Research Article

Xing Wang*, Mingming Wu, and Jianglong Wang

On-line monitoring of steel ball stamping by mechatronics cold heading equipment based on PVDF polymer sensing material

https://doi.org/10.1515/nleng-2022-0014
received October 28, 2021; accepted February 27, 2022

Abstract: In order to explore the influence of cold heading equipment based on polyvinylidene fluoride (PVDF) polymer sensing material on steel ball stamping, a new method was proposed to reflect the defects of cold heading forming of steel ball by load signal. PVDF piezoelectric film is used as the sensor design of force and support structure of steel ball cold heading electromechanical sensor model. PVDF piezoelectric thin film force sensor is used for the structural optimization and simulation. The structural parameters affecting the natural frequency are numerically analyzed by MATLAB software. The mapping relationship between the external load and the output load of the sensor is obtained by using ANSYS software, and the simulation curve of the natural frequency of the sensor is compared with the theoretical curve to verify the factors affecting the natural frequency. The results show that the nonlinear error of sensors refers to the measured curve and the maximum deviation between the fitting line and the percentage of full-scale output.

Keywords: PVDF polymer, mechatronics, cold heading equipment, piezoelectric thin film force sensor

1 Introduction

The application of sensor technology is very extensive, especially with the continuous improvement of people’s environmental protection awareness level, air pollution, and industrial waste gas, environmental quality monitoring has higher requirements, so that people’s requirements for sensor sensing performance has also improved; On the other hand, the development of traditional chemical sensor materials has great limitations. Even though they are improved in various ways, they still cannot meet the needs of the current society, thus promoting the research and development of excellent sensitive materials [1]. Since the performance of gas-sensitive materials directly affects the performance and life of sensors, the research and development of new sensing materials with high sensitivity, selectivity, and stability for different gases have attracted more and more attention [2]. Good reproducibility or long-term stability is another important parameter of the sensor, that is the response repeatability of PVDF/CB composite film to acetone vapor after oxygen plasma treatment. The advantages of organic polymer gas sensitive material is that it is rich, the price is low, the membrane process is simple, has good selectivity in room temperature, and easily compatible with other technologies, at the same time, organic polymer gas sensitive materials can also be modified by functionalized doping, modification, and other methods to improve their sensitivity to various monitoring gases [3,4]. As an important component of forming quality monitoring system, the pressure sensor can be used to obtain the load signal of the cold pier process and reflect it in the form of waveform through the conversion equipment. The commonly used pressure sensors and their disadvantages are shown in Table 1.

In the process of mechanical power transmission, bearing plays a role of reducing the coefficient of load friction and fixing the central position of the shaft. It is widely used in agricultural equipment, automobile,
The quality of steel balls is closely related to the performance of the bearings, for 77%, which objectively shows that the quality of steel balls bear loads in the form of rolling bodies. As a key component of bearings, steel balls are widely used in military industry, and aerospace, and is a basic part with strong versatility. As a key component of bearings, the proportion of cold-heading equipment, hydroforming, photoelectric appearance inspection and size grouping, the quality defects often occur in the process of cold piercing, which directly affects the subsequent processing and actual working conditions of the steel balls, so they are regarded as the source of quality hidden trouble and defective products. Wu and others proposed a flexible pressure sensor array based on PVDF film. The sensor is a sandwich structure, the middle layer is a piezoelectric layer, and the upper and lower layers are electrode layer arrays. They fabricated the prototype device of flexible pressure sensor array by etching and encapsulated it with PDMS. Akbulut, M., mainly focused on the flexible physical characteristics of polyvinylidene fluoride (PVDF), summarized the outstanding application direction of PVDF piezoelectric film as a flexible sensor, and demonstrated the unique advantages and broad application prospects of PVDF as a flexible sensor by comparing it with the existing flexible sensor technology. The calibration methods of PVDF sensor are summarized comprehensively, and the limitations of various calibration methods are pointed out. Finally, the aspects needing further improvement of PVDF piezoelectric film as a sensor are given.

Table 1: The commonly used pressure sensors and their advantages and disadvantages

| Sensing principle     | Accuracy | Merit                                      | Shortcoming                                      |
|-----------------------|----------|--------------------------------------------|-------------------------------------------------|
| Meet an emergency     | High     | Mature technology, high precision, suitable for static or quasi-static measurement, and generally used for sensor calibration | The measurement speed is relatively slow, the bridge road is susceptible to temperature, humidity, and large drift |
| Piezoelectricity      | High     | Good rigidity, can achieve multi-dimensional force integration testing, flexible processing, and fast measurement speed, especially suitable for dynamic testing | High input impedance requirement is required in high temperature environment |
| Pressure resistance   | Same as  | High sensitivity                           | Cooling problems and heavy loading must be considered |
| Magnetic pressure     | Same as  | Large output signal, anti-interference, and strong overload capacity | Multidimensional interdirection coupling has to be decoupled |

Military industry, and aerospace, is a basic part with strong versatility. As a key component of bearings, steel balls bear loads in the form of rolling bodies. According to the statistics of the bearing industry, the proportion of bearing failure caused by damage of steel balls accounts for 77%, which objectively shows that the quality of steel balls is closely related to the performance of the bearings, so people have higher and higher requirements for the quality of steel balls. At present, the basic process of steel ball manufacturing involves cold (hot) block, light grinding, heat treatment, hard grinding, surface strengthening treatment, finishing, photoelectric appearance inspection and size grouping, fine washing, and oil packaging. Small and medium-sized steel balls adopt cold piercing technology as the first process of steel ball forming. Forming quality defects often occur in the process of cold piercing, which directly affects the subsequent processing and actual working conditions of the steel balls, so they are regarded as the source of quality hidden trouble and defective products. Wu and others proposed a flexible pressure sensor array based on PVDF film. The sensor is a sandwich structure, the middle layer is a piezoelectric layer, and the upper and lower layers are electrode layer arrays. They fabricated the prototype device of flexible pressure sensor array by etching and encapsulated it with PDMS. Akbulut. M., mainly focused on the flexible physical characteristics of polyvinylidene fluoride (PVDF), summarized the outstanding application direction of PVDF piezoelectric film as a flexible sensor, and demonstrated the unique advantages and broad application prospects of PVDF as a flexible sensor by comparing it with the existing flexible sensor technology. The calibration methods of PVDF sensor are summarized comprehensively, and the limitations of various calibration methods are pointed out. Finally, the aspects needing further improvement of PVDF piezoelectric film as a sensor are given.

Bairagi. S shows a shooting auxiliary training system based on PVDF membrane pressure sensor, which is used to detect, record and analyze the pressure change of shooter’s hand strength position in real time, including athlete terminal, smartphone terminal and cloud database system. The athlete terminal is composed of integrated power module, multi-channel PVDF membrane pressure sensor, amplification filter circuit, analog-to-digital conversion module, processor unit and wireless transmission module. Multi-channel PVDF film pressure sensor, amplifying filter circuit, and analog-to-digital conversion module are responsible for collecting and processing the real-time pressure signal of the key force generating parts of athletes when shooting. The processor unit is used to analyze, process, and store pressure data for a certain period of time. Wireless transmission module is used to transfer the data from the storage unit to the smart phone terminal. The multi-channel PVDF film pressure sensor is laid at multiple stress positions where the trigger and the gun handle contact with the athlete’s hand to collect multi-channel pressure signals. Jo et al. designed and manufactured a forming tool in the laboratory without using computer CNC machine tools. The manufactured molding tools are then processed using plasma nitride at different temperatures (400–500°C) and the results are compared with the existing tools provided by the nail manufacturer. Compared with the existing molding tools, plasma nitride has significantly increased the hardness, nail production (for civil buildings), and better wear resistance, especially at 400°C. Based on this, this paper presents a mechatronics cold heading equipment based on PVDF polymer sensing material to study the influence of steel ball stamping.
2 Research methods

2.1 Measurement principle of piezoelectric thin film force sensor for steel ball cold pier machine

2.1.1 Piezoelectric equation for a PVDF piezoelectric film

During the cold pier of steel ball, the PVDF piezoelectric film is mechanically deformed and stretched under the action of impact force.

The expression of the piezoelectric equation for the PVDF piezoelectric film under the polarization is:

\[
\begin{bmatrix}
D_x \\
D_y \\
D_z
\end{bmatrix}_{E=0} =
\begin{bmatrix}
0 & 0 & 0 & d_{31} & 0 & 0 \\
0 & 0 & 0 & d_{32} & 0 & 0 \\
d_{31}d_{32}d_{33} & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{xz} \\
\sigma_{yz}
\end{bmatrix},
\]

(1)

According to the sensor measurement requirements, the PVDF piezoelectric film only bears a positive stress \(\sigma_{xx}\) perpendicular to its plane, so that the force area is \(A\), and the charge amount \(Q\) generated perpendicular to its plane is:

\[
Q = D_x A = d_{33}\sigma_{yy}A.
\]

(2)

The carrying area \(A\) and the piezoelectric constant \(d_{33}\) are constant, so it can be concluded that in the \(Z\) direction, when the PVDF piezoelectric film loads, the resulting load increases, thus providing a certain theoretical basis for the study of the design and performance of the sensor.

2.2 The experiment

Medium pigment furnace carbon black (CB), model 750B, produced by Mitsubishi Chemical Co., LTD, was cleaned in benzene by ultrasonic before use and then vacuum dried at 110°C for 48 h. Triallyl cyanate (TAIC), PVDF, dioxane, acetone, sodium hydroxide, \(N,N\)-dimethylformamide (DMF), anhydrous ethanol, tetrahydrofuran (THF), dimethyl sulfoxide (DMSO) were all analytically pure.

2.3 Preparation and treatment of samples

2.3.1 Plasma treatment

After being fully dissolved in 8 mL of DMF solvent, 0.025 g CB was added. After ultrasonic treatment for 100 min, the mixture was evenly mixed. If necessary, add crosslinking agent TAIC to disperse for 1 h to obtain PVDF and CB paste. The electrodes were pulled out to get uniform PVDF/CB composite film. After vacuum drying, a part of the coated electrodes was used for plasma treatment. Plasma treatment reactor with discharge frequency of 13.56 MHz is capacitive coupled and self-made [10,11]. The electrode was placed on the carrier platform under the plasma, and the vacuum pump was started. After the limit, vacuum was pre-pumped to 0.48 Pa, and O\(_2\)/Ar was passed through. The gas flow rate was 31 mL/min (SCCM) under the standard state, the discharge pressure was 50 Pa, the vacuum electrode spacing was 7 cm, the discharge time was 10 min, and the discharge power was between 60 and 100 W, respectively.

2.3.2 Determination of gas-sensitive response performance of samples

The film element prepared above is connected with an ohmmeter, and the change in the resistance value of the film element is recorded at room temperature and pressure. The steps are as follows: first the initial resistance value \((R_0)\) of the element in the air was determined. Then, the film element was quickly placed in a closed system filled with solvent atmosphere, and the change in the resistance value \((\Delta R)\) of the film element with time in the measured atmosphere was recorded. When the resistance value of the thin film element tends to be stable, the element is taken out quickly, and the recovery performance of the resistance in air, the responsiveness of the solvent vapor, and the response sensitivity of the element are recorded. \((S = \frac{\Delta R_{\text{max}}}{R_0})\), where \(\Delta R_{\text{max}}\) is the maximum resistance change value of the element in the solvent atmosphere during the measurement process.

3 Result analysis

Through the analysis of the sensor force, the sensor model is constructed, and the theoretical calculation formula of the sensor size parameters, the inherent frequency of the sensor, the influence of the transmission efficiency of the inherent frequency and force, and the main factors affecting the sensor performance are determined.

3.1 Response sensitivity of PVDF/CB to organic solvent vapor

The experiment first measured the sensitivity of the composite film without any plasma treatment to obtain the
initial data to be compared with the sensitivity of the film after plasma treatment so as to obtain the characteristics of its response behavior. Figure 1 shows the response sensitivity of the composite films with different CB contents (ωCB) in different solvent vapors. PVDF/CB composite membranes with 10% ωCB showed a certain sensitivity to acetone solvent vapor, but the response of PVDF/CB composite membranes to all the solvents tested was found to be low. In comparison, PVDF/CB composite membrane with 12% ωCB showed the maximum response strength to acetone solvent vapor, with response sensitivity $S$ up to 5,000, and also showed obvious response behavior to THF, with response sensitivity $S$ up to 1,000. From the perspective of thermodynamics, the permeability of the solvent molecules depends on their solubility and diffusion in polymer membranes. The solubility of PVDF in acetone is good, so it can quickly penetrate into the membrane matrix, so that PVDF macromolecules dissolve and swell, which will change the original state of CB in the film, the distance between CB will increase with the matrix swelling, and the resistance of the film will increase. When CB content is low, its distribution is more dispersed in the matrix, spacing will be bigger, and the initial value of the resistance $R_0$ is bigger, when placed in a solvent atmosphere. Because this kind of solvent penetration ability is very strong, the matrix of CB in matrix spacing expands with higher resistance $r_T$, but as the initial resistance $R_0$ is also relatively high, the response sensitivity is not obvious [12]. When the content of CB is high, CB is densely distributed in the matrix, and the initial resistance $R_0$ value is relatively low. When the solvent with good solubility of CB is encountered, the film resistance $r_T$ increases significantly, and it will show high response sensitivity.

Figure 1 shows the response characteristic curve of the composite film to acetone and THF vapor. According to Figure 1, when PVDF/CB with ωCB content of 10% is exposed to THF gas, the resistance response is slow, indicating that the permeability of THF to matrix is low, but the permeability of PVDF/CB with ωCB content of 12% is high, indicating that the increase in CB content will improve the permeability of solvent to matrix polymer. When the sensor moves from the solvent vapor to the dry air, the resistance returns to the initial value relatively slowly, indicating that the solvent molecules diffuse into the air at a slower rate of desorption.

### 3.2 Influence of PVDF/CB on the reactivity of solvent vapor

The effect of discharge power of plasma treatment reactor on gas sensitive response intensity of thin film element was further studied. It can be seen from Figure 2 that the gas response speed of PVDF/CB thin film element is significantly improved after the PVDF/CB thin film element is treated in Ar and O$_2$ plasma atmosphere, and the maximum response value is reached in a very short time. Ar gas is an inert gas. After bombarding the material surface as an ionospheric gas, a relatively close cross-linked
layer is formed on the surface. The formation of cross-linking layer not only changes the surface free energy of the material but also reduces the leakage of low molecular matter in the polymer material. Similarly, it also reduces the infiltration of low molecular substances such as solvent vapors. The reactive gas O₂ atmosphere reacts with the material, and the chemical composition of the material surface can be changed due to their direct contact with the material surface. When the discharge power of the ion-treated reactor is 60 W, the solvent molecules of acetone and vinyl acetate can penetrate into the PVDF matrix well, and the response strength reaches the maximum.

3.3 Resistance response of PVDF/CB to organic solvent vapor

TAIC (1%), a crosslinker, was added to PVDF/CB conductive polymer composites to prepare conductive thin films. The surface modification of the thin films by plasma treatment and its resistance response in several solvents were studied. Figure 3 shows the sensitivity and responsiveness of the conductive film to different organic solvent vapors before and after plasma-treated surface crosslinking. After plasma treatment in Ar atmosphere, the gas-sensitive response strength of THF and DMF vapor to PVDF/CB film element is very low compared with that of acetone, indicating that the permeability of these two solvent molecules in PVDF matrix is worse than that of acetone. However, the response strength of THF, acetone, and DMF to PVDF/CB thin film elements also decreases with the increase in discharge power, which further verifies the conclusion that the formation of cross-linking layer reduces the infiltration of solvent vapor and other low molecular substances. In O₂ atmosphere, the strength of the response of the vinyl acetate and acetone vapor reach maximum at a power of 60 W. When the discharge power is 100 W, the THF response sensitivity is the largest, O₂ atmosphere and produce a 10 variety of physical and chemical changes in the role of material, but the film morphology of the surface density of crosslinking layer or etching and rough, the effect on the permeability of different solvent molecules is different. The above experiments also showed that plasma treatment improved the adsorption and desorption ability of PVDF matrix to solvent molecules at varying degrees, and their response speed and recovery ability of gas molecules were improved.

3.4 Response repeatability study

Good reproducibility or long-term stability is another important parameter of the sensor, namely the repeatability of the PVDF/CB composite film's response to acetone vapor after oxygen plasma treatment. As can be seen from Figure 4, PVDF/CB composite thin film elements crosslinked without plasma surface treatment have a slow rate of adsorption and desorption capacity for solvent gas molecules. After cyclic response for 5 times, a trend of slow decline appears. After cyclic response for 10 times, the
response value of PVDF/CB composite thin film elements cross-linked with plasma surface treatment is still not significantly decreased, and the adsorption and desorption capacity of the solvent gas molecules is fast, forming a clear response repeat curve, and the sensor shows good reproducibility and stability.

4 Conclusion

This article, combined with the whole process of the steel ball cold pier, analyzed the stress distribution in the process of steel ball blank in the pier, based on the selection of load signal direction, designed a kind of PVDF piezoelectric film as the force sensor and support structure of the steel ball cold heading machine electricity sensor model. The model does not affect the cold heading machine assembly and satisfies the measurement requirements under the premise of combining with steel ball cold heading forming process. The force of the blank in the mold was analyzed to determine the best installation position of the sensor, the piezoelectric equation satisfying the cold heading process was deduced, the cold heading force was calculated, the shape and size parameters of the PVDF piezoelectric film were designed, and the strength of each component of the sensor prototype was analyzed. By analyzing the mechanical characteristics of the sensor, the mathematical model of the sensor was determined through the force analysis of the cold heading process, and the theoretical derivation formula for calculating the natural frequency was obtained. Combined with the design parameters of the sensor, the theoretical value of the natural frequency of the sensor was obtained, and the structural parameters affecting the natural frequency were numerically analyzed by MATLAB software. The mapping relationship between the applied load and the output load was obtained by ANSYS software, and the simulation curve and theoretical curve of the natural frequency of the sensor were compared to verify the factors affecting the natural frequency. The results show that the nonlinear error of sensors refers to the measured curve and the maximum deviation between the fitting line and the percentage of full scale output. The calculated nonlinear error of PVDF piezoelectric film force sensor is 0.6522%, Which is less than 1% of the design requirements. A good linear relationship can be seen in the selection between the applied load and the output voltage, as the applied load increases gradually, the output voltage also increases. The structure improvement and simulation optimization of PVDF piezoelectric film force sensor were carried out, and the influence of the structure parameters on the output load was analyzed. Combined with the theoretical analysis results, the maximum output load was determined, the optimal structure parameters were obtained, and the sensor performance under the optimal parameters was obtained.

Using the combination of structural design, mathematical modeling, numerical simulation and test analysis, the performance of piezoelectric film force sensor of steel ball cold pier is studied to meet the requirements of monitoring the cold pier forming process, and finally achieve the purpose of solving the forming defects.

Funding information: 1. Academic Funding Project for Top Talents in Disciplines ( Majors) of Universities in Anhui Province (gxbjZD56); 2. College Natural Science Key Project of Education Department of Anhui Province, No. KJ2018A0604.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

References

[1] Chaus AS, Sitkevich MV, Pokorn P, Sahul M, Babincová P. Wear resistance and cutting performance of high-speed steel ball nose end mills related to the initial state of tool surface. Wear. 2021;472–473:203711.
[2] Sanchez LC, Beatrice C, Lotti C, Marini j, Costa LC. Rheological approach for an additive manufacturing printer based on material extrusion. Int J Adv Manuf Technol. 2019;105(5–6):1–12.
[3] Dacol V, Caetano E, Correia JR. A combined exponential-powerlaw method for interconversion between viscoelastic functions of polymers and polymer-based materials. Polymers. 2020;12(12):3001.
[4] Jing J, Liu Y, Cong L, Zhang B, Lu W, Zhang X, et al. High-performance PVDF-HFP based gel polymer electrolyte with a safe solvent in Li metal polymer battery. J Energy Chem. 2020;49(10):96–104.
[5] Bystrov VS, Bdkin IK, Silibin MV, Meng XJ, Paramonova EV. Pyroelectric properties of ferroelectric composites based on polyvinylidene fluoride (PVDF) with graphene and graphene oxide. Ferroelectrics. 2019;541(1):17–24.
[6] Su F, Zhao Z, Liu Y, Si W, Leng C, Du Y, et al. Efficient preparation of PDMS-based conductive composites using self-designed automatic equipment and an application example. J Polym Eng. 2019;39(10):892–901.
[7] Wu X, Gao Y, Wang Y, Fan R, Shao W. Recent developments on epoxy-based syntactic foams for deep sea exploration. J Mater Sci. 2021;56(3):1–40.
[8] Tuichai W, Kum-On Sa P, Danwittayakul S, Manyam J, Chindaprasirt P. Significantly enhanced dielectric properties of Ag-deposited (In2O3/2Nd2/3O3) TiO2/pvd polymer composites. Polymers. 2021;13(11):1788–92.
[9] Sharma A, Kumar R, Kaur P. Study of issues and challenges of different routing protocols in wireless sensor network. 2019 Fifth International Conference on Image Information Processing (ICIIP); 2019.

[10] Wu T, Jin H, Dong S, Xuan W, Luo J. A flexible film bulk acoustic resonator based on β-phase polyvinylidene fluoride polymer. Sensors. 2020;20(5):1–12.

[11] Abdolmaleki H, Agarwala S. PvdF-BaTiO₃ nanocomposite inkjet inks with enhanced β-phase crystallinity for printed electronics. Polymers. 2020;12(10):2430–6.

[12] Cheng L, Wang R, Hao X, Liu G. Design of flexible pressure sensor based on conical microstructure PDMS-bilayer graphene. Sensors. 2021;1(1):289.