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# Hardness Change of Ferrous Martensite by Deformation

By

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A series of Fe-Ni-C martensites having transformation twins and an Fe-Cr-Ni-C martensite not having transformation twins but dislocations were rolled at 200°C, room temperature and liquid nitrogen temperature. The hardness change and the deformation mode of the martensite were examined. The twinned martensites were deformed by slip, when the carbon content of the martensite was low or the deformation temperature was high. In this case, the hardness change with reduction of deformation showed usual strain-hardening. However, when the carbon content was high or the deformation temperature was low, the martensite was deformed by twinning. In this case, the martensite showed strain-softening at a small percent of reduction, and then it was strain-hardened rapidly beyond the minimum hardness with increase in reduction. The untwinned martensite was deformed by slip, and the hardness change with reduction showed a usual strain-hardening curve.

## 1. Introduction

Recently, the fine structure of martensite has been clarified by means of transmission electron microscopy<sup>1)</sup>. In the ferrous martensites, there are twinned martensite and untwinned martensite with dislocations. The former can be observed in high carbon steel, Fe-high Ni and Fe-high Ni-C alloys, etc., and the latter is in low carbon steel, Cr-steel, stainless steel, etc.

The ferrous martensites are usually very hard and brittle. But, low carbon martensites are fairly ductile, so the investigation of high-strength materials will make much progress by cold working in low carbon martensite such as PH stainless steels and maraging steels. However, the hardness change and deformation mode of martensite by deformation have not yet been examined fundamentally.

The authors considered that the deformation mode and the hardness change of martensite by deformation should have some relation to the kind of lattice defects in the martensite. The purpose of this work is to clarify those behaviors. In the previous paper<sup>2)</sup>, it was explained that Fe-27.6% Ni-0.44%C martensite having transformation twins was deformed by twinning at room temperature, and the

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detwinning of transformation twins was observed at a small percent of reduction and hence such a slightly deformed martensite showed strain-softening.

In relation to this, R.H. Richman<sup>3)</sup> examined the deformation modes of Fe-Ni-C martensites at room temperature by means of optical microscopy and X-ray studies. According to his results, when the carbon content of the alloy was less than 0.05 or 0.1%, the martensite was deformed by a wavy slip. When the carbon content was 0.1-0.4%, the martensite was deformed by both modes of slip and twinning. Containing more than about 0.4%C, it was deformed by twinning at room temperature. Moreover, he discussed the habit plane of deformation twins. G. Krauss and W. Pitsch<sup>4)</sup> reported the deformation twins of Fe-33%Ni martensite.

## 2. Specimens and Experimental Procedure

A series of Fe-Ni-C martensites having transformation twins (twinned martensite) and an Fe-Cr-Ni-C martensite having no transformation twins but dislocations (untwinned martensite) were used as the specimens. The commercial pure iron, electrolytic nickel and electrolytic chromium were melted in vacuum, hot-forged and rolled to get plate-shaped specimens of 3 mm in thickness. The chemical compositions are shown in Table 1.

Table 1. Chemical compositions of alloys (%).

Alloys	C	Ni	Cr	Fe
Fe-Ni-C	0.09	26.6	—	Bal.
	0.28	24.8	—	Bal.
	0.60	19.4	—	Bal.
Fe-Cr-Ni-C	0.38	7.6	12.7	Bal.

These specimens were full-annealed at 1150°C for 5 hours in vacuum, and cooled in the furnace. They were austenitized at 900°C for 3 hours, cooled in the furnace and then deep-cooled in liquid nitrogen (−196°C) for 30 minutes. The martensitic transformation was accomplished by these processes. The Ms temperature of these specimens was laid in the range from −20 to −50°C. These martensitic specimens were rolled at three temperatures, that is, 200°C (oil bath), room temperature and liquid nitrogen temperature.

After rolling, the specimens were polished electrolytically, etched by HCl-pical and the microstructures were observed by optical microscopy. The microhardness tests were performed at room temperature by 25 or 50 g load. The hardness values indicated in Figures were the average of 8 readings except the

maximum and minimum values from 10 readings, and the marks of I represented the fluctuation of the 8 readings.

### 3. Results and Considerations

#### 3.1 Fe-Ni-C Martensite (Twinned Martensite)

The Fe-26.6%Ni-0.09%C martensite shown in Table 1 was rolled at 200°C, room temperature and liquid nitrogen temperature. Photo. 1 shows an optical micrograph of the specimen rolled 21% in reduction at room temperature. It is shown that the specimen is deformed by slip. Photo. 2 shows a structure of the specimen rolled 20% in reduction at liquid nitrogen temperature. Although the deformation twinning was slightly found by careful observation as shown in Photo.



Photo. 1. Optical microstructure of Fe-26.6%Ni-0.09%C martensite deformed 21% in reduction at room temperature. Etchant: HCl-picral,  $\times 800$ .



Photo. 2. Optical microstructure of Fe-26.6%Ni-0.09%C martensite deformed 20% in reduction at boiling point of liquid nitrogen. Etchant: HCl-picral,  $\times 800$ .

2, the specimen was mainly deformed by slip. Such a little bit of deformation twinning in the martensitic structure was occasionally observed even in non-deformed Fe-Ni martensite<sup>4</sup>). After all, in Fe-26.6%Ni-0.09%C martensite, the deformation mode was slip at the temperature range from 200°C to liquid nitrogen temperature.

The hardness change of this martensite with reduction at these temperatures showed usual strain-hardening as illustrated in Fig. 1. There is no trend of strain-softening in these curves. In Fig. 1, three curves approach one another, and then

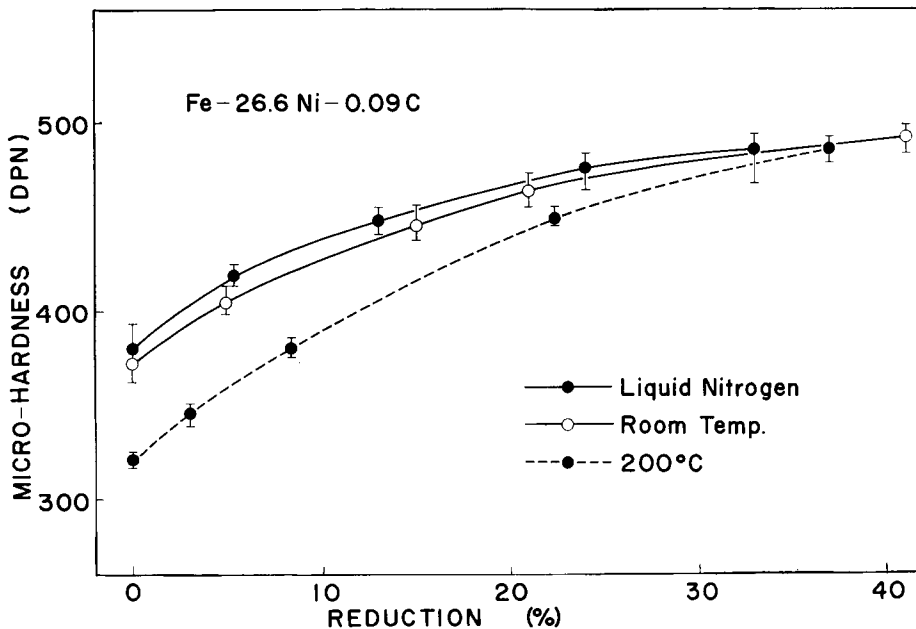


Fig. 1. Hardness changes of Fe-26.6%Ni-0.09%C martensite with reduction by rolling at three temperatures.

beyond 30%-reduction they show almost the same hardness. Namely, the higher the rolling temperature, the more the degree of hardening rises, because of strain ageing effect. In these experiments, every specimen even in non-deformed (0%-reduction) was held at the deformation temperature illustrated by Fig. 1 for about 10 minutes. Therefore, the hardness of specimens deformed at 200°C were lowered by tempering effect.

In Fe-24.8%Ni-0.28%C martensite, the specimens were deformed by slip at 200°C (Photo. 3), by both modes of slip and twinning at room temperature (Photo. 4) and by twinning at liquid nitrogen temperature (Photo. 5). In the case of deformation at room temperature, since the specimen was polycrystalline,



Photo. 3. Optical microstructure of Fe-24.8%Ni-0.28%C martensite deformed 19% in reduction at 200°C. Etchant: HCl-picral,  $\times 800$ .



Photo. 4. Optical microstructure of Fe-24.8%Ni-0.28%C martensite deformed 20% in reduction at room temperature. Etchant: HCl-picral,  $\times 800$ .

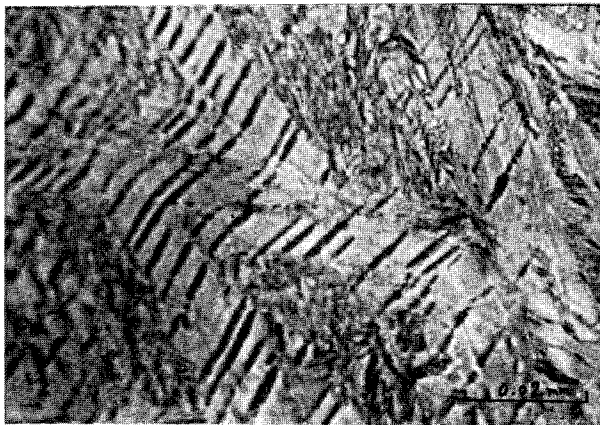


Photo. 5. Optical microstructure of Fe-24.8%Ni-0.28%C martensite deformed 3% in reduction at boiling point of liquid nitrogen. Etchant: HCl-picral,  $\times 800$ .

some of martensite plates in which favourable shearing stress for slip was applied were deformed by slip, and the others in which favourable shearing stress for twinning was applied were deformed by twinning, because the critical resolved shearing stress for slip was nearly equal to that for twinning at this temperature.

The hardness changes of Fe-24.8%Ni-0.28%C martensite by deformation at these temperatures are shown in Fig. 2. By deformation at 200°C, the speci-

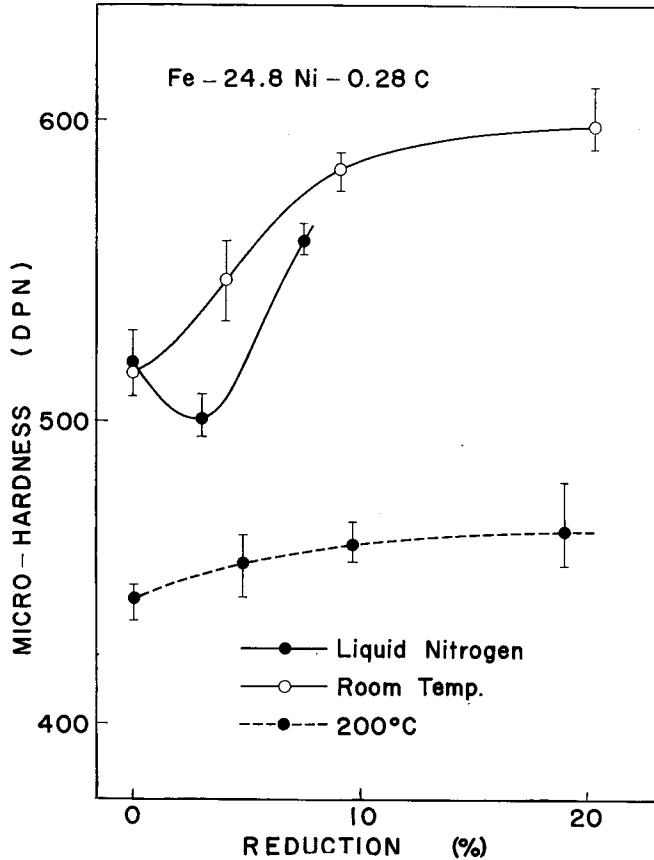


Fig. 2. Hardness changes of Fe-24.8%Ni-0.28%C martensite with reduction by rolling at three temperatures.

men was deformed by slip, and showed usual strain-hardening. At room temperature, the specimen was deformed by slip and twinning, and showed a trend of strain-softening at a small percent of reduction. At liquid nitrogen temperature, the specimen was deformed by twinning, and showed obvious strain-softening at a small percent of reduction and then, a rapid increase in hardness. This tendency of hardness change was the same as former results<sup>2)</sup> of Fe-27.6%Ni-0.44%C martensite.

In the case of Fe-19.4%Ni-0.6%C martensite, the specimens were deformed by slip at 200°C, and by twinning at room temperature and liquid nitrogen temperature. Photo. 6 shows deformation twinning in the specimen deformed 7.6% in reduction at room temperature. The hardness changes of the specimens deformed

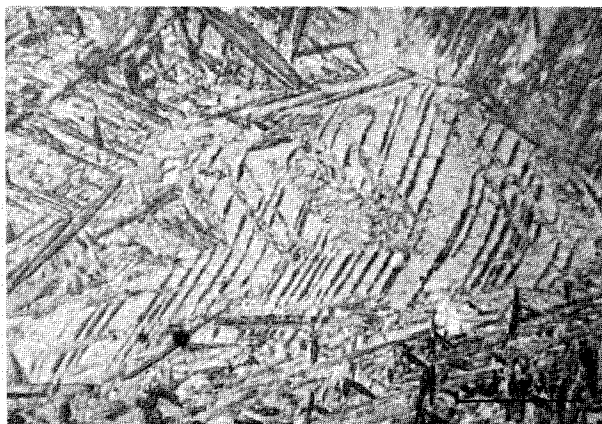


Photo. 6. Optical microstructure of Fe-19.4%Ni-0.6%C martensite deformed 7.6% in reduction at room temperature. Etchant: HCl-picral,  $\times 800$ .

at these temperatures are shown in Fig. 3. The specimen deformed at 200°C shows usual strain-hardening but the specimens deformed at room temperature and liquid nitrogen temperature show obvious strain-softening and then hardening.

In the Fe-Ni-C martensites with transformation twins, when the carbon content was low, the martensite was deformed by slip, and when the carbon content was high, the martensite became deformed by twinning. Also, when the deformation temperature was high, the martensite was deformed by slip, and when the deformation temperature was low, the deformation twinning took the place of slip. This tendency is the same as the deformation mode of  $\alpha$ -iron. It would, therefore, be expected that the martensite would be easily deformed by twinning at high strain rate.

It was noticed that when the martensites having transformation twins were deformed by twinning, they showed strain-softening. As described in the previous paper<sup>2)</sup>, the transformation twins were introduced into Fe-Ni-C martensite in the spacing of 100–400Å. The strain-softening of Fe-Ni-C martensite at low reduction was caused by detwinning of the transformation twins associated with the deformation twinning on the same plane and in the same twinning direction as the transformation twins. The rapid strain-hardening of the martensite at high reduction after softening was caused by multiple deformation twinning intersected with



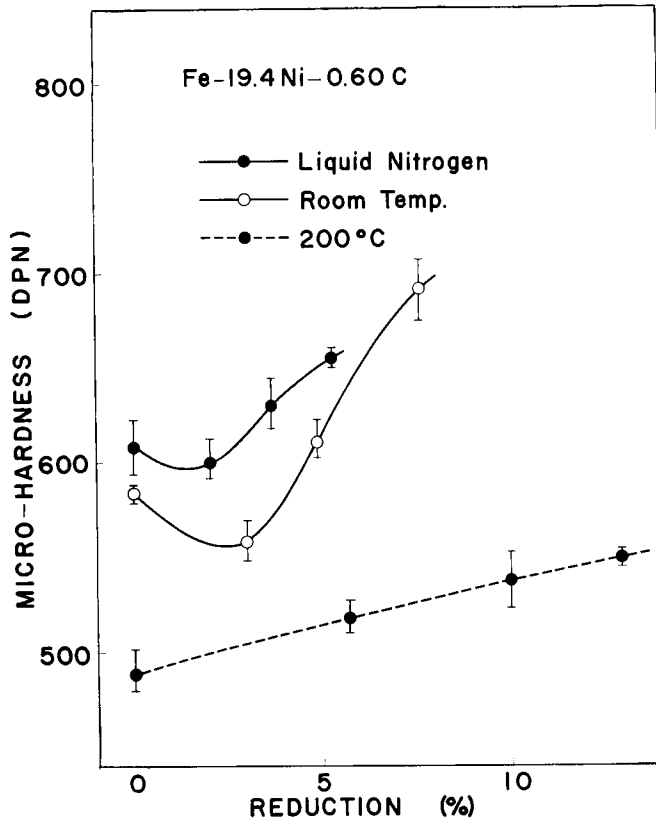


Fig. 3. Hardness changes of Fe-19.4%-Ni-0.6%C martensite with reduction by rolling at three temperatures.

the transformation twins and the deformation twins each other.

When the martensite is deformed by slip, there has been the opinion that the twin boundaries do not play as any kind of obstacles for dislocation motion in the martensite<sup>5-7)</sup>. For example, G. R. Speich et al<sup>7)</sup> reported that in the Fe-Ni martensites, the twinned martensite (containing more than about 25%Ni) had not higher yield strength than the untwinned martensite containing less than about 25% Ni. They considered for this fact that the twin boundaries could not play as obstacles for deformation. However, this could be questionable.

Fe-32%Ni (0.004%C) martensite was deformed by slip at room temperature. Photo. 7(a) shows a transmission electron micrograph of this martensite at 40% in reduction. The mark "→" indicated in the micrograph shows the trace of transformation twinning plane of  $(\bar{1}21)$  and "→" shows the trace of slip plane of (011) which passes through the matrix and the twin. It can be observed that the trace of transformation twins are finely kinked by the trace of slip plane at the

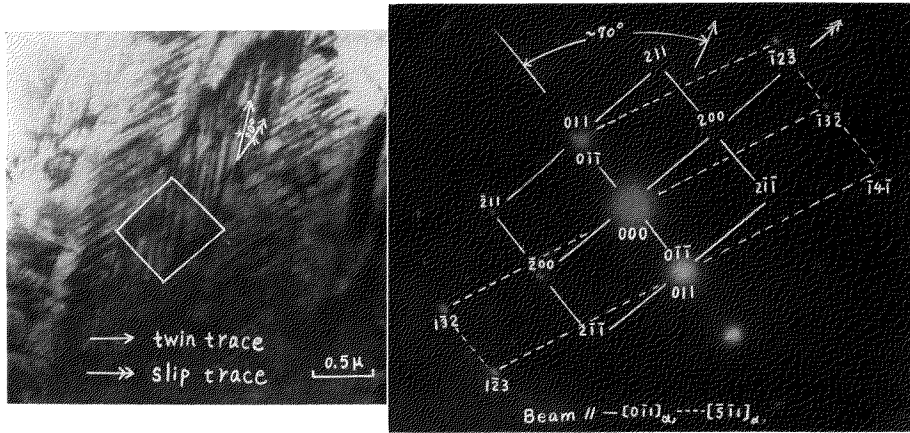


Photo. 7. (a) Transmission electron microstructure of Fe-32%Ni martensite deformed 40% in reduction at room temperature, and (b) electron diffraction pattern at the selected area framed in the micrograph (a).

intersections, and that the slip has taken place on the same slip plane in matrix and twin across the twin boundary. Generally, the slip deformation on the slip plane passing through the matrix and the twin is the simplest and the easiest mode. Even in such a simple case, the direction of slip is  $[\bar{1}\bar{1}\bar{1}]_m$  in the matrix and is  $[1\bar{1}\bar{1}]_t$  in the twin. The direction of slip should change at the twin boundary. In the case of Photo. 7, changing angle of direction of slip at the twin boundary was about  $70^\circ$ . Therefore, the twin boundary could be a kind of obstacle against to deformation by slip, especially in the case that lots of twin boundaries lay closely in the martensite with transformation twins. P.M. Kelly et al<sup>8)</sup> have reported that although the twin boundary is also one of the considerable obstacles against to deformation by slip, twinned martensite in Fe-Ni alloy, in the case of results by Speich et al<sup>7)</sup>, has lower dislocation density than the untwinned martensite, because of the difference of second shear mechanism in accommodation during martensitic transformation. And hence, twinned martensite does not show a particularly higher strength than untwinned martensite. This would be reasonable.

When twinned Fe-Ni-C martensite was deformed by slip, the martensite was strain-hardened in the usual manner by increasing dislocation density.

### 3.2 Fe-Cr-Ni-C Martensite (Untwinned Martensite)

Fe-12.7%Cr-7.5%Ni-0.38%C martensite having no transformation twins but dislocations were deformed by rolling at room temperature and liquid nitrogen temperature. The hardness of the martensite with reduction of deformation was gradually increased at both temperatures in the same manner as strain-hardening of usual metals, as shown in Fig. 4. Photo. 8 shows optical microstructure of the

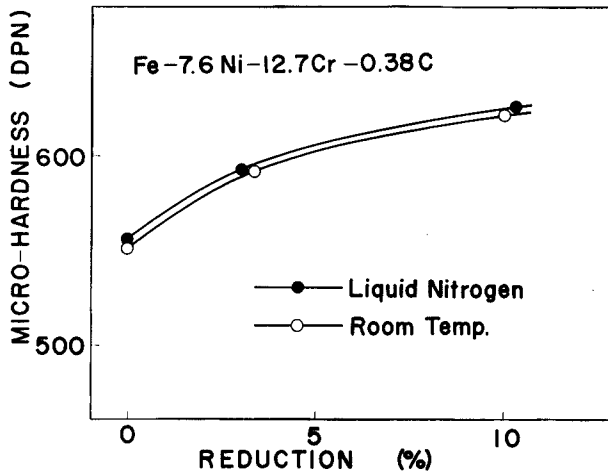


Fig. 4. Hardness changes of Fe-7.6%Ni-12.7%Cr-0.38% C martensite with reduction by rolling at two temperatures.

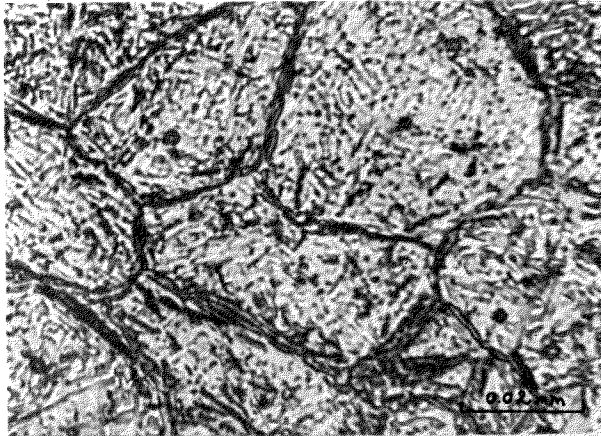


Photo. 8. Optical microstructure of Fe-7.6%Ni-12.7%Cr-0.38% C martensite deformed 10.3% in reduction at liquid nitrogen temperature. Etchant: HCl-pical,  $\times 800$

martensite deformed 10.3% in reduction at liquid nitrogen temperature. The microstructure did not show any information on deformation twinning in the deformed martensite. The martensite was deformed by slip at both temperatures.

#### 4. Summary

The deformation mode of twinned martensite (Fe-Ni-C) depended on carbon content and deformation temperature. When the carbon content was low or the deformation temperature was high, the martensite was deformed by slip and

showed usual strain-hardening. With increasing carbon content or with decreasing deformation temperature, the martensite became deformed by twinning and showed stain-softening at low reduction and then rapid strain-hardening at high reduction.

In the case of untwinned martensite (Fe-Cr-Ni-C), the martensite was deformed by slip at all temperatures and showed usual strain-hardening.

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