Note

Effect of Absorbed Nitrogen on the Microstructure and Core Loss Property of Non-oriented Electrical Steel

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1. Introduction

Presence of nitrogen is undesirable for electrical steel because nitrogen both as interstitial and nitride particle, enhances the core loss value of the electrical steel. Interstitial nitrogen atom distorts the surrounding ferrite matrix and this distorted matrix obstructs the movement of magnetic domain walls during magnetization. On the other hand, nitride particle *per se* is an obstruction to the movement of magnetic domain walls. As in case of other impurities, the extent of obstruction caused by nitride particle depends upon its size, its morphology and its capability to inhibit grain growth. Presence of such obstacles to the movement to magnetic domains finally results in the enhancement of core loss value of the steel.

In spite of such significant influence of nitrogen on the core loss value, very limited information¹⁾ is presently available to show how the nitrogen content quantitatively increases the core loss of electrical steel. Moreover, the available information deals with influence of lower amounts of nitrogen (less than 60 ppm) on core loss property. Present study, in fact, establishes a quantitative relationship between higher nitrogen content and core loss value in the non-oriented electrical steel. This study was originally taken up to find out the reasons for varying core loss values achieved in the fully processed coils of a commercially produced non oriented electrical steel. The chemistry and the process parameters of this steel were originally designed to achieve a core loss value of around 4.0 watt/kg at a magnetic field of 1.5 Tesla and frequency of 50 Hz. The steel chemistry included 2.7% silicon while aluminum content was maintained at 0.20%. The steel was made in basic oxygen furnace and processed through vacuum arc refining unit to restrict nitrogen to ~50 ppm. Concast slabs of this steel were hot rolled to 2.2 mm thick strips. In the first campaign, some of these strips were processed to produce coils of

non-oriented electrical steel by adopting conventional processing practice which included pickling, cold rolling to 0.5 mm thickness, decarburization and then annealing of coils. Decarburization was carried out at 850°C in a furnace with an atmosphere comprising N_2+H_2 and controlled amount of moisture while annealing was performed at 1000°C. Evaluation of magnetic properties showed that the core loss value of annealed coils was higher than 4.0 watt/kg. In addition, large variation in the core loss value was observed in the coils. A metallurgical investigation was then conducted to find out the reasons for higher as well as scattered values of core loss values.

2. Work Done

Samples were collected from few hot rolled strips (which were not processed in first campaign) and annealed coils. The nitrogen content of these samples was evaluated by Leco Analyzer. In addition, through thickness microstructures of hot rolled strips and annealed coils were examined by Optical Metallography. The results obtained from these activities were analyzed and a relationship was developed between nitrogen content and core loss value. Based on these results, the decarburization process was modified with the objective of minimizing the absorption of nitrogen by the coils during their decarburization. A second campaign was then taken up in which few more hot rolled strips of the same steel were processed with modified decarburization practice. The core loss value of fully processed coils was evaluated and nitrogen content of the coils was estimated. The influence of nitrogen content on the core loss value was examined for the coils processed in this second campaign. The through thickness microstructure of fully processed coils was examined in Optical Metallography.

3. Results and Discussions

The nitrogen content in hot rolled strips was ~50 ppm while the nitrogen content in the annealed coils was high and varied between 140 to 460 ppm. This showed that there was absorption of substantial amount of nitrogen during subsequent processing of hot rolled strips. It has been reported²⁾ that during decarburization of non-oriented electrical steel in an atmosphere comprising H_2+N_2 and moisture, there is some absorption of nitrogen, particularly under the conditions which favour occurrence of internal oxidation along with decarburization. Internal oxidation is caused by diffusion of oxygen atoms in the steel matrix and subsequent precipitation of oxides beneath the surface. The conditions which favour internal oxidation include low decarburization temperature, high moisture content and low concentration of solute atoms. In the present study, it seems that the conditions in decarburization furnace had favoured occurrence of internal oxidation which, in turn, had led to the ingress of nitrogen in the coils. This resulted in higher nitrogen content in the annealed coils. The variation in the nitrogen content in different coils was perhaps due to some fluctuations in the furnace atmosphere since similar decarburizing temperature and line speed were maintained during decarburization of the coils.

The through thickness microstructure of fully processed

coils comprised predominantly coarse ferrite grains with presence of fine ferrite grains near both the surfaces of the coils (**Fig. 1**). However, the through thickness microstructure of hot rolled strips did not show any evidence of fine grains near the surfaces. On the other hand, microstructure of hot rolled strips comprised deformed structure across the thickness with coarse polygonal ferrite near the surfaces (**Fig. 2**). This type of microstructure is archetypal for hot rolled strips of high silicon steels. From the above observations, it is evident that genesis of finer ferrite grains near the surfaces was associated with the annealing of coils. In case of non-oriented electrical steel, annealing of decarburized coils is carried out to ensure ferrite grain growth since coarse ferrite grains are desirable for achieving lower core loss value. In the present study, it seems that the absorbed nitrogen had combined with the solute aluminum atoms present near surfaces and formed fine AlN particles during decarburization. Formation of fine AlN particles had taken place because limited amount of soluble aluminum was available to form AlN with absorbed nitrogen. This availability of limited aluminum was due to the fact that larger amount of aluminum had already combined with nitrogen during steel making to form coarse AlN.³⁾ The small quantity of soluble aluminum favoured formation of fine AlN particles at decarburization temperature of 850°C as is evident from the relationship between solubility product of AlN and temperature.⁴⁾ Presence of fine AlN particles must have inhibited the ferrite grain growth during annealing resulting in the formation of fine grains near the surface.⁵⁾ Also, since the microstructural examination revealed that fine ferrite grains were evolved near surfaces only, it showed that bulk of absorbed nitrogen was concentrated near surface. To further confirm this, one sample from an annealed coil containing 435 ppm of nitrogen was thinned down through mechanical grinding from both sides to reduce its thickness to 0.30 mm from initial thickness of 0.50 mm. This thinning ensured the complete removal of area consisting of fine ferrite grains near both the surfaces. The nitrogen content of this thinned sample was evaluated and found to be 120 ppm. This reduction in the nitrogen in thinned sample showed that the absorbed nitrogen was predominantly concentrated near the surfaces only. This finding further showed that small quantity of nitrogen diffused beyond the area of fine grains in the coils because nitrogen content in the thinned sample was still 120 ppm which was higher than the nitrogen content found in hot rolled strips. Since coarse grains were formed in the interior of the annealed coils, it showed that such small quantity of absorbed nitrogen was not adequate to combine with the solute aluminum to form fine AlN particles in the interior of the coils.

From the above results, the influence of nitrogen content on the core loss value was analyzed and a strong correlation was established between the nitrogen content and the core loss value (**Fig. 3**). This relationship showed that nitrogen content should be restricted to below 150 ppm to achieve a core loss value of 4.0 watt/kg in the annealed coils of given chemistry.

The nitrogen content of coils processed in second campaign was found to be in the range of 90 to 150 ppm which showed that there was still ingress 40–100 ppm of nitrogen

Fig. 1. Typical through thickness microstructure of decarburized and annealed coils showing fine ferrite grains near the surface.

Fig. 2. Typical through thickness microstructure of hot rolled strips showing deformed grains across the thickness and polygonal grains near the surface.

Fig. 3. A correlation established between nitrogen content and core loss value of decarburized and annealed coils processed in first campaign.

even with modified decarburization process. However, the core loss value in these coils was below 4.0 watt/kg coils. In this campaign also, a strong relationship of core loss value with the nitrogen content was observed which was similar to what was found in first campaign as shown in **Fig. 4**. In this figure, round points represents observations of second campaign while broken line shows the correlation between core loss and nitrogen content as developed in first campaign. However, examination of through thickness microstructure in the coils of second campaign did not show presence of finer ferrite grains near the surface (**Fig. 5**) which showed that no fine AlN particle was formed during decarburization. This illustrates that 100 ppm nitrogen and

Fig. 4. Influence of nitrogen content on core loss value of decarburized and annealed coils processed in second campaign. The round points shows this effect in second campaign while broken line shows the relationship developed in first campaign.

Fig. 5. Typical through thickness microstructure of decarburized and annealed coils with lower nitrogen content. No fine grains are present near the surface.

the available solute aluminum could not combine together to form fine AlN particles and therefore, there was no pinning of growing ferrite grains even near the surface during

annealing of decarburized coils.

4. Conclusions

The study showed that absorption of nitrogen had taken place during decarburization of cold rolled coils of non-oriented electrical steel. Actual quantity of absorbed nitrogen varied with variation in decarburizing conditions. When the quantity of absorbed nitrogen was more than 150 ppm, bulk of the nitrogen was concentrated near the surfaces of the coils. This nitrogen combined with solute aluminum to form fine AlN particles. These AlN particles were effective in pinning down the grain growth during annealing of decarburized coils and thereby resulted in the formation of fine ferrite grains near the surface. However, when quantity of absorbed nitrogen was less than 100 ppm, finer ferrite grains were not form near the surfaces.

A strong relationship was developed between nitrogen content and core loss value of non-oriented electrical steel. The relationship showed that the nitrogen content should be restricted to below 150 ppm to achieve a core loss value of 4.0 watt/kg in non-oriented electrical steel with silicon content of 2.7% and aluminum content of 0.20%.

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