Development Trends of Soft Magnetic Iron

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Driven by advances in electronically controlled systems for automobiles, the demand is growing for soft magnetic steels that can generate a large electromagnetic force with low electric power. New steels with very low carbon content have been developed in consideration of their DC electromagnetic properties, their cold forgeability, and machinability. This paper describes the recent development trends of soft magnetic steel and the advantages of our developed steel (ELCH2 series).

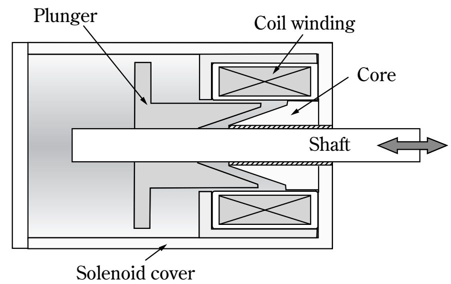


Fig. 1 Example of solenoid structure

Introduction

Recently automobiles are being heavily equipped with various systems operated electrically, electronically and/or electromagnetically to ensure safety, comfort and fuel economy. Such systems include computer controlled automatic transmissions, electronic power steering (EPS) and anti-lock braking systems (ABS)[1, 2].

In the early years (1950s-1960s) when electric and electronic devices started to be used in automobiles, the main purpose was to improve and upgrade the performance of individual systems. Highly complicated vehicle control in recent years, however, is incomplete without high-speed linkage and movements coordinated among different systems. Hence electronically and/or electromagnetically controlled components are becoming increasingly important.

Among these electronically and/or electromagnetically controlled systems, components that utilize electromagnetic force incorporate iron cores in their coils to generate magnetic fields. Many conventional cores consist of low carbon steel, containing about 0.1% of carbon, to improve the response to control signals and increase energy efficiency.[3] With the remarkable advancement of electromagnetic control in recent years, it has become essential for electromagnetic components to have even higher performance and lower power consumption.

This paper describes the trend of soft magnetic materials, such as those for iron cores used in electromagnetic components, and introduces the characteristics of the pure iron-based soft magnetic materials in the ELCH2 (Extra Low Carbon Cold Heading Wire) series developed by Kobe Steel.

1. Transition of soft magnetic materials

Fig. 1 depicts the structure of a solenoid device for hydraulic control. This is a typical example of the electromagnetic components used in automobiles. Soft magnetic materials are usually used for iron cores that form magnetic circuits and for the housings, including covers.

Early solenoid devices for automobiles were mainly used for controlling the oil flow by on-off switching. Thus, the availability and workability of iron core materials were more important than their magnetic characteristics. As a result, low carbon steels such as SWRCH10A (JIS G 3507-1) and SUM23 (JIS G 4804) were used for the iron cores.

Recent solenoid devices, however, must be able to control hydraulics swiftly and stably. To achieve this, the on-off control is being replaced by linear control in many cases.[4), 5)] For linear control, the control current must be proportional to the pulling force (electromagnetic force) of the iron cores, which necessitates soft magnetic materials having low coercivity (low hysteresis) at high flux density. The latest iron core materials for linear solenoids are required to have magnetic characteristics better than those of SUY-1 (JIS C 2504), making it difficult for low carbon steel, formerly used for on-off control, to satisfy the required characteristics of magnetic flux density and coercivity (**Fig. 2**).

In the mid-1980s, Kobe Steel worked to totally eliminate factors that can adversely affect the magnetic characteristics of soft magnetic materials and developed a soft magnetic material, ELCH2, based on pure iron, which can achieve the best characteristics among JIS grade (JIS SUY-0) materials.[6] The company has studied parts forming using a forging process and parts function. Now this material is being widely used as a soft magnetic material for cold forging.

In the late 1990s, there was an increasing need for

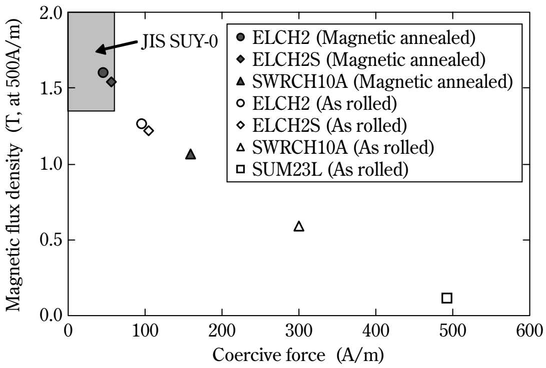


Fig. 2 Comparison of magnetic properties

parts having more complex shapes and higher accuracy. This required machining after cold forging, increasing the importance of the machinability of soft magnetic materials. Pure iron based materials have excellent magnetic characteristics, but they are more difficult to machine than is carbon steel, due to factors such as chip handling during machining and decreased tool life. To resolve this issue, a small amount of Pb was added to the materials.[7] However, Pb is a substance with a heavy environmental burden, hence forming parts without Pb has become an important issue.

Kobe Steel studied techniques to improve machinability without sacrificing magnetic characteristics and developed, in 2001, a new Pb-free steel with improved machinability, ELCH2S.[8] The commercial production of iron cores of large electromagnetic clutches started in 2004. The newly developed material, as well as the previously developed basic steel, is used for many automotive electromagnetic systems with high-functionality.

2. Concept of developed steel

The magnetic characteristics of a soft magnetic material depend on the magnetic moment of the material, as well as its metallic structure, including the size of crystal grains and precipitates. In the case of a polycrystal, in particular, its magnetic characteristics may deteriorate because of its crystal grain boundaries and precipitates, both working as pinning sites of domain walls.[9]

Therefore, the magnetic characteristics of the ELCH2 series have been improved along the following lines:

i) Making the structure a single phase of highly pure ferrite to increase the magnetic moment of the material, or reducing C content to no higher than 0.01% (**Fig. 3**)
ii) Decreasing the grain boundary area to reduce resistance against domain wall migration, or reducing Al and N content

Furthermore, the following aspects were considered, taking into account the fact that metallic soft magnetic materials have the advantage of superior workability and high productivity:

iii) Improving cold forgeability by reducing Si and adding Mn to render S harmless
iv) Improving the machinability of ELCH2S by increasing S to disperse an appropriate amount of MnS

Fig. 4 shows the relationship between the amount of S added to ultra-low carbon steel and tool wear width during turn cutting. It is expected that by increasing the S content to about 0.025%, the tool wear width will be decreased by half compared with the conventional pure iron based material containing less than 0.010% of S.

However, as shown in **Fig. 5**, an excessive addition of S deteriorates magnetic characteristics significantly, while increasing the width of variation in coercive force. Precipitation of FeS is observed at prior austenite grain boundaries.[8] This indicates that the deterioration of magnetic characteristics is attributable to FeS, which decreases the compression ratio of ferrite phase determining magnetic moment and increases the resistance against domain wall migration. Because of this, the newly developed steel

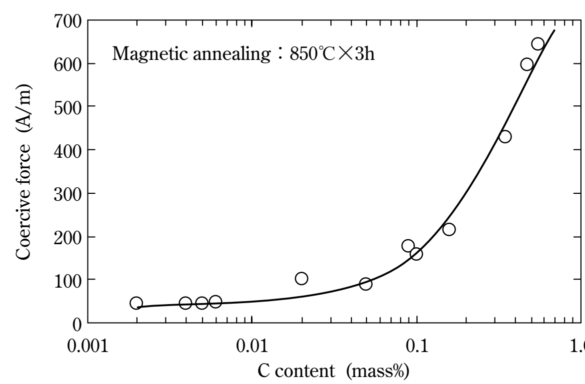


Fig. 3 C content dependence of coercive force

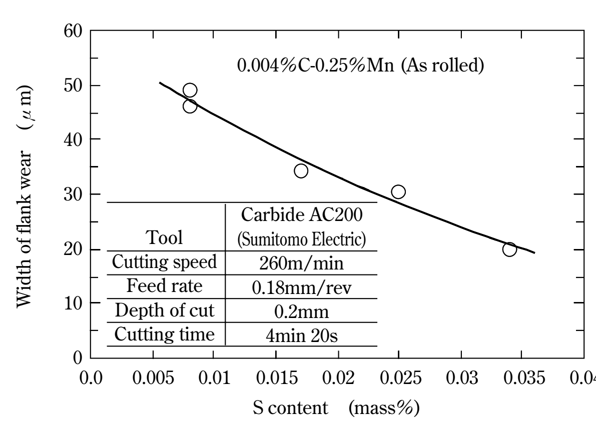


Fig. 4 Relation between S content and width of flank wear

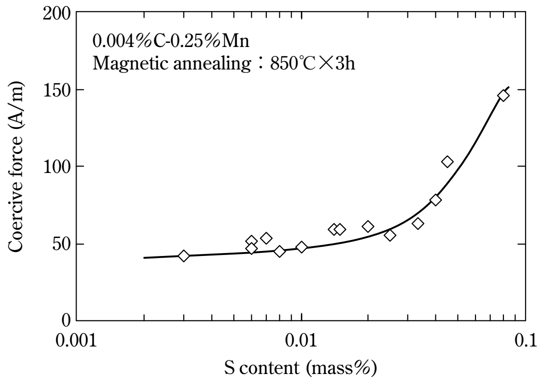


Fig. 5 S content dependence of coercive force

with improved machinability, ELCH2S, is designed to have an optimum Mn/S ratio, such that no FeS phase remains with increased S.

3. Specimens and experimental method

Table 1 shows the chemical compositions of steels that were studied: i.e., ELCH2 as a base composition, ELCH2S with improved machinability and SWRCH10A as a reference composition. These tested materials were melted in a converter furnace and rolled into wire rods, each having a diameter of ϕ20mm. The rolled materials were evaluated for their direct current magnetic characteristics, mechanical properties, machinability and corrosion resistance.

3.1 Magnetic characteristics

Magnetic characteristics were evaluated on ring-shaped specimens made of the respective test materials. The evaluation was conducted according to JIS C 2504 (Soft magnetic iron). An automatic magnetometer (BHS-40, manufactured by Riken Denshi Co., Ltd.) was used to obtain an initial magnetization curve and hysteresis curve, and these curves were used to determine coercivity and magnetic permeability. Also determined was the magnetic flux density under each magnetic field. It should be noted that the sweep rate (200~250(A/ms)) of the applied magnetic field during each measurement was set within a range in which eddy-current loss does not affect the hysteresis curve.

3.2 Mechanical properties

Mechanical properties were evaluated by tensile testing at room temperature. Tensile test pieces, 14 A according to JIS Z 2201 (Tensile Test for Metallic Materials), were prepared from the respective sample materials.

Table 1 Chemical composition of steels used in this study

(mass%)

Steel	C	Si	Mn	P	S
ELCH2S	0.005	0.004	0.26	0.010	0.025
ELCH2	0.005	0.004	0.25	0.009	0.008
SWRCH10A	0.10	0.04	0.45	0.014	0.009
JIS SUY	max. 0.03	max. 0.20	max. 0.50	max. 0.03	max. 0.03

3.3 Cold forgeability (deformability)

Deformability of the developed steel was evaluated on specimens (ϕ20×30mm), each having a notch on its lateral face. An upsetting test was conducted using a mechanical press while restraining the ends of each specimen. Deformability was determined from the critical upsetting ratio at which no cracking occurs from the notch.

3.4 Machinability

Machinability (i.e., burr height, chip disruption and wear width of cutting tool) was evaluated by a drill penetration test and cutting test using a carbide tool.

3.5 Corrosion resistance

Corrosion resistance was evaluated by the salt spray test according to JIS Z 2371 (salt spray test method), using 5% brine water. After the salt spray, the specimens were immersed in a 10% solution of ammonium citrate at 70℃ for rust removal before measuring the mass change.

4. Experiment results and discussion

4.1 Magnetic characteristics

Fig. 6 shows the relationship between the strength of the applied magnetic field and magnetic flux density for ELCH2 series steels and SWRCH10A. The tested materials had been annealed in a vacuum at 850℃ for 3 hrs. This magnetic annealing condition is widely used in the industry.

The ELCH2 series steels exhibit higher magnetic flux density for a given applied magnetic field compared with the reference steel, showing significant improvement for the magnetic field below 2,000A/m. The improvement effect seen in flux density lessens with a higher magnetic field. This is because, as magnetization approaches saturation, the magnetization mechanism shifts from domain wall migration to rotation magnetization, decreasing the effect of domain wall migration governed by metallic structure.

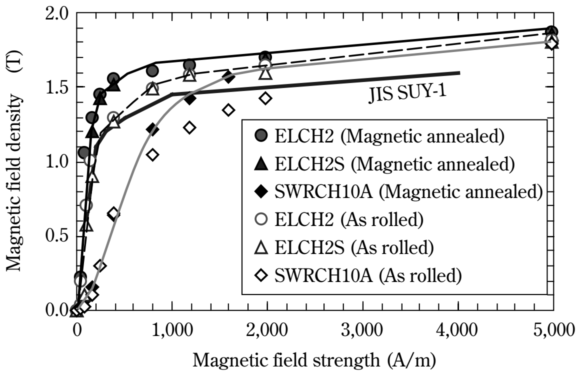


Fig. 6 Magnetic field dependence of magnetic flux density

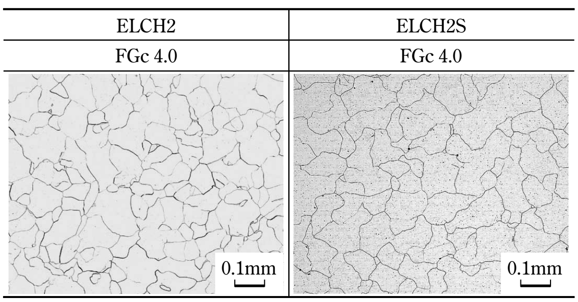


Fig. 7 Microstructure of developed steel after magnetic annealing

Fig. 7 compares the microstructures after the magnetic annealing of ELCH2 series steels. Each material shows a clean structure of single phase ferrite. It has been reported that, in the case of ELCH2S with improved machinability, MnS may provide pinning points against the growth of crystal grain during magnetic annealing[10]; however, the tested steels have almost the same size of ferrite grains, and no adverse effect was observed. Thus, in the case of the ELCH2 series, both the base composition and modified steel with improved machinability can have almost the same magnetic characteristics, as long as the heat treatment conditions are the same.

Table 2 shows typical magnetic characteristics of the ELCH2 series. Both of the base compositions, ELCH2 and ELCH2S with improved machinability, satisfy the superb magnetic characteristics achieved by JIS SUY-0. Also, they can exert electromagnetic force, comparable with that exerted by conventional low carbon steel, with a smaller applied magnetic field or smaller electric current, providing solutions for the improvement of component characteristics and power saving.

For example, assuming the magnetic flux density required to actuate an electromagnetic device to be 1.6T, SWRCH10A requires a magnetic field of 1,200A/m, while the ELCH2 series materials require only about 400A/m, reducing the energy for magnetomotive force required to produce magnetic flux by about 65%.

In addition, as shown in Fig. 6, ELCH2 series materials, as-rolled, satisfy magnetic characteristics comparable with those achieved by SWRCH10A, magnetic annealed. Thus, the magnetic annealing step can be omitted for the parts currently made of SWRCH10A, or of materials equivalent to it.

4.2 Mechanical properties

Table 3 shows the mechanical properties of the developed steels, as-rolled. The as-rolled materials have a tensile strength of about 300MPa and are comparable to spheroidized SWRCH10A. The tensile strength is increased by working, such as wire drawing, however, the softening that occurs during magnetic annealing makes the ultimate tensile strength about 230MPa regardless of the drawing reduction.

4.3 Cold forgeability

Fig. 8 compares the critical upsetting ratios at which the notched specimens start to exhibit cracks. The spheroidize annealed SWRCH10A exhibits a critical upsetting ratio as high as 70%, while the

Table 2 Magnetic properties of ELCH2 series (Magnetic annealed)

Steel	Magnetic field density (T)						Coercive force (A/m)
	B100	B200	B300	B500	B1000	B4000	
ELCH2S	0.90	1.24	1.47	1.54	1.64	1.80	55.7
ELCH2	0.92	1.30	1.50	1.60	1.65	1.81	45.2
SUY-1	≧0.60	≧1.10	≧1.20	≧1.30	≧1.45	≧1.60	≦80
SUY-0	≧0.90	≧1.15	≧1.25	≧1.35	≧1.45	≧1.60	≦60

Table 3 Mechanical properties of ELCH2 series

Steel	Tensile strength (MPa)	Young modulus (GPa)	Elongation (%)	Reduction area (%)
ELCH2	305	208	38.1	90.1
ELCH2S	306	209	36.7	92.8

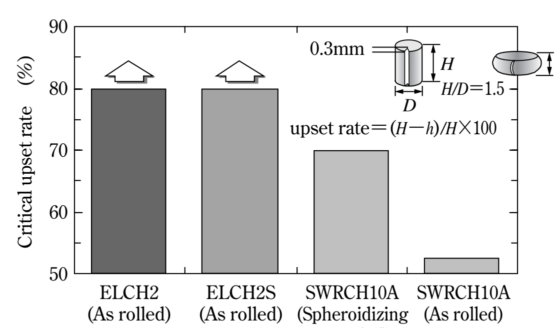


Fig. 8 Critical upset rate

newly developed steels exhibit no cracking at an upsetting ratio of 80%, even without softening annealing, demonstrating excellent deformability. Thus, ELCH2 series materials are effective in omitting process steps, such as heat treatment for softening before cold forging, and reducing the production cost of components.

4.4 Machinability

(1) Drillability

Fig. 9 shows the chips and average burr height observed for the through holes drilled under the conditions summarized in **Table 4**. In the case of ELCH2S with improved machinability, the chips are shorter and segmented with burr height significantly reduced when compared with the base composition, ELCH2. The ELCH2S steel has MnS precipitated and dispersed in its matrix. The precipitates behave effectively as stress concentration sites in the chips, improving the drillability.

(2) Turnability

Fig.10 shows the relationship between cutting speed and flank wear width for ELCH2S with improved machinability. The steel was cut under the conditions shown in **Table 5**. For a given cutting length (800m), the wear width tends to decrease with increased cutting speed. An increase in cutting speed from 80m/min to 700m/min decreased the tool wear to about 1/3 from 0.117mm to 0.038mm. The improvement effect is significant in the cutting speed range up to about 250m/min. High-speed cutting, with a cutting speed higher than 250m/min, has turned out to be effective in reducing tool wear when cutting pure iron based material as the newly-developed steel. The following are considered to be the reasons for reduced wear width during high-speed cutting[11]:

i) The temperature increase associated with cutting heat softens the work material, decreasing the cutting resistance.
ii) A lower cutting speed suppresses the generation of built-up edge on the cutting tool, which promote tool wear.

Fig.10 shows the tool wear width for the base composition, ELCH2, cut at a speed of 260m/min. For the same cutting condition, the wear width for the developed steel is about half that of the conventional steel, which verifies the effectiveness of the newly developed steel from the aspect of tool life.

4.5 Corrosion resistance

Salt spray tests were conducted on both the developed steel, ELCH2, and reference steel, SWRCH10A. **Fig.11** shows the changes in corrosion weight loss. The newly developed steel exhibits a corrosion weight loss about 40% smaller than that of the reference steel, SWRCH10A, demonstrating superior corrosion resistance compared with the reference material. The newly developed steel can be used without any problem for parts that have been made of conventional SWRCH10A or its equivalent.

ELCH2 series materials are designed to have ultra-low carbon content and a homogeneous structure with suppressed precipitation to achieve improved magnetic characteristics. This is considered to

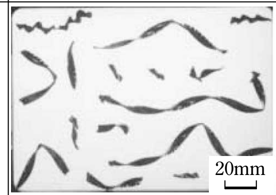
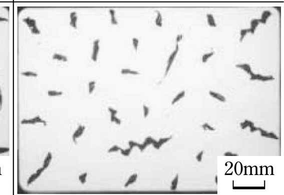
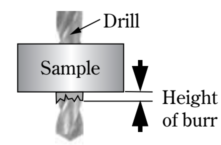
	ELCH2	ELCH2S
Chip		
Height of burr	4.11mm	0.94mm

Fig. 9 Comparison of chip and height of burr

Table 4 Conditions for turning test

Tool	SKH straight drill
Cutting speed	30m/min
Feed rate	0.20mm/rev
Coolant	Dry



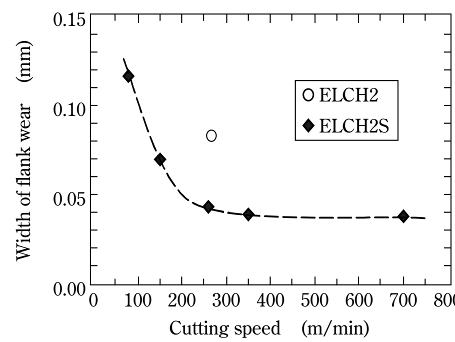


Fig.10 Relation between cutting speed and width of flank wear

Table 5 Conditions for turning test

Tool	Carbide AC200 (Sumitomo Electric)
Cutting speed (m/min)	80, 150, 260, 350, 700
Feed rate (mm/rev)	0.15
Depth of cut (mm)	0.2
Coolant	Water-solube

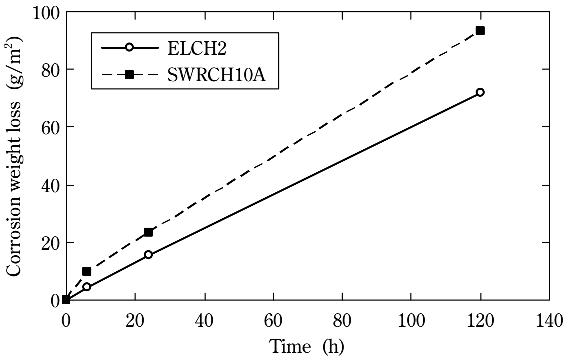


Fig.11 Corrosion weight loss

suppress the generation of local cell in the corrosive environment, leading to excellent corrosion resistance.

5. Application examples

ELCH2 series offer soft magnetic materials which are effective in improving and upgrading the performance of electromagnetically controlled systems and in reducing the cost of parts production.

The materials have been employed for iron cores for hydraulic control solenoids, as well as for large iron cores for electromagnetic clutches, greatly contributing to the reduction of power consumption and improvement of parts productivity[12), 13)].

Conclusions

Pure iron based soft magnetic materials, the ELCH2 series, having excellent magnetic characteristics and cold forgeability have been developed with the following features:

i) Reduced power for generating electromagnetic force, suppressing heat generation from components and reducing the load imposed on control circuits
ii) Cold forgeability, enabling the production of complex shaped parts, which greatly contributes to the performance improvement of electromagnetic devices and to the reduction of their production costs
iii) A steel with improved machinability featured by significantly reduced burrs and tool wear during cutting, which reduces the work load during cutting, compared with the base composition, which highly prioritizes magnetic characteristics

With the prevalence of hybrid electric vehicles and electric vehicles, electromagnetically controlled systems of new types are expected to be developed and applied. Kobe Steel strives to reduce the environmental burden and thus to contribute to society by providing pure iron based soft magnetic materials, the ELCH2 series, which make it possible to improve the performance of electromagnetic devices, save energy and reduce production costs.

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