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Recent Activities in Research of Electrical Steels

Michiro Komatsubara

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The integrated manufacture of electrical steels in Mizushima Works since 1995 has bestowed upon electrical steel research much development, because the research department has been obliged to rightly reply to many difficult questions as to conditions in operating several new process lines. Especially, the efforts to the progress of electrical steel research have been made on quantative estimation for adequate values of materials such as components, precipitates, crystal structures, textures, surface microstructures, and so on. Moreover, the efforts have been made on constructing new theory of secondary recrystallization. Additionally, a research on magnetism has progressed in the field of magnetic domain refining techniques and in the area of applications of electrical steels for model transformers or model motors. These progresses have greatly contributed to the improvement of electrical steels and the development of new products at Kawasaki Steel.

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Michiro Komatsubara
Dr. Eng.,
General Manager,
Electrical Steel Lab.,
Technical Res. Labs.

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1 Introduction

Electrical steel is an important functional material which is used in the cores of generators, motors, transformers and other power supply and conversion systems. In particular, low iron loss has been required in recent years as a means of contributing to a reduction in CO_2 emissions into the atmosphere by achieving higher efficiency, and hence, energy savings in these devices.

Since Kawasaki Steel began to manufacture hot rolled electrical steel sheets in 1932, the company has continued to make diligent efforts to improve the quality of its electrical steel products. These efforts include a change to non-oriented cold rolled electrical steel in 1954, the start of production of grain oriented electrical steel in 1959, and the start of production of high permeability grain oriented electrical steel (RGH) in 1973. Reviewing the last ten years, in 1995, the company completed the transfer and new construction of all production equipment for electrical steel at Mizushima Works, aiming at integrated production at Mizushima Works, in order to realize more efficient production and the development of a number of new products.

The electrical steel laboratory has played a large role in the development of new products and new processes during this period. This paper will present an outline of the new technologies which formed the foundation for these developments, together with their concepts, and will introduce briefly the main new products and their features.

2 Topics in Grain Oriented Electrical Steel

A distinctive feature of grain oriented electrical steel is the fact that a component, called an inhibitor, which inhibits grain growth in the steel sheet is introduced into the steel. Specifically, with this technology, products with excellent magnetic properties are obtained by strongly suppressing grain growth by fine dispersion of the inhibitor in the steel, performing high temperature, long sustained annealing (termed final annealing) in a condition which maintains a fine grain structure, and selectively promoting rapid growth of grains in this fine structure which possess a specific orientation favorable to magnetic properties, in a process termed secondary recrystallization.

Accordingly, the important points for the manufacturing process are (1) a technique which causes fine dispersive precipitation of the inhibitor in the steel, (2) a technique which enables fine control of the grain structure, and (3) a technique for selectively promoting the growth of grains with the specified orientation.

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2.1 Research on Desolution-Fine Precipitation Techniques for Inhibitors

The principal points of this technology are causing the inhibitor to desolute in the steel during stab reheating, and then precipitate finely during working in the hot rolling process.

Conventionally, slab reheating had been performed by long sustained soaking treatment in a gas furnace. In this treatment, the crystal grains grew to enormous size simultaneously with desolution of the inhibitor in the steel, and could not be completely refined by working and recrystallization in hot rolling. In contrast to this, it is possible to suppress coarse grain growth in slabs and also promote complete desolution of the inhibitor if short term, high temperature heat treatment is performed in slab reheating. For this, Kawasaki Steel introduced the world's first induction heating furnace for slab reheating in electrical steel production.[1] However, in an industrial operation, it is difficult to decide conditions which will ensure complete desolution of the inhibitor, which has precipitated in the slab in a coarse size during continuous casting. For this reason, a desolution-diffusion model was constructed for inhibitors, corresponding to the successive temperature changes which can be applied in complex heat treatments, including the heating up process.[2]

With regard to the precipitation of inhibitors under high temperature slab reheating conditions, not only was the starting temperature for hot rolling high in the conventional practice, but it was also necessary to obtain inhibitor precipitation conditions that would be compatible with the hot rolling line at Mizushima Works, which is long in comparison with the former No. 1 hot rolling line at Chiba Works. Accordingly, research on the precipitation behavior of inhibitors was carried out once again,[3] working back to the fundamental stage, and the optimum hot rolling process conditions were investigated. As a result, it was found that, in order to secure fine precipitation of inhibitors, it is essential that a high density of dislocations exist in the steel, and favorable conditions are therefore determined based on a temperature and time at which the dislocations do not disappear. **Photo 1** shows an example of an investigation of the changes in the precipitation of MnSe over time.[3] This technique suppresses the band-like occurrence of the incomplete secondary recrystallization which had long been one of the principal causes of inhomogeneity in magnetic properties.

Moreover, dramatic progress has been made in research on the grain growth inhibition force of inhibitors. One example is the technique of enhancing the inhibition force by causing complex precipitation of heterogeneous inhibitors.[4] This is a technique in which one type of inhibitor is made to precipitate extremely finely during the hot rolling process, and then, in the initial heating up process during annealing in the cold rolling process, complex precipitation is realized by contact between a different type of inhibitor and the inhibitor which had precipitated previously. It has been found that this makes it possible to obtain a stronger inhibiting effect. Further, with regard to the role of the segregative inhibitors such as Sb and others, research has clarified the fact that, in addition to inhibiting grain growth by segregation at grain boundaries, these substances also inhibit nitriding and oxidation of the steel strip during final annealing by segregating at the strip surface, and thus have a secondary function in stabilizing secondary recrystallization.[5,6]

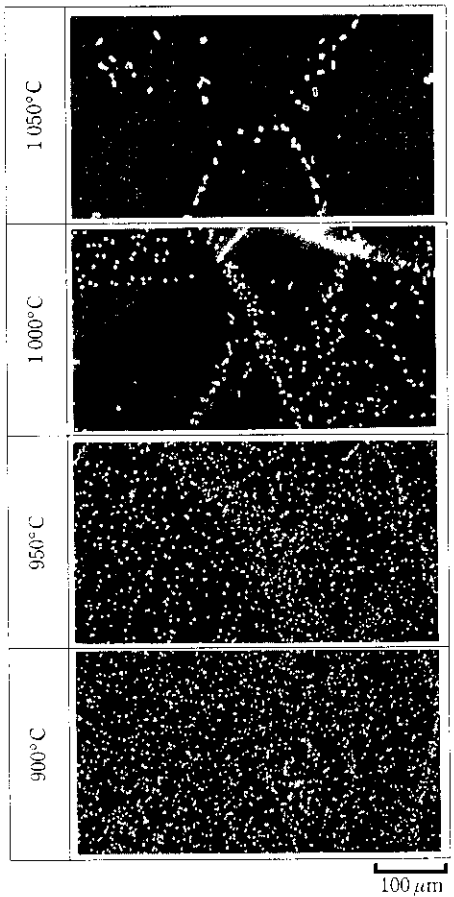

Photo 1 Effect of deformation temperature on the MnSe precipitation in the steel deformed and held for 60 s at various temperatures

2.2 Progress in Research on Cold Rolling Process

In the cold rolling process, optimization of the primary crystal structure and texture of the steel sheet and the structure of the surface layer of the sheet is the main technique. In terms of hardware, the technical innovations achieved in realizing the integrated production of grain oriented electrical steel at Mizushima Works included the world's first continuous rolling for high silicon steel by the tandem mill, high speed decarburization annealing equipment, and the adoption of rotary hearth continuous furnaces in all the final annealing furnaces. Accompanying this kind of technical innovation, great progress was also made in research on the cold rolling process. In particular, for performing decarburization annealing, progress was made in research on annealing immediately before final cold rolling, which has a large influence on the primary recrystallization structure and formation of subscale during decarburization annealing.

Specifically, this research has yielded a clearer understanding of the meaning of the slight decarburization and slight desiliconization of the surface layer of steel sheets in annealing immediately before final cold rolling, which has been employed since an early date, and strict indices were given for the control of this practice. In addition, the conditions for precipitation treatment of the extremely fine carbides, which precipitate in steel during rapid cooling treatment, were obtained more rigorously so as to be suitable for the new decarburization annealing furnace.

As rolling technologies, research was conducted on texture control by warm rolling and the control of texture or steel surface in tandem rolling.

To enable processing of various electrical steels on one line with the high speed decarburization annealing furnace, it was necessary to carry out deeper research on decarburizatin annealing. For this, an evaluation method was developed which applies electrochemistry to the analysis of the structure and composition of the subscale that forms in the steel surface layer.[7] This effort resulted in the establishment of a pretreatment technique which is used as a method of controlling the quality of the subscale that forms in the surface layer. These technologies were applied to develop new products.

In final annealing, remarkable progress has been achieved in secondary recrystallization theory,[8] clarifying the mechanism of incomplete secondary recrystallization, the mechanism responsible for the appearance of secondary recrystallized grains with unfavorable grain orientations, and the boundary between the conditions for obtaining these and a favorable secondary recrystallization structure. A technique which enables non-destructive observation of the growth behavior of secondary recrystallized grains using an ultrasonic method was also developed, providing a deeper understanding of secondary recrystallization. In **Photo 2**, the growth process of secondary recrystallized grains in RGH is traced non-destructively by the ultrasonic resonance method.[9] Accompanying this deep understanding of secondary recrystallization phenomena, it has been possible to establish methods of quantitative evaluation for the normal grain growth, quantitative evaluation of inhibition force of inhibitors, which is the basis for increasing the driving force of secondary recrystallized grain growth, quantitative evaluation of the size of primary recrystallized grains, quantitative evaluation of the primary recrystallization texture, and quantitative evaluation of the condition of the steel sheet surface, which has a great influence on secondary recrystallization. It might be noted that a full automatic EBSD (electron back scattering diffraction) device, which Kawasaki Steel was the first company to introduce in Japan, proved to be effective in the quantitative evaluation of the primary recrystallization texture. **Figure 1** shows an example of the quantitative evaluation of the texture using this device. New theories and evaluation methods mentioned above have also been actively applied in the diagnosis of operations and quality control in the works, and thus are now able to contribute to a broad improvement in the quality of products.

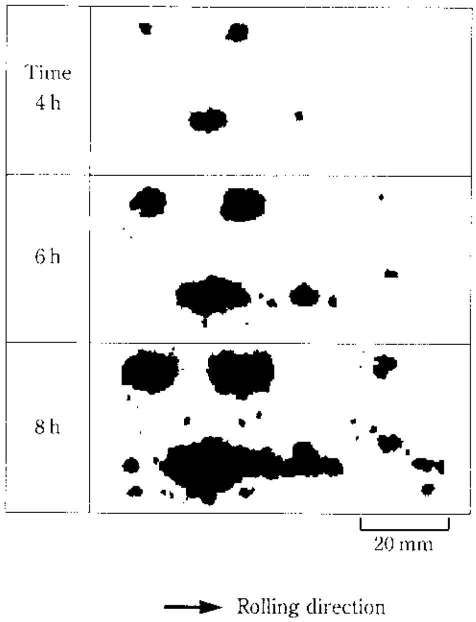

Photo 2 Secondary recrystallization behavior of RGH at 870°C observed by a newly developed ultrasonic method

2.3 Progress in Magnetic Domain Refinement Technique and Product Evaluation Techniques

Iron loss is substantially reduced when magnetic domain refinement is applied to grain oriented electrical steel sheets. As a means of achieving this, the conventional method of irradiation with a plasma jet was improved and unified with the method of providing grooves on the surface of the sheet after final cold rolling.[10] This technique makes use of the phenomenon in which magnetic domains are refined by the demagnetization field created by the magnetic poles that form in the grooved parts. The shape, depth, pitch, and angle of the grooves which make it possible to obtain the optimum properties were obtained experimentally and theoretically.[11]

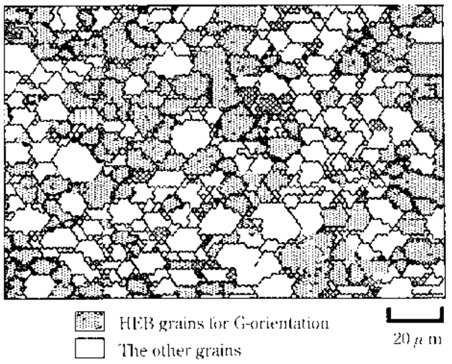

Fig. 1 Distribution of HEB grains (grains having high energy grain-boundary for a certain orientation) for G-orientation in primary recrystallized microstructure of high permeability 3% Si grain oriented steel: G-orientation is (110) [001], the ratio of HEB grains for which is 0.78. This means that G-orientation has a great advantage for grain growth.

The performance of transformers depends heavily on the magnetic properties of the grain oriented electrical steel sheets which are used, but this is not a matter that can be determined completely on the basis of those properties. In particular, new materials for stacked core transformers with T-joint or L-joint parts, in which a complex flow of magnetic flux occurs, had long been evaluated using model transformers. This technique for evaluating materials was improved, making it possible to measure accurately what kind of effect the pressure applied to the steel sheets and the harmonics of higher orders have on the exciting current, iron loss, and noise in the model transformer.[12,13] This in turn has enabled a more accurate evaluation of how the excellent properties of new products will be reflected in actual transformers, and thus is an effective tool for presenting new products.

The grain size of grain oriented steel sheets normally varies from several mm to several tens of mm, depending on the manufacturing method. It had been expected that the configuration of the crystal structure would influence the condition of magnetization of steel sheets, and therefore would control the magnetic properties. In order to clarify this mechanism, a measuring device for local magnetic properties, which uses a needle as the probe, was newly developed, and it was found that the shape and size of grains has a large effect on the flow of the magnetic flux in the steel sheet as a whole.[14] **Figure 2** shows a condition in which magnetic properties were deteriorated due to the abnormal flow of magnetic flux that occurs in the vicinity of crystal grains with large deviating orientations, as detected with this device. This technique provides an indicator for optimizing the configuration and size distribution of secondary recrystallized grains, and is expected to be used effective in the future.

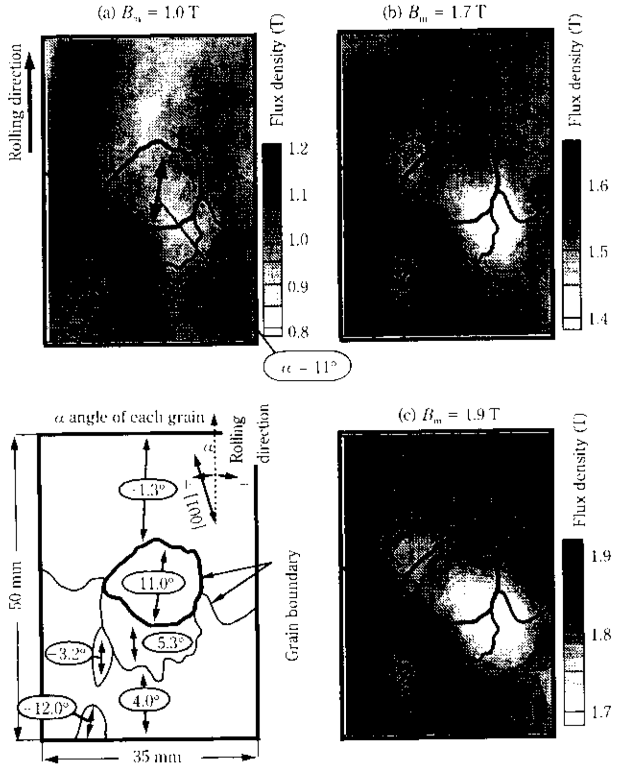

Fig. 2 Increase in distribution of flux flow around a large α angle-grain (α = 11°) with increasing magnetization of grain oriented Si steel shown in local flux density map observed by needle-probe method

3 Topics in Research on Development of Non-oriented Electrical Steel

In the field of non-oriented electrical steel, improving the purity of the steel, increasing the size of crystal grains in the product, increasing the magnetic flux density, and improving the surface properties of steel sheets are the essential techniques.

3.1 Research on High Purity Steel Refining and Manufacturing Technologies

With regard to the composition of non-oriented electrical steel sheets, it has long been known that minimizing the contents of impurities other than Si, Al, and Mn is a basic necessity. However, in recent years, it has been possible to achieve a further degree of reduction in the contents of C, S, N, and O as a result of progress in steelmaking technology. Moreover, progress has been made in research on the morphology and dispersion of inclusions and precipitates in steel, and in research on technical innovations in this regard.[15] Progress has also been made in research aimed at ensuring that the properties of such high purity steels are reflected well in improved magnetic properties.

3.2 Control of Texture

Non-oriented electrical steel has an advantage in the fact that reducing the intensities of the (111) and (112) textures and increasing the intensities of the (100) and (110) textures improves the magnetic properties of the product. The technique by which this type of crystal structure is created is called texture control. Traditionally, Kawasaki Steel had developed the technique of adding Sb and Sn to steel,[16-18] and then also expanded the application of this technique to include low Si steel, enabling the company to produce products with extremely high permeability.[19,20]

In passing, it might be mentioned that induction motors account for the overwhelming majority of the motors which are used in household appliances. Because the energy loss in these motors is mainly copper loss, it is beneficial to increase the magnetic flux density of the motor core. Furthermore, high magnetic flux density is also required in the materials for the cores of EI, which are small transformers, in order to realize higher efficiency. Because further improvement in the texture of electrical steel sheets in the direction described above is necessary for this purpose, innovative research has been carried out on the steel composition, inclusions, and crystal structure,[21] resulting in the development of a succession of new products in the RP and RMA series.

3.3 Progress in Research on Coatings

Non-oriented steel sheets are used in a variety of applications, which require forming into diverse shapes by punching and shearing; moreover, in many cases, the processed sheet is subjected to stress relief annealing in order to keep its magnetic properties. Insulation coating is applied to the surface of non-oriented electrical steel to impart electrical insulation, but when a product is to be used by the methods mentioned above, not only insulation, but also punchability, heat resistance, corrosion resistance, weldability, etc. are required as properties of the coating. Although the A series coating is an all purpose coating which satisfies these requirements, progress has been made in improvement research aimed at obtaining a higher level of properties. Advances have also been made in research on compositions which enable high speed application and baking treatment in the factory with this all purpose coating.

Research and development were also carried out on a bonding coating, "B Coat," which enables heat bonding of steel sheets and is suitable for applications that do not permit joining by welding, etc. and applications that require air tightness by stacking.

3.4 Development of Technique for Evaluation of Characteristics of Motors and Research on Suitable Material

Although two dimensional measurement[22] of the magnetic properties of non-oriented electrical steel sheets and other methods have been proposed, these have not reached the stage of adoption, and as in the past, evaluations continue to be made using the Epstein method, which is specified in JIS 2550. However, the actual applications of non-oriented electrical steels are diverse, including motors, switches, choke coils, EI cores, and others, and it cannot necessarily be said that the Epstein characteristics cover all these cases equally well. In particular, there had been active debate with regard to motor characteristics for some time.

To solve this problem, Kawasaki Steel developed a method of evaluating the effect of the material properties of a series of non-oriented electrical steels on torque and motor efficiency, as represented by iron loss and copper loss, covering a full range of motors, including the single phase induction motor, inverter motor, DC brushless type inverter motor, and others.[23] Although this research has not been completely finished, the results are being actively applied as indicators for the development of new materials, and are also proving useful in making recommendations to customers on the most suitable product for the type of motor.

4 Conclusion

Electrical steel sheets have been called a "work of art in steel," and the most advanced iron and steel manufacturing technologies of the day are incorporated in the production process. However, while these advanced technologies are remarkable, importance must also be given to the various requirements of industrial products, such as productivity in mass production, stable product quality, and others. For this reason, Kawasaki Steel succeeded in establishing an integrated production system with high efficiency and high product quality by transferring the production of electrical steel to its Mizushima Works. During the same period, research on electrical steel sheets produced impressive results in new manufacturing techniques, as described briefly in this report, and new product development, as presented in the "Special Issue on Electrical Steel"[24] of Kawasaki Steel Technical Report.

In the future, the needs of society will continue to move rapidly in the direction of energy saving and reduced noise, and the demand for lower iron loss and higher magnetic flux density in electrical steels will be greater than ever. Moreover, customers have large expectations for more precise control of the mechanical properties of electrical steel sheets, higher accuracy control of sheet dimensions, and similar improvements. In responding to these requirements, Kawasaki Steel will continue with its efforts in research on electrical steel and new product development by listening positively to the needs of customers and making full use of new technologies.

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