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Formation of texture of $Ni_{48}Mn_{31}Ga_{21}$ polycrystalline alloy by thermal simulation pack rolling technology

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Abstract: The hot deformation behavior of $Ni_{48}Mn_{31}Ga_{21}$ alloy was studied by thermal simulation rolling technology. Microstructure evolution of the alloys under different rolling processes was studied by optical microscopy(OM) and X-ray diffractometry(XRD).The results show that, by thermal simulation pack rolling technology, textures appear in polycrystalline $Ni_{48}Mn_{31}Ga_{21}$ alloy, and big cracks can be avoided under large deformation ratio. The rolling process with few passes and strong deformation makes $Ni_{48}Mn_{31}Ga_{21}$ alloy obtain (202), (400) and (323) textures of martensitic variants more easily, especially (400) texture. Besides the interface between package materials and the $Ni_{48}Mn_{31}Ga_{21}$ alloy is clear, which is beneficial for $Ni_{48}Mn_{31}Ga_{21}$ alloy to separate from pack.

Key words: Ni-Mn-Ga alloys; magnetic shape memory alloys; thermal simulation; rolling; martensitic transformation; texture

1 Introduction

Heusler type Ni_2MnGa magnetic shape memory alloy, which is a new kind of functional material with ferromagnetism and thermoelastic martensitic transformation, attracts the interests of many people all over the world in recent years. The alloy can produce large output strain and stress under the control of magnetic field, and it has combined characteristics of rapid response and accurate control. Therefore Ni_2MnGa alloys are expected to be a new generation of actuating and sensing materials[1−3].

At present, the investigations of Ni_2MnGa alloys were mostly focused on the characteristics of strain [4,5], the mechanism of strain[6], prestrain[7] and biasing field[8] of single crystalline materials. Due to the complex process of single crystalline preparation and high production cost, it is not easy to produce in a large scale. Moreover, nonhomogeneous composition of prepared single crystalline resulted in the unstabile property of martensitic transformation and magnetic-field-induced strain, which was unsatisfied for the need of practical applications[9]. Therefore, the investigations of Ni_2MnGa polycrystalline materials were enhanced[10−12] in recent years. As to polycrystalline materials, the presence of some interfaces (grain boundaries) and different orientations of grains resulted in small strain and very low mechanical response. Some textures, which are introduced to the Ni_2MnGa polycrystalline materials, will induce preferred orientation of martensitic variants. This is expected to enhance these properties[13]. At present, the investigations of possibility of obtaining textures in Ni_2MnGa polycrystalline alloys were carried out by directional solidification[14] and rapid solidification technology[15], and some good results were achieved. An effective method of obtaining texture is plastic deformation. In this paper, the possibility of obtaining texture in Ni_2MnGa polycrystalline materials was investigated by rolling process with pack and thermal simuilation technology. This will provide a new technology which can obtain much large magneic-field-induced shape memory effect in polycrystalline Ni-Mn-Ga alloy.

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2 Experimental

$Ni_{48}Mn_{31}Ga_{21}$(mole fraction, %) alloy was prepared by vacuum induction furnace, and the purity of the component metals (Ni, Mn and Ga) is at least 99.99%. Then the ingots were homogenized at 900 ℃ for 24 h in vacuum furnace. Rolling with pack was carried out at GLEEBLE 1500 thermal simulation test machine. The package is A3 steel, the dimensions of the samples are 110 mm×80 mm×60 mm, the rolling temperature is 850 ℃, and the strain rate is 1 s^{-1}. The rolling processes with more passes and weak deformation (Project 1) and with few passes and strong deformation (Project 2) were used, respectively. The characteristic transformation temperatures of homogeneous sample before rolling were analyzed by alternating current susceptibility test, of which M_s=305.3 K, M_f=297.4 K, A_s=312.6 K, A_f=318 K, T_c=336.3 K, and the martensitic transformation temperature was above the room temperature. The microstructures of samples before and after rolling were observed by Polyvar-Met metallographic microscope. The structure of the alloy was analyzed by XRD of Japanese science max-RBX.

3 Analysis of results

3.1 Behaviour of deformation during rolling process

The deformation behaviour of $Ni_{48}Mn_{31}Ga_{21}$ polycrystalline alloys during the rolling process was investigated by thermal simulation technology with the design of pack. Fig.1 shows the rolling deformation force dependence of displacement of sample 1 (using project 1) and sample 2 (using project 2) during the rolling process, and the compressive ratio of each sample is presented in Table 1. The rolling deformation forces of both sample 1 and sample 2 increase with rolling pass, the rolling deformation force of the first two passes of sample 1 has little difference, but the rolling deformation force of its third and fourth pass increased obviously. This phenomena is more obvious in sample 2, and its rolling deformation force is bigger than that of sample 1.

Table 1 Comparison of rolling ratio

Sample No.	Designed ratio/%	Practical ratio/%
1	80	77.7
2	80	76.0

The austenitic crystalline structure of $Ni_{48}Mn_{31}Ga_{21}$ alloy is $L2_1$[3], during hot processing, it can produce deformation through not only dislocation glide but also dislocation cross slip and climb. Dislocation movement can produce aggregating and tangling, then results in work hardening. At the same time, dislocation movement can also result in softening due to dynamic recovery induced by dislocation cross slip and climb. Especially, unlike dislocation counteracts on the same slip plane by dislocation climbing at high temperature, which results in the decrease of dislocation density. When work hardening rate and softening rate were in dynamical equilibrium, hot rolling phenomena of the first two passes of sample 1 (Fig.1) appeare. The density of dislocation aggregating and tangling increases with the degree of deformation, which makes softening rate smaller than work hardening rate. As a result, rolling deformation force increased with the degree of deformation. As to Ni_2MnGa alloys, dynamic recovery is its main softening mechanism. If the residual stored energy is large enough after dynamic recovery, maybe dynamic recrystallization would happen. Besides, static recovery and static recrystallization can also happen during the process of thermal retardation between two passes of rolling. The time of thermal retardation of more passes is longer than that of few passes, thus static recovery and static recrystallization happened more easily, which results in the difference of their rolling deformation force.

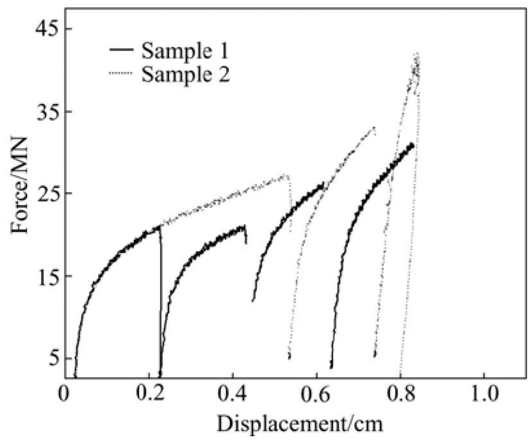

Fig.1 Compressive stress dependence of displacement of samples 1 and 2 during process of thermal simulation

Moreover, there is little difference between practical compressive ratio and designed compressive ratio. This shows that it is feasible for Ni-Mn-Ga alloys to be rolled with steel pack, and this technology can realize the goal of rolling process design.

3.2 Metallography of samples before and after rolling

Fig.2 shows the optical microstructure of homogeneous sample and rolled samples. Appearance of martensitic relief on the surfaces of samples shows that the martensitic transformation temperature is above room temperature, which is in accordance with the result of alternating current susceptibility test. Besides, marten-

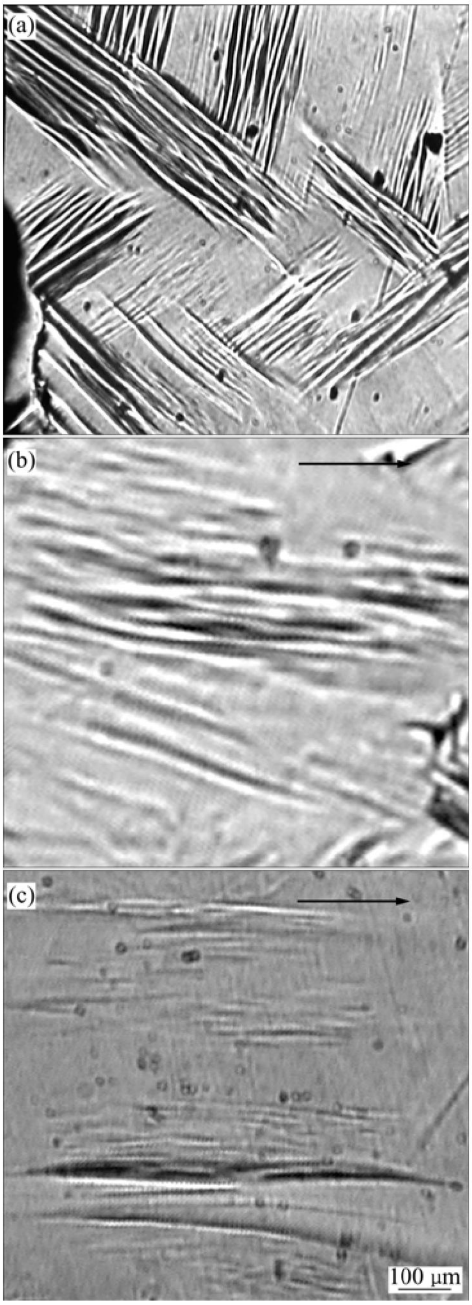

Fig.2 Metallographs of $Ni_{48}Mn_{31}Ga_{21}$ alloy before and after rolling(Arrow refers to direction of rolling): (a) Homogeneous sample; (b) Sample 1; (c) Sample 2

sitic variants stagger with each other and arrange harmoniously through self-accommodation in the homogeneous sample. After rolling, martensitic variants tend to arrange along the rolling direction, that is to say, martensitic variants form preferred orientation after rolling, which shows the formation of texture at a certain extent in polycrystalline material. LI et al[16] investigated Ni_2MnGa single crystalline alloy, and the results show that, due to the temperature gradient on the interface of growth during the growing process of single crystalline, larger oriented internal stress was produced in crystalline. According to the model of competition of elastic energy[16], when there is oriented internal stress, during competition of elastic energy, the martensitic variants whose *c* axises (short axises) is consistent with the growing direction (the direction of internal stress) are on the most favorable situation, and will nucleate and grow at first. At last, martensitic variants with preferred orientation formed. The melt-spinning technique can produce textrue in melt-spun ribbons[17]. Namely, it can produce internal stress which makes the alloy have preferred orientation. Rolling of Ni-Mn-Ga alloy can also produce texture along the rolling direction, so it can also produce oriented internal stress. Therefore, the same phenomena just like in single crystalline can happen in polycrystalline materials. During the transformation from austensite to martensite, the existence of oriented internal stress resulted in the formation of orientational texture of martensitic variants.

Fig.3 shows the interface between steel pack and $Ni_{48}Mn_{31}Ga_{21}$ alloy after rolling. The interface is very clear, which shows that no reaction happens during rolling. It is beneficial for $Ni_{48}Mn_{31}Ga_{21}$ alloy to separate from pack.

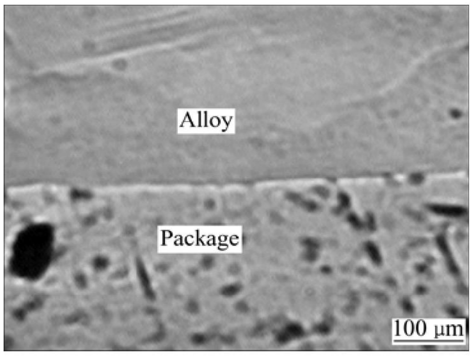

Fig.3 Interface between package materials $Ni_{48}Mn_{31}Ga_{21}$ alloy

Besides, big cracks, as reported in Ref.[13], didn't appear in the $Ni_{48}Mn_{31}Ga_{21}$ alloy. So, plastic deformation can be performed on this alloy. The deformation is related to the rolling parameters such as rolling temperature and rolling rate. In a word, reasonable process of pack rolling could decrease the brittleness and prevent the presence of big cracks.

3.3 XRD analysis of samples before and after rolling

Fig.4 shows the XRD spectra of $Ni_{48}Mn_{31}Ga_{21}$ samples before and after rolling. The calibration results of diffraction index shown that the interplanar distance of every diffraction peak was almost the same as martensitic phase with tetragonal structure, and its crystalline parameters were a=0.595 8 nm and c=0.567 7 nm. By comparison, the position of peaks of sample 1 is the same as sample 0, but their relative diffracting intensities are different. $(202)_M$ peak of sample 2 are stronger than that of sample 0, and extra $(400)_M$ and $(323)_M$ peaks with strong intensity appear. This shows that the compositive phases of sample after rolling do not change, but textures of $(202)_M$, $(400)_M$ and $(323)_M$ form in sample 2 with intense deformation. And it is easier to obtain textures by process with few passes and strong deformation than by process with more passes and weak deformation. The reason is not clear, and it is worth studing further.

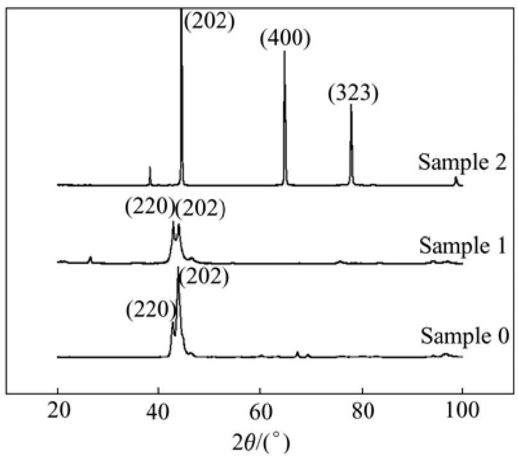

Fig.4 XRD spectrum of $Ni_{48}Mn_{31}Ga_{21}$ sample before and after rolling

4 Discussion

During the deformation of polycrystalline, in every grain only when at least five glide systems move, the alloy has plasticity. But in fact, the motion of few glide systems palys the main role in every grain. The formation of textures should attribute to rotation of grains of different orientations during the deformation. The rolling process means that there is tension stress along the rolling direction and compressive stress perpenducular to the rolling direction. During rolling, mutual interaction of the two stresses makes tension axis turn to glide direction, and every grain arranges accommodately along the rolling direction. The analysis of metallography shows that most of the grains extend along rolling direction in samples after rolling, and subgrains appear. The formation of subgrains is due to recovery and recrystallization, and the subgrains are elongated along the rolling direction. At last, deformation textures form in the samples. Just because of the existence of deformation textures, they restrict the accommodation of martensitic variants during cooling, which makes martensitic variants perfectly arrange along the rolling direction and results in the formation of martensitic structure with texture orientation. The investigation of CHEN et al[18], shows that the preferred growing direction of Ni_2MnGa single crystalline is [100], and it can also grow along other directions. So, as to Ni_2MnGa polycrystalline, during hot rolling, under the action of oriented stress, grains should also be elongated along the [100] directon. Then the preferred directon results in the formation of martensitic textures along [100] direction during cooling, which is in accordance with the presence of (400) peak with strong intensity in XRD spectrum. Besides, the results in this paper are mostly in accordance with investigation of LI et al[15]. They obtained exclusive (400) texture by melt-spinning technology, however, several texture directions were obtained in this paper. So, what should be done furtherly is to optimize the parameters of process in order to prepare alloys only with (400) texture by hot rolling technology.

It produces strong anisotropy in Ni_2MnGa alloy due to the existence of textures, and this is benificial for the alloy to obtain large transformation strain and magnetic-induced-strain. According to O'Handley's analytic thermodynamics model[19], the formula of magnetic-field-induced strain (ε_{MFIS}) is as follows:

$$\varepsilon_{MFIS}=\frac{2K_U h(1-\frac{h}{2})-\sigma\varepsilon_0}{C_{eff}\varepsilon_0} \quad (1)$$

Here,

$$h=\frac{\mu_0 M_S H}{2K_U}$$

where K_U is anistropic energy. It can be seen from Eqn.(1) that ε_{MFIS} is increased with anistropic energy. So, the textures, which are obtained by hot rolling, are beneficial for Ni_2MnGa to obtain much large magnetic-field-induced strain in the martensitic state, and hot rolling provides a way for Ni_2MnGa alloy to obtain large strain.

5 Conclusions

1) It is feasible for $Ni_{48}Mn_{31}Ga_{21}$ polycrystalline alloys to be deformed plasticly by thermal simulation pack rolling technology. And it can not only obtain textures, but also prevent the appearance of big cracks under larger deformation ratio. Furthermore, the interface between package materials and the $Ni_{48}Mn_{31}Ga_{21}$ alloy is clear, which is beneficial for $Ni_{48}Mn_{31}Ga_{21}$ alloy to separate from packing.

2) The rolling process with few passes and strong deformation makes $Ni_{48}Mn_{31}Ga_{21}$ alloy more easily obtain (202), (400) and (323) textures of martensitic variants, especially (400) texture.

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