Development of the Atmosphere Controlled Roller Hearth Type Kiln for High Performance Mn-Zn Ferrites

Shin-ichi Kijima, Kiyoshi Arie, Kunihiro Gotoh

Synopsis:
A new roller hearth kiln (RHK) has been developed, resulting in both the highest quality and productivity for MnZn ferrites. Using the RHK, the total sintering time is reduced to less than 11 h, that is, a half of the case of the pusher type kiln. The productive capacity of the RHK achieved 100 t/month. Moreover, two different types of MnZn ferrite, i.e., high-permeability and low-power-loss materials, can be sintered simultaneously in the RHK, because the control of oxygen content during the sintering and the subsequent cooling zone is performed precisely. The electromagnetic properties of these materials reach the highest level in mass production. The initial permeability ($\mu_i$) of the high-permeability material, MA100, reaches 10 000 at 100 kHz, and the power loss ($P_{cv}$) of the low-power-loss material, MB4, is reduced to 270 kW·m(-3) at 100 kHz, 200 mT and 95°C.

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1 Introduction
The Mizushima Factory of Kawasaki Magnex Corp. (Kawasaki Ferrite Corp. at present) started producing soft magnetic Mn-Zn ferrite cores in the Mizushima Works of Kawasaki Steel in October 1990. The manufacturing of Mn-Zn ferrite cores is a part of the new business development at Kawasaki Steel. Kawasaki Ferrite Corp. (KFC) conducts integrated production to ferrite cores from a main material, the high-purity iron oxide, which is manufactured in the Mizushima Works of Kawasaki Steel. The market for Mn-Zn ferrite has grown rapidly because of the increase in small, thin and high-frequency types of electronic equipment such as power supply transformers and noise filters. KFC’s mass production has continuously increased with market growth, reaching 240 t/month now.

Mn-Zn ferrite is an oxide ceramic with excellent magnetic properties. KFC offers two main types of material; one acts as a low power loss material in electric power supplies and the other is of high initial permeability.

When manufacturing Mn-Zn ferrites, sintering influences the magnetic properties of the products the most. The initial permeability ($\mu_i$) and power loss ($P_{ul}$), especially, are quite sensitive to the temperature and the oxygen content throughout the sintering process. On the other hand, as well as better performance, higher productivity is also required in the sintering process which determines the manufacturing capacity of Mn-Zn ferrite.

Three types of kiln are commonly used for Mn-Zn ferrites: the batch kiln (BK), continuous pusher kiln (PK), and continuous roller hearth kiln (RHK)\(^1\). The BK allows a batch of cores to occupy the kiln at a constant capacity. Sintering undergoes a fixed pattern of temperature and atmospheric changes. The cores are then removed after cooling. The sintering conditions of the BK can be controlled precisely and changed for each batch. The PK and RHK are continuous furnaces in which ferrite cores are sintered on refractory plates, passing through furnace tunnels at a constant speed under fixed temperature and the atmospheric conditions. As for the RK, ferrite cores are transported on high-strength refractory plates which are pushed starting from the entrance of the kiln by means of high-power oil cylinders. The maximum length of the RK is about 30 m because the refractory plate has a limited strength to endure this pushing pressure. Electric heaters are used

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during the entire heating and sintering. With both the entrance and the exit sealed by double doors. This is to decrease the oxygen content to only a few ppm during cooling. The RHK transportation method, generally used for manufacturing pottery, uses light refractory plates and rotating ceramic rollers. The RHK, therefore, has the largest production capacity. But the RHK hardly allows the control of the sintering conditions, particularly the oxygen concentration, because it is directly heated by gas (e.g. LPG), and has no closed type entrance and exit. The BK and/or PK are therefore usually used for high-quality Mn-Zn ferrites. But these types of kiln have reached full production capacity at about 70 t/month.

KFC and Kawasaki Steel have developed three RHKs at the KFC Mizushima Factory. The third one serves to produce high quality and high productivity in the mass production of Mn-Zn ferrites.

The newly developed RHK and the characteristics of its products are described in this paper.

2 Atmosphere Controlled RHK

2.1 The Short History of Development of the RHK at KFC

KFC and Kawasaki Steel, as mentioned previously, have constructed three RHKs and a PK. Their specifications and capabilities are shown in Table 1. The first RHK was introduced in December 1989 as a test furnace to search for possibilities. The first RHK allowed the accumulation of basic data and precise temperature and atmosphere control methods to be developed. The PK was introduced as the second furnace in March 1990 when production began. The next RHK was the third furnace made in May 1991 based on the technologies and mass produced at this time. The third furnace has a simple structure of a tunnel furnace in comparison to the PK, so that few troubles arise in this machine and system. The third furnace has a production capacity of 70 t/month, which is four times that of the first RHK. As for the magnetic properties of Mn-Zn ferrite cores, the initial permeability (μ₀) of high-μ₀ materials is not able to surpass that of the PK which sinters materials simultaneously with low-Pₑ materials.

The new RHK (the fourth) was developed in May 1994, for the purpose of improving the magnetic properties of Mn-Zn ferrite. The high-μ₀ materials from the new RHK have the relative permeability (μ/μ₀; μ₀ is the permeability of free space) that exceeds 7000, and the low-Pₑ materials can be sintered simultaneously. The total sintering time of the new RHK is reduced to less than 1 h, which is less than half the time needed by the PK. The production capacity in this RHK (50 m long) is thus 100 t/month.

2.2 The Structures and Characteristics of the New RHK

The kiln is divided into the four zones as shown in Fig. 1. (1) Total decarbonization occurs during the pre-sintering phase of the first zone so that the cores can be sintered more rapidly afterward. This zone is 10 m long and is separated from the sintering kiln so that no organic gases flow from the binder into the next zone. With pre-sintering very large cores e.g. R128 (ring core: OD = 128, ID = 96, H = 30 mm, weight = 850 g) can be sintered. (2) In the heating-up zone, direct-gas-firing from both above and beneath the refractory plates increases the heating rate. During testing, the maximum heating rate reached 1800°C/h. Figure 2 compares the heating of the RHK to the PK. It takes about 3 h for the RHK to reach its maximum temperature, less than half of the time needed by the PK. (3) In the 3rd zone of the kiln, the maximum sintering temperature is maintained for a relatively long time, resulting in shorter heating and cooling zones, in spite of the short overall sintering period. In the RHK, the 3rd zone is 24% of the total sintering cycle, which is larger than that of the PK, 13%.

The relation of the magnetic properties of Mn-Zn ferrites to the holding time at maximum temperature is shown in Fig. 3. The Pₑ of the low-Pₑ materials is saturated for 2 h during the holding time. The μₚ₀ of the high-μ₀ materials increases monotonously in proportion to the holding time. Two hours of holding time is enough for both materials. (4) In the 4th zone, the cooling zone is most important for the magnetic properties of Mn-Zn ferrites because these characteristics strongly depend on the degree that the ferrites oxidize. In order to preserve the composition and the structure of the spinel's single phase, it is necessary to control the partial pressure of oxygen, PO₂, above the temperature, particu-

<table>
<thead>
<tr>
<th>RHK</th>
<th>Start</th>
<th>Length of kiln (m)</th>
<th>Pre-sintering furnace (m)</th>
<th>Kiln time (h)</th>
<th>Productive capacity (t/month)</th>
<th>Loading plate (mm × mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>Dec., 1989</td>
<td>20</td>
<td>—</td>
<td>10</td>
<td>15</td>
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</tr>
<tr>
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<td>May, 1991</td>
<td>40</td>
<td>—</td>
<td>11</td>
<td>70</td>
<td>350 × 350 (2 lines)</td>
</tr>
<tr>
<td>No. 4</td>
<td>May, 1994</td>
<td>40</td>
<td>10</td>
<td>11</td>
<td>100</td>
<td>350 × 350 (2 lines)</td>
</tr>
<tr>
<td>PK</td>
<td>Mar., 1990</td>
<td>30</td>
<td>10 (With pre-sintering)</td>
<td>22</td>
<td>65</td>
<td>340 × 340 (2 lines)</td>
</tr>
</tbody>
</table>

KAWASAKI STEEL TECHNICAL REPORT
Fig. 1 The schematic view of the new RHK and the sintering conditions

Fig. 2 The difference of the heating step between PK and RHK

Fig. 3 Holding time dependence of the magnetic properties

Thus the aperture optimizes the relation of temperature to oxygen content during the Mn-Zn ferrite phases. The narrow aperture at the cooling zone is able to accelerate the cooling rate. As shown in Fig. 5, the cooling period of the RHK is 40% shorter than that of the PK.

2.3 Magnetic Properties of Mn-Zn Ferrites Sintered by the RHK

The core loss, $P_{\mu}$, is shown in Fig. 6 for the lowest $P_{\mu}$ material in mass production, MB4, in comparison to the conventional low-$P_{\mu}$ material MB3. The $P_{\mu}$ of MB4
is $270 \text{ kW} \cdot \text{m}^{-3}$ at the conditions of 100 kHz, 200 mT and 95°C. The initial permeability $\mu/\mu_0$ is shown in Fig. 7 for various high-$\mu$ materials. The highest $\mu/\mu_0$ is 10,000 (MA100) at 23°C and is maintained up to 100 kHz. These two different types of Mn-Zn ferrites can be sintered simultaneously in the RHK, thus proving the kiln to make history in the mass production of Mn-Zn ferrites.

Fig. 4 Time dependence of $P_{o_2}$ in the cooling zone before and after improvement

Fig. 5 The difference of the cooling step between PK and RHK

Fig. 6 Temperature dependence of the core loss, $P_{\text{core}}$ for MB3 and MB4

Fig. 7 Frequency dependence of the initial permeability, $\mu/\mu_0$, for various high-permeability materials

3 Discussion

3.1 Comparison with the PK

The merits of the newly developed RHK is discussed in relation to the PK. In general, the most important difference between the RHK and PK is the rates of heating and cooling, which influence both the productivity and the magnetic properties of the products. For example, the $\mu$ value increases with an increase in the sintering density determined by the rate of heating.\(^{(1,5)}\)

The difference of the rates arises from the two reasons. One is the heat capacity of the moving refractory plates. The plate used in the PK is 5 times heavier than that in the RHK. The other is the ability of the oil-cylinders to transport the plates by pushing. The characteristics of MA100 and MB4, for example, are shown in Table 2. Their magnetic properties are shown to improve at a higher sintering density.

However, the problem of how to prolong the life time of the refractory plate arises through this higher heating and cooling rate in the RHK. We have been developing refractory plates that resist the stress from this rapid heat cycle.

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Table 2 Magnetic properties of MA100 and MB4 compared between the RHK and the PK

<table>
<thead>
<tr>
<th></th>
<th>MA100</th>
<th></th>
<th>MB4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHK</td>
<td>$11,020$</td>
<td>5.04</td>
<td>$253$</td>
</tr>
<tr>
<td>PK</td>
<td>$9,640$</td>
<td>5.60</td>
<td>$273$</td>
</tr>
</tbody>
</table>

$\mu_0/\mu_0$, Sintered density (kg/m$^2$), Core loss $P_c$, Sintered density (kg/m$^2$)

$\times 10^6$ Hz **10 kHz, 200 mT, 90–100°C

3.2 Improvement of the Transportation Equipment

In mass production using the RHK, the risk of an accident from damaged roller is very serious. If an accident happens, operation should be stopped for 2 or 3 days. In order to prevent such an accident, three improvements were made. First, the materials used for the ceramic rollers in the high temperature region was changed to silicon carbide. Second, a sensor has been developed which will give a warning if only one roller is defect. Finally, the refractory plate was also reinforced against any damage incurred by the rapid heating and cooling.

4 Conclusion

The total sintering time of a new RHK is reduced to less than 11 h, which is less than half the time needed by the PK. The production capacity in this RHK (50 m long) thereby reaches 100 t/month. Two different types of Mn-Zn ferrite, i.e. high-$\mu$, and low-$P_c$, materials, can be sintered simultaneously in the RHK. The $\mu_0/\mu_0$ of high-$\mu$, material, MA100, reaches 10,000 at up to 100 kHz, and the $P_c$ value of low-$P_c$, material, MB4, is reduced to 270 kW·m$^{-2}$ at 100 kHz, 200 mT and 95°C in mass production.

5 Acknowledgments

We are grateful to Mr. H. Oshima, the manager of Noritake Co., Ltd., and his staff for contributing to the development of the RHK.

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2) Kawasaki Steel Corp.: Jpn. Koukoku 4–77234
3) Kawasaki Steel Corp.: Jpn. Koukoku 6–76257