Correlating the Aluminum Content with Ferrite Grain Size and Core Loss in Non-oriented Electrical Steel

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1. Introduction

Core loss property of a magnetic material, is defined as dissipation of electrical energy in the form of heat during magnetization by an alternating current. Therefore, efforts are always made to minimize core loss value of magnetic materials. In case of electrical steels, core loss can be reduced by controlling a number of metallurgical factors that include inter alia ferrite grain size. It has been reported that, for a given silicon content, core loss value in the steel initially decreases with the increase in the ferrite grain size. However, after attaining an optimum grain size, core loss value starts increasing with further increase in ferrite grain size. Such type of distinct influence of ferrite grain size on core loss property is due to the fact that the size of magnetic domains present in the steel, is directly linked with the ferrite grain size. Therefore, an increase in ferrite grain size results in corresponding increase in the size of magnetic domains and hence, there is lesser number of domain walls to move during magnetisation, which results in lowering of core loss. However, when magnetic domain size becomes very large, the domain walls have to move faster to cover the same distance during magnetisation which results in enhancing the core loss value of the steel which contains ferrite grains coarser than an optimum grain size.

In industrial practice, ferrite grain size of non-oriented electrical steels is increased by adopting suitable hot strip rolling parameters which include low finishing and high cooling temperatures. Further to this, both hot rolled and cold rolled coils are required to be annealed to promote coarsening of ferrite grains. It has, also, been reported that addition of higher amounts of aluminum facilitates coarsening of ferrite grain size, though aluminum is generally considered as an effective ferrite grain refiner. In this context, the present study was taken up to understand the efficacy of aluminum addition on ferrite grain size and on core loss property in non-oriented electrical steel with silicon content around 1.5%.

It may be mentioned that aluminum is added to the non-oriented electrical steels to form AlN by combining with the nitrogen available in the liquid steel and consequently, to minimize the detrimental effect of free nitrogen on the magnetic properties of the steel. Also, aluminum addition lowers core loss value by increasing electrical resistivity of the steel and, under specific processing conditions, by developing favorable texture for magnetization.

2. Experimental

A number of heats were made in a 65 tons basic oxygen furnace and subsequently, liquid steel was treated in vacuum arc refining unit to control both sulphur and dissolved gases. The aluminum content was varied in the range of 0.03–0.3% while maintaining other alloying elements in the steel at their fixed level. Typical chemistry of steel was as follows:

%C: 0.030; %Mn: 0.25; %P: 0.015; %S: 0.01; %Si: 1.5; N\textsubscript{2}: 80 ppm

Continuous cast slabs of above chemistry with varied amounts of aluminum content, were reheated at 1250°C and hot rolled into strips of 2.2 mm thickness under similar hot rolling conditions (i.e. maintaining finish rolling and coiling temperatures of −860°C and −700°C respectively). These hot strips were pickled in HCl and cold rolled to 0.5 mm thickness. The cold rolled coils were subsequently decarburised to reduce the carbon level to around 0.003% and were annealed at 1 000°C for a duration of 4 min. The core loss property of annealed coils was evaluated at a magnetic induction of 1.5 T and frequency of 50 Hz, in an Epstein Tester. The average ferrite grain size of fully processed coils was measured using linear intercept method in optical microscopy and morphology of AlN particles was examined through transmission electron microscopy. Based on the data generated, a nomogram was developed to correlate total aluminum content with average ferrite grain size and core loss value for fully processed coils.

3. Results and Discussions

Figure 1 shows that average ferrite grain size of fully processed coils increased with increase in aluminum content and a strong relationship was found to exist between average ferrite grain size and core loss value. For example, lower aluminum content of 0.05% led to the formation of less coarser ferrite grains of 25 \( \mu m \) (Fig. 2) which resulted in higher core loss value of 5.8 W/kg. On the other hand, average ferrite grain size of 61 \( \mu m \) (Fig. 3) and corresponding core loss value of 3.5 W/kg were achieved for coil with 0.30% aluminum. Such type of unique behaviour of aluminum addition in controlling the ferrite grain size, was because of the formation of AlN particles of various sizes in coils with different aluminum contents. Transmission electron microscopy showed presence of smaller AlN particles of 0.05 \( \mu m \) size in the coil having 0.05% aluminum while coarser AlN particles of around 1.2 \( \mu m \) size were observed in the coil with 0.3% aluminum (Figs. 4(a) and 4(b)). The reason for formation of coarser AlN particles in high aluminum content electrical steels was because addition of aluminum reduced the solubility of AlN in steel, resulting in precipitation of AlN particles at high temperature. Subsequently, these AlN particles coagulated to give rise to fewer coarser AlN particles as observed by Rickett and
Leslie. The population density of coarser AlN particles increased with increase in aluminum content, as is evident from the relationship between solubility product of AlN and temperature. During reheating of slabs, these coarser AlN particles remained undissolved. Presence of such coarser AlN particles restricted precipitation of finer AlN particles during annealing of cold rolled coils of higher aluminum content steels. On the other hand, in low aluminum content steels, limited amount of coarser AlN particles was initially formed due to greater solubility of AlN at higher temperatures for such steels. This finally resulted in precipitation of a larger number of finer AlN particles during annealing. Therefore, coils corresponding to higher aluminum content were having higher volume fraction of coarser AlN particles while coils with lower aluminum content were having larger volume fraction of finer AlN particles during annealing.

Presence of such coarser AlN particles facilitated the ferrite grain growth in higher aluminum content steels because these particles were ineffective in pinning the movement of grain boundaries during annealing. This is owing to the fact that the pinning force (which is equal to $6f/\gamma r$, where $f$ is the volume fraction of particles, $\gamma$ is the grain boundary energy and $r$ is the particle radius) of a particle diminishes with increase in its size. If the size of a particle exceeds a critical size, the pinning effect of the particle disappears and grain coarsening occurs with lowering of energy associated with grain boundary–particle interaction. The critical size of particles depends upon a number of factors and is
described as follows:

\[ r_c = \frac{6R_0 f}{\pi} \left( \frac{3}{2} \frac{2}{Z} \right) \]  

Where \( r_c \) is the radius of critical size of particles, \( f \) is the volume fraction of particles, \( R_0 \) is the matrix grain radius and \( Z \) is the ratio of radii of growing grains and matrix grains. In the present study, the size of the AlN particles started increasing with the addition of aluminium and eventually exceeded the critical size. Such coarser AlN lost their capability to pin down grain boundary movement during annealing and allowed uninterrupted grain coarsening, once recrystallisation was completed.

The present investigation confirmed that addition of aluminium facilitated coarsening of ferrite grain and consequently lowered core loss value. However, aluminium addition can also lower the core loss value by increasing the electrical resistivity of the steel, as mentioned earlier. Therefore, it is important to evaluate the contribution of increased electrical resistivity on lowering of core loss in the present study. The electrical resistivity of iron is 10.5 \( \mu \Omega \)-cm when 0.05% aluminium is added while it increases to 13.0 \( \mu \Omega \)-cm when 0.3% aluminium is added.\(^7\) This small increase in electrical resistivity with the addition of 0.25% extra aluminium, can reduce core loss value only marginally. This was confirmed by determining eddy current loss, using Golding formula,\(^8\) for above mentioned two values of electrical resistivities corresponding to 0.05% and 0.3% aluminium content steels. It was observed that there was no significant lowering of eddy current loss with such minor increase in electrical resistivity. Therefore, addition of higher amount of aluminium lowered the core loss value of steel almost entirely owing to coarsening of ferrite grains.

4. Conclusions

The average ferrite grain size in fully processed electrical steel with silicon content of 1.5%, increased from 25 to 61 \( \mu \)m with the increase in addition of aluminium content from 0.05 to 0.3%. The coarsening of ferrite grains resulted in the lowering of core loss value from 5.8 to 3.5 W/kg.

Coarsening of ferrite grains in high aluminium content steel was due to the evolution of larger size AlN particles which were unable to prevent ferrite grain growth during annealing of cold rolled and decarburised coils.

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