Magnetization and Shape Memory Effect in Fe-Mn-Cr-Si Alloy

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1. Abstract

Shape memory alloy, which is a form of Fe-Mn-Cr-Si, was thermally treated in an argon and air atmosphere, and the magnetization and shape memory effect were then measured. In both cases the variables were the time and temperature of the heat treatment. As results obtained later results show, those factors had a significant influence on the magnetization and shape memory effect. The magnetization was measured by using a vibrating sample magnetometer, and the shape memory effect was determined by measuring the recovery angle of a bent wire made of the investigated alloy.

Key words: magnetization, SMA, shape memory alloy

2. Introduction

Shape memory alloys are a unique class of materials which are able to remember their original shape and are able to return to that shape even after being bent. This ability is known as the shape memory effect. In order to understand the way in which the shape memory effect occurs it is useful to understand the crystal structure of a SMA.

The crystal structure of well known shape memory alloy NiTi is shown in Fig. 1.

Fig. 1 Lattice structure of the Martensite and Austenite phases of Nitinol.

All shape memory alloys exhibit two very distinct crystal structures or phases, which existence depend on the temperature and the amount of stress being applied to the SMA. These phases are known as martensite which exists at lower temperatures and austenite for higher temperatures. The properties of a SMA depends on which

the amount of each phase present. The exact structure of the two phases varies depending on the type of SMA, so each case should be consider separately. An alloy being in the martensite phase can be easily deformed. When pressure is applied to the lattice, the side of the martensite lattice will change length to compensate for the increased pressure. Since the molecular bonds are not broken, the SMA can recover its precise shape when return to austenite .

Figure 2 illustrates a typical thermal cycle of a SMA.

Fig. 2 The Thermal cycle of an SMA wire and phase boundary variation with temperature (T) and stress (δ).

The phase boundary (whether the SMA is in martensite or austenite) varies with stress(δ), temperature(T) and the composition of the SMA. The dotted lines on the plot show the variation of these boundaries. After the SMA is formed and allowed to cool down it will remain 100% austenite until it reaches martensite start (M_s) for the temperature and stress being applied. When temperature has cooled down below martensite finish (M_f) all of the crystals in the SMA will be in the martensite phase. The shape is not changed by this process. In the martensite phase the wire is easily bent due to the variability of lattice parameters. Realizing the wire does not return to its original shape since the temperature is below M_f . If the wire is then heated it will begin to recover its shape when temperature rises above austenite start (A_f) and will be back in its original shape when it gets to austenite finish (A_f).

It is also important to notice that it is possible to get from the austenite phase to the martensite phase in constant temperature by increasing significantly the pressure.

Most of the transformation occurs over a relatively narrow temperature range, although the beginning and the end of the transformation during heating and cooling extends over a much larger temperature range. The usual way of characterizing the transformation is shown in Fig. 3.

Fig. 3 Typical transformation versus temperature curve for a specimen under constant load (stress) as it is cooled and heated.

The transformation also exhibits hysteresis, so the curves during cooling and heating phases do not overlap. In figure 3 the hysteresis was marked as T1. Both the hysteresis width and the temperature range of this phenomenon varies with the alloy system. For NiTi the transformation occurs at about 60°C.

Almost all known alloys are nonferrous alloys with some exemptions like Fe-Pd or Ni₂MnGa. This paper presents the properties of the magnetic alloy Fe-Mn-Cr-Si.

3. Experimental procedure

In our experiment a specimen was a wire produced by cold wire drawing (Awaji Sangyo, Co., Ltd.), had a diameter of 1.2mm and it was cut to be 14.5mm in length.

The chemical composition is shown in Tab.1.

Table 1 Chemical composition of the specimen (wt%).

Fe	Mn	Cr	Si	Rest
62	27.2	5.02	5.69	0.09

After pre-heating specified by maker (950°C for 5 min, in order to use the wire as a SMA), the wire was cut into small parts (14.5mm) and was heat-treated in air at the temperatures form 500 to 800°C for 5 to 3 hours and in argon gas for 30min to 2hours at 550, 650 and 750°C.

For such prepared specimens the magnetization B-H curves were measured by using VSM. The shape memory effect was measured by measurement a recovery angle of a wire (Fig. 4), previously bent 45degrees and the result was evaluated by using the following equation (1).

$$SME = (45 - \alpha)/45 * 100(\%) \quad (1)$$

Procedure of the SME evaluation is shown in Fig.4.

Fig. 4 SME evaluation.

At the beginning of a B-H measurement , we measured the Curie point of our investigated alloy.

The result : T_C= 596°C as shown in Fig. 5.

Fig. 5 Curie point.

The next steps were measurement of the specimens annealed in air.

Fig. 6 Magnetization at 900°C for 5, 10, 20, 60 and 120 min.

Both in Fig. 6 and in 7 the magnetization increases with the increase of the temperature and the time of the heat-treatment.

The increase of the magnetization is caused by oxidation of the surface and the formation of a ferromagnetic magnetite Fe_3O_4 . The surface formation speed increases with the temperature as shown in Fig. 7, where the maximum value is obtained at 900°C . The formation of the oxidized layer is shown in Fig. 8.

Fig. 7 B-H curves for various annealing temperatures and a constant time of 20min.

Fig. 8 Cross-sections of specimen.

Fig. 9 Magnetization vs. annealing temperature for specimens annealed in air for 10 and 20 min

Fig. 9 shows, as mentioned before, the increase of magnetization which is faster for annealing time equal to 20min. Similar situation in Fig. 10, here the variable is time at constant temperature 900°C . The magnetization increases with the longer time of annealing.

Fig. 10. Magnetization versus annealing time for a specimen annealed in air at 900°C .

In case of annealing the specimen in argon, such a increase of magnetization can not be seen (see Fig. 11).

Fig. 11 Magnetization vs. annealing time for a specimen annealed in Ar at 750°C .

There is no forming of oxidized layer on a surface of the wire, so there is no factor responsible for increase of magnetization. For the times of 30min and 1 h the curves almost overlap. Only for 2 hours a slightly increase of the magnetization can be observed.

A second step of experiment were measurements of a shape memory effect (SME).

Before experiment has begun, the specimen was heat-treated in air for one to six hours at 800°C .

Obtained results shows Fig. 12.

Fig. 12 Shape memory effect vs. annealing time.

When the wire is bent 45 degrees as shown in Fig. 4, after heating it begins to recover to its original shape memorized as being bent. The magnitude of this recovery is defined as the SME. We must notice however, that such defined Shape Memory Effect has some error of method caused by the dislocation density at the vending point. In order to obtain the same measurement condition the vending radius must be the same for all samples, because the essential factor in shape memory alloy is not the vending angle but dislocation density.

As we see in Fig.12 longer time of the heat treatment causes a decrease in magnitude of the SMA. We may say, that in this case the heat treatment has an unfavorable influence on the shape memory effect. It is important to notice that in case of the magnetization, the longer time of oxidation causes better magnetization.

4. Conclusions

The obtained results may be summarized as follows :

For the alloy made of Fe-Mn-Cr-Si the increase of the magnetization is caused by the formation of oxide layer Fe_3O_4 .

SME decreases according to the propagation of this layer.

The same increase of the magnetization has been not observed when the heat treatment was carried out in argon.

The propagation of oxidation has an unfavorable influence on the shape memory effect.

5. References

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