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Effect of Annealing Texture on Shape Memory Effect in an Fe–Mn–Si–Cr Alloy Wire

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The annealing textures were analyzed by means of an ODF software in an Fe–27Mn–6Si–5Cr alloy wire annealed at various temperatures from 873 ~ 1223 K. At the same time, the shape-recoverable degrees of the wire specimens were measured by tensile strain at room temperature followed by recovery heating. A nearly unique ⟨001⟩ texture appears in the wire specimen annealed at 973 K, in which the highest shape recovery ratio is obtained. A synthesis orientation factor S has been definded as a parameter for estimating the tendency for polycrystalline materials to stress-induced martensitic transformation. The reason for the influence of texture on the shape memory effect is discussed.

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Keywords: *texture, orientation distribution function analysis, shape memory effect, iron-manganese-silicon alloys*

1. Introduction

The shape memory effect (SME) in Fe–Mn–Si based alloys is known to be closely related to the stress-induced $\gamma \rightarrow \varepsilon$ transformation and subsequent reverse transformation on heating. As known to all, the $\gamma \rightarrow \varepsilon$ transformation proceeds through the motion of 1/6 ⟨211⟩ partial dislocation on $\{111\}_\gamma$ planes. Therefore the preferred orientation of crystal grains in γ-phase will act an important effect on the stress-induced transformation. In the other words the component and the extent of texture of γ-phase in Fe–Mn–Si based alloys will have a great influence on the SME. There are several reports concerning to the anisotropy of polycrystalline shape memory alloys (SMAs), but most are on NiTi alloys.[1–3] W. Y. Jang *et al.*[4] had mentioned the effect of texture on SME in an Fe–15Mn–5Cr–5Co–3Si alloy. However, by means of an orientation distribution function (ODF) technique to analyze the effect of texture on SME in Fe–Mn–Si alloys has not yet been seen in the literature. In fact, the texture can be expressed by ODF more accurately and quantitatively, and the ODF analysis can be combined with many behaviours sensitive to orientation of crystal materials. In this work the annealing textures of wire samples in an Fe–27Mn–6Si–5Cr alloy were analyzed by ODF in Bunge system,[5,6] and the correlation between the recovery behaviors and annealing fiber texture is studied.

2. Experimental Procedure

The tested alloy was melted in a vacuum induction furnace by using high purity materials. The analyzed compositions of the tested alloy are as follows, Fe 67.4%, Mn 27.28%, Si 6.73% and Cr 5.25% (in mass percent). After homogenization at 1373 K for 8 h, the ingot was hot forged and hot rolled followed by hot drawing into Φ3.5 mm. All specimens were annealed at various temperatures of 873, 973, 1073 and 1223 K.

The wire specimens with a length of 2 mm were cut down from Φ3.5 mm wire and were pieced together into a ring with a diameter of 30 mm. The cross section plane of the wire specimens, which is perpendicular to the axis of wires, was mechanically ground and chemically polished for pole figure measurement. In the present work, the $\{001\}_\gamma$, $\{011\}_\gamma$ and $\{111\}_\gamma$ pole figures were measured by CoKα radiation for calculation of ODF.

The pre-straining of the wire specimens with a gage length of 50 mm was proceeded at room temperature on a tensile instrument. The residual strain of specimens was controlled in ~2% followed by recovery treatment at 873 K for 10 min. The recovery ratio η was calculated by following equation:

$$\eta = \frac{l_1 - l_2}{l_1 - l_0} \times 100(\%) \quad (1)$$

where l_0—the length of specimen before tension, l_1—the length of specimen after tension, l_2—the length of specimen after recovery.

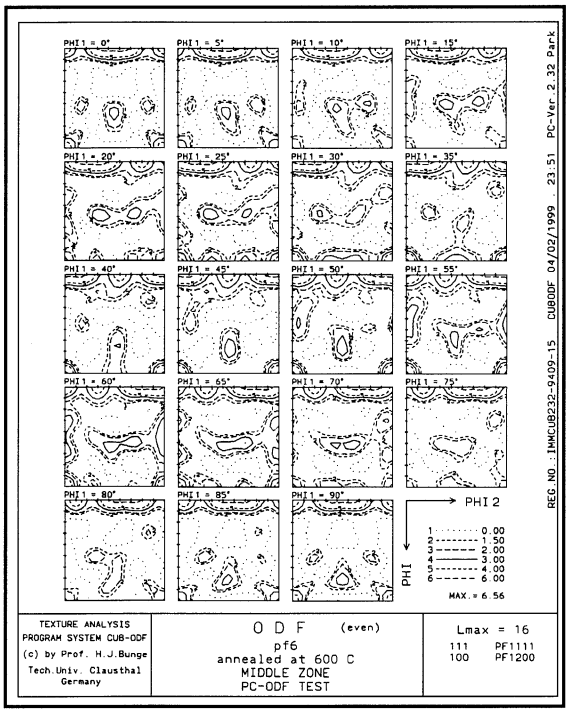
The microstructure of specimens was observed by SEM.

3. Experimental Results

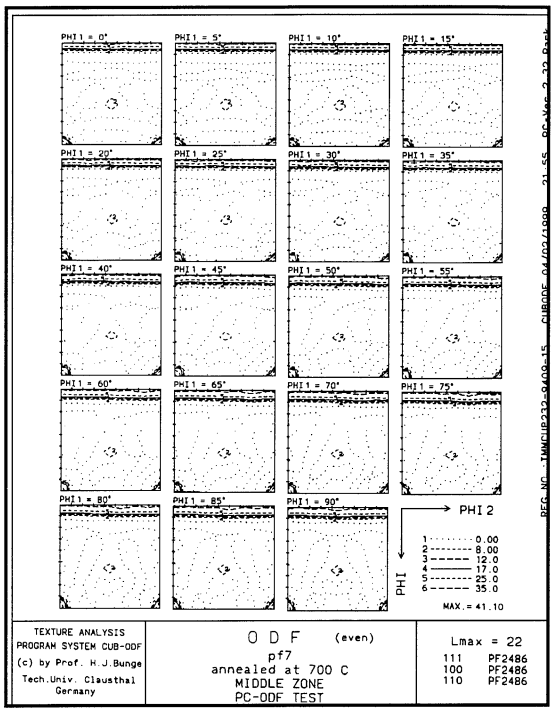
3.1 Effects of the annealing temperature on the texture

According to the measuring data of {001} {011} and {111} pole figures, the ODF figures can be obtained by the Bunge's software of analysis as shown in Fig. 1. From figures of ODF a series of skeleton lines can be obtained. Figure 2 shows one set of the skeleton lines corresponding to the Euler's angle as $\phi_1 = 45°$, $\phi = 0 \sim 90°$ and $\phi_2 = 0°$. The components and the intensity of texture in the specimens annealed at various temperatures can be determined from the skeleton lines as given in Table 1, in which the maximum intensity of texture is taken as 100%. The shape recovery ratio η and the synthesis orientation factor S are also listed in Table 1 for comparison.

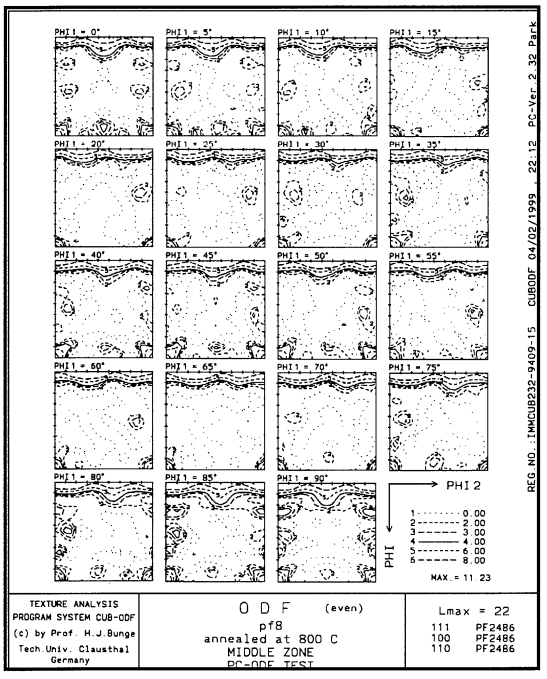
There are several kinds of fiber textures appeared in the specimens, which change with annealing temperature. The ⟨001⟩ texture in the specimen annealed at 873 K is weak and the ⟨011⟩ is very weak. At the same time, there coexist another two weak texture components ⟨111⟩ and ⟨221⟩, which appear in another skeleton lines figure, and here are not shown. While after annealing at 973 K, the ⟨001⟩ compo-



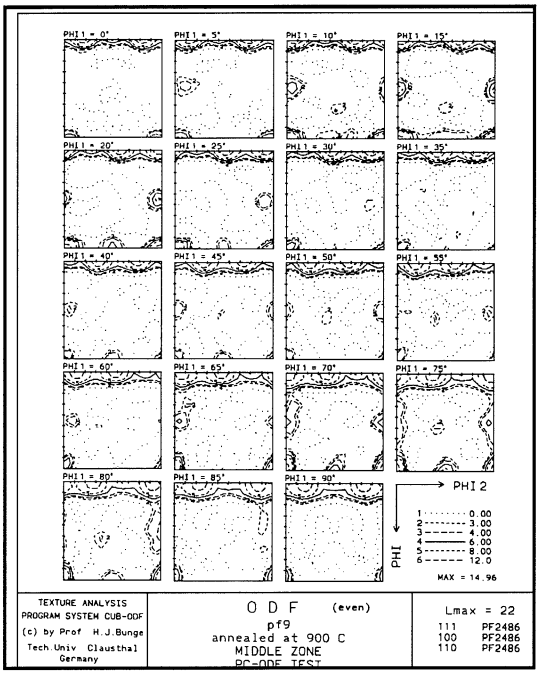
(a)



(b)



(c)



(d)

Fig. 1 ODF figures of Fe–Mn–Si–Cr wires. (a) annealed at 873 K, (b) annealed at 973 K, (c) annealed at 1073 K, (d) annealed at 1223 K.

nent becomes very strong, and other components disappear or maintain weak densities. After annealing at 1073 and 1223 K, the ⟨001⟩ texture turns to weak, though ⟨011⟩ reappears and gradually increases its intensity. The change of the intensity of texture components with annealing temperature is given in Fig. 3(a). It shows that there are multiple and weak textures in the wire specimen annealed at 873 K, while nearly unique ⟨001⟩ texture exists in that annealed at 973 K and multiple texture reappears with increasing annealing temperature.

3.2 The shape recovery ratio η

The shape recovery ratio η of the specimens annealed at

Table 1 The indices and intensity (%) of fiber texture and shape recovery ratio η of specimens annealed at different temperatures.

Anneal. temp. (K)	Indies of fiber axis $\langle uvw \rangle$					η (%)	S
	001	011	111	012	221		
873	16	1	4	0	9	38	21
973	100	4	25	0	0	72 ~ 78	100
1073	27	8	0	11	0	61	34
1223	20	15	0	0	0	55	24

different temperatures are also shown in Table 1 and Fig. 3(b). It is indicated that, the maximum of η is obtained after annealing at 973 K.

3.3 The microstructure

The microstructure observation under SEM shows that, a great number of deformed grains and recrystallized grains coexist in the specimen annealed at 873 K (see Fig. 4(a)). While after annealing at 973 K the primary recrystallization was just completed resulting in getting fine grains in the specimen (see Fig. 4(b)). After annealing at 1073 and 1223 K, the recrystallized grains grow continuously (Figs. 4(c) and (d)).

4. Discussion

4.1 The texture of wire specimens annealed at different temperatures

From Table 1 and Fig. 3(a) we can see that texture of wire specimens changes its components and intensity with annealing temperature. The reason of this phenomenon has not yet been exactly resolved. Combining with the microstructure observation, we put forward a primary explanation as follows. For annealing at 873 K, a great number of deformed grains were still retained. Correspondingly the deformation texture certainly can be detected, and at the same time a number of grains were recrystallized resulting in the appearance of recrystallization texture. While after annealing at 973 K, the recrystallization process was just completed to get homogeneous and fine grains, and the deformation texture disappears

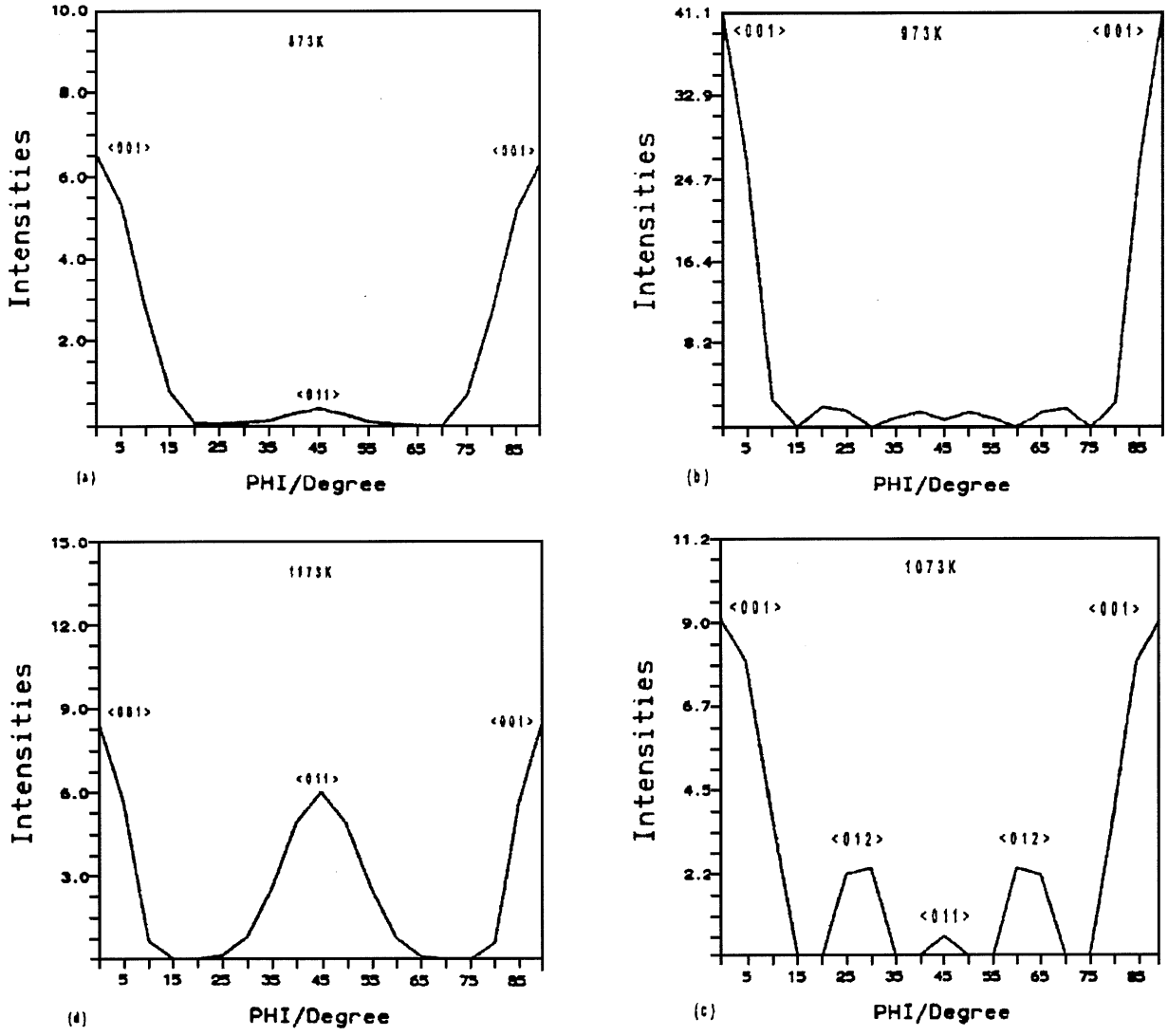


Fig. 2 Skeleton line of Fe–Mn–Si–Cr wires ($\phi_1 = 45°$, $\phi = 0 \sim 90°$ and $\phi_2 = 0°$). (a) annealed at 873 K, (b) annealed at 973 K, (c) annealed at 1073 K, (d) annealed at 1223 K.

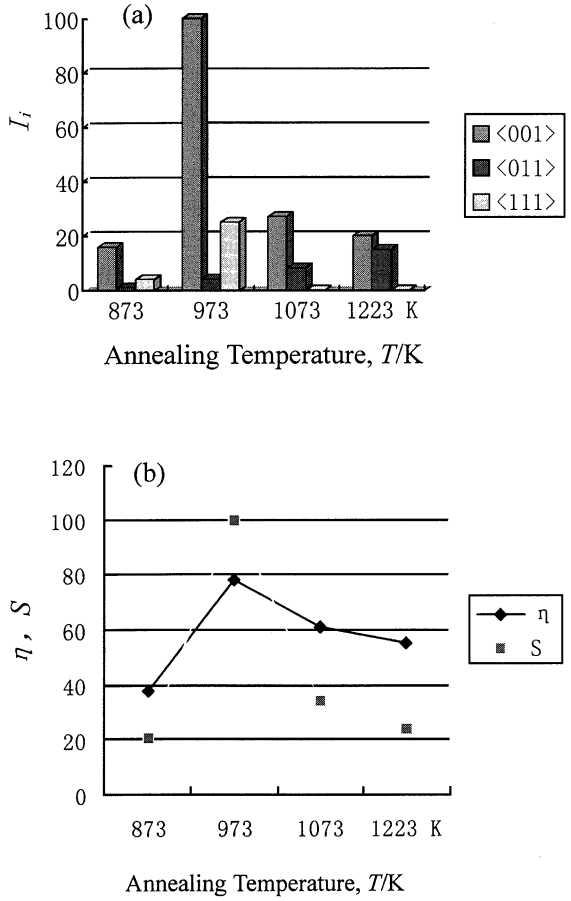


Fig. 3 Relationship between texture and shape memory effect. (a) Intensity of texture components of specimens annealed at various temperature. (b) Shape recovery ratio η and synthesis orientation factor S vs. annealing temperature T.

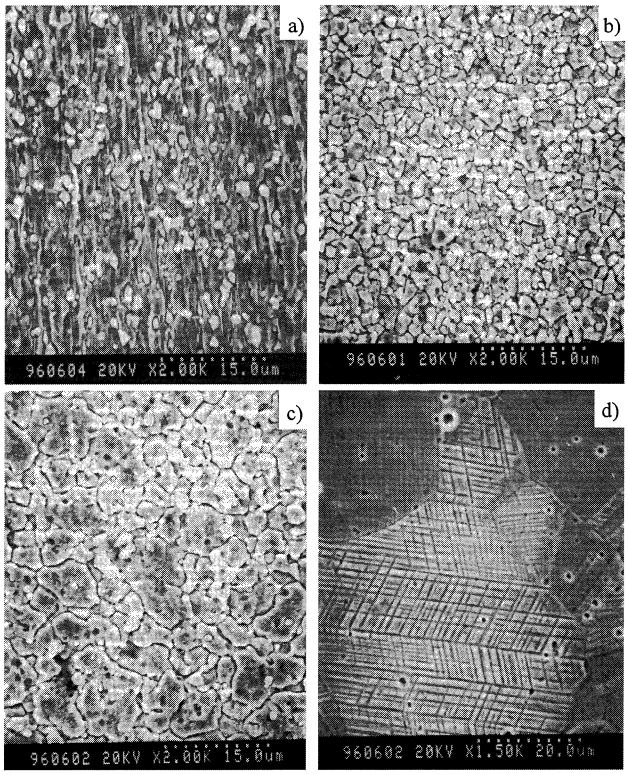


Fig. 4 SME images after annealing at different temperature. (a) 873 K, (b) 973 K, (c) 1073 K, (d) 1223 K.

resulting in nearly unique ⟨001⟩ texture. The new recrystallization texture, however, forms with increasing the annealing temperature accompanying with the directional or selective growing of grains.

4.2 The effect of texture on SME

It has been indicated that in previous work of the authors, the recovery behavior partly related to the change of grain size in the specimens[7] and also the stacking fault probability of parent phase.[8] As a rule, the structure consisted of finer grains shows a higher strength and resulting in higher shape recovery ratio in Fe–Mn–Si based SMAs. In this work, the highest shape recovery ratio η appears in the wire specimen annealed at 973 K, but not in that at 873 K. Therefore, the texture in wire materials perhaps may also take an important factor on recovery behavior of the alloys. It is worthy to notice an interesting phenomenon that, nearly unique ⟨001⟩ texture appears in the specimen annealed at 973 K, where the highest shape recovery rate is obtained. It can be explained due to the orientation correlation between the moving direction of partial dislocations ⟨211⟩ in wire specimen and the direction of the maximum shear stress during tension. As known to all, the direction of the maximum shear stress makes an angle of 45° with the tension direction. If the ⟨211⟩ direction of a grain, which is the shear deformation direction for forming stress-induced martensite, closes to the direction of the maximum shear stress, the ε-martensite transformation will be more easily induced in that grain under a smaller external stress. This orientation correlation can be expressed by Schmid factor used for the presentation of relationship between the directions of load and slip system. When a tensile direction is parallel with fiber axis, the Schmid factor (Ω) of the fiber axis ⟨uvw⟩ corresponding to ⟨211⟩ direction on {111} plane can be calculated as follows (see Fig. 5):

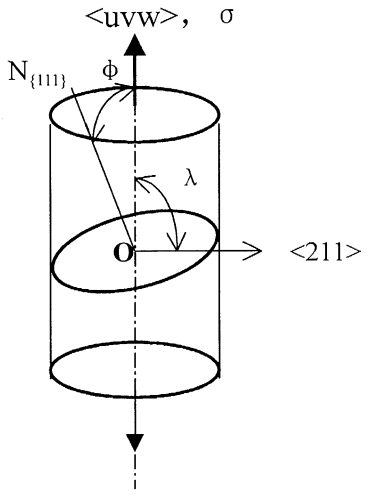


Fig. 5 Geometric relation for calculation of Schmid factor.

$$\Omega = \cos\lambda \cos\phi. \tag{2}$$

Table 2 The "average Schmid factor" of various fiber texture.

Fiber axis	Average Schmid factor corresponding ⟨211⟩ direction
⟨001⟩	0.314
⟨011⟩	0.157
⟨111⟩	0.157
⟨012⟩	0.220
⟨221⟩	0.184

The "averaged Schmid factors" along ⟨211⟩ directions on {111} planes of various fiber axes are calculated and listed in Table 2. The "average" indicates the weighted average, which includes all possible orientation relationships between fiber axis ⟨uvw⟩ and ⟨211⟩ directions on {111} planes. Obviously, the ⟨001⟩ fiber texture shows the maximum value of the averaged Schmid factor. If ⟨001⟩ directions of most of grains align along the line of tension axis, the martensite with nearly single orientation will be formed from γ-phase with the preferred orientation, which will easily reversibly transform to matrix phase during heating resulting in the enhancement of recoverable ratio. A synthesis orientation factor (S) can be defined in order to express the combined effect of the Schmid factor (Ω_i) and texture component intensity (I_i), which is calculated as follows,

$$S = \sum I_i \Omega_i . \tag{3}$$

Where I_i—the texture component intensity, which can be obtained from skeleton line; Ω_i—the Schmid factor of texture component i. The calculated results are listed in Table 1, in which S values are calculated due to setting the maximum value equal to 100. The change tendency of S is consistent with that of shape recovery ratio η. Therefore the synthesis orientation factor S may become a valuable parameter for estimating the effects of texture on SME.

5. Conclusions

(1) There are several kinds of texture components in Fe–Mn–Si–Cr SMA wire specimens annealed at different temperatures, such as ⟨001⟩, ⟨011⟩, ⟨111⟩, ⟨012⟩, ⟨221⟩ *etc.* However, nearly unique ⟨001⟩ texture appears in the wire specimens annealed at 973 K, and at the same time, it forms fine homogeneous recrystallized grains.

(2) The texture in SMA acts an important effect on its SME. The ⟨001⟩ fiber texture is beneficial to the formation of stress-induced ε martensite during tension. Therefore, the best shape recovery ratio is obtained in Fe–Mn–Si–Cr wire annealed at 973 K.

(3) The defined synthesis orientation factor S may become a valuable parameter for estimating the effect of texture on SME.

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REFERENCES

1) S. Eucken and J. Hirsch: Mater. Sci. Forum, **56–58** (1990), 487–492.
2) D. Y. Li, X. F. Wu and T. Ko: Acta metall. mater., **38** (1990), 19–24.
3) P. F. Willemse, B. J. Koopman and J. Beyer: J. Phys., **C4** (1991), 329–333.
4) W. Y. Jang, J. W. Kang, K. K. Jee, M. C. Shin and J. H. Hong: Advanced Materials '93, V/B: Shape Memory Materials and Hydrides, edited by K. Otsuka *et al.* Trans. Mat. Res. Soc. Jpn., Elsevier Science B. V., **18B** (1994), 993–996.
5) H. J. Bunge: Z. Metallkd., **56** (1965), 872–874.
6) H. J. Bunge: Textures and Microstructures, **6** (1984), 81–96.
7) B. H. Jiang, L. M. Sun, R. Li and T. Y. Hsu (Xu Zuyao): Scripta Metall. et Mater., **33** (1995), 63–68.
8) B. H. Jiang, X. Qi, S. X. Yang, W. M. Zhou and T. Y. Hsu (Xu Zuyao): Acta mater., **46** (1998), 501–510.