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A new method to measure volume resistivity during tension for strain rate sensitivity in deformation and transformation behavior of Fe-28Mn-6Si-5Cr shape memory alloy

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ABSTRACT

This paper is concerned with the measurement method of volume resistivity in Fe-based shape memory alloy (Fe-SMA) during tensile tests using the circuit with a higher precision based on the Kelvin double bridge. In order to evaluate an amount of martensite associated with shape memory effect (SME), especially at higher deformation rate, it is convenient to capture the change in volume resistivity, which has a correlation with the amount of martensite. On the other hand, it is necessary to consider rate sensitivity of martensitic transformation behavior which is the key of SME as well as deformation behavior in Fe-SMA because the alloy is unavoidable to deform at higher strain rate. In this study, at first, a circuit with a higher precision based on the Kelvin double bridge is assembled. Then, tensile tests of Fe-28Mn-6Si-5Cr alloy at different strain rates are conducted by using two different testing apparatuses such as the conventional material testing machine and impact testing machine based on the split Hopkinson pressure bar technique. The rate sensitivity of the volume resistivity in Fe-SMA is experimentally captured by using the assembled circuit during the tensile testing at various strain rates. Shape recovery strain due to SME is measured by heating the specimens deformed quasi-statically at various strain rates up to above reverse transformation temperature.

1. Introduction

Fe-based shape memory alloy (Fe-SMA) is developed at a lower cost since it is mainly composed of the low cost elements such as Fe, Mn and Si. Fe-SMA has some disadvantages as smaller shape memory effect (SME) compared with the widely-used Ni-Ti alloy [1–3], and its super elasticity (SE) is not excellent. However, it has good machinability, weldability, good formability, etc. [4–6]. Processing to a wide variety of shapes for final products gets relatively simple. More importantly, Fe-SMA has been widely investigated during the last years because its relatively-low cost coming from mass-productions is quite attractive for applications with large structural members [1,7–9]. In addition, Fe-SMA has a great potential in such members for civil engineering structures, especially in damping and vibration control [2]. However, the applications are still in a pioneer stage. In order to promote and extend the applications, the mechanical properties as well as SME should be clarified experimentally. Additionally, it is necessary to consider the rate sensitivity in Fe-SMA because it is attempted to be applied to not only the civil but also the many other engineering fields under different working environments with excessive loading [4] such as earthquake, ocean waves, flood, typhoon, soil movement and so on. A clarification of the tensile deformation behavior in the members at various strain rates from quasi-static to impact test is strongly required for designing safe and reliable structures [10]. Comprehensive experimental works have been carried out in the past [11–14]. In these works, especially, positive strain rate sensitivity in stress–strain relationship can be clearly shown in some tests by using Fe-SMA [11,12]. At the same time, SME by heating after loading at different quasi-static strain rates and unloading is investigated and strain rate insensitivity of SME is reported [12]. The remarkable and unique property of Fe-SMA to recover to a memorized shape is governed by forward and reverse transformation of stress-induced ε-martensite [15]. Therefore, it is necessary to evaluate an amount of martensite in a wide range of strain rates for increasing a reliability of the alloy. However, up to now, it can be considered that methods to evaluate the amount of martensite in Fe-SMA during deformation at various strain rates, especially at higher strain rate, becomes quite complicated and are not still well-established. Additionally, in the case of a tensile test at higher strain rate, the stress wave is propagating back and forth for many times inevitably after the test. It is quite hard to take away the specimens from the testing machine when the defor-

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mation just achieves to a certain level. Thus, the measurement method of the amount of martensite during a real-time process is required.

Meanwhile, the model which can describe stress–strain relationship with martensitic phase transformation have attracted much more attentions. Tanaka [16] proposed this kind of a model in 1986, and the Tanaka's model is one of the first models for Ni-Ti shape memory alloys. In addition, a calibration method of the models from experimentally-obtained true stress-plastic strain and the volume fraction of martensite-plastic strain relations in TRIP steel is proposed by Iwamoto et al [17]. Focusing on Fe-SMA, transformation kinetics models are also proposed [18,19] in the past. Therefore, in order to confirm the availability of the models, capturing an amount of martensite experimentally is indispensable. In order to capture the amount of martensite experimentally which can control such excellent performances for recognizing a great reliability of the alloy, the measurement methods by X-ray diffraction, density and resistance, etc. can be employed [20–22]. As described above, the more important and difficult factor for measuring the volume fraction of martensite is the rate sensitivity. In the austenitic stainless steel, Cao and Iwamoto [23] attempted to evaluate the volume fraction of α'-martensite by measuring the relative magnetic permeability during deformation at various quasi-static strain rates. However, the non-magnetic ε-martensite in Fe-SMA cannot be monitored by permeability. So far, only resistance measurement method can capture the amount of martensite in Fe-SMA during deformation [24], especially higher strain rate.

The electrical resistivity of martensitic product phase is different from that of an austenitic parent phase and its variation can be used as an indicator of phase transformation [25]. Therefore, the resistance measurement method is applicable to evaluate volume fraction of martensite during deformation. It has an advantage as the quite fast response of the measurement. Even though the volume fraction of martensite during deformation through use of the resistance is measured, some problems still exist. It is quite hard to measure the change in volume resistivity at room temperature because it can be considered that the volume fraction of martensite becomes much smaller. In addition, as compared with other materials, basically the resistance of metallic materials is much lower. Until now, the four-probe method [4,24] is the most commonly-used when the volume fraction of martensite is evaluated. In the case of the other materials, the volume resistivity is measured to capture the volume fraction of α'-martensite. In type 304 austenitic stainless steel, temperature-dependent linear relations between the resistivity and the volume fraction of α'-martensite are confirmed by Date [24] from the tensile test under three fixed test temperatures by using the four-probe method. It is clarified that the resistivity could be used as a measure of estimating the strain-induced α'-martensite in the steel. However, the accuracy and responsivity of the four-probe method is still not good at higher strain rate because of much change in temperature. In addition, considering the disadvantages of the four-probe method which are a requirement of a strictly-precise reference resistor without self-heating by huge current and it is easily affected from noise and temperature change, a new method is necessary to measure the volume fraction of martensite during the deformation in Fe-SMA.

As compared with the four-probe method [4], the accuracy of the circuit based on the bridge method will become higher because the advantage of the bridge method is an ability to apply an active-dummy method for vanishing the effect of the environmental temperature as well as the other noises coming from the environment. When measuring the resistance value in the range from Ω to MΩ orders, the relatively-easy and accurate circuit based on the Wheatstone bridge is widely used. However, it is difficult to measure the resistance accurately in the measurement of the extremely-low resistance in the range of mΩ or μΩ orders because influences of the wire and the contact resistance still cannot be ignored. Therefore, the more accurate circuit based on the Kelvin double bridge should be introduced.

In this paper, a circuit based on the Kelvin double bridge is manufactured. Then, tensile tests of commercially-available Fe-28Mn-6Si-5Cr alloy, which is a kind of Fe-SMA, at different strain rates are conducted by two different testing apparatuses such as the conventional material testing machine and impact testing machine based on the split Hopkinson pressure bar (SHPB) technique. By using the manufactured circuit, it is attempted that the rate sensitivity in the relationship between resistance and true strain under the tensile test is measured as well as stress–strain and temperature–strain curves. Furthermore, change in diameter is captured by using the commercially-provided laser scan micrometer for quasi-static test and laser vibrometer for impact test, respectively. As a result, it is attempted that the rate sensitivity in the relationship between the volume resistivity and true stress is discussed. Then, shape recovery strain due to SME is measured by heating up the specimens deformed quasi-statically at various strain and strain rates to A_f (Austenite finish temperature).

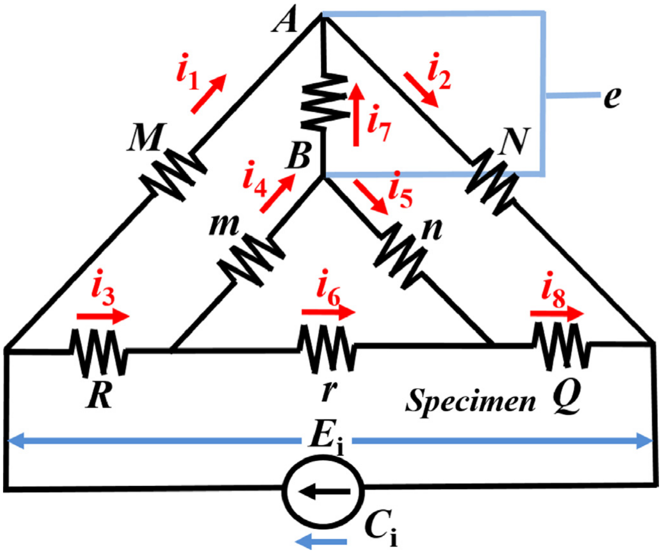

Fig. 1. A schematic representation of a circuit based on the Kelvin double bridge.

2. Principle of measurement

Fig. 1 shows a schematic representation of a circuit based on the Kelvin double bridge. This circuit consists of five reference resistors with known value of resistances denoted by M, N, m, n and r, and a variable resistor denoted by R [26]. The specimen with an unknown resistance denoted by Q. E_i is the total constant input voltage during the tests.

If relationships of resistors such as both $N/M = n/m$ and $N/M = Q/R$ can be satisfied after adjusting the resistance of R at the same time, the equilibrium state which the output voltage $e = 0$ can be achieved. Meanwhile, the resistance of specimen can be obtained by one of the above conditions $Q/N = R/M$. When the resistance of the specimen changes with deformation, the equilibrium state is lost and the potential difference between nodes A and B is generated [27,28]. A similar derivation to the Wheatstone bridge for this circuit is applied as follows. According to the Kirchhoff 's first and second laws, nine following equations with respect to unknown variables as currents from i_1 to i_8 and total current C_i can be derived as

$$C_i = i_1 + i_2, \tag{1a}$$

$$i_2 = i_1 + i_7, \tag{1b}$$

$$i_3 = i_4 + i_6, \tag{1c}$$

$$i_4 = i_7 + i_5, \tag{1d}$$