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Occurrence of shear bands in the order–disordered FeCo–2V alloy

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Shear bands have been observed at about 35° to the rolling plane when the alloy was cold rolled to about 5 to 10% reduction. Although this alloy consists essentially of a bcc lattice in the disordered state, brought about by quenching, and of a CsCl type of lattice in the ordered state, the bands can similarly be obtained for both states. From TEM observations, the planes on which the bands may be formed seemed to be {011} and {112}, corresponding to the slip and twinning planes, respectively, of bcc metals and alloys. An attempt has been made to interpret the formation of the shear bands: since cross slip may be difficult to obtain in the alloy because of the existence of the superlattice, sites of stress concentrations are produced relatively easily, and these are relaxed by the localized shearing and formation of shear bands.

1. Introduction

Since shear bands were first observed with deformation by Adcok [1] on Cu–Ni alloy and also by Cook and Richards [2] on Cu–Zn alloy, many investigators have reported the same phenomenon. Most of the bands have been observed in fcc metals and their alloys: Cu [3–6], Ag [7, 8], Cu–Ni [1], Cu–Zn [2, 3, 9–19], Cu–Cr [20], Cu–Al [4, 21], Al–Cu [2], Al–Mg [23, 24] and austenitic stainless steel [25]. For bcc alloys, a few cases are known: maraging steels [26, 27], aluminium-killed steels [28], and niobium-stabilized steels [29]. The bands in fcc alloys have been seen at relatively low reductions by cold rolling, but those in bcc alloys have hitherto been observed only by relatively high reductions, e.g. about 70% or in the vicinity of the necking region. The present paper reports the occurrence of the bands in an FeCo–2V alloy under a small cold-rolling reduction, i.e. about 5 to 10%, in contrast to others reported so far for bcc metals.

The structure of the FeCo–2V alloy used is mainly bcc when quenched from the temperature above 800° C, and it can convert into a CsCl type of superlattice when aged at a temperature below about 730° C [30, 31]. If the atoms involved, iron and cobalt, could be taken as equivalent in size, then the lattice of this alloy can be considered to be basically bcc, in both disordered and ordered states. This unexpected occurrence of shear bands in the bcc lattice, thus, is believed to arise from the difficulty to cross slip because of the existence of the ordered lattice. (Buckley [32] has shown in an FeCo–0.4 Cr alloy, bands similar to that obtained in the present study, although he has recognized it to be deformation bands, rather than shear bands.)

2. Experimental procedures

The experimental procedures and specimens are the same as those reported in previous papers [30, 31]. Electrolytic-iron and -cobalt and ferro–vanadium alloy were melted in vacuo, and were cast into a 17 kg ingot. The ingot was heated at 1200° C for 4 h and hot rolled to plates 1 to 5 mm thick and 30 to 60 mm wide. Plates with a thickness of 5 mm were mainly used for the observation of shear bands. The plates were heated in the range 800 to 1100° C and quenched in iced-brine prior to the cold rolling which produces the shear bands.

The chemical composition of the ingot is approximately as follows: Fe 49.6 wt %, Co 48.5 wt %, V 1.75 wt %.

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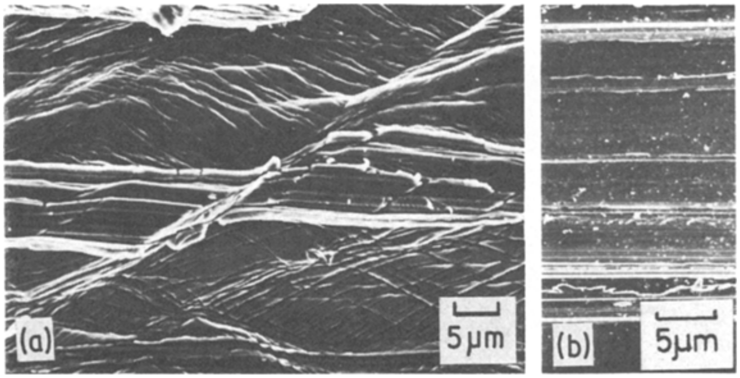

Figure 1 A shear band occurring in the specimen cold rolled to 30% after quenching from 800° C: (a) a typical band, and (b) scratches before rolling.

3. Experimental results

3.1. Microscopical observation of the shear bands

Fig. 1 is a scanning electron micrograph of a typical shear band. The specimen was quenched from 800° C, one side of the specimen was polished and scratches were drawn parallel to the rolling direction, on the polished surface. The specimen thus obtained was cold rolled to a 50% reduction. It can be seen that a group of several scratches has been sheared diagonally and the surface is also covered with numerous wavy slip lines. The micrograph of Fig. 2 was obtained by etching a section of the same specimen as that in Fig. 1, and shows the bands on a longitudinal (Fig. 2a) and a transverse section (Fig. 2b). The bands occur at about 35° to the rolling plane, also as observed in fcc metals and alloys.

As explained in a previous paper [30], this alloy can show three different structures, depending on the temperature of the heat treatment. A massive martensitic structure, a mixed structure consisting of ferrite and martensite, and a ferritic structure are obtained by quenching from temperatures of >1000, 925 to 980, and 730 to 840° C, respectively. Shear bands, however, can be observed in all the specimens independently of the different structures, and the length of the bands has been recognized to be proportional to the grain size. Fig. 3 shows the structure of the bands after a 20% (Fig. 3a) and a 90% (Fig. 3b) reduction of a specimen which was, prior to quenching from 800° C, subjected to a martensitic transformation to refine the grains. The bands are clearly shorter and denser than those shown in Fig. 2. Shear bands can be formed at about 5 to 10% reduction, and their number increases with the increasing reduction, but after a reduction of 70% they became difficult to observe under optical microscopy, as shown in Fig. 3b, although they still exist. The angle between the shear bands and the rolling plane seems to be about 35° below about a 50% reduction, and to approach about 30° over about 70% reduction is required.

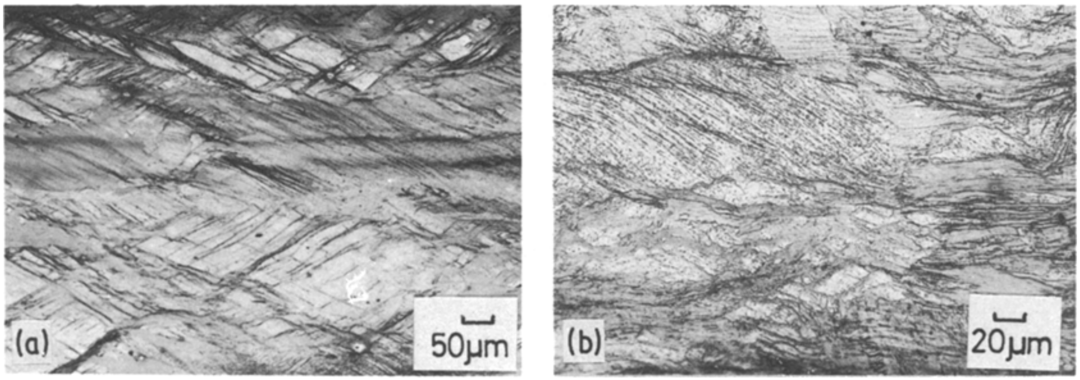

Figure 2 Shear bands on different sections occurring in the specimen cold rolled to 50% after quenching from 800° C: (a) longitudinal section, and (b) transverse section.

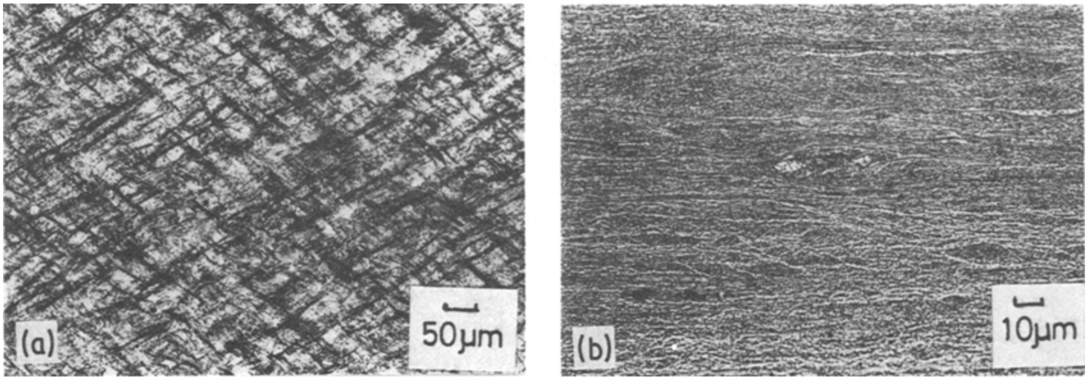

Figure 3 Shear bands varying with cold rolling reduction for the specimens quenched from 800° C: (a) 20%, and (b) 90%.

Fig. 4 shows the shear bands occurring, after about 30% cold rolling, on the specimens ordered at 500° C for 1 h (Fig. 4a) and at 600° C for 16 h (Fig. 4b). The specimens were first subjected to a martensitic transformation to refine the grains, cold rolled to 90% reduction, quenched after annealing at 800° C for 5 min, separately aged under the stated conditions, and finally cold rolled to about 30%. The bands are more homogeneous and denser than those showing in Figs. 1 to 3. Although shear bands can be more clearly seen in the transverse section in Fig. 4; the number of bands decreases with an increasing degree of ordering (higher in the latter than in the former ageing

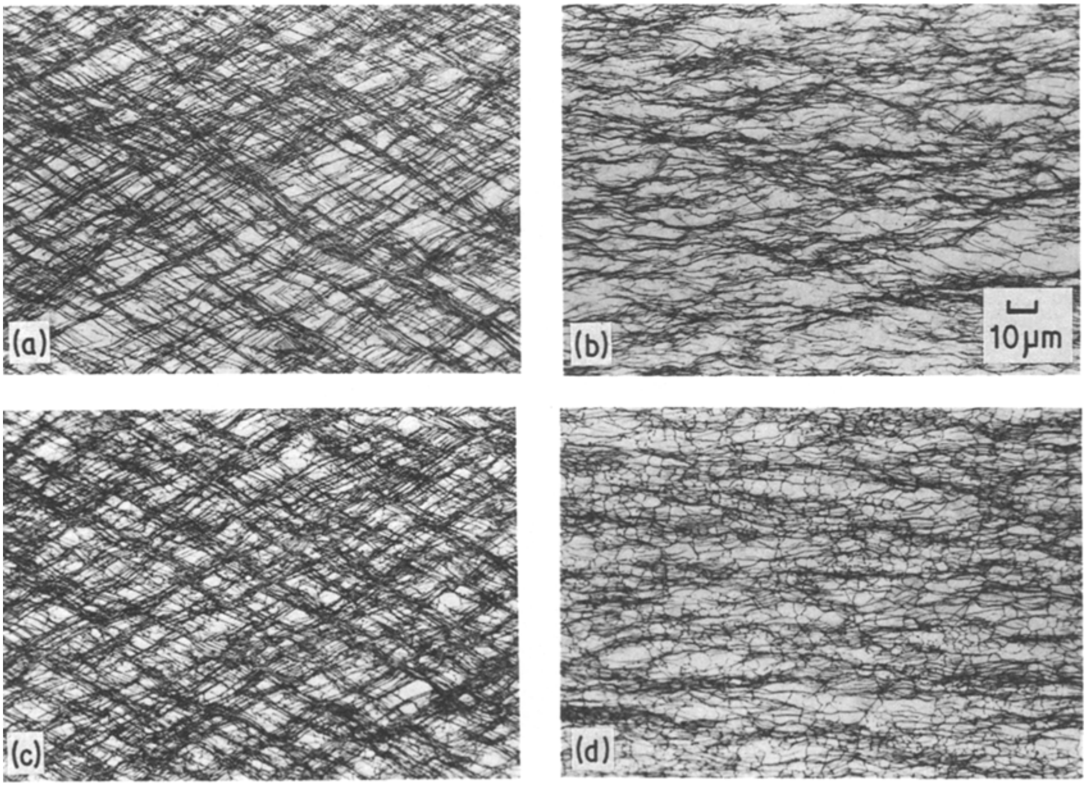

Figure 4 Shear bands occurring on ordered specimens. The specimens, prior to rolling after ordering, are followed by the processes: transformed martensitically, cold rolled to 90%, reannealed at 800° C, and then quenched from the temperature (all the same magnification): (a) longitudinal section of the specimen cold rolled to 30% after ageing at 500° C for 1 h; (b) the transverse section for the same as (a); (c) longitudinal section of the specimen cold rolled to 30% after ageing at 600° C for 16 h; (d) the transverse section for the same as (c).

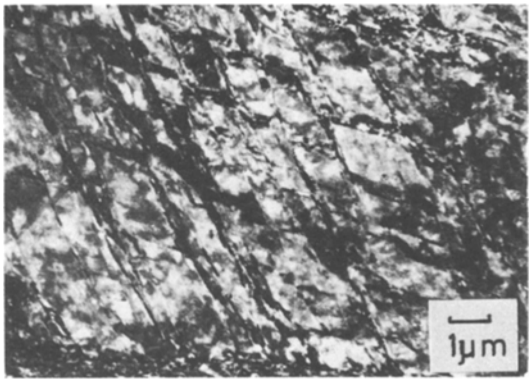

Figure 5 Crossing shear bands in thin foil micrograph occurring in the same specimen as Fig. 2.

process [31]). Since the textures both in specimens are almost identical to each other [31], the difference in the waviness of bands may be considered to indicate a difference in the ability to cross slip.

3.2. Transmission electron microscopic observations

To observe the shear bands, thin folis were prepared from the specimens which were cold rolled to 50% reduction after quenching from 800° C; the observations were carried out on the foils perpendicular to the transverse direction of the plates. In Fig. 5, bands which were sheared along two different directions are observed, corresponding just to the optical micrograph above. In a higher magnification, thin and sheared plates can be recognized, as in Fig. 6, where one plate is seen to be sheared by another plate. Fig. 7 shows two kinds of (1 1 1) planes; in Fig. 7a, there are several bands running from the right top to the left bottom, and arcs in the diffraction pattern occur. This arcs suggest that the individual interior of the bands is divided into many orientations, and is preferentially deformed, compared to other regions. Such arcs have been observed also in fcc metals and alloys, where the deformation has been seen to occur preferentially in the shear bands [5, 12, 23]. In Fig. 7b, where there are two bands parallel to the $[\bar{1}2\bar{1}]$ and $[2\bar{1}\bar{1}]$ directions, no arcing can be seen, presumably these bands being thin twins accompanied by the deformation.

An analysis of the traces of the bands has been carried out on sixty eight photographs. The results are listed in Table I. Planes (1 1 1) are observed in the greatest quantity, and secondly followed by (0 1 1) and (1 1 3) planes. If these three kinds of planes are observed from the direction of the rolling plane, they can be regarded as the planes of (1 1 2), (1 0 0), and (1 1 1), respectively. There is no contradiction between the observed planes and the measured texture [31]. From these results it is suggested that the traces on the foils consist of three planes, i.e. {0 1 1}, {1 1 2}, {1 2 3}. The correspondence between traces and planes for two planes, {0 1 1} and {1 1 2}, can be confirmed easily, based on the orientation relationship, but no traces corresponding to the {1 2 3} plane are obtained, because of the mixing of the other two planes. In fcc materials, shear bands have generally been associated with twinning [5, 7, 12–15, 17, 21, 33–35], with some exceptions [3, 5]. The twinning plane is parallel to the rolling plane with increasing rolling reduction [5, 34], and has been confirmed on the basis of the observation of Moire fringes in the thin foil of the rolling plane [34, 35]. In the present experiment, it was rare to observe diffraction patterns indicative of a twinning relationship between the observed plates and the matrix in foils cut in the transverse direction. In the foils parallel to the rolling planes in the specimen rolled to 90%, as is shown in Fig. 8, Moire fringes have very occasionally been

Figure 6 Typical shear bands in thin foil micrograph occurring in the same specimen as Fig. 2.

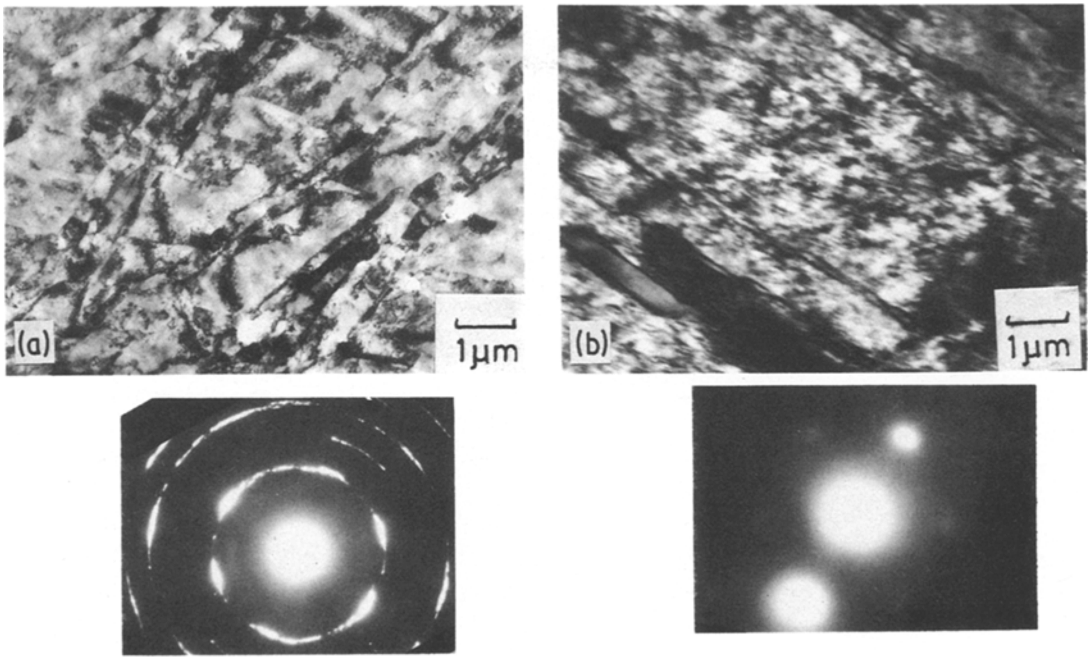

Figure 7 Different structures of shear bands occurring in two (1 1 1) planes of the same specimen as Fig. 2: (a) arcing, and (b) no arcing.

obtained, and hence it can be argued, in view of the differences between Figs. 7a and b, that shear bands in this alloy form on the {0 1 1} slip plane, together with twinning on the {1 1 2} plane.

4. Discussion

So far shear bands have merely been known in fcc materials [1–25]. Although such bands have been observed also in bcc materials, they have been

TABLE I Possible planes for shear bands predicted from the trace analysis on thin foils cut perpendicular to the transverse direction

Foil plane	Number of plane observed	Trace directions	Number of trace observed	Possible planes for shear bands		
				{011}	{112}	{123}
(001)	5	[100]	2	○		
		$[1\bar{1}0]$	3	○	○	
(011)	15	[100]	8	○		
		$[1\bar{1}1]$	6	○	○	○
		$[\bar{2}\bar{1}1]$	6	○		○
(012)	2	$[1\bar{2}1]$	1	○		○
		[100]	2	○		
(111)	23	$[\bar{2}11]$	27	○		○
		$[0\bar{1}1]$	4	○	○	
		$[\bar{1}\bar{2}3]$	1		○	
(112)	2	$[11\bar{1}]$	2	○	○	○
		$[2\bar{4}1]$	1		○	○
(113)	14	$[\bar{3}\bar{3}2]$	8	○		
		$[3\bar{6}1]$	5		○	
		$[2\bar{5}1]$	4		○	
		$[1\bar{4}1]$	6	○		
(115)	2	$[1\bar{6}1]$	2	○		
		$[55\bar{2}]$	1	○		
(123)	2	$[1\bar{2}1]$	1	○		○
		$[\bar{2}10]$	1		○	○
(135)	2	$[\bar{1}2\bar{1}]$	1	○		○
(133)	1	$[\bar{3}\bar{2}3]$	1		○	

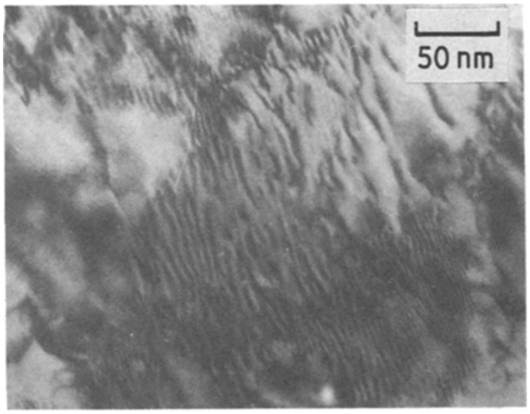

Figure 8 Moire fringes occurring in the rolling plane of the martensitic specimen cold rolled to 90%.

thought to occur only when a plate was severely cold rolled, e.g. over about 70% reduction or in the vicinity of necking due to plastic instability [26–29]. However, in the present alloy shear bands have been found to be easily produced at about 5 to 10% reduction. This difference in occurrence of the banding for identical bcc materials is very attractive because whilst the properties of the materials are greatly infleunced by such shear bands this alloy is also useful for investigating the formation mechanism of the bands.

Strictly speaking, the lattice of the FeCo–2V alloy used is not always bcc, because some ordering (probably short range) is formed during quenching. It is known that the deformation in FeCo alloys is accommodated by the movement of paired dislocations, whose existence is widely confirmed in ordered alloys. If the alloy used is ordered, then the deformation will be caused by such movement of the dislocations, and consequently cross slip which occurs easily in bcc materials becomes difficult [36, 37]. In fcc materials the formation of shear bands is closely related to the value of stacking fault energy (SFE), and the ease of occurrence increases with decreasing SFE [4, 17, 33]. The rare occurrence of the bands in bcc materials has been attributed to the higher strains which are required to develop shear bands from the equiaxed cell structures which form at low strains [33], and 45° shears, rather than shear bands, are produced because work hardening is difficult to produce [38]. This requirement of higher strains to produce the bands in bcc metals is in fact in agreement with observations. Nevertheless, in this alloy which is more or less associated with ordering, shear bands are observed at relatively low strains, namely, at about 5 to 10% reduction, and eventually this may be explained as follows: since in this alloy cross slip is made difficult by the existence or ordered regions similar to an fcc material having a low SFE, it is expected that on increasing reduction of rolling slip will be concentrated on the weaker regions, and this will result in shearing in the direction of slip. In fcc, the planes in which shear bands occur do not belong to neither slip planes nor twinning planes [11–13, 15], but in bcc, as shown in the present study, the bands are seen to be on the slip planes, (011) and (112), on the basis of the foil observations. This conclusion is reasonable also in view of the texture. The texture is essentially identical to iron-based materials, consisting of $(001)[1\bar{1}0]$, $(112)[1\bar{1}0]$, $(111)[1\bar{1}0]$, $(111)[2\bar{1}\bar{1}]$, as indicated in a previous paper [31]. If the shearing occurs on the slip plane of the bcc lattice, traces of the bands can be seen at angles of 35.26°, 30.0°, 31.48°, and 19.48°, respectively, to the direction of the rolling plane. Assuming that the first three exist predominantly, the possible traces are within the range of 30 to 35°, in good agreement with the experimental results. Dillamore *et al.* [39] has pointed out without crystallographic consideration that traces occurring in both bcc and fcc would occur at about 35° to the direction of the rolling plane, and that the propagation of shear bands would be inhibited by the existence of the component $\{112\}\langle 110\rangle$. However, in the present observation the angles of the bands could mainly be about 30° to the rolling plane, and many bands occur irrespective of the existence of the component $\{112\}\langle 110\rangle$ which is known to be a main component for the cold-rolled specimens [31].

The diffraction pattern of Fig. 7b shows that there are bands in which no fragmentation of orientation is observed. These bands may be interpreted as being twin plates. Consequently, two kinds of bands are observed, i.e. shear bands and twin plates. If there are twin plates, they can be sheared during the formation of the shear bands, when there is a possibility that the plates can be crossed by the bands. Both shear bands and twin plates are considered to be caused as a means of stress relaxation. As the magnitude of SFE can be related to the ability for relieving regions of stress concentrations in fcc, the existence of the ordering may be important in bcc alloys. It follows from the discussion that in fcc alloys, stress concentrations may be relieved by the formation of stacking fault and twinning, while in partly ordered bcc alloy the relaxation may be done by the formation of shear banding and twinning, and that the degree of difficulty in cross slipping is closely related to the formation of shear bands.

FeCo–2V alloys can not be fabricated unless quenching from over 800° C is carried out, and they become brittle even though slightly ordered, e.g. slow cooled from this temperature [30, 31]. Therefore, in general, shear bands in an ordered state of this alloy are difficult to form, and the susceptibility to cracking increases with the increasing degree of ordering because of the increased difficulty of cross slip. However, in the samples cold rolled over a critical reduction it is known that the ordering does not always bring about embrittlement [31, 39, 40]. As shown in Fig. 4, shear bands are in fact seen even in the ordered samples, without cracking. The fact that cold rolling has been accomplished even in the ordered samples can be explained as follows. With increasing ordering the precipitation of a certain compound, e.g. Co_3V in the vanadium bearing FeCo alloys, occurs throughout the matrix, and the local concentration-disordered zones, LCD zones, are produced around the individual particle of the precipitates [30, 31, 39, 41]. As a result the nucleation and the propagation of the cracks tend to decrease or to be prevented, because the formation of such zones which correspond just to disordered zones may affect their advancement, probably because they are disturbed or suppressed owing to the widely densely-distributed zones which may individually be ductile.

5. Conclusion

In both disordered and ordered states of an FeCo–2V alloy, shear bands have been observed to occur on cold rolling to 5 to 10% reduction, and to develop in a direction of 30 to 35° to the rolling plane. On thin foil observation, the bands may be regarded as resulting from shearing on the slip plane {011}, with twinning on the {112} plane. This occurrence, which is exceptional for a bcc lattice, may be interpreted as follows: since a difficulty to cross slip will be brought about by existence of the ordered lattice, stress concentration regions are easily formed compared with ordinary bcc lattices, so that shear bands occasionally with twinning would be formed on the slip plane as a means of relieving the stress concentrations.

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