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Evaluation of properties for a passive damping device with TiNi alloy rings as energy dissipating element

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Abstract: A new kind of passive damping device that is composed of TiNi shape memory alloy (SMA) rings is designed. The basic mechanical behaviors of the device are investigated and its damping capacity is analyzed. There still exist hysteresis loops during loading and unloading when the deformation of the ring(s) is restricted in the horizontal direction properly, but the force-displacement curves are tilted and not parallel to the abscissa, which can improve the ability to withstand overloading. If there is no restriction, the force-displacement curves of the rings are near linear though the unloading paths are slightly different from those of loading. The basic mechanical and damping properties of the device may be changed by using different numbers of TiNi alloy rings, and the damping capacity will be increased markedly by increasing the number of rings.

Key words: TiNi; shape memory alloy; hysteresis loop; damping property

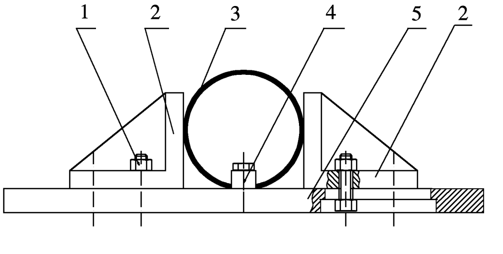
TiNi shape memory alloy (SMA) is considered an excellent damping material due to its high damping capacity both in the austenite state as a result of stress induced martensitic transformation, and in the martensite state as a result of the stress-induced martensite variant reorientation[1-6].

Nowadays, there is much research work on the damping properties of TiNi alloy. Most of this is on the damping effect of TiNi alloy wires, though there are research works on solid and hollow SMA bars[6-11]. In the present study, a new kind of passive damping device using TiNi SMA rings as energy dissipating element is designed and its basic mechanical behaviors are evaluated.

1 Design of Damping Device

TiNi shape memory alloy with Ni 50.8% (mass fraction) and Ti 49.2% was used in this study. Because TiNi SMA has both high-energy dissipation capacity and large reversible deformations when in the pseudoelasticity state, a proper heat treatment was selected to control the critical temperature of TiNi alloy rings. The TiNi alloy strips 1 mm thick and 25 mm wide were annealed at 823 K for 30 min in order to lower their stiffness, and the softened strips were fixed in a mould to form the desired round ring shape. The samples in the mould were solubilized at 1 173 K for 20 min and quenched in water at room temperature, then annealed at 523 K for another 20 min and also cooled in water. The measured transformation temperatures were $M_s = 289$ K, $M_f = 273$ K, $A_s = 265$ K and $A_f = 283$ K.

A passive damping device composed of fixation bolts, sliding blocks, TiNi alloy rings and foundation (see Fig. 1) was designed. The treated TiNi alloy rings were used as energy dissipating elements in the damping device and their free diameter is 96 mm. In this device, the deformation of TiNi alloy rings may be restricted by the two sliding blocks (see Fig. 1). Without the two sliding blocks, the TiNi alloy rings will undergo a free form deformation. Through the use of the two blocks, the horizontal deformation of the rings may be restricted. Furthermore, there may be more than one TiNi alloy ring used in the device as needed. These variations will cause the change of output force and damping capacity and make the device suitable for more wide uses.



1—Bolts for the fixation and adjustment of sliding blocks; 2—Sliding blocks; 3—Shape memory alloy rings; 4—Fastening bolts of the rings; 5—Foundation plate

Fig. 1 Scheme of damping device

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2 Experiment

The loading-unloading tests of the device were conducted on a fatigue testing machine. A press force is applied vertically on the ring's top, and the cross head is 35 mm in diameter and its moving speed is 20 mm/min. The maximum displacements of the force are 10 mm and 15 mm respectively, and the data of the second loading and unloading cycle were recorded for the analysis. Test temperature was 285 K and the alloy would exhibit pseudoelastic properties at this temperature.

3 Results and Discussion

When the sliding blocks are not used, there is no restriction to the TiNi alloy ring and it deforms freely. Fig. 2 shows the reverse forces generated by one, two and three TiNi alloy rings without sliding blocks to restrict their free deformation in the horizontal direction. The reverse forces generated by TiNi alloy rings increase with the displacements near linearly in all the cases though the unloading paths are slightly different from those of loading.

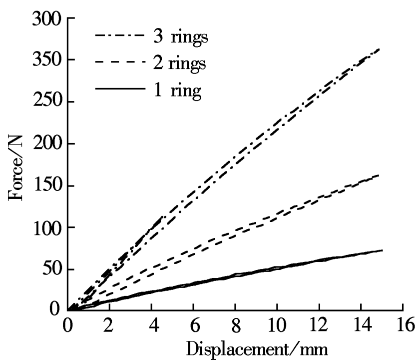

Fig. 2 Force-displacement curves of one, two and three TiNi alloy rings without sliding blocks to restrict their free deformation in the horizontal direction

The closed force-displacement loops are formed when the free deformation of TiNi alloy rings is restricted by sliding blocks in horizontal direction. Fig. 3 (a) shows the force-displacement curves with sliding blocks to restrict their free deformation in the horizontal direction, its maximum displacement is 10 mm.

Increasing the maximum displacement to 15 mm, the reverse forces and the area of hysteresis loops increase significantly. The results are shown in Fig. 3 (b). Compared with the maximum displacement of 10 mm, all the hysteresis loops expand.

As in the state of pseudoelasticity, the austenite phase of TiNi SMA is the stable phase, and it can be transformed to martensite under mechanical loading when it reaches a critical value. However, the martensite phase is unstable for any stress below a critical stress in this region and unloading produces a reverse transformation to austenite with a complete recovery of strain and a substantial hysteresis loop. A stress plateau appears and the force-displacement (stress-strain) curves during loading and unloading are nearly straight and parallel to the abscissa.

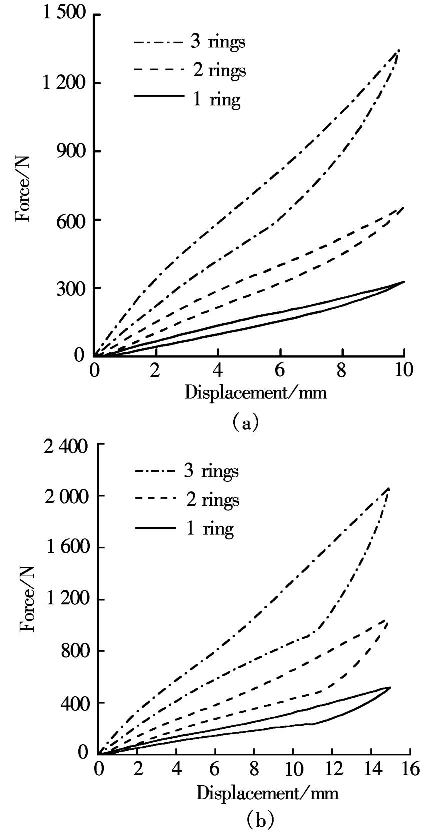

Fig. 3 Force-displacement curves of one, two and three TiNi alloy rings with sliding blocks to restrict their free deformation in the horizontal direction. (a) 10 mm maximum displacement; (b) 15 mm maximum displacement

The damping capacity of SMA is represented by the energy, which is dissipated during the loading and unloading cycle. The region of the hysteresis loop *ABCD* represents the dissipated energy, whereas the region *OBCE* represents the elastic strain energy (see Fig. 4 (a)). The ratio of the dissipated energy to the elastic strain energy is defined as the special damping capacity and calculated as

$$\varphi = S_{ABCD}/S_{OBCE} \tag{1}$$

In this work, the force-displacement curves during loading and unloading are still not in the same way and produce closed curves but they do not appear parallel to the abscissa (see Fig. 3). In this case, the dissipated energy would be represented by the region of $S_{\triangle O'A'B'}$ and the elastic strain energy by that of $S_{\triangle O'A'C'}$ (see Fig. 4(b)). The special damping capacity can be calculated as

$$\varphi = S_{\triangle O'A'B'}/S_{\triangle O'A'C'} \tag{2}$$

In the free state, there is no restriction to the de-

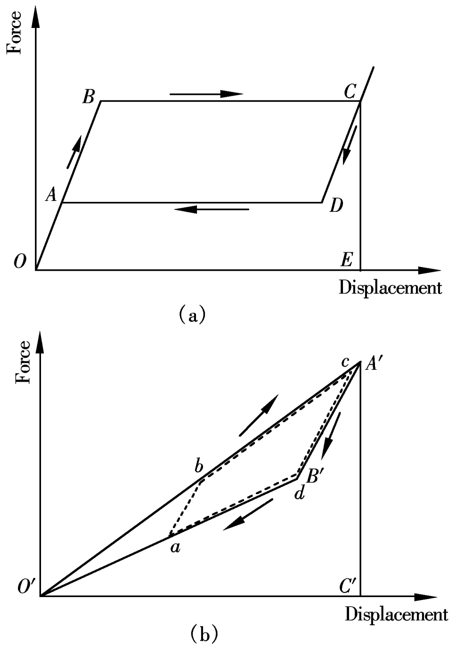

Fig. 4 Simplified stress-strain diagram of TiNi alloy. (a) Wire; (b) Ring

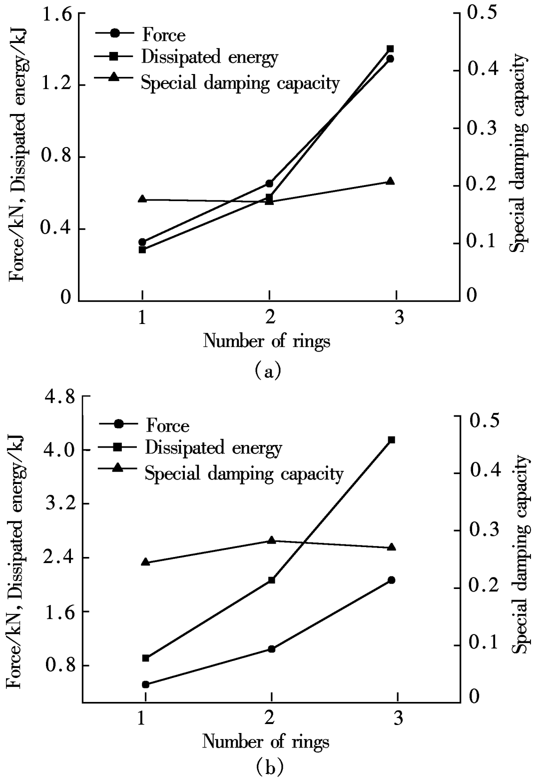

Fig. 5 Comparison of mechanical behaviors of different rings under different displacements. (a) 10 mm; (b) 15 mm

formation of TiNi alloy rings and the curves of force-displacement are near straight lines (see Fig. 2). The mechanical behaviors of TiNi alloy rings are like a soft spring and there will be a significant deformation with a small force though the unloading paths are slightly different from those of loading.

When the sliding blocks are used, they restrict the free deformation of TiNi alloy rings and make their mechanical behaviors changed (see Fig. 3). The special damping capacities calculated by Eq. (2), dissipated energy and reverse forces of different conditions are shown in Fig. 5. The reverse force and dissipated energy increase with the increasing number of used TiNi alloy rings in two different displacements. However, the special damping capacity is not the same.

During the compression test, the different parts of the rings experience different deformation procedures. The strain caused in the ring is not uniform when a force acts on the ring's top in a downward direction. Due to the different stress generated in different parts, the phase transformation is not in the same time and this makes the shape of the hysteresis loop changed.

A damper can be designed with TiNi alloy SMA rings pre-compressed (or pre-stressed) to a level somewhere in the middle of the pseudoelastic range. Cyclic variations of force and displacement around the baseline will result in a quadrilateral loop (see Fig. 4 (b)). As the system undergoes vibration, energy dissipation due to hysteresis in the SMA will appear.

Masuda et al. [1] analyzed the effect of a hysteresis loop's shape on the damping performance of a damping device and thought the damping ability was affected by not only a closed loop's area, but also the loop's shape. For damping purpose, the optimal force-displacement loop would be a triangle. In engineering practice, the loaded force is unexpected and may sometimes be over loaded. This would cause a permanent deformation in the dissipating element and the damping properties would decline or even fail. In the new device, because the force-displacement (stress-strain) curves during loading and unloading are tilted, the reverse force increases with increasing displacement (deformation) and does not remain constant, which may improve the ability to withstand overloading.

On the other hand, the basic mechanical and damping properties of the device may be changed by different numbers of rings. Fig. 6 shows the variation of reverse force and dissipated energy with the increase of displacement when different numbers of TiNi alloy rings are used. The lines of reverse force and dissipated energy of three TiNi alloy rings possess the highest slope, which mean that the values increase most quickly with increasing displacement. The results show that the damping properties can be improved by using different numbers of SMA rings, but the properties are not directly proportional to the number of rings because the TiNi alloy SMA is not a linear material.

4 Conclusion

A new kind of passive damping device using Ti-

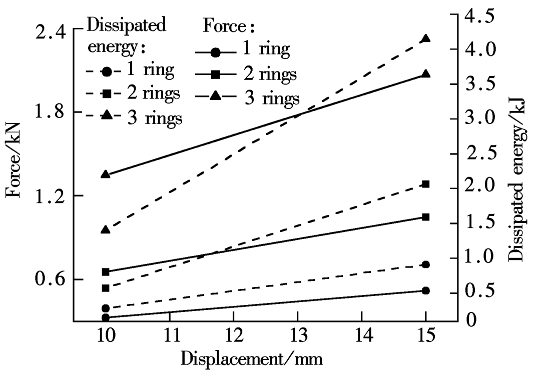

Fig. 6 Variation of reverse force and dissipated energy due to displacement

Ni shape memory alloy rings as energy dissipating element is designed. The basic mechanical behaviors of the device are investigated and its damping capacity is analyzed. The basic mechanical and damping properties of the device can be changed by using different numbers of rings. Applying a force on the top of the rings and restricting the free form in the horizontal direction of them, the hysteresis loops during loading and unloading still exist, but the force-displacement curves are tilted and not parallel to the abscissa, which can improve the ability to withstand overloading and give the device potential for practical use.

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用 TiNi 合金环作耗能元件的被动减振装置性能评价

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摘要:设计了应用 TiNi 形状记忆合金环作耗能元件的被动减振装置,并对装置的力学和减振性能进行了初步评价. 对加载和卸载过程中力-位移曲线进行了研究,当不对环水平方向的变形进行约束时,力-位移曲线为近似于直线且接近重合的 2 条曲线;若应用滑块对环水平方向的变形进行约束,在力-位移曲线上能形成滞回环,且随位移增加变得更饱满. 滞回环的加载和卸载部分不与横坐标平行,而是 2 条斜线,装置受力时的这种变形特点,可提高装置的抗过载能力. 增加环的数量,在相同位移时装置的耗能量明显增加.

关键词: TiNi;形状记忆合金;滞回环;减振性能

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