., Wang Z. L. A universal self-charging system driven by random biomechanical energy for sustainable operation of mobile electronics. Nat. Commun., 2015, 6: 8975–8986.

[6]. Lin L., Wang S. H., Xie Y. N., Jing Q. S., Niu S. M., Hu Y. F., Wang Z. L. Segmentally structured disk triboelectric nanogenerator for harvesting rotational mechanical energy. Nano Lett, 2013, 13: 2916–2923.

[7]. C. He, C. Han, G. Gu, T. Jiang, B. Chen, Z. Gao, Z. L. Wang. Hourglass triboelectric nanogenerator as a “Direct Current” power source, Adv. Energy Mater. 2017, 1700644. [8] Wang, Z. L. Catch wave power in floating nets. Nature, 2017, 542, 159-160.

[8]. J. Chen, Z. L. Wang. Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator, Joule 2017, 1, 480–521.

[9]. U. Khan, S.-W. Kim, Triboelectric nanogenerators for blue energy harvesting. ACS Nano 2016, 10, 6429–6432.

[10]. X. Pu, W. Song, M. Liu, C. Sun, C. Du, C. Jiang, X. Huang, D. Zou, W. Hu, Z. L. Wang. Wearable power-textiles by integrating fabric triboelectric nanogenerators and fiber-shaped dye-sensitized solar cells. Adv. Energy Mater. 2016, 6, 1601048.