JOURNAL OF MATERIALS SCIENCE 30 (1995) 5979–5984

Effects of vanadium on magnetic properties of semi-processed non-oriented electrical steel sheets

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The effects of vanadium inclusions on the magnetic properties of non-oriented electrical steel sheets were investigated. The magnetic induction and core loss of test specimens deteriorated at a vanadium content of 0.016 wt%. Electron microscope study revealed that the deterioration was caused by the "pinning effects" of vanadium carbonitrides on the recrystallization of cold-rolled sheets.

1. Introduction

Electrical steel sheets are consumed in millions of tons annually as the core material of small motors and ballasts [1]. Due to environmental problems, decreasing total carbon dioxide emission must be an urgent process. Thus, much attention has been paid to improving the magnetic properties, which leads to a decrease in the consumption of power supply. As improved magnetic properties are realized through the control of chemistry, grain size and texture, several new products with low core loss and high induction have been developed by precise control of the chemistry and mill processing [2–4]. This improvement has been achieved with the advances in steelmaking technology, which turns out to be the relationship between structure and magnetic properties. Advances in steelmaking technology now allow production of ultra-low carbon lean-alloyed steels, which realize high induction, or relative permeability, and low core loss on semi-processed non-oriented steel sheets. Ultra-low carbon steels are expected to have improved magnetic properties with respect to typical low carbon (0.02–0.06 wt % carbon) steels having similar alloy compositions. Lowering carbon contents leads to improved magnetic properties [5].

On the point of processing, hot rolling, cold rolling, annealing and temper rolling strongly affect the magnetic properties. Yashiki and Okamoto [6] investigated the effect of hot-band grain size on magnetic properties of non-oriented electrical steel sheets and concluded that core loss decreased with an increase in hot-band grain size. It indicated that the thermomechanical history affected the magnetic properties. Lee *et al.* [7] studied the effect of cold reduction on the magnetic properties of non-oriented, low silicon, electrical steel and concluded that core loss was independent of the percentage of cold reduction but permeability improved with increased cold reduction.

In this study, we investigated the effect of lean alloying, especially the effect of vanadium, on magnetic properties of semi-processed electrical steel sheets.

2. Experimental procedure

The heat of various vanadium content steels were prepared in a 50 kg vacuum induction furnace. Table I lists the chemical composition of steels. The proportions of vanadium were 0.001, 0.002, 0.003, 0.005, 0.007, 0.016, 0.041, 0.087 and 0.128 wt %, denoted V-1, V-2, V-3, V-5, V-7, V-16, V-39, V-89 and V-124, respectively. The contents of other elements are 0.35 wt % silicon, 0.31 wt % manganese, 0.075 wt % phosphor, 0.005 wt % sulphur, <0.001 wt % carbon and <0.001 wt % nitrogen. The steel ingots were machined to 45 mm thick and reheated to 1453 K, then hot rolled to 4.5 mm thick sheets at the finishing temperature of 1103 K. After being air cooled to 943 K, the hot-rolled sheets were kept in a furnace at 943 K for 5 h, and then furnace cooled. These sheets were uniformly ground to 2.3 mm in thickness to remove any scale, and cold rolled to 0.5 mm thickness by a four-high-pilot cold-rolling mill with a total reduction of 78%. The continuous annealing was performed with a Shinku-Riko ULVAC CCT-QB simulator along the heat diagram shown in Fig. 1. Continuous annealed sheets were cut to 30×100 mm in dimension, either longitudinally or transversely to the rolling direction, for 10 cm Epstein frame specimens. These specimens were annealed at 1023 K for 2 h in nitrogen gas (for stress relieving) and furnace cooled. Magnetic properties, including core loss and induction, were measured on a 10 cm Epstein frame

TABLE I Chemical composition of the steels (wt %)

Steels	C	Si	Mn	P	S	Sol. Al	V	N	O
V-1	0.0033	0.33	0.31	0.070	0.005	< 0.001	0.001	0.0010	0.0074
V-2	0.0033	0.33	0.31	0.070	0.005	< 0.001	0.002	0.0012	0.0075
V-3	0.0031	0.33	0.31	0.070	0.005	< 0.001	0.003	0.0013	0.0078
V-5	0.0022	0.34	0.31	0.070	0.005	< 0.001	0.005	0.0010	0.0075
V-7	0.0027	0.34	0.31	0.071	0.005	< 0.001	0.007	0.0014	0.0078
V-16	0.0024	0.34	0.31	0.071	0.005	< 0.001	0.016	0.0011	0.0076
V-39	0.0027	0.33	0.31	0.072	0.004	< 0.001	0.039	0.0010	0.0079
V-89	0.0024	0.33	0.30	0.072	0.004	< 0.001	0.089	0.0012	0.0079
V-124	0.0030	0.32	0.30	0.071	0.005	< 0.001	0.124	0.0012	0.0075

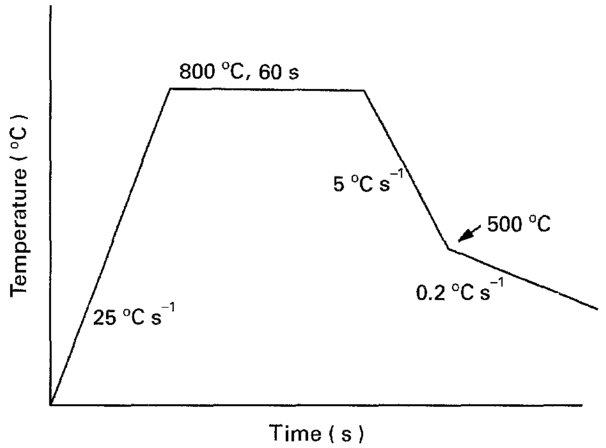

Figure 1 Heat diagram of continuous annealing.

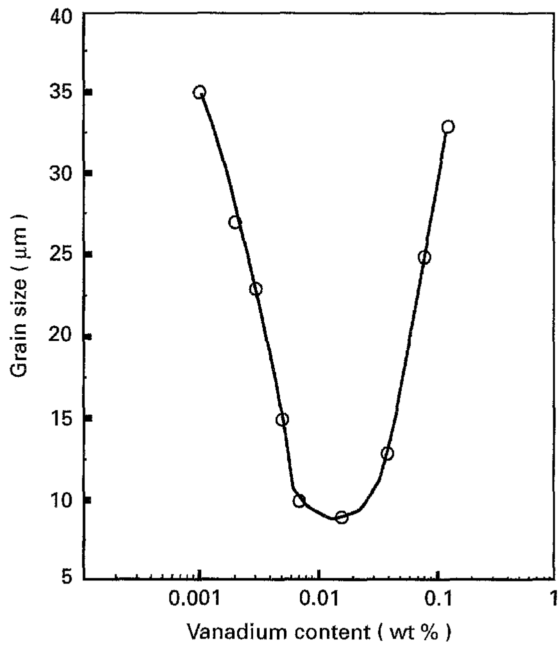

Figure 2 Effect of vanadium content on final grain size after stress-relief annealing at 1023 K in a nitrogen atmosphere.

(Yokogawa Electric Works Magnetic Measuring System). Texture examinations were performed by X-ray diffraction (Material Analysis and Characterization Inc., MXP-3), specimens were attached to a Mo target operated at 46 kV and 16 mA. An inclusion study was done by an extraction replica method using a transmission electron microscope attached to an EDAX for chemical analysis (Hitachi HU-700H operating at 100 kV).

3. Results and discussion

3.1. Grain size and microstructure

Fig. 2 shows the grain size of the stress-relief annealed sheets as a function of vanadium content. The grain size decreases with an increase in vanadium content <0.016 wt %. However, when the vanadium content is > 0.016 wt %, the steel grains again grow towards the lower vanadium content size. Hou *et al.* [8] studied the effect of aluminium on the magnetic properties of lamination steels and pointed out that the size and distribution of aluminium nitride precipitates in hot-rolled plates influenced the final grain size after continuous annealing. Therefore, the magnetic properties, core loss and permeability decreased with an increase in grain size. In our case, vanadium nitride precipitates influenced the final grain size. Fig. 3 shows the TEM replica of the various vanadium-containing steel sheets after continuous annealing. No vanadium inclusions were observed, but a MnS one was observed in steel V-1. In steel V-16 (vanadium carbonitride) inclusions were observed along the grain boundary when it was "pinned down". Therefore, the effect of vanadium carbonitride on the retardation of grain growth is more pronounced than that of compound inclusions in steel V-1. However, this "pinning" effect is weak in steels with vanadium contents >0.016 wt %, whose carbonitrides are larger than those with lower vanadium contents (Fig. 3). This behaviour is very similar to that with aluminium nitride [9].

3.2. Magnetic properties

Fig. 4 shows the relationship between core loss at 1.5 T and 50 Hz (W15/50) and vanadium content after stress-relief annealing. It is well known that grain size affects magnetic properties [10–12]. Matsumura and Fukuda [13] reviewed non-oriented electrical steel sheets and stated that the grain size affected the core loss and that the lowest core loss was achieved at ca. 150 µm. At grain sizes <150 µm core loss increased with a decease in grain size. In our case, the grain size was <40 µm, so the profile of the core loss versus vanadium content (Fig. 4) was the same as that of grain size versus vanadium content (Fig. 2). Therefore, core loss is low at 0.001 wt % vanadium content, as there is no vanadium carbonitride region; at 0.124 wt % vanadium content there is a large vanadium carbonitride region in the inclusion study.

By contrast with the core loss, magnetic induction at 5000 A m^{-1} (B50) decreased with an increase in vanadium content <0.016 wt %, but increased at contents >0.016 wt % (Fig. 5). Magnetic induction or permeability is affected by the grain size and texture of hot-bands. The effect between the hot-band grain

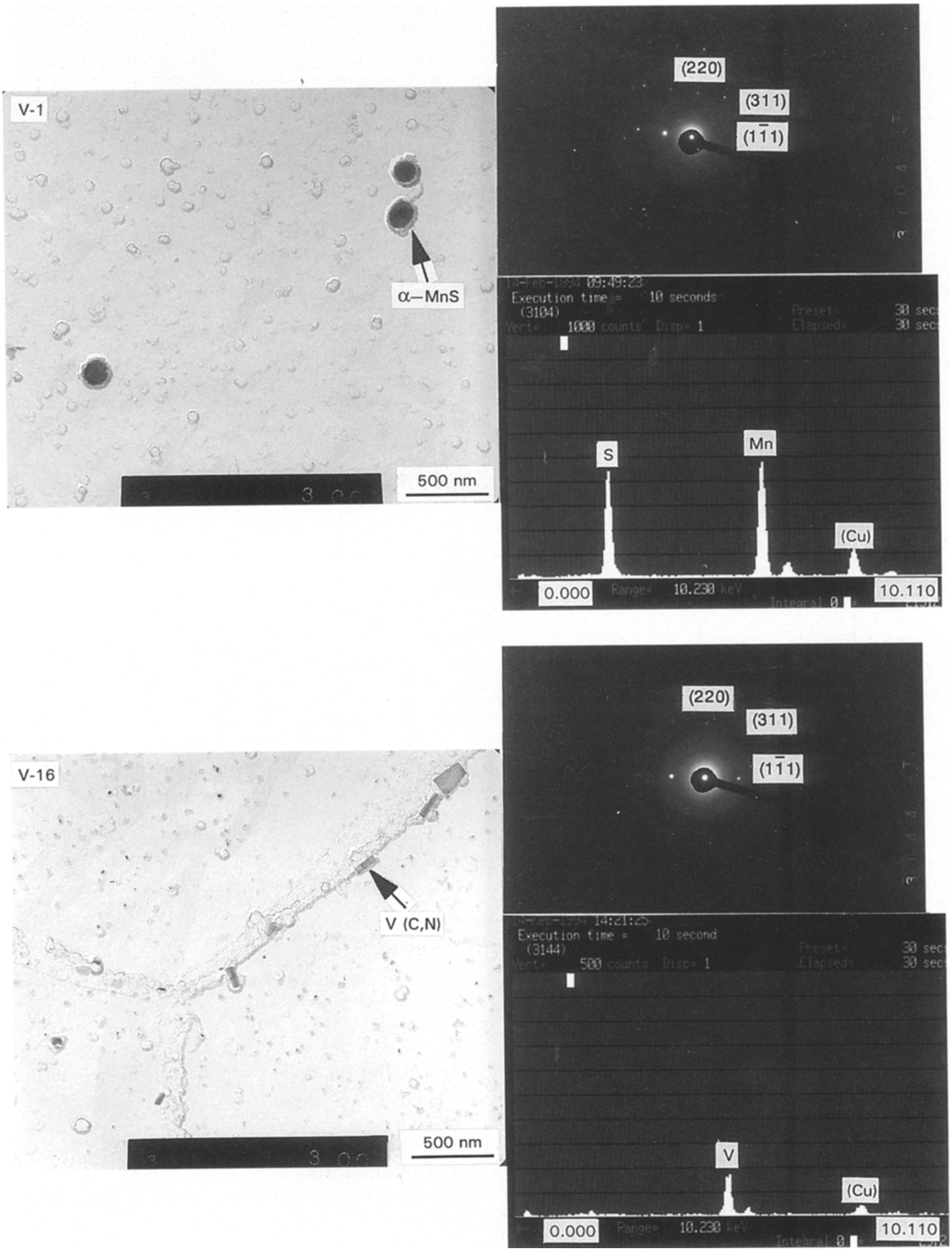

Figure 3 Inclusions observed by transmission electron microscope (TEM) after stress-relief annealing (×29 100).

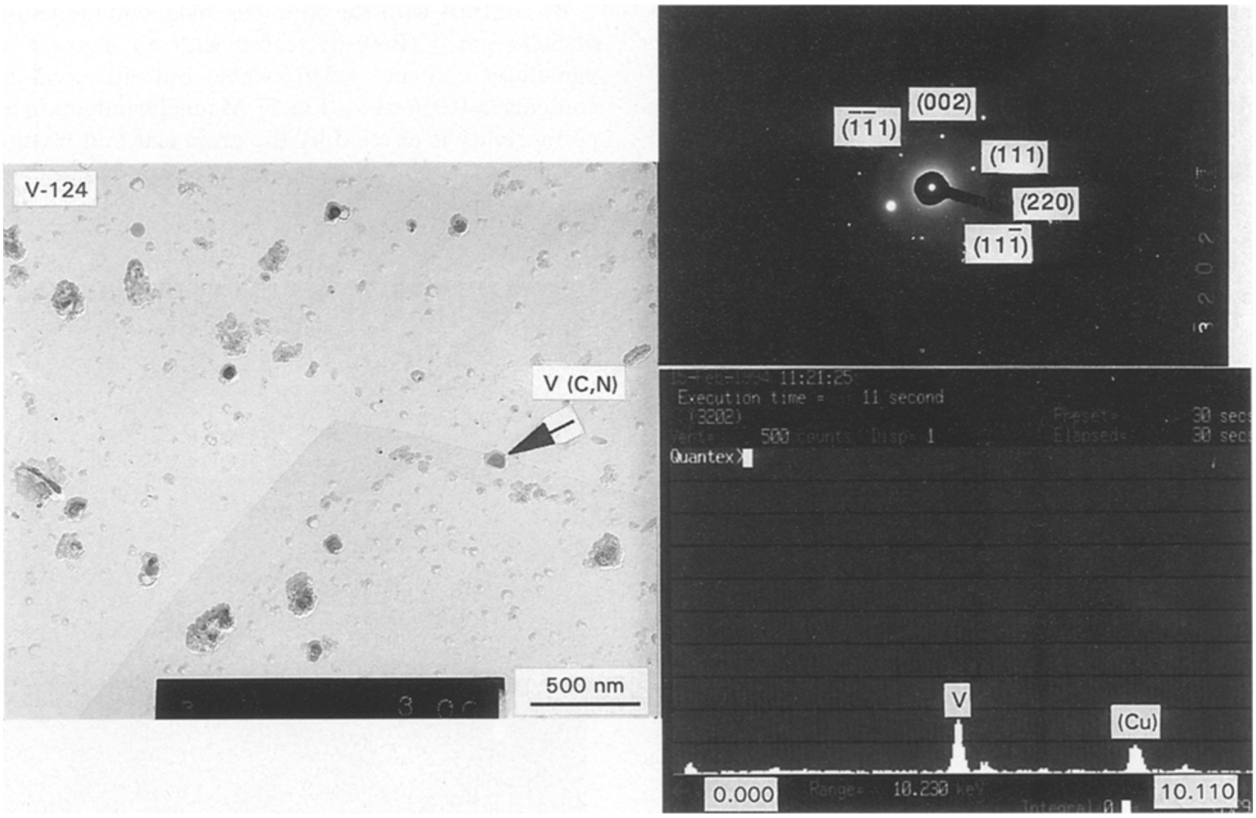

Figure 3 Continued

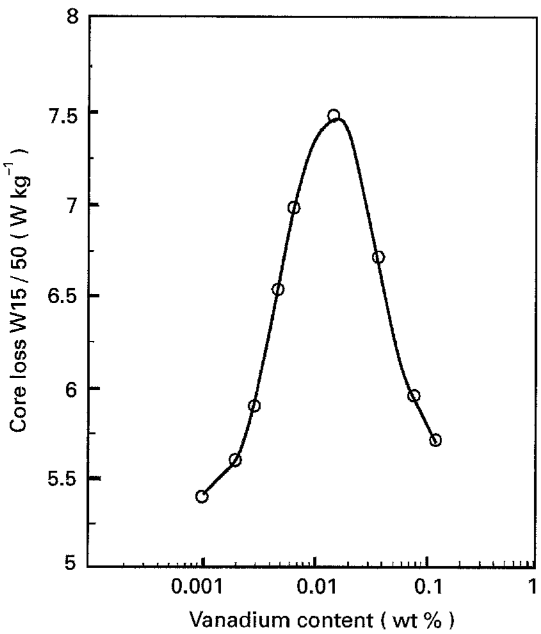

Figure 4 Relationship between core loss (W15/50) and vanadium content after stress-relief annealing.

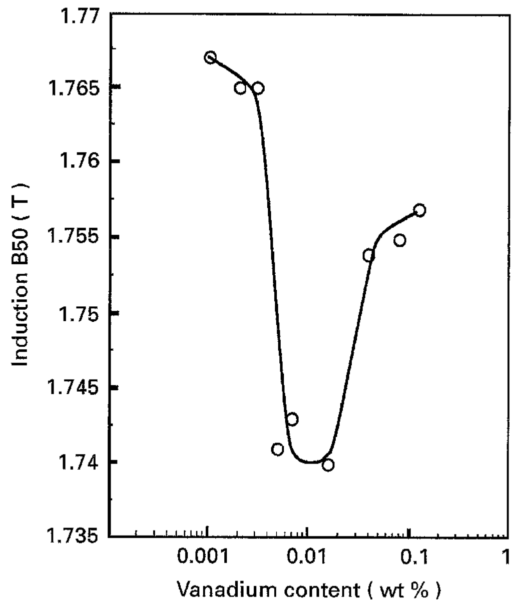

Figure 5 Relationship between induction (B50) and vanadium content after stress-relief annealing.

size and magnetic induction is shown in Fig. 6– 0.016 wt % vanadium content steel V-16 was the smallest grain size. TEM study (Fig. 7) made it clear that the vanadium carbonitrides precipitated during hot rolling "pinned down" the grain boundary in V-16. Therefore, these small hot-band grains lead to a low magnetic induction at 5000 A m^{-1}. Fig. 8 shows that the inverse pole intensity as a function of vanadium content, which is not easy to magnetize, developed at a vanadium content of 0.016 wt %. This is also the reason why the magnetic induction was low in V-16 steel.

4. Conclusions

The effect of the vanadium in silicon steels are as follows:

1. The grain size decreases with an increase in vanadium content <0.016 wt %, and grow towards

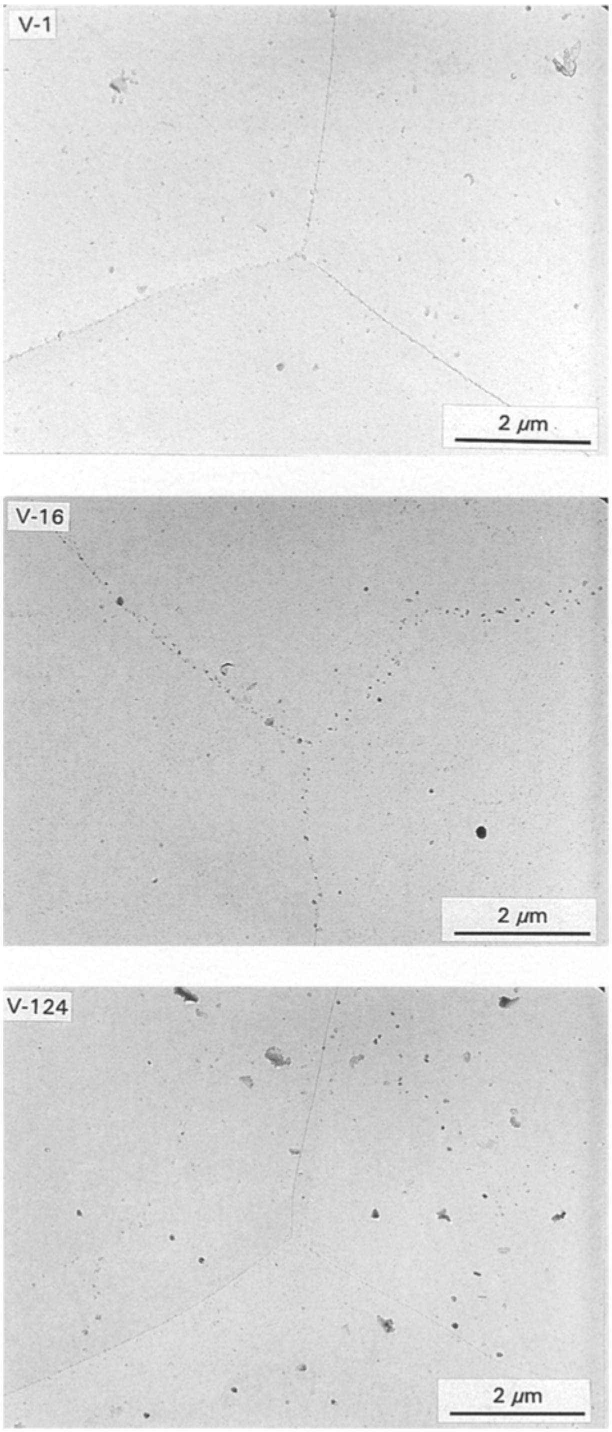

Figure 7 Inclusions observed by TEM in hot-bands (×8800).

the lower vanadium content sizes at >0.016 wt %. This phenomena is caused by vanadium carbonitride along the grain boundary as "pinning" inclusions. In steel V-1, containing 0.001 wt % vanadium, no vanadium carbonitrides were observed, while large vanadium carbonitrides were observed in steel V-124, containing 0.124 wt % vanadium. No "pinning" effect by inclusions were observed in either V-1 or V-124.

2. Magnetic properties were affected by the vanadium content. The highest core loss at 1.5 T and 50 Hz (W15/50) was observed in V-16, containing 0.016 wt% vanadium, due to the smallest grain size after stress-relief annealing. The lowest induction was observed in steel V-16, due to the smallest grain size after hot

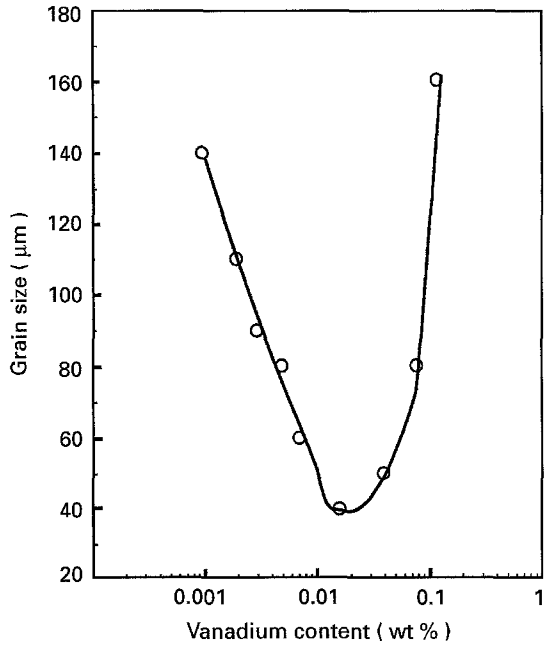

Figure 6 Effect of vanadium content on hot-band grain size.

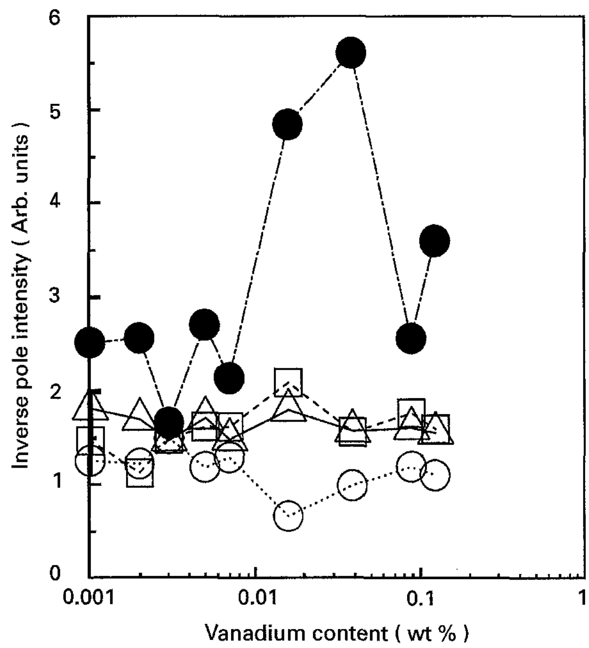

Figure 8 Relationship between inverse pole intensity and vanadium content after stress-relief annealing. ●, (2 2 2); □, (2 0 0); △, (2 1 1); ○, (1 1 0).

rolling, and magnetically unfavourable texture after stress-relief annealing.

References

1. F. E. WERNER, in "Energy efficient electrical steels" edited by A. R. Marder and E. D. Stephenson (Warrendale PA, TMS-AIME, 1981) p. 1.
2. E. T. STEPHENSON and A. R. MARDER, *IEEE Trans. Mag.* **22** (1986) 101.
3. A. R. MARDER, *Metall. Trans. A* **17A** (1986) 1277.
4. J. M. SHAPIRO, in "Energy efficient electrical steels", edited by A. R. Marder and E. D. Stephenson (Warrendale PA, TMS-AIME, 1981) p. 33.

5. P. K. RASTOGI and G. LYUDKOVSKY, in Proceedings of the International Coil Winding Association, Boston, MA (1985) p. 1.
6. H. YASHIKI and A. OKAMOTO, *IEEE Trans. Mag.* **23** (1987) 3086.
7. Y. W. LEE, R. ORIGEL and D. BHATTACHARYA, *J. Mater. Engng.* **11** (1989) 61.
8. C.-K. HOU, C.-T. HU and S. LEE, *IEEE Trans. Mag.* **27** (1991) 4305.
9. *Idem. Mater. Sci. Engng.* **A125** (1990) 241.
10. T. D. YENSEN, *Trans Am* **43** (1924) 145.
11. T. D. YENSEN and N. A. ZIEGLER, *Trans. ASM* **23** (1935) 556.
12. *Idem., ibid.* **24** (1936) 337.
13. K. MATSUMURA and B. FUKUDA, *IEEE Trans. Mag.* **20** (1984) 1533.

Received 6 March
and accepted 24 May 1995