Experimental investigation on static and dynamic energy dissipation characteristics of composite sandwich structure with entangled metallic wire materials and disc springs

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Abstract

In this paper, a novel composite sandwich structure with entangled metallic wire materials and disc springs (EMWM/DS) was proposed to improve the high temperature resistance and energy absorption characteristic of disc spring structure (DSS). The performance superiority of the proposed structure was verified by a series of quasi-static and low-velocity impact tests. On the one hand, the static energy dissipation characteristics of the EMWM/DS and DSS are compared through quasi-static test. Furthermore, the influences of the key experimental parameters and the densities of EMWM sandwich layers on the dynamic energy absorption characteristics of EMWM/DS are respectively studied by associating the mechanical properties of EMWM/DS with the helix wires based on curved cantilever beam of variable length. The experimental observations show that by increasing the density of the EMWM sandwich layer or increasing the compression deformation, the energy dissipation characteristics of EMWM/DS can be effectively enhanced. The composite sandwich structures still have good compression resistance and energy dissipation characteristics at high temperatures with increased environmental temperature. On the other hand, the dynamic energy absorption performance of the EMWM/DS and the DSS via low-velocity impact (LVI) is evaluated. The experimental results show that the complete impact energy absorption, specific energy absorption, and impact energy loss rate of the EMWM/DS can be increased by more than 93% compared with the DSS under the low-velocity impact (0.5 m s\(^{-1}\)–2 m s\(^{-1}\)).

1. Introduction

Disc spring is a kind of disc washer spring formed by stamping a steel plate [1]. It has the advantages of small volume, large energy storage, and convenient combination. Different load characteristics of disc springs structures (DSS) can be obtained by changing the number and combination forms of disc springs (series, parallel, and recombination). On the other hand, there are conical friction and edge friction between the disc reeds, which can dissipate energy under reciprocating loads. Disc spring has been widely used in national defense, metallurgy, machine tool, construction, biomedical and other industries [2–5].

Xiao et al [6] studied the response of the dish-spring bolted connection structure to the step impact load. The results showed that the system could effectively reduce the peak stress of bolts and rapidly attenuate the vibration caused by the impact. Meram et al [7] studied a buffer device combining a hydraulic damper and a disc spring, which performed better vibration reduction and impact resistance. Shou et al [8] proposed a disc spring/ magnetorheological energy absorber design method considering the inertia effect under high-velocity impact. Zhang et al [9] used slotted disc springs to improve four different rotor structures. The results showed that their performance was better than that of the rotor structure without disc springs under a high-impact acceleration environment. You et al [10] proposed a mechanical energy storage method combining disc springs and modified the existing equipment to store high-impact energy.
To improve the damping performance of disc spring and its assembly, people have done a lot of research work based on material or structure. Some scholars proposed to set a viscoelastic damping layer in the vibration isolation and buffer device of the disc spring, which constituted the compound vibration isolation device of the disc spring. Wang et al. studied the effects of loading preload, displacement amplitude, and loading frequency on the mechanical properties of the disc spring isolation bearing by combining it with viscoelastic damping materials. Furthermore, the results showed that viscoelastic damping materials could effectively improve the energy dissipation capacity of the composite structure. Jia et al. studied the mechanical properties of disc springs before and after adding polyurethane (PU). The experimental results showed that PU could reduce the dynamic stiffness while keeping the static stiffness of disc springs unchanged. The composite structure had an optimal damping ratio under the same impact force. Existing studies mainly use polymer damping materials to improve the energy dissipation level of disk spring vibration isolation and buffer device. However, in some harsh application environments (high temperature, high corrosion), polymer materials will accelerate ageing, sharply decline performance, or even fail.

Entangled metallic wire materials (EMWM) is a kind of elastic-damping-porous materials, which is made of various fine metal wires by a serious special process. EMWM can meet the vibration isolation and buffering equipment requirements in different harsh application environments by selecting suitable wire materials. The energy dissipation mechanism of EMWM is that EMWM will deform under the external load, and the wire helix in contact with each other will slip and friction, then the vibration energy will be converted into heat energy for energy dissipation. Ma et al. applied to shape memory alloy EMWM to intelligent rotor support. The results showed that its structure had good damping characteristics under high-temperature and significant amplitude vibration. Xiao et al. studied the energy dissipation characteristics of EMWM-clad damping structures in high-temperature steam pipelines. The results showed that the EMWM had stable and good damping performance at high temperatures. Yan conducted a random vibration test on an EMWM vibration isolator in a high-temperature environment. The results showed that the temperature had little influence on its vibration isolation efficiency and damping ratio.

Although the existing research shows that the disc springs and damping materials combine to form composite buffer structures can improve the energy level of the disc springs group. However, the composite structures’ damping materials are used in the polymer materials, which means that the saucer reed composite structure with polymer materials is also affected by ambient temperature, limiting the DSS application temperature range. This paper proposed to improve the damping performance of the DSS at different ambient temperatures, composite sandwich structures with entangled metallic wire materials, and disc springs (EMWM/DS). Firstly, EMWM/DS sandwich structures are fabricated by filled the EMWM sandwich layers between two pieces of disc springs. Subsequently, the quasi-static and dynamic test setup is introduced. The quasi-static compression and low-velocity impact behavior of EMWM/DS and DSS are investigated via experimental method. Finally, the influence of the key experimental parameters (the densities of EMWM sandwich layers and the ambient temperature) on static and dynamic damping performance is analyzed by associating the mechanical properties of EMWM/DS with the configuration and contact states of the wire helices.

2. Composite sandwich structures with entangled metallic wire materials and disc springs

2.1. Structure design

The scheme of the existing disc springs structures (DSS) and the proposed composite sandwich structures with entangled metallic wire materials and disc springs (EMWM/DS) are shown in figure 1.

The traditional disc springs composite structures consist of series and parallel connections of multiple disc springs. The composite sandwich structure with entangled metallic wire materials and disc springs (EMWM/DS)
is composed of two disc-springs and an entangled metallic wire materials (EMWM) sandwich layer. The structure absorbs the impact energy through sliding friction in the inner wire helixes of the EMWM at the contact point, and sliding friction between the outer wire helixes of the EMWM and the disc springs.

### 2.2. Fabrication of composite sandwich structures

The DSS is composed of three pieces of disc springs in parallel. A batch of disc springs (GB/T 1972-2005) manufactured by Yangzhou Spring Co. Ltd (Jiangsu Province China) is selected. The material is 60Si2MnA, and the specific parameters are listed in table 1.

The size of the EMWM component is determined with the consideration of the size of DSS. The outer diameter is 140 mm, the inner diameter is 72 mm, and the thickness is 20 mm. The disc-spring-like entangled metallic wire materials can be fabricated in a four-step process [17], which is shown as figure 2. (i) figure 2(a), 304 stainless steel wire with a diameter of 0.3 mm is selected as the raw material for the preparation of EMWM specimen, the composite sandwich structure material mechanical properties are shown in table 2. (ii) figure 2(b), according to the preparation principle of spiral spring, the straight 304 wire is processed into dense wire helixes. (iii) figure 2(c), the dense wire helixes are stretched at a fixed pitch and wound on a specific mandrel to make a blank of EMWM. (iv) figure 2(d), the EMWM sample is obtained by pressing the blank by using a specific mould and hydraulic press. Table 3 lists the manufacturing parameters of EMWM. Figure 3 is one sample of EMWM/DS.
3. Experimental procedures

In this paper, a series of quasi-static compression test and low-velocity drop impact test were carried out to compare the energy dissipation characteristics between the DSS and EMWM/DS.

3.1. Quasi-static test

The quasi-static compression tests for DSS and EMWM/DS were conducted by using an electronic universal testing machine (WDW-T200, Jinan Tianchen, China). The displacement resolution is 0.001 mm, and the maximum test force can reach 200 kN. The environmental test box equipped with the WDW-T200 can provide different ambient temperatures from room temperature to 800 °C, and the temperature control accuracy is ±1 °C.

Figure 4 shows one EMWM/DS was installed on the test equipment. The WDW-T200 was used in displacement-control mode and was coordinated with the environmental test box to analyze the influence of temperature, loading-unloading speed, sandwich layer density, compression amount, and other factors on the mechanical properties of EMWM/DS. The specific parameters are as follows: ambient temperature is 25 °C, 50 °C, 100 °C, 150 °C; the loading-unloading speed is set as 0.6 mm min⁻¹, 1.8 mm min⁻¹, 6 mm min⁻¹ and 18 mm min⁻¹ respectively; the densities of metal rubber sandwich layer are 1.75 g cm⁻³, 1.98 g cm⁻³, 2.22 g cm⁻³, 2.46 g cm⁻³, and 2.70 g cm⁻³, respectively; the amplitude of compression displacement is 1 mm, 1.5 mm, 2 mm, 2.5 mm, and 3 mm, respectively.

3.2. Low-velocity impact test

The dynamic energy dissipation characteristics of EMWM/DS under low-velocity drop impact were investigated by a self-designed low-velocity impact test system. The experimental device is mainly composed of an electric winch, an electromagnet, a hemispherical impactor, a charge amplifier, a magnetic railings ruler, a fixed support tool, a real-time data acquisition system, and a control system, as shown in figure 5. The technical parameters of each module of the test equipment are shown in table 4.

Using a smooth hemispherical impactor, the impact of point contact reduces collision interference. The hammer is lifted to the corresponding height of the predetermined impact speed by the electric winch. Then the electromagnet is powered off to release the hammer until it collides with the buffer structures. In the impact process, the displacement sensor and the impact sensor measure the compression displacement and impact force at a sampling rate of 20 kHz. The data of the displacement sensor are differentiated once to obtain the initial impact velocity before impact and the velocity of the hammerhead leaving the specimen. Impact velocities are shown in table 5.

![Figure 3. EMWM/DS sample: (a) disc spring-like EMWM layer; (b) SEM (×35); (c) the composite sandwich structures with entangled metallic wire materials and disc springs.](image)

| Specimen | Density (g cm⁻³) | Mass (g) | Forming pressures (kN) |
|----------|------------------|---------|------------------------|
| EMWM-1   | 1.75             | 395.36  | 23.01                  |
| EMWM-2   | 1.98             | 449.30  | 26.26                  |
| EMWM-3   | 2.22             | 503.06  | 40.80                  |
| EMWM-4   | 2.46             | 556.01  | 46.57                  |
| EMWM-5   | 2.70             | 610.54  | 54.23                  |
Figure 4. Quasi-static compression test system and special fixture: (a) specimen fixture; (b) test system (c) schematic of test setup.

Figure 5. Low-velocity impact test system.

Table 4. The corresponding technical specifications of the equipment for the impact test.

| No. | Systems | Equipment       | Models          | Parameters                   | Manufacturer            |
|-----|---------|-----------------|-----------------|------------------------------|-------------------------|
| 1   | Impact  | Electric capstan| WINCH2000LB     | v: 3–50 mm s⁻¹, F ≤ 9060 kg | Shenyang, China         |
|     |         | Electromagnet   | XDA-240/80      | F ≤ 2000kg                   | Yueqing, China          |
| 2   | Sensors | Force sensor    | YX-60T          | F: 0–600kN, Sensitivity: 1.95pC/N | Yangzhou, China         |
|     |         | Displacement sensor | MTS-H10C       | Resolution: 10um             | Nova Milanese, Italy    |
| 3   | Data    | Charge amplifier | KD5002N         | Output voltage: ± 10 V       | Yangzhou, China         |
|     |         | Data Acquisition Card | PCIe-6351 | Sample rate: 1.00 MS/s      | Austin, TX, USA         |
3.3. Mechanical properties characterization

In this paper, total energy dissipation, specific energy absorption, quasi-static average stiffness, and static loss factors are used to evaluate the quasi-static mechanical properties of DSS and EMWM/DS.

Figure 6 shows a hysteresis curve of a typical damping structure in the quasi-static compression test. The total energy dissipation $\Delta W$ is the energy dissipated by a loading-unloading cycle, and its value is the area surrounded by the load-unloading curve. The specific energy absorption $SEA_{qs}$ is the energy dissipated per unit mass, which is the ratio of energy dissipation $\Delta W$ to structural mass $m$. The quasi-static average stiffness $k_{qs}$ is defined as the ratio of the maximum loading load $F_{\text{max}}$ to the corresponding displacement (deformation) $X$ during the quasi-static compression test. The maximum stored energy of the structure $U$ can be calculated from the region below the middle (dashed line, figure 6) of the hysteresis curve. The static loss factor $\eta_{qs}$ can be defined as:

$$\eta_{qs} = \frac{\Delta W}{\pi U}$$ (1)

The dynamic energy dissipation, specific energy absorption, average impact stiffness, and impact energy loss rate are used to evaluate the dynamic mechanical properties of buffer structures (DSS and EMWM/DS).

The magnetic railings ruler can convert the displacement of the hammerhead into a pulse signal, and the velocity of the hammerhead can be calculated according to the number of pulses per unit of time $v_i = \Delta x/\Delta t$. According to the principle of energy conservation, the total impact energy $E_0$ of the hammerhead impact buffer structure of the free-falling body can be expressed as:

$$E_0 = mgh = \frac{1}{2}mv_0^2$$ (2)

where $m$ is the mass of the falling hammer, $m = 76$ kg; $g$ is gravitational acceleration, $g = 9.8$ m s$^{-2}$; $h$ is the height of the free-falling body before the release of the falling hammer; $v_0$ is the initial impact velocity.

The total energy $E_D$ absorbed by the buffer structure in the process of impact loading and unloading is expressed as:

$$E_D = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_0^2$$ (3)

where $v_i$ is the velocity of the drop hammer leaving the specimen after impact.
Specific energy absorption $SEAD$ is the ratio of the total energy absorbed to the mass of the structure:

$$SEAD = \frac{E_D}{m} \quad (4)$$

The impact energy loss rate $\eta_D$ is defined as the ratio of the total absorbed energy to the total impact energy:

$$\eta_D = \frac{E_D}{E_0} \quad (5)$$

The impact energy loss rate $\eta_D$ can be obtained by the combination of equations (2), (3), and (5). $\eta_D$ can be re-expressed as:

$$\eta_D = \frac{\nu_0^2 - \nu_f^2}{\nu_0^2} \times 100\% \quad (6)$$

The impact stiffness $k_D$, represents the bearing capacity of the structure, which can be expressed as:

$$k_D = \frac{F_{\text{max}}}{X} \quad (7)$$

where $F_{\text{max}}$ and $X$ represent the maximum impact force and corresponding structural displacement (deformation), respectively.

4. Results and discussion

4.1. Quasi-static characteristics

4.1.1. Influence of EMWM sandwich layer on quasi-static characteristic of buffer structures

As illustrated in figure 7, DS1 and DS2 represent the single disc spring, DSS represents the disc springs structures (figure 1(a)). The EMWM-2 represents the EMWM layer with density of 1.98 g cm$^{-3}$. EMWM/DS-2 represents the composite sandwich structures of the EMWM sandwich layer ($\rho_{\text{AIR}} = 1.98$ g cm$^{-3}$) in series with the disc springs (figure 1(b)). It can be seen that the disc springs DS1 and DS2 have a good consistency. According to the measured load-displacement hysteresis curve, the total energy dissipation, static average stiffness, static loss factor, specific energy absorption, and other characterization parameters were calculated and listed in table 6.

![Figure 7. Hysteretic curves with different buffer structures: (a) contrast curves; (b) typical curve.](image_url)
The disc spring has an approximate linear stiffness characteristic, and the series and parallel of multiple disc springs will produce friction energy dissipation\(^{[18]}\). Figure 7(a) exhibits the gradual softening characteristics of stiffness of DS1, DS2, and DSS. The typical force-displacement hysteretic curve of EMWM sandwich layer under quasi-static load\(^{[16]}\) can be divided into a near-linear elastic region, plateau softening region, and stiffening region. Then, it is not extraordinarily obvious the critical characteristics of these three stages.

In the first stage, the EMWM/DS with a lower density of the EMWM sandwich layer shows short linear elastic properties and approximately deformation characteristics of entangled metallic wire materials. With the increase of EMWM density, this stage may not appear. The second stage, which can be regarded as the strengthening stage, results from combining the two energy dissipation mechanisms of the EMWM and the disc springs.

It can be seen from table 6, the total energy dissipation \(\Delta W\) of EMWM-2 is 8.2 times that of DSS, the static loss factor \(\eta_{qs}\) is 10.7 times that of DSS, and the specific energy absorption \(\text{SEA}_{qs}\) is 7.9 times that of DSS. It means that the damping capability of EMWM is significantly better than that of DSS. There are three contact states of the wire helices inside the EMWM layer\(^{[19]}\): no contact, slip contact, and extrusion contact (figure 8).

The wire helices slide relative to each other at the contact point and dissipate energy in the form of dry friction, and the relative slip between the EMWM surface wire helices and fixture dissipates energy. The number of EMWM slips contact points, and slip travel significantly influences the energy dissipation level. The disc springs mainly depend on the dry friction between the disc springs and the contact surface between the disc springs and fixture to dissipate the energy. Therefore, the energy dissipation characteristic of EMWM is better than that of disc springs.

Table 6 also details the energy dissipation \(\Delta W\) of EMWM/DS-2 is 4.6 times that of DSS, the static loss factor \(\eta_{qs}\) is 13.6 times that of DSS, and the specific energy absorption \(\text{SEA}_{qs}\) is 1.5 times that of DSS, which indicates that the EMWM sandwich layer can effectively improve the total energy absorption performance of the disc springs. There is a series relationship between the disc spring and the EMWM sandwich layer in the composite sandwich structure (EMWM/DS). In the case of the same total deformation, part of the disc spring is deformed, while the EMWM sandwich layer is deformed in another part; that is, the deformation of the EMWM sandwich layer is smaller than that of EMWM-2, which leads to the reduction of energy dissipation. On the other hand, the total stiffness of the series structure is lower, and the energy storage of the composite sandwich structure is smaller than that of EMWM-2 and DSS in the loading process of the same total deformation. Thus, the static loss factor of the composite sandwich structure is more significant than that of EMWM-2.

Therefore, it can be concluded that the EMWM sandwich layer can effectively improve the damping and stiffness characteristics of the composite sandwich structure.

4.1.2. Influence of loading-unloading rate on quasi-static characteristic

In order to analyze the influence of quasi-static loading-unloading speed on the energy dissipation characteristics of the proposed composite sandwich structures (EMWM/DS), at room temperature (25 °C), the composite sandwich structure was loaded to the same deformation (2.5 mm) at different loading speeds.
The hysteretic curves of the EMWM/DS under different loading-unloading speed are presented in figure 9. Table 7 shows that, with the increase of loading-unloading speed, the total energy dissipation $\Delta W$ and static loss factor $\eta_{qs}$ of EMWM/DS gradually decrease. The experimental results are consistent with those obtained by Zhang et al [19] and Kartik et al [20] in quasi-static and low-frequency dynamic tests. The lower the loading speed is, the more sufficient the sliding friction between the internal wire helixes of the EMWM sandwich layer will be, and then more energy will be dissipated by dry friction. However, with the increase in loading-unloading speed, the variation of static average stiffness is less than 4.5%, which indicates that the static average stiffness largely depends on the amount of deformation.

### 4.1.3. Influence of density of EMWM on quasi-static characteristic

To investigate the influence of the density of EMWM on the stiffness and damping characteristic of the composite sandwich structure (EMWM/DS), the EMWM with density of 1.75 g cm$^{-3}$, 1.98 g cm$^{-3}$, 2.22 g cm$^{-3}$, 2.46 g cm$^{-3}$, and 2.70 g cm$^{-3}$ were used as sandwich layer of the proposed composite sandwich structure (EMWM/DS), and a series of quasi-static tests were carried out at the same ambient temperature (25 °C). The maximum deformation was set as 2.5 mm. The loading-unloading speed was set as 0.6 mm min$^{-1}$. The corresponding hysteretic curves of EMWM/DS with different EMWM densities are presented in figure 10.

According to figure 10, the maximum compression load and the area surrounded by the hysteresis curve of the composite sandwich structure increases with the increase of the density of the EMWM sandwich layer under the same deformation. It means that the bearing and damping capacity of the composite sandwich structure increases with the density of the EMWM. In order to facilitate the comparative analysis, the total energy dissipation $\Delta W$, specific energy absorption $SEA_{qs}$, and average static stiffness $k_{qs}$ and loss factor were calculated, as shown in figure 11.

Based on figure 11, the total energy dissipation $\Delta W$, specific energy absorption $SEA_{qs}$, and average static stiffness $k_{qs}$ increase with the increase of the densities of EMWM sandwich layer. This phenomenon can be interpreted based on the curved cantilever beam of variable length for EMWM proposed by Cao [21] (figure 12). The EMWM is equivalent to a complex composed of multiple parallel cantilever curved beams with single-turn

### Table 7. Characteristic parameters of EMWM/DS at different quasi-static loading-unloading speed.

| Loading-unloading speed (mm min$^{-1}$) | $\Delta W$ (kN mm) | $k_{qs}$ (kN mm$^{-1}$) | $\eta_{qs}$ |
|----------------------------------------|-------------------|------------------------|-------------|
| 0.6                                    | 2.331             | 1.663                  | 0.253       |
| 1.8                                    | 2.142             | 1.659                  | 0.235       |
| 6                                      | 1.985             | 1.587                  | 0.231       |
| 18                                     | 2.056             | 1.597                  | 0.215       |

(0.6, 1.8, 6, and 18 mm min$^{-1}$), and then unloaded at the same speed (0.6, 1.8, 6, and 18 mm min$^{-1}$). The hysteretic curves of the EMWM/DS under different loading-unloading speed are presented in figure 9.

Figure 9. Influence of quasi-static loading-unloading speed on the quasi-static properties of EMWM/DS.
Figure 10. Influence of densities of EMWM sandwich layer on quasi-static properties.

Figure 11. Quasi-static characteristic of EMWM/DS with different densities of EMWM sandwich layer.

Figure 12. Stress analysis diagram of the curved cantilever beam: (a) small curved beam AB; (b) in the a-A-b coordinate plane.
wire helix AB separated by contact points. The deformation process of EMWM can be regarded as the process that the number of contact points of wire helixes gradually increases, and the length of the curved beam gradually becomes shorter. The changes in the length of the curved beam will change the overall stiffness of the EMWM, and the number of contact points largely varies the damping property of the EMWM. The two kinds of action together form the changes in the mechanical properties of the EMWM.

For the same volume of EMWM, the higher the density, the more wire helixes in contact with each other, which means that more wire helixes can participate in friction energy dissipation. The internal wire helixes of the EMWM are spirally connected, and the contact point can be regarded as a constraint of the wire helix segment. Therefore, the wire helix between the two contact points can be viewed as a small curved beam constrained at both ends, as shown in figure 12(a). The shorter the length of the small curved beam is, the greater the stiffness is. Therefore, the stiffness $k_{qs}$ (bearing capacity) of the composite sandwich structure (EMWM/DS) will increase with the EMWM sandwich layer’s density. When the rise of energy dissipation $\Delta W$ is less than the increase of maximum stored energy $U$, the static loss factor $\eta_{qs}$ decreases with density $\rho_{MR}$, and vice versa. Therefore, the static loss factor $\eta_{qs}$ of the composite sandwich structure shows certain volatility.

### 4.1.4. Influence of compressing displacement on quasi-static characteristic

The effect of compressing displacement on the quasi-static properties of EMWM/DS was investigated through the quasi-static experiments with different compressing displacements (1, 1.5, 2, 2.5, and 3 mm) at the same loading-unloading speed (0.6 mm min$^{-1}$) and ambient temperature (25°C). The results are presented in figure 13.

Within the compression deformation range of 1 ~ 3 mm, EMWM/DS energy dissipation is positively correlated with the compression displacement. Static average stiffness $k_{qs}$ and static loss factor $\eta_{qs}$ also increase with the increase of compression displacement, as listed in table 8. It indicates that the compression displacement has a significant effect on the alignment static characteristics. As the compression displacement increases, when the compression load is greater than the sliding friction force, sliding occurs at the contact point (figure 8(b)), resulting in a shorter length and an increased number of the small curved beam AB, thus changing the overall stiffness and damping energy dissipation.

| Displacement (mm) | $\Delta W$ (kN mm) | $k_{qs}$ (kN mm$^{-1}$) | $\eta_{qs}$ |
|-------------------|-------------------|-----------------|----------|
| 1                 | 0.254             | 1.195           | 0.223    |
| 1.5               | 0.741             | 1.367           | 0.254    |
| 2                 | 1.507             | 1.464           | 0.268    |
| 2.5               | 2.467             | 1.552           | 0.271    |

**Figure 13.** Influence of compressing displacement on quasi-static properties.
4.1.5. Influence of ambient temperature on quasi-static characteristic

In this work, to analyze the influence of ambient temperature on the mechanical characteristic of the composite sandwich structure, a series of quasi-static test for EMWM/DS with different ambient temperatures (25 °C, 50 °C, 100 °C, and 150 °C) and a constant compressing displacement of 2.5 mm was carried out in figure 14.

As shown in figure 14, the maximum compression load of EMWM/DS-2 decreases with the increase of ambient temperatures. The area of the hysteresis loop reaches its maximum at 25 °C. When the temperature gradually increases, the area decreases slightly, but the overall change is not significant. The experimental results are consistent with those obtained by Xiao et al [15]. As shown in table 9, with the increase of temperature, the dissipated energy of the composite sandwich structure gradually decreases. At the same time, the static loss factor and static average stiffness only show a slight decrease, which indicates that the composite sandwich structure still has good load-bearing and energy dissipation characteristics at high temperatures. With the gradual increase of ambient temperature, an oxide film is formed on the surface of the wire due to oxidation, and the friction coefficient is gradually reduced [22]. Therefore, the energy dissipation, static average stiffness, and static loss factor at 25 °C are higher than those at other temperatures. An increase in temperature from 100 °C to 150 °C results in a slight fluctuation of stiffness and loss factor, i.e., 0.2% and 1.5%, respectively. It also means that temperature has little effect on the damping characteristics of composite structures, which is negligible in engineering applications.

4.2. Dynamic energy absorption of low-velocity drop impact test

To investigate the dynamic energy dissipation characteristics of composite sandwich structure with entangled metallic wire materials and disc springs, a CMOS high-speed camera (VEO 410 L, Phantom, USA) recording at 1,000 frames/s, was used to observe the whole process of low-speed impact of composite sandwich structure (EMWM/DS-1). Figure 15 shows the entire impact process of the composite sandwich structure (EMWM/DS-1) with an initial impact velocity of 2 m s⁻¹ recorded by the high-speed camera.

According to figure 15, the impact process can be divided into three stages: (1) the loading stage (0–6 ms), from the process when the hammer contacts the auxiliary indenters to the maximum deformation of the composite sandwich structure; (2) the unloading stage (6–10 ms), the maximum deformation of the composite sandwich structure occurs until the hammer leaves the auxiliary pressure head; (3) complete recovery.

| Temperature (°C) | ΔW (kN-mm) | kqs (kN mm⁻¹) | ηqs |
|------------------|------------|--------------|-----|
| 25               | 4.024      | 1.559        | 0.276|
| 50               | 3.754      | 1.504        | 0.263|
| 100              | 3.494      | 1.411        | 0.260|
| 150              | 3.488      | 1.415        | 0.264|
Figure 15. Impact process of composite sandwich structure under low-speed impact (EMWM/DS-1, \(v_0 = 2 \text{ m s}^{-1}\)), and the white arrow represents the movement direction of the hammer.

Figure 16. Impact force and displacement hysteresis loops of disc spring structure and composite sandwich structure: (a) DSS; (b) EMWM/DS-1; (c) EMWM/DS-2; (d) typical impact-displacement hysteresis curve.
(10–13 ms), the process from the hammer is leaving the auxiliary indenters to the composite sandwich structure restoring its original shape.

Figures 16(a)–(c) presents the impact force and displacement hysteresis loop of DSS and EMWM/DS. The whole deformation process can be divided into a linear elastic, plateau, and stiffened stages, corresponding to I, II, and III in figure 16(d). In the initial compression stage of the composite sandwich structure, the porosity of EMWM is more prominent, which means that its internal small curved beam (AB, figure 12) is less constrained, and the length of the small curved beam is longer. Thus, the force of the composite sandwich structure is approximately proportional to the amount of deformation, as shown in figure 16(d) (I stage). With the increase of the impact force, the internal wire helices of the EMWM will overcome the static friction at the contact point and begin to slip and deform, and the constraints of the curved beam AB increase. The EMWM sandwich layer tends radial diffusion, and its surface has friction with the disc spring. In stage II (figure 16(d)), the impact force grows slowly with the increase of the deformation. It is the stage that a large amount of energy is absorbed in the form of dry friction. In stage III (figure 16(d)), with the increase of the deformation, the porosity of EMWM will gradually decrease, and the wire helices in the sliding state will slowly enter the state of extrusion. Therefore, the impact force will increase rapidly in stage III, and the macro shape structure changes into a ‘drum’ (as shown in figure 15(c)).

Figure 17 shows the maximum impact force, corresponding deformation, and impact stiffness under different initial impact velocities. As can be seen from figure 17(c), the impact stiffness of the composite sandwich structure (EMWM/DS) increases with the increase of impact velocity, while the impact stiffness of DSS is almost unchanged.

Based on figure 18, the impact energy dissipation, specific energy absorption, and impact energy loss rates of EMWM/DS at different impact velocities are relatively consistent. Under the same conditions, the impact energy dissipation, specific energy absorption, and impact energy loss rates of the composite sandwich structure are higher than those of DSS, which indicates that the EMWM sandwich layer can improve the ability to absorb impact energy. Under low-velocity impact (0.5 m s⁻¹–2 m s⁻¹), the impact energy dissipation, specific energy absorption, and impact energy loss rates of EMWM/DS-1 are 2.26 times, 2.01 times, and 2.32 times higher than those of DSS. The impact energy dissipation, specific energy absorption, and impact energy loss rates of EMWM/DS-2 are higher than those of DSS, which were 1.93 times, 2.01 times, and 1.98 times, respectively.
5. Conclusions

In this paper, a novel composite sandwich structure with entangled metallic wire materials and disc springs (EMWM/DS) was proposed to improve the high temperature resistance and energy absorption characteristic of disc springs structures (DSS). The performance superiority of the proposed structure was verified by a series of quasi-static and low-velocity impact tests. The main conclusions, which can be drawn from the conducted experiments are as follows:

1. In the case of the same compression deformation, the energy dissipation of EMWM/DS-2 is significantly better than DSS, more specific energy absorbed and better static loss factor in the quasi-static tests.

2. The static compression of EMWM/DS is almost not affected by the quasi-static loading, environmental temperature and unloading rate. By increasing the density of EMWM sandwich layer or increasing the compression deformation, the energy dissipation characteristics of EMWM/DS can be effectively enhanced.

3. Under the low-velocity impact, the impact energy absorption, specific energy absorption, and impact energy loss rate of the EMWM/DS can be increased by more than 93% compared with the DSS.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

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