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Superelastic damping of TiNi alloy wire under heavy mechanical shock in structural engineering①

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Abstract: Based on superelastic damping application in structural engineering, the damping characteristics of commercial Ti-50.8Ni(mole fraction, %) alloy have been systematically studied by adjusting frequency of mechanical shock, temperature, stress, strain and number of cycling. The results show that at extremely low frequency mechanical shock at room temperature, the superelastic damping capacity increases with controlled strain, and such capacity of each cycle is greater than 50%. When the frequency of mechanical shock is 0.1 - 0.3 Hz, the superelastic damping capacity above room temperature is relatively large at high strain; when the temperature approaches to M_d, the damping begins at low stress. For specimen cycled under 0.5 Hz, above 6% strain mechanical shock at relatively high temperature, further large-strain cycling exhibits more than 35% damping capacity. The superelastic damping of trained specimen is relatively stable at 20 - 50 ℃ and 0.1 - 0.5 Hz frequency mechanical shock.

Key words: NiTi alloy; superelastic damping; low frequency mechanical shock; structural engineering

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1 INTRODUCTION

Passive damp controlling devices can improve the performance of civil engineering structure, and significantly reduce the reactions of structures in strong wind and earthquakes. However there are problems[1] in the present damping devices used in engineering such as ageing and durability, reliability, renewing and replacing, mechanical property dependent on temperature and resuming difficulty after strong shock. Materials researchers found that shape memory alloys possess superelasticity and high damping capacity, in addition to their shape memory effect[2-5]. Such materials exhibit compatible high damping capacity, high product gene (α) of vibration-reducing coefficient and the strength[6] over other high damping materials such as Mn-Cu alloy, dull-mute (Fe-12Cr-3Al) alloy and graphite-flake cast iron. Hodgson[7] recently summarized three basic damping mechanisms of shape memory alloys as internal friction, martensite twin reorientation and stress-induced martensitic transformations. The characteristics of martensite twin reorientation of TiNi alloy have been given by Ref. [8]. The stress-induced martensite transformation is essentially the lattice "friction" caused by the lattice transition under the stress change, with typical mechanical behavior of superelasticity. Superelastic damping is the energy absorbed by the occurrence of superelasticity under certain low-frequency mechanical load change. Since the area covered by the superelastic curves during one load-unload cycle can be regarded as direct measurement of the energy absorbed, the ratio of this area to the pure strain energy can be regarded as the damping capacity under these conditions[9, 10]. It can be specially utilized when the element shape is thin and long such as wires and thin plates, because best mechanical properties and maximum recoverable superelastic strain[11] can be obtained. Such element can be effective heat transformers to avoid transformation heat accumulation during cycling, and cooling can be promoted. Many measurement reports in engineering structures show that the vibration main frequency and the resonance frequency are normally smaller than 5 Hz, and this frequency range should be that of shock-waves considered for damping elements made of shape memory alloys. In this paper the influences of temperature, mechanical loading frequency, number of cycling and controlled strain on superelastic damping characteristics of TiNi wires are studied under relatively low-frequency mechanical shock.

2 MATERIALS AND EXPERIMENTAL

According to the damp working temperature, commercial Ti-50.8Ni wire has been selected to utilize the high $\sigma^{P\to M}$ and $\sigma^{M\to P}$ characteristics under heavy mechanical shock. The material was drawn to

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wire of 1.0 mm in diameter with accumulated deformation up to 40%, then hot-straightened at 500 ℃ for 20 s. The transformation temperatures of the wire measured by differential scanning calorimetry are: M_s = 3.0 ℃, M_p = − 2.0 ℃, M_f = − 20 ℃; A_s = − 5.7 ℃, A_p = 3.9 ℃ and A_f = 6.0 ℃, respectively. Tensile tests at 25 ℃ show that the stress deviating from linear stress-strain relation is 670 MPa, the yield stress 700 MPa, the tensile stress 1 290 MPa, and the elongation over 22%. The microstructure of the tested wire is fiber-like austenite. The length of specimen is 180 mm and the gauge length is 100 mm. All damping experiments are made on Instron Model 5569, the temperature range is 20 − 50 ℃, and the mechanical shock frequency is changed by adjusting the clip moving velocity. Experimental data such as testing time, temperature, stress, strain and clip moving velocity are automatically collected and processed once every 50 ms by computer. If the load change is over 50 N within the interval of 50 ms, the data collecting system would automatically collect twice.

3 RESULTS AND DISCUSSION

3.1 Superelastic damping characteristics at R. T. under rather low frequency mechanical shock

Figs. 1(a), (b) and (c) show superelastic damping curves in the former three cycles at R.T. under mechanical shock frequency no greater than 0.025 Hz with controlled strain of 1%, 3% and 7.5%, respectively. It can be seen that the stresses deviating from linear stress-strain relation in the initial cycle of every controlled stain is apparently higher than the corresponding value of later cycles. Each unloading curve overlaps well with the previous one, which indicates that during the reverse transformation of stress-induced martensitic transformation, the "spring-back friction" of lattice changes little with cycling. With increasing controlled strain, the area covered by the superelastic loop increases, the damping effect becomes more evident, and the corresponding initial superelastic yielding stress decreases. Similar experimental results have been obtained in Ref. [12]. It is measured that such superelastic yielding stress of the alloy is 485 MPa at 1% controlled strain, 460 MPa at 3%, 420 MPa at 6% and 400 MPa at 7.5%, respectively. When the controlled strain is over 3%, the superelastic damping capacity is over 50% for each cycling.

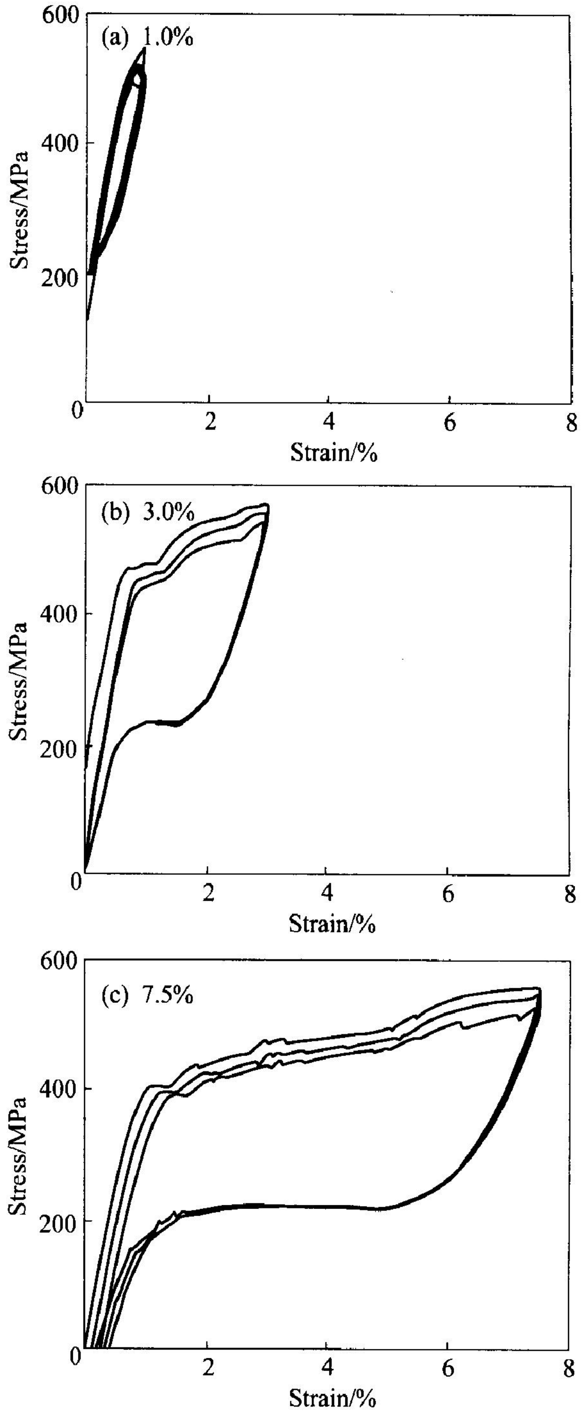

Fig. 1 Superelastic tri-cycle damping characteristics of Ti-50.8Ni alloy at 25 ℃, clip moving velocity of 0.05 mm/s

3.2 Effect of loading/unloading frequency on superelastic damping at different temperatures

If the loading/unloading frequency is increased and the austenitic TiNi wires are tested at different temperatures by stepwise increasing strain and cycled for 3 times at each strain along 1% →3% →6% →7.5% → tensile to fracture, some of the superelastic damping results are shown in Figs. 2(a), (b) and (c), respectively. By comparing Fig. 2(a) with Fig. 1(a), it can be seen that at 25 ℃ and 1% controlled strain, there is little superelastic damping effect, and little energy dissipation[7]. However, when the controlled strain is 3%, due to increasing loading-unloading frequency, the superelastic damping loop area of the second cycle decreases apparently. Analysis on experimental data shows that when the controlled strain is 3%, the initial stress and strain reach their maximums simultaneously, and reach their minimums with the strain lagging stress for 200 ms; in the second cycle the stress

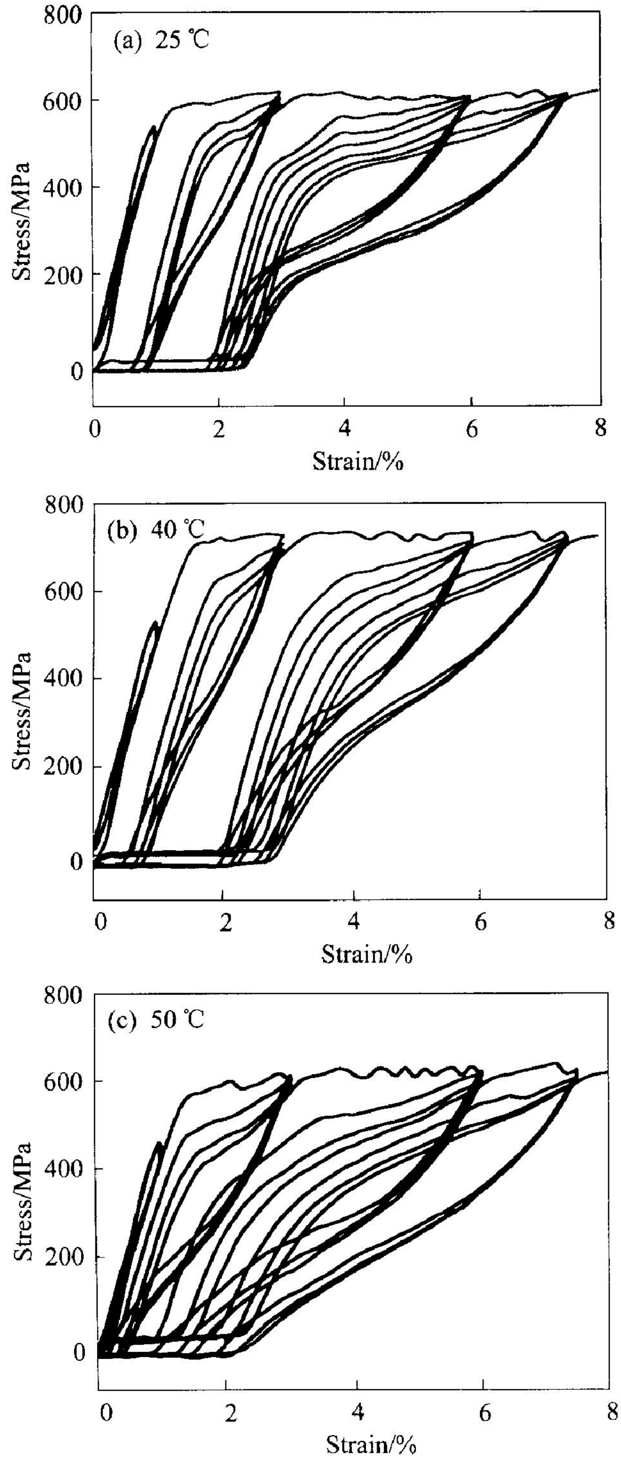

Fig. 2 Effect of strain increase on superelastic tri-cycle damping characteristics of Ti-50.8Ni at various temperatures under clip moving velocity of 3 mm/s

and strain reach their maximums simultaneously, and reach their minimums with strain lagging stress for 400 ms. Because of frequency increasing, the adaptation of deformation to loading is not quick enough, and the heat exchange for the stress-induced martensitic transformation is not complete, which results in the distinct difference between "dynamic" loading/unloading and "static" loading/unloading. The superelastic yielding stress lowers obviously with cycling going on, which bears the same trends with static loading/unloading[12]. When the controlled strain is greater than 6%, the area covered by superelastic loop increases, and the damping capacity is enhanced. When the controlled strain is 3%-7.5%, the superelastic damping capacity does not change greatly; however, the stress exhibiting superelastic damping is enhanced with increasing testing temperature. This means more energy is needed to induce martensitic transformation as the temperature is increased, which can be well explained by modified Clausius-Clapeyron formula[13]. When testing temperature approaches to M_d, the superelastic starting stress is lowered.

3.3 Superelastic damping under increasing heavy strain cycling at different temperatures

Fig. 3 shows the superelastic damping characteristics of stepwise increasing single-cycle strain (6% → 7% → 8% → 10% → tensile to fracture) at different temperatures, when clip moving velocity is 3 mm/s. Within the measured temperature range, the superelastic yielding plateau stress is stable in a narrow range. All the big-strain superelastic damping loops at different temperatures cover roughly the same damping area. This is of engineering importance for damping application in the civil structures. With stepwise increasing of single-cycle strain at 50 ℃, the area covered by superelastic damping loop (dotted line) decreases gradually, which might not favor reducing shock and energy absorption.

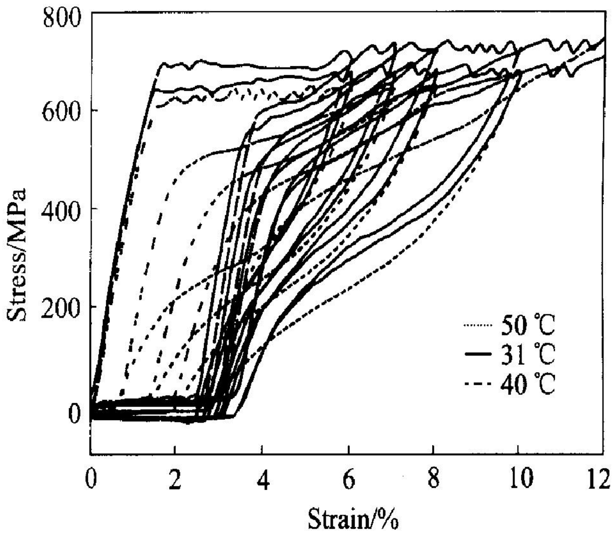

Fig. 3 Influence of big-strain increase on damping at various temperature

3.4 Superelastic damping under 0.5 Hz shock by stepwise increasing strain cycling at different temperatures

By stepwise increasing the cycling strain as 1% →2% →3% →4% →5% →6% →7.5% with clip moving velocity of 6 mm/s being applied at different temperatures, some of the results are shown in Figs. 4 (a), (b) and (c), respectively. The superelastic starting stress decreases with increasing controlled strain under such frequency mechanical shock at R.T.; at the same time the superelastic-yielding plateau stress increases slowly with increasing controlled strain. The unloading curves for different temperatures change greatly, and the area covered by superelastic damping loop increases with testing temperature, which means the larger energy dissipation. This trend maintains until the temperature approaches to M_d of the alloy, when the plateau stress lowers, which is consistent with the results in Fig. 2(c).

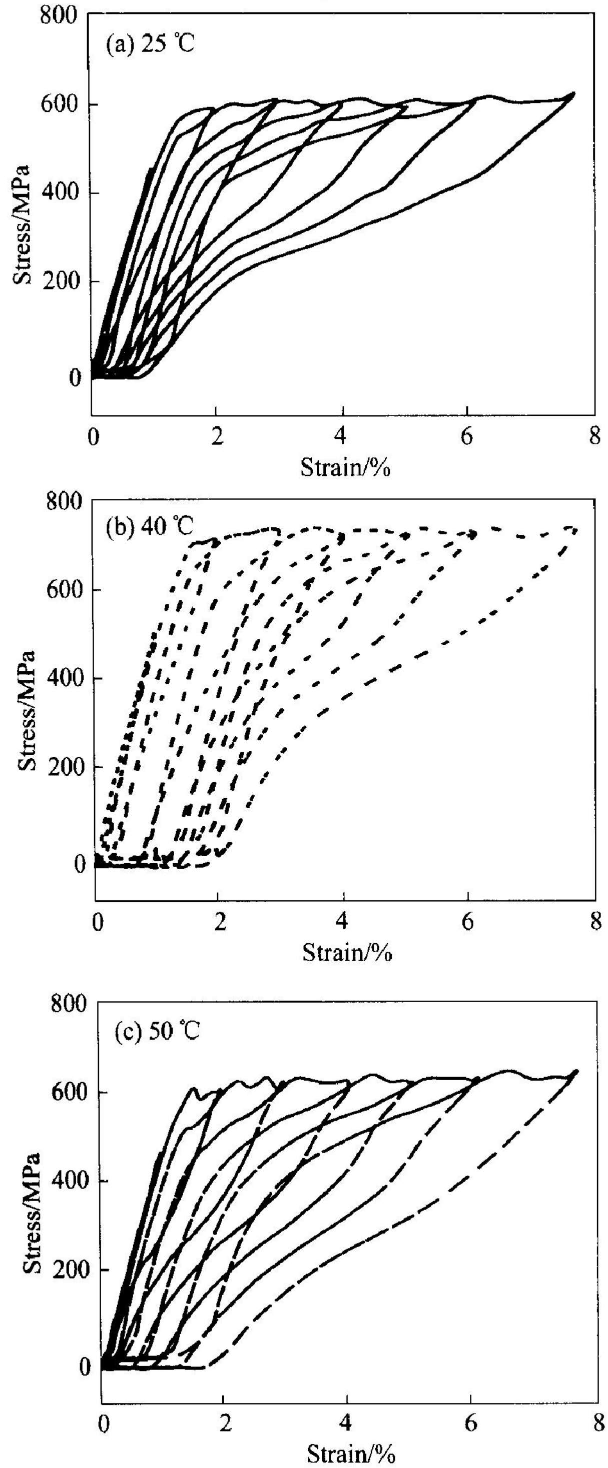

Fig. 4 Effect of strain increase on damping of Ti-50.8Ni at various temperatures under clip moving velocity of 6 mm/s

3.5 Superelastic damping under repeated heavy strain, 0.5 Hz mechanical shock cycling

As shown in Fig. 5, with multiple big-strain (6%) and high frequency mechanical shock cycling at 35 ℃ going on, the damping area covered by the loop is getting smaller gradually and finally tends to a stable value. If the above cycled specimen is subject to further 1% → 2% → 3% → 4% → 5% → 6% → 7.5% cycling under the same shock frequency at different temperatures, some of their superelastic damping curves are shown in Figs. 6(a), (b) and (c), respectively. Because the previous cycling temperature 35 ℃ lies in the $T_R < T < T_x$[12] (where T_R is transformation temperature from austenite to R-phase, and T_x is the temperature where the critical stress for stress-induced R-phase and the critical stress for stress-induced martensitic transformation are equal), it results in the preferential occurrence of stress-induced R-phase in the initial deformation and the formation of the superelastic loop, which differs from those curves shown in Figs. 6(b) and (c). With increasing testing temperature, the loading part of the superelastic curve is lifted, while the unloading part changes little; and the area covered by the loop increases, and the damping capacity enhances accordingly. Quantitative analysis on the area of the loops shows that for the specimen through the training shown in Fig. 5, further controlled 7.5% strain cycling at the same frequency and 35-50 ℃ will bring the damping capacity over 35%. These characteristics are of importance for the superelastic damping application.

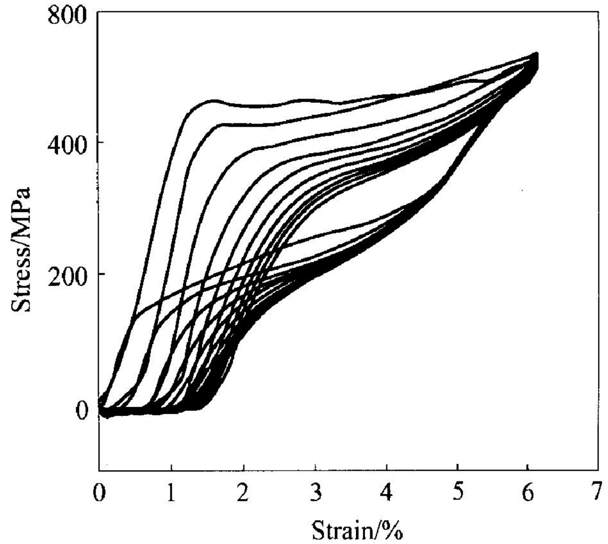

Fig. 5 Superelastic damping curves of Ti-50.8Ni wire at 35 ℃ under clip moving velocity of 6 mm/s

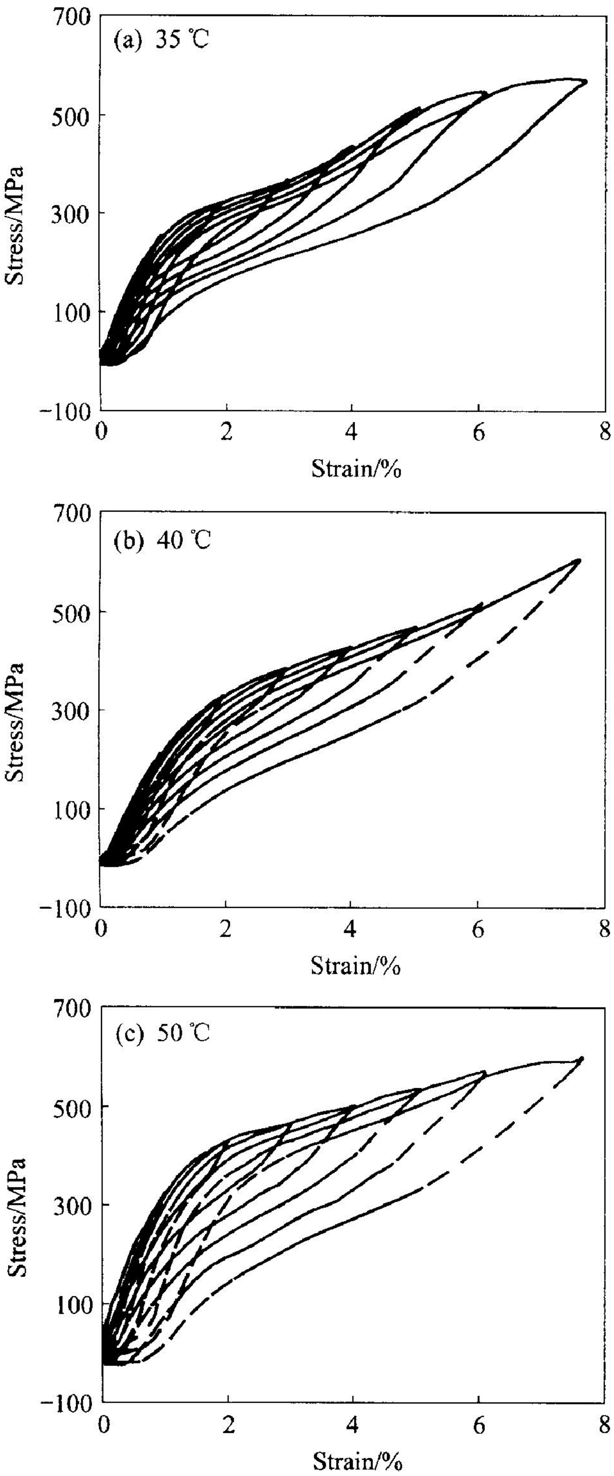

Fig. 6 Effect of controlled strain increase on superelastic damping of 10-cycled Ti-50.8Ni at various temperatures under clip moving velocity of 6 mm/s

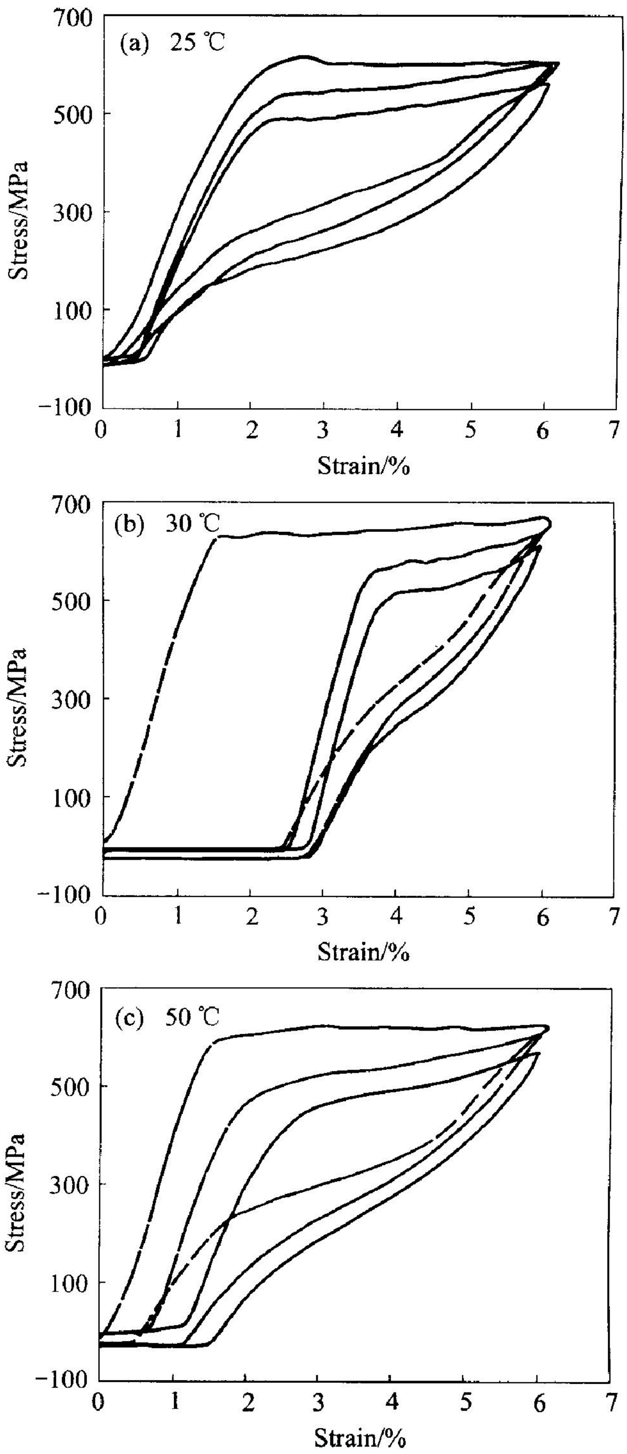

Fig. 7 Effect of frequency decrease on damping of Ti-50.8Ni at various temperatures and clip moving velocity of 6 mm/s

3.6 Superelastic damping for specimen with different training history, temperature and shock frequency

Non-trained specimen are tested with the procedures of loading 0.5 Hz→0.3 Hz→0.1 Hz at different temperatures, and some of their superelastic damping curves are shown in Figs. 7(a), (b) and (c), respectively. The superelastic yielding plateau stress at R.T. lowers gradually with decreasing mechanical shock frequency, but the areas covered by these three loops are almost the same, indicating that almost the same damping capacity. Nevertheless, when the testing temperature is 30−40 ℃, the area covered by initial loop for 0.5 Hz(6 mm/s) mechanical shock is significantly larger than those of subsequent mechanical shocks for 0.3 Hz and 0.1 Hz, although the difference between the later two areas is small. The damping capacity of the non-trained one at 50 ℃ is also quite large.

After the wire has been subject to the training shown in Fig. 5, it is further cycled by the procedures of 0.5 Hz→0.3 Hz→0.1 Hz mechanical shock, its superelastic damping curves are shown in Fig. 8, together with the overlapping results of non-training specimen. The damping capacity of the trained specimen is significantly improved.

When the specimen are respectively trained at 40 ℃, 45 ℃ and 50 ℃ with 0.5 Hz mechanical shock and controlled strain of 6% for 10 cycles, then further subject to 0.5 Hz→0.3 Hz→0.1 Hz mechanical shock, the corresponding superelastic damping curves are shown in Fig. 9. No retained deformation is observed and the damping capacity at various temperatures maintains at relatively stable value; the areas covered by loops at the same temperature change little. The superelastic damping capacity for trained specimen is relatively stable when the temperature is 30 - 50 ℃ and the mechanical shock frequency is 0.1 - 0.5 Hz. Such stable damping capacity results from the optimum combination of thermodynamically driven energy for the forward and reverse stress induced martensite transformations, in addition to the least retained deformation of the damping behavior.

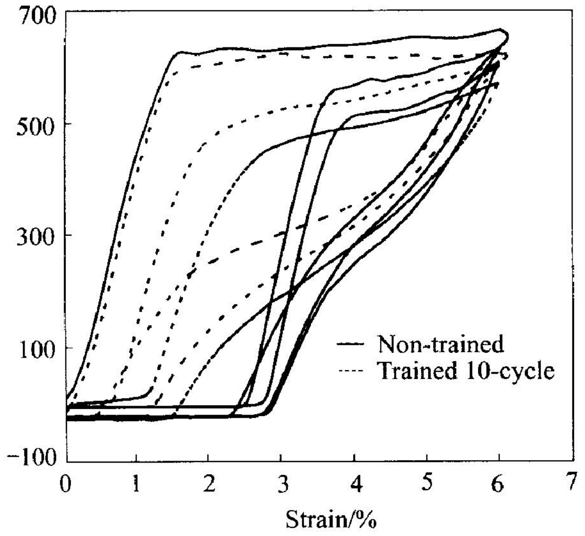

Fig. 8 Effect of frequency decrease on damping of trained and non-trained sample at 35 ℃ and clip moving velocity of 6 mm/s

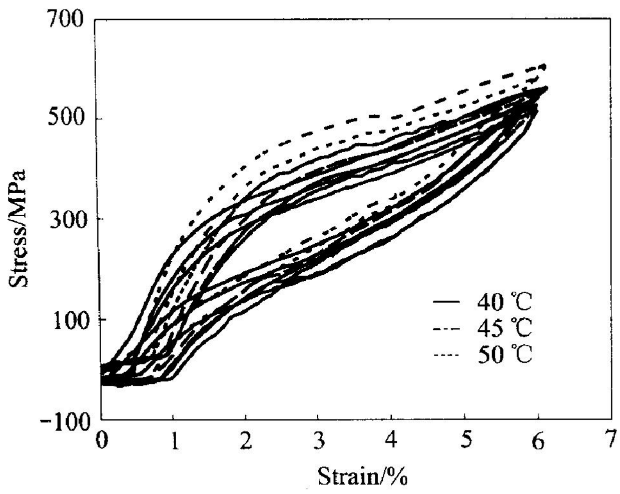

Fig. 9 Effect of frequency decrease on damping of 10-cycled Ti-50.8Ni under clip moving velocity 6 mm/s

REFERENCES

[1] Dolce M, Cardone D, Marnetto R. Implementation and testing of passive control devices based on shape memory alloys[J]. Earthquake Engineering and Structural Dynamics, 2000, 29: 945 - 968.

[2] van Humbeeck J, Delaey L. Role of interfaces on materials damping[A]. Roth B R, Misa M S. Proc of International Conference on Martensitic Transformations[C]. Toronto, ASM-USA, 1985. 59 - 64

[3] Hodgson D, Kramer G. High damping superelastic collects for high speed drilling[A]. Duerig T, Wayman C M. SMST-94 Proc 1st Intl Conf on Shape Memory and Superelastic Technologies[C]. Califronia, USA, 1994. 371 - 376.

[4] Chiodo J D, Anson A W, Billett E H, et al. Eco-design for active reassembly using smart materials[A]. Pelton Alan, Hodgson Dared, Russell Scott, et al. SMST-97 Proc 2nd Intl Conf on Shape Memory and Superelastic Technologies[C]. California, USA, 1997. 269 - 274.

[5] van Humbeeck J. Non-medical applications of SMAs[J]. Mater Sci and Eng, 1999, A273 - 275: 134 - 148.

[6] Ma R Z, Jiang M H, Xu Z Y. Introduction to Functional Materials[B]. Beijing: Metallurgical Industry Press, 1999. 550 - 562.

[7] Hodgson D E. Damping application of shape memory alloys[J]. Materials Science Forum, 2002, 394 - 395: 69 - 74.

[8] Dolce M, Cardone D. Mechanical behavior of shape memory alloys for seismic applications 2. Austenite NiTi wires subjected to tension[J]. International Journal of Mechanical Sciences, 2001, 43: 2657 - 2677.

[9] van Humbeeck J, Stoiber J, Delaey L, et al. High damping capacity of shape memory alloys[J]. Zeitschrift fuer Metallkunde, 1995, 86(3): 176 - 183.

[10] van Humbeeck J. Damping properties of shape memory alloys during phase transformation [J]. Journal de Physique IV, 1996, 6(8): 371 - 379.

[11] ZHAO L C, CAI W, ZHENG Y F. Shape Memory Effect and Superelasticity in Alloys[M]. Beijing: National Defense Industry Press, 2001. 174 - 175. (in Chinese)

[12] HUANG B M, WANG Y Q, CHENG J X. Superelasticity of near-equal atom NiTi alloys[J]. The Chinese Journal of Nonferrous Metals, 1996, 6(4): 110 - 136. (in Chinese)

[13] Stalmans R, van Humbeeck J, Delaey L. Thermomechanical cycling, two way memory and concomitant effects in CuZnAl alloys[J]. Acta Metall Mater, 1992, 40: 501 - 511.

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