The research of electrothermal driving characteristics of NiTiCu shape memory alloy wire

Shengliang Zhu[1, a],Hongbo Dong[1, b],Guihua Zhang[1, c],Yulong Wu,Jihang Wu,Li Zhao

[1]School of Aeronautical Manufacturing Engineering, Nanchang Hangkong University, Nanchang 330063, China

[a]380418167@qq.com, [b]donghbo@nchu.edu.cn, [c]453903787@qq.com

Keywords: NiTiCu alloy, Shape memory effect, driving current, deformation time.

Abstract. The effects of current on restoring velocity and deformation time of NiTiCu shape memory alloy wire were investigated by loading different electrical current. The results show that the deformation time decreases rapidly with increasing driving current, but the deformation time decreases slowly when the current increases to a certain value. The deformation angle and time shows nonlinear increasing when the driving current is constant. The rate of deformation increases firstly and then reduces with the time passing. The relationship between driving current and the deformation time of NiTiCu shape memory alloy wire can be expressed by the empirical formula $I=1.41(1-e^{-0.0199t})^{-1/2}+1$, and the calculation curves agrees well with the test data.

Introduction

Shape memory alloy(SMA) is a new material with both sensing and actuating functions, The control to driving force of deformation process and stroke can be obtained by heating and cooling it[1]. With SMA made to driving component ,some advantages follows: more compact structure, higher power mass ratio and no noise, etc[2,3]. The electrothermal drive of SMA is termed when the power is on, SMA converts electrical energy into thermal energy to raise its temperature, hence induces reverse martensitic transformation , output restoring force and generates restoring distortion , and then completes drive action[4-8] . It had been used in aerospace, machinery, construction and medical equipment and other fields. With the application of SMA is unceasingly thorough, people requires quickly response of SMA and precise control to it, for the deformation rate and deformation time has great influence on the sensitivity and controllability of driving element.

NiTiCu shape memory alloy is one of the earlier development of shape memory alloy which has more excellent properties and potential applications compared with other common conventional NiTi based shape memory alloy[9]. The filamentous shape memory alloy is a more popular application form due to its low manufacturing cost[10]. In the past, the research mostly concentrated in the effect of shape memory, stress, strain, the constitutive model of temperature, phase transformation and performance[11-15], but spend less time to study the characteristics of electrothermal drive, deformation velocity and time of NiTiCu alloy wire. The authors study how the load current affect the deformation velocity and time in the process of electrothermal drive, which provides a reference for the development and application of it.

Sample preparation and testing method

NiTiCu shape memory alloy with the diameter of 1.2mm experimented is provided by Baoji Haipeng metal material Co., has one-way shape memory effect. The chemical composition of this material is Ni-40.02Ti-6.73Cu(wt%).through using 404F3/200F3 differential scanning calorimeter (DSC) fabricated by NETZSCH company to measure the martensitic transformation temperature of NiTiCu shape memory alloy, as shown in table 1.

Cut the NiTiCu shape memory alloy wire 80mm long and bend it into a U shaped sample, and the radius of semicircle of U shaped sample is 10mm, and install the sample in the test circuit as shown in the figure 1.One end of the specimen is fixed by screws, and the other end is movable and deformable which connected with resistance angle sensor to measure the opening angle result from electrothermal drive (∠A), as shown in figure 2. The test used a 220V AC power apply, different driving current can be obtained by adjusting the rheostat, under the condition of current I, close the switch circuit to raise the temperature of the alloy up to the temperature (58C～70C) of the reverse martensitic transformation when the deformation occurs. When the deformation completed (at this time the opening angle is ∠A), off the circuit, and get the deformation time (t).

Table 1 Martensitic transformation temperatures of NiTiCu

M_f(C)	M_s (C)	A_s (C)	A_f(C)
30	45	58	70

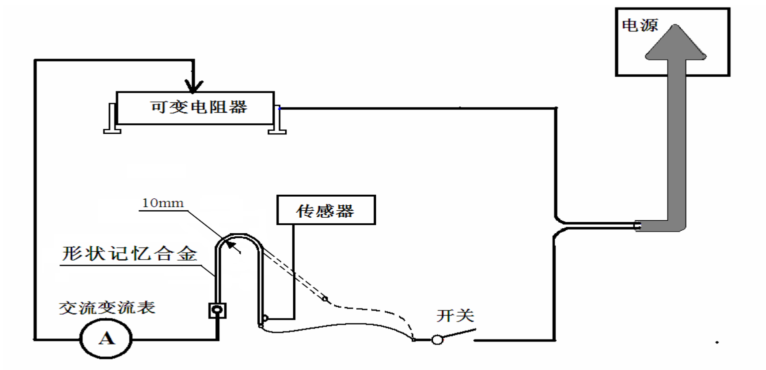

Fig.1 The experimental circuit of SMA wire electrothermal driving

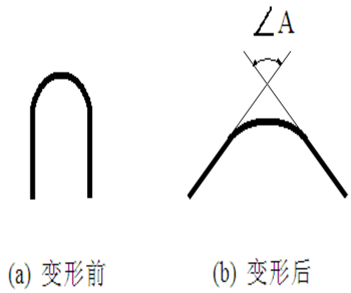

Fig.2 Electrothermal driving deformation of SMA wire

Analysis and discussion

1 NiTiCu alloy DSC curve analysis. Fig3 is the DSC curve of NiTiCu alloy. Basing on the tangent method[16], the phase transition temperature of NiTiCu alloy is as follow: As =58C, Af =71C, Ms =45C, Mf =58C. Fig3 shows that phase transition of M-A of NiTiCu alloy occur in the heating or cooling process. A small peak appeares in the heating process of A phase to B phase transition, which is the endothermic peak of formation of Rr phase. Rr phase is the parent phase of R phase. R phase produces in the process of transition from parent phase to M phase, which result that resistivity of the alloy rise, thus the resistance of NiTiCu alloy rise. According to Joule law, the same current and the same time of energizing, the resistance of the material is larger, the heat who pruduce is more, which cause that the temperature of NiTiCu alloy increased, and deformation occur when the temperature reaches the phase transition temperature.

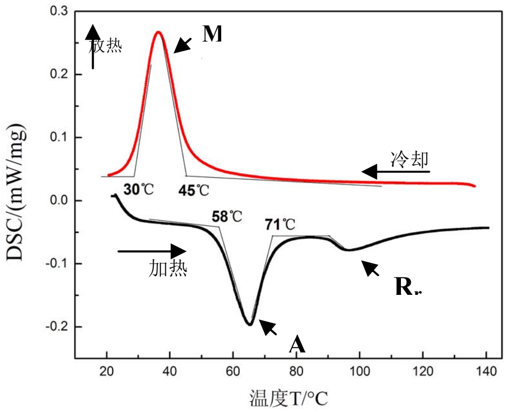

Fig.3 The DSC curve

2 NiTiCu Shape memory alloy load current and the time required for the relationship between the action. NiTiCu Shape memory alloy wire electric drive agility relate to speed of response deformation, and the deformation of time (*t*) reflects the overall speed of the deformation. Figure4 shows the relationship between the drive current (*I*) and deformation of time (*t*), the trends of four curves are basically the same, driving current smaller, longer time alloy deformation, resulting in slow response alloy electric drive. Taking the length of 80mm NiTiCu Shape memory alloy wire for example, when $I < 2A$, deformation of time (t) tends to infinity, and that the energy which electricity generated is less than or equal to the amount of energy, the shape memory alloy wire temperature of less than the reverse martensitic transformation point. No deformation occurred Reply. With the increase of the driving current, the wire heating rate faster, deformation time is reduced, alloy heating to drive the reaction faster. But when $I > 5A$, continue to increase the current time has little effect on deformation, even a large current also so NiTiCu shape memory alloy wire overheating damage, loss of memory function.

At the same current, the length of the alloy to the operating time also has a certain impact. In Figure4, the action time of the alloy which the length of 80mm occurred significantly shorter length than the other to be. This is because the resistance is proportional to the length of the alloy, the heat in a large length of the material to produce greater power, to achieve faster martensitic transformation temperature, and the less time is deformed to break a circuit.

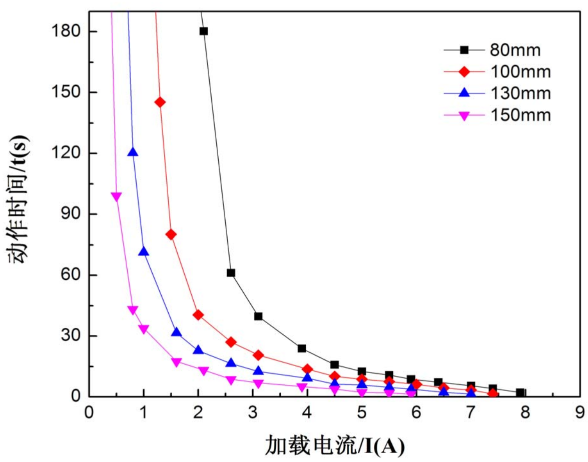

Fig.4 The I~t current

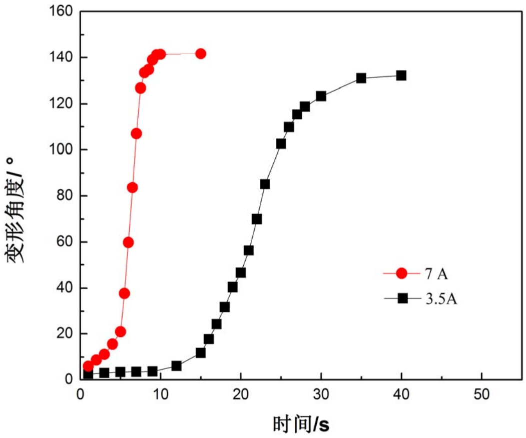

Fig.5 The relationship between deformation angle and time

3 Influence of driving current on the angle and rate of deformation. The drive current of 3.5A and 7A was loaded in NiTiCu shape memory alloy wire respectively, then measure the relationship between the electric driven deformation angle（∠*A*）and the time（*t*）, as shown in Fig5. The figure shows the dynamic speed variation characteristics of single electrothermal drive recovery deformation regard to NiTiCu shape memory alloy wire, the curve present S type, which indicated that with the time increasing, the deformation rate increases firstly and then decreases. In the initial stage of deformation, the deformation rate is low, the temperature of the alloy begin to growth in the current drive, which break the balance of intrinsic stress and cause the deformation which is similar to elastic recovery[4]; When the temperature reaches the point of martensite reverse transformation, a greater recovery energy is emerged, to increase the deformation rate rapidly. With the completion of the martensitic transformation, the recovery of the alloy is finished as well. Through the comparison of two different drive current ∠*A*-*t* curves found that the radian of curve with drive current at 7A is steeper than 3.5A, as well as a shorter deformation time and fast deformation rate.

4 Dicuss. NiTiCu Shape Memory Alloy Wire can be regarded as a heat source on the electric heating process, assuming that there is no temperature gradient in the cross-section, then according to the heat transfer theory that the heat Φ generated by the alloy wire is electrified is equal to the heat Φ_c absorbed by the alloy and air convection heat transfer with Φ_h alloy and heat radiation to the surrounding environment with Φ_r [17]. But in order to simplify the heat conduction model, radiation heat transfer can be ignored alloy wire to the surrounding environment and do not consider the alloy resistance changes with temperature. The heat transfer equation of the NiTiCu shape memory alloy wire for electric heating is expressed by[18]:

$$\Phi = \Phi_c + \Phi_h \qquad (1)$$

(1) Suppose *I* is the electric current of alloy, *R* is the resistance, *C* is the specific heat capacity, *m* is the alloy mass, h_c is the convective heat transfer coefficient, *A* is the alloy surface area, *T* is the alloy temperature, T_0 is the room temperature. NiTiCu shape memory alloy wire elevated temperature within the time (*dt*), then $\Phi = I^2Rdt$, $\Phi c = Cmdt$, $\Phi_h = h_cA\ (T\text{-}T_0)\ dt$, substitute into equation (1),

$$I^2Rdt = CmdT + h_cA(T - T_0)dt \qquad (2)$$

(2)In order to get the formula between deformation time (*t*) and drive electric current (*I*) of NiTiCu shape memory alloy, assuming that the alloy wire by heated temperature after the time (*t*) reaches the end temperature of transformation of A_f (T_1), completing recovery of deformation of alloy, and consolidation and integral to equation (1), then getting the deformation time(*t*)-the drive electric current(*I*) relationship as follows:

$$I = \sqrt{\frac{Ah_c(T_1 - T_0)}{R}}(1 - e^{-(\frac{Ah_c}{mC})t})^{-\frac{1}{2}} + k \qquad (3)$$

(3) The alloy wire was examined with $R=0.4\Omega$, $m=1.62\times10^{-3}kg$; specific heat capacity

$C=550J/(kg·K)$; alloy wire diameter d is 1.2mm; l is the length of 80mm, then the surface area $A=0.885\times10^{-3}m^2$; test at room temperature and end temperature of A_f alloy phase change were $T_0=298K$, $T_1=343K$; from the literature [4] desirable for the convective heat transfer coefficient hc is 20W / ($m^2·K$). Take the above parameters into the formula (3) obtain:

$$I = 1.41(1-e^{-0.0199t})^{-\frac{1}{2}} + k \quad (4)$$

Where K is the empirical constant of the shape memory alloy wire NiTiCu and the K values can be calculated through the difference of between the original data point on the curve and assuming $k = 0$ in empirical formula. This paper did not consider the heat radiation of the wire resistance and the change of material properties with temperature when the model was established, in which resulting the theoretical and experimental values must exist difference and the empirical constant k can be introduced to compensate at certain extent.

As shown a dashed lines in Fig.6, the theoretical curve of empirical constant $K=0$ can be calculated through the shape memory alloy wire NiTiCu test data(as shown in Table2) into Equation(4). The resulting shows that between the calculated curve and the measured data points exists difference values about 1A. Therefore, the empirical formula curve (as shown a solid line in Fig6) will be agree well with the test data points if the K value is 1 while the difference can be compensated. Then the empirical formula can be written as Equation(5).

$$I = 1.41(1-e^{-0.0199t})^{-\frac{1}{2}} + 1 \quad (5)$$

The Equation (5) can better express the relationship between the drive current and the alloy deformation time and provide reference for the shape memory alloy wire NiTiCu actual deformation controlling applications in this article.

Table.2 The measured I and t data of NiTiCu SMA wire

Numer	Electric current/A	Time/s	Numer	Electric current/A	Time/s	Numer	Electric current/A	Time/s
1	9.0	1.0	7	6.0	5.1	13	3.0	39.2
2	8.5	1.4	8	5.4	6.0	14	2.7	47.5
3	7.9	2.3	9	5.0	6.9	15	2.6	60.8
4	7.5	2.3	10	4.5	12.0	16	2.4	117.1
5	7.0	3.7	11	4.1	16.1	17	2.2	180.6
6	6.5	3.2	12	3.5	26.3			

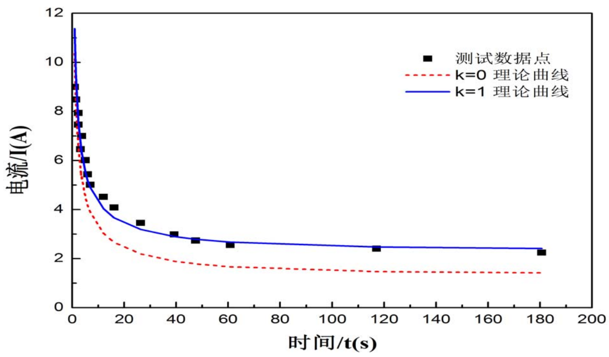

Fig.6 The measured I~t data and calculated curves

Summary

(1)Increased the driving current could reduce the time of NiTiCu-shape-memory-alloy-wire deformation, and improve the sensitivity of action. But when the driving current reached a certain value, the driving current had less impact on the time of the deformation, even excessive current could have an overheating damage, affecting the shape memory effect of the alloy.

(2)When the driving current was constant, the relation curve of NiTiCu-shape-memory-alloy deformation angle and the time was the S-type. In the initial stage, the deformation rate was slow;

When temperature of the alloy reached As starting temperature of the martensitic reverse transformation, the deformation rate was fast; when the martensitic reverse transformation was completed, the deformation was end.

(3)For test of NiTiCu-shape-memory-alloy-wire in this article, the empirical formulas $I=1.41(1-e^{-0.0199t})^{-1/2}+1$ between the driving current and deformation time which was derived based on heat transfer theory, it could better describe the relationship between I and t, and provided a reference for the actual deformation control applications.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (No. 51164029), the Natural Science Foundation of Jiangxi Province of China (No. 20142BAB206021) and(No. YC2013-S209).

Corresponding Author: Hongbo Dong TEL:13065107162

E-mail: donghbo@nchu.edu.cn

References

[1] J.M. Gong, H.k. Tobushi: Journal of Functional Materials, Vol.33(2002)No.4, p.391-393.

[2] H. Wang, X.L. Yao: Transducer and Microsystem Technologies , Vol. 25(2006) No.10, p.41-43.

[3] S.G. Zuo, X.J. Jin and M.J. Jin: Materials for Mechanical Engineering , Vol.38(2014)No.01, p.1-5.

[4] Z.L. Zhang, Y.H. Liu and Y. Yang, et al: Journal of the University Petroleum,China (Edition of Natural Science), Vol.24(2000)No.2, p.95-97.

[5] G.R. Hang, Z.L. Wang: Micromotors, Vol. 40(2007)No.11, p.54-58.

[6] J. Matovic，K. Reichenberger: Procedia Engineering, (2010)No.5, p.1372-1375.

[7] L. Janke, C. Czaderski and M. Motavalli, et al: Materials and Structures, Vol.38(2005)No.5, p.578-592.

[8] M. Tomozawa, H.Y. Kim and S. Miyazaki: Acta Materialia, Vol.57(2008)No.2,p.441-452.

[9] Y. Yin, Y.T. Xu and J. Shen, et al: Materials Review, Vol.20(2006)No.12,p.70-73.

[10] S.B Yang, M. Xu: Computer Simulation, Vol.29(2012)No.2,p.27-31.

[11] W.Y. Xiong, B.H. Luo and Li bin, et al: Materials for Mechanical Engineering, Vol.38(2014)No.03,p.70-79.

[12] Z.Y. Zhang, Y. Wu and H. Wang, et al: Journal of Functional Materials, Vol.15(2013)No.44,p.2152-2155.

[13] C.Y. Wu, C.Y. Wu and X. Wang, et al: Materials for Mechanical Engineering, Vol.38(2014)No.2,p.28-31.

[14] Y.H.Li,Z.X.Zhao,et al:Journal of Functional Materials, Vol.4(2006)No.37,p.650-652.

[15] B.C. Chang, J.A. Shaw and M.A. Iadicola: Continuum Mechanics and Thermodynamics, Vol.18(2006)No.1,p.83-118.

[16] J.S. Xu: Study of Transformation Temperature testing system for Shape Memory Alloys(Ph.D, Heifei University of Technology, China 2010),p.3-4.

[17] X.D. Niu, L. Wang and L.V. Haotun, et al: Journal of Projectiles, Rockets, Missiles and Guidance, Vol.28(2008)No.4,p.306-308.

[18] X.L. Li, Y.L. Fu and Wang Shu-guo, et al: Chinese Journal of Biomedical Engineering, Vol.27(2008)No.3,p.416-421.