Soft Magnetic Iron Wire Rod and Sheet: Estimation of Their Benefit for Electromagnetic Components

Yukihiro HISAI*1 · Shinya KAWASHIMA*2 · Dr. Masamichi CHIBA*1 · Kenshi IKEDA*3 · Shinya MORITA*4

*1 Wire Rod & Bar Products Unit, Steel & Aluminum Business
*2 Materials Research Laboratory, Technical Development Group
*3 Wire Rod & Bar Products Unit, Steel & Aluminum Business (currently Wire Rod & Bar Products Development Department, Research & Development Laboratory, Steel & Aluminum Business)
*4 Applied Physics Research Laboratory, Technical Development Group

Abstract

Electrification and decarbonization in the automotive field are raising the demand for higher-performance electromagnetic components. The pure iron-based soft magnetic wire rod (ELCH2 series), which features high magnetic flux density and cold forgeability, is a newly developed material that has contributed to the downsizing of electromagnetic components and energy saving. Furthermore, development is underway on pure iron-based soft magnetic wire rod (ELAC series) with improved responsiveness and alternating current properties to meet diversifying demands. An electromagnetic pure iron steel sheet (KELMOS) is also being developed. This paper introduces the magnetic properties and processability of pure iron-based soft magnetic materials. Also introduced are the results of the magnetic field analysis of electromagnetic relay components, which confirm that the magnetic force and responsiveness have been improved by using pure iron-based soft magnetic material and electromagnetic pure steel sheets instead of typical low-carbon steel in electromagnetic components.

Introduction

Progress in the EV (electric vehicle) sector and the shift toward carbon neutrality in the automotive field have increased the demands placed on automotive electronics.[1)] EVs are complex systems that rely heavily on the performance and specifications of the battery. Alongside the recent industry developments imposing changes regarding EVs, the requirements for electromagnetic components such as motors, solenoids, and relays incorporated in automotive electronics are becoming more varied and sophisticated. Such components must be more responsive for quicker operation, smaller to reduce weight and space, and more efficient to reduce load on the battery. In addition, inverters increase the number of components subjected to superimposed AC magnetic fields, and eddy current losses must be minimized. Low-carbon steel with a carbon content of 0.1% has been widely used for these electromagnetic parts. However, to meet the demands for more advanced components, it is essential to use higher-performing materials.

Kobe Steel's pure iron-based soft magnetic wire rod ELCH2 [Note)] (extra-low-carbon cold heading wire rod) has excellent magnetic properties and has been used in valve parts (solenoids) of electronic transmission control systems, helping satisfy the need for high-performance electromagnetic parts. Kobe Steel is also pursuing further developments to propose pure iron-based soft magnetic materials suitable for a broad range of needs.

Fig. 1 shows examples of the operating frequency ranges and magnetic flux densities of Kobe Steel's pure iron-based soft magnetic materials.

Our developments beyond the ELCH2 series designed for DC components include the ELAC [Note)] series, which has added elements to improve responsiveness and suppress eddy current; KELMOS [Note)], an electromagnetic pure iron steel sheet that builds on expertise gained from ELCH2; and MAGMEL [Note)], a magnetic iron powder featuring low iron loss and high efficiency that is also suitable for three-dimensional magnetic circuit design. These products constitute a sample of our magnetic material solutions developed in conjunction with magnetic field analysis technology and secondary processing technology. This paper introduces the main characteristics and applications of Kobe Steel's ELCH2 series and ELAC series of pure iron-based soft magnetic wire and KELMOS electromagnetic pure iron steel sheets.

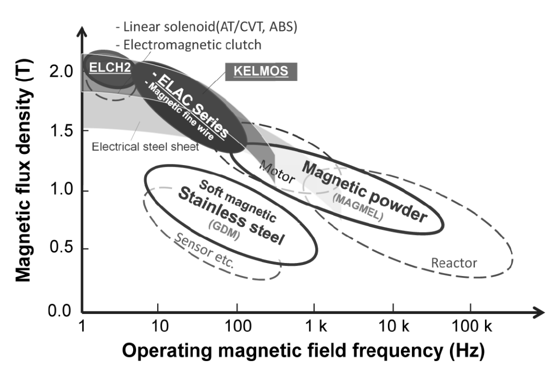

Fig. 1 Examples of operating frequency range and magnetic flux density

Note) ELCH, ELAC, KELMOS, and MAGMEL are trademarks of Kobe Steel (4812504, 6788096, 6668543, 4669506).

1. ELCH2 and ELAC series

1.1 Chemical composition and magnetic properties

Kobe Steel develops advanced steels by designing the chemical composition and material microstructure based on the desired properties. Soft magnetic materials used in electromagnetic components must have high magnetic flux density and low coercive force to ensure sufficient magnetic force and output control. At the same time, high electrical resistivity is desirable in support of time response and AC characteristics. **Table 1** shows the chemical compositions of the ELCH2 series (ELCH2 and ELCH2S), ELAC series (ELAC20 and ELAC30), and S10C, a conventional general-purpose steel. **Table 2** shows the magnetic properties and electrical resistivity of each steel. The ELCH2 series and ELAC series are characterized by their high magnetic flux density and low coercive force. While the ELCH2 series has a particularly high maximum magnetic flux density, the ELAC series exhibits both high magnetic flux density and high electrical resistivity.

We achieved a high saturation magnetic flux density in the ELCH2 series by eliminating factors that adversely affect the magnetic properties of soft magnetic materials. The magnetic properties of soft magnetic materials depend on the material structure and the magnitude of the magnetic moment in the material. The extremely low carbon content of the ELCH2 series yields a single-phase structure of highly pure ferrite, resulting in a high magnetic moment and saturation magnetic flux density (which corresponds to the magnetic force of an electromagnetic component). Additionally, this series has a reduced content of Al and N, which act as pinning sources for grain growth. This decreases the area of the grain boundaries that inhibit domain wall migration. The resulting low coercive force facilitates the control of electrical current.[2)]

The ELAC (ELectromagnetic wire rod for AC application) series has a higher electrical resistivity than the ELCH2 series due to the addition of elements to a degree that preserves the target magnetic properties and forgeability. This suppresses the generation of eddy currents that interfere with the magnetization of materials, improving the time response to changes in the external magnetic field and reducing eddy current loss (power consumption) in AC applications. The ELAC series offers steel materials with different electrical resistivities, such as ELAC20 and ELAC30 (approximate electrical resistivity 20 $\mu\Omega$cm and 30 $\mu\Omega$cm, respectively), making it possible to propose materials based on the characteristics needed. The saturation magnetic flux density of this series is slightly lower than that of the ELCH2 series as a trade-off for the addition of elements. However, as shown in the *B1* column of Table 2, the ELAC series has good magnetic properties in the low magnetic field region, making it suitable for AC applications and components that require a fast response speed.

1.2 Cold forgeability

ELCH2 has high cold forgeability due to the minimized concentration of added elements. Even in the as-rolled state, it has a lower flow stress and

Table 1 Characteristics and example of chemical composition of steels

Characteristic	Steel	Elements (mass%)				
		C	Si	Mn	P	S
Magnetic properties and forgeability	ELCH2	0.005	0.004	0.25	0.009	0.008
Cutting workability	ELCH2S	0.005	0.004	0.26	0.010	0.025
Responsivity and energy efficiency for AC use	ELAC20	0.006	Added a little	0.27	0.005	0.005
	ELAC30	0.008	Added	0.26	0.005	0.005
Conventional steel	S10C	0.08 / 0.13	0.15 / 0.35	0.30 / 0.60	≤ 0.030	≤ 0.035

Table 2 Example of magnetic properties and electrical resistivity of steels

Steel	Magnetic flux density (T)				Coercive force (A/m)	Electrical resistivity ($\mu\Omega$cm)
	B1	*B5*	*B10*	*B50*		
ELCH2	1.35	1.60	1.65	1.90	37	12
ELCH2S	1.33	1.46	1.64	1.89	47	12
ELAC20	1.46	1.57	1.62	1.80	35	22
ELAC30	1.40	1.51	1.55	1.72	31	30
S10C	0.45	1.40	1.54	1.74	86	16

a higher critical upset rate before cracking occurs in comparison with the spheroidized annealed general-purpose carbon steel S10C.[3] **Fig. 2** shows the flow stresses of ELCH2, ELAC20, and ELAC30 as determined by cold upset testing.

Cylindrical specimens of ϕ10 mm × 15 mm were prepared and compressed at a strain rate of 10/s and a compression rate of 60%. ELCH2 has lower flow stress and is superior in terms of tool life. Because the ELAC series has added elements to increase electrical resistivity, it has a higher flow stress than the ELCH2 series; however, at less than 600 MPa, this value is low. Additionally, the cold forgeability of the ELAC series is superior to that of spheroidized annealed S30C and S45C (both at least 600 MPa flow stress).[4] As described above, the ELCH2 and ELAC series have excellent magnetic properties and cold forgeability, enabling reduced manufacturing and component costs through, for example, single-piece forgeability.

On the other hand, high cold forgeability runs counter to high ductility, increasing the likelihood of adhesion to tool edges and increased burr height during cutting. An effective method of improving the machinability of pure iron-based soft magnetic materials is to add sulfur to disperse an appropriate amount of MnS.[5] As such, Kobe Steel developed ELCH2S and ELAC20S for enhanced machinability and can propose materials and solutions that not only account for the required magnetic properties of electromagnetic parts, but also account for the manufacturing process.[6]

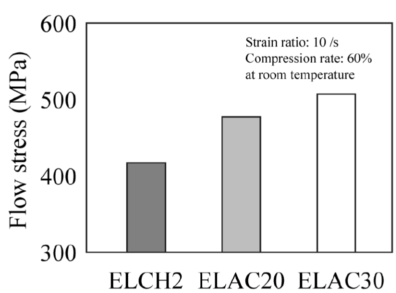

Fig. 2 Flow stress of steels at room temperature

2. KELMOS

2.1 Chemical composition and mechanical properties

By using soft magnetic materials with appropriate component-specific geometries and processing characteristics, it is possible to develop electromagnetic components that meet targets in both magnetic properties and manufacturing cost. As such, Kobe Steel is applying the expertise gained from ELCH2 wire rod to steel sheets in developing KELMOS (Kobe extra-low-carbon electro-magnetic of steel), an electromagnetic pure iron steel sheet with magnetic properties equivalent to those of ELCH2.

Soft magnetic materials must have (1) high saturation magnetic flux density and (2) low coercive force. **Table 3** shows example chemical compositions of KELMOS and conventional mild steel. In line with the ELCH2 series, KELMOS has improved magnetic properties owing to the ultra-low carbon content, which increases the magnetic moment to yield a high saturation magnetic flux density. In addition, this new material has a reduced proportion of Al and N. This composition suppresses the formation of grain boundaries, which inhibit magnetic responsiveness, and the formation of aluminum nitride, which reduces the uniformity of grain growth.[2] As such, this design achieves low coercive force.

With these features, KELMOS will improve control functionality and reduce size, weight, and energy consumption in electromagnetic components.

In addition to its excellent magnetic properties, KELMOS is also characterized by excellent processability. **Table 4** shows examples of the mechanical properties of KELMOS and SPCC, a

Table 3 Example of chemical composition of KELMOS

Steel	Elements (mass%)				
	C	Si	Mn	P	S
KELMOS	≤ 0.02	≤ 0.03	0.20 / 0.30	≤ 0.030	≤ 0.030
JIS SUY-0	≤ 0.030	≤ 0.20	≤ 0.50	≤ 0.030	≤ 0.030

Table 4 Example of mechanical properties of steels

Steel	YS (MPa)	TS (MPa)	Elongation (%)	Hardness (HV)
KELMOS	236	332	44	98
SPCC #1	215	340	42	103
SPCC #2	262	350	41	109

conventional mild steel. SPCC has a wide range of composition specifications, so its mechanical properties can vary. KELMOS has low hardness, high elongation, and excellent processability because the alloying elements and impurities have been reduced to the extent possible, as described above.

2.2 DC magnetic properties

Figs. 3 and **4** show examples of the DC magnetic properties of KELMOS and conventional mild steel. One sheet each (60 mm x 60 mm, 1.0 mm thickness) of the steels tested was annealed for magnetic properties in hydrogen at 850℃ for 3 hours. The initial magnetization curve and hysteresis curve were developed in accordance with JIS C 2556, and the magnetic flux density and coercive force were determined at various specific magnetic field strengths. Fig. 3 shows that KELMOS exhibits a rapid rise in magnetic flux density starting from the low-field strength side and a high saturation magnetic flux density at the high-field strength side.

Fig. 4 shows that only some SPCC materials satisfy the upper limit for coercive force of 60 A/m per JIS SUY-0 (SUY: steel use for yoke) due to compositional variations, analogous to the mechanical properties of these materials. KELMOS, on the other hand, has a sufficiently low coercive force; its magnetic properties meet or surpass the specifications in SUY-0. Therefore, this material will improve the performance of electromagnetic components such as relays and linear solenoids.

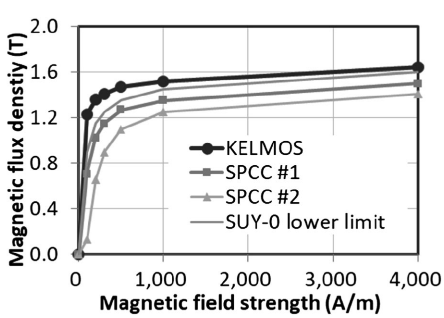

Fig. 3 Example of magnetization curves of steels

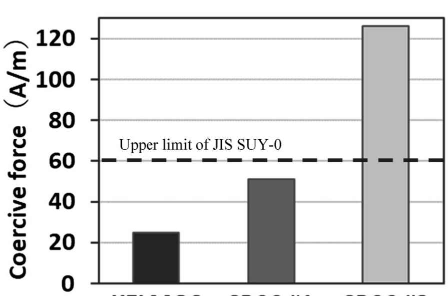

Fig. 4 Example of coercive force of steels

2.3 AC magnetic properties

Fig. 5 shows a sample of the AC magnetic properties of KELMOS. We annealed for magnetic properties 12 samples measuring 30 mm × 300 mm, 0.8 mm thickness in hydrogen at 850℃ for 3 hours. The samples were subjected to testing via an Epstein frame per JIS C 2550, and the iron loss of each magnetic field was evaluated at the frequencies from 50-1,000 Hz shown in Fig. 5. Curve fitting was performed at each frequency using Equation (1) below. **Fig. 6** shows the results converted to indicate the AC magnetic properties for a sheet thickness of 0.5 mm.

$$P = K_h f B_m^{1.6} + K_e \frac{(tfB_m)^2}{\rho} \quad \cdots\cdots (1)$$

Here, f is the frequency, B_m is the maximum magnetic flux density, t is the thickness of the steel sheet, ρ is the electrical resistivity of the magnetic material, and K_h and K_e are proportionality constants. For example, 50A700 per JIS C 2552, a non-oriented magnetic steel sheet, has an iron loss of 7 W/kg (0.5 mm thickness) at 1.5 T and 50 Hz. The iron loss of KELMOS is about 7 W/kg under the same conditions, implying that this material can also be used in low-frequency (50-60 Hz) applications.

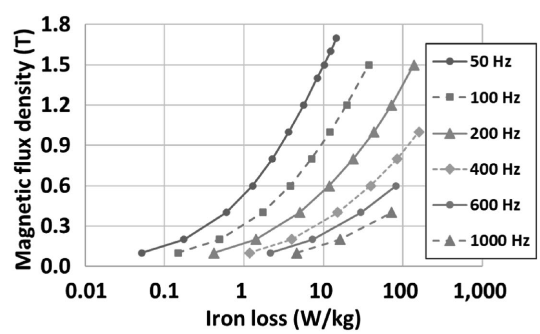

Fig. 5 AC magnetic properties of KELMOS (thickness 0.8 mm)

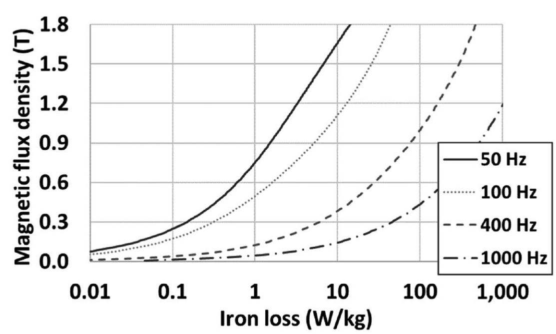

Fig. 6 AC magnetic properties of KELMOS (converted to 0.5 mm thickness)

3. Research into the application in electromagnetic components

We used magnetic field analysis to study the effectiveness and suitability of pure iron-based soft magnetic materials in electromagnetic components. JMAG (Ver. 22.3), made by JSOL Corporation, was used as the electromagnetic field analysis software. **Fig. 7** depicts the model of the relay component used in this study. It is an electromagnetic component consisting of an excitation coil, core, armature, and yoke. A magnetic circuit is formed when an excitation current flows through the coil, generating a magnetic force. For this study, we analyzed and compared the electromagnetic force and response time with S10C, ELCH2, or ELAC20 as the material of the core, and SPCC or KELMOS as the material of the armature and yoke. The number of coil turns was 5,400, and the excitation voltage was 24 VDC. The response time was defined as the time it takes for the angle θ of the armature to move from 5° to 0°. We analyzed the electromagnetic force when the armature was at 0°, that is, when the iron core and armature were in contact and the relay was held, and calculated the maximum torque (corresponding to the magnetic force of the relay components) **Table 5** shows the results of the analysis. When the core material was changed from S10C to ELCH2 (Case 2), the maximum torque increased, reflecting the higher magnetic flux density. Furthermore, when the core material was ELCH2 and the armature and yoke were made of KELMOS (Case 3), this yielded the highest torque, which was 12.4% higher than with general-purpose steel (S10C and SPCC, Case 1). The response times of Cases 2 and 3 were almost the same as Case 1. Although eddy currents hinder magnetization due to low electrical resistance in pure iron-based soft magnetic materials, the high magnetic flux density strongly attracted the armature, which is thought to have a compensatory effect on response time. Thus, ELCH2 is effective in applications in which torque is a priority. The greater capacity to generate a higher torque means that the same torque can be achieved with a lower excitation current. Beneficial results include reductions in power consumption, heat generation, copper usage, and size.

The core made of ELAC20 (Cases 4 and 5) also achieved a higher torque than did the core made of general-purpose steel (Case 1). In addition, the response time was about 2% faster than with S10C and ELCH2 as core materials (Cases 1 to 3). **Fig. 8** shows the eddy current distribution 4 ms after the circuit was energized, with ELCH2 and ELAC20 as core materials (Cases 2 and 4). Because the electrical resistivity of ELAC20 is higher than that of ELCH2, the current density is lower on the surface of the

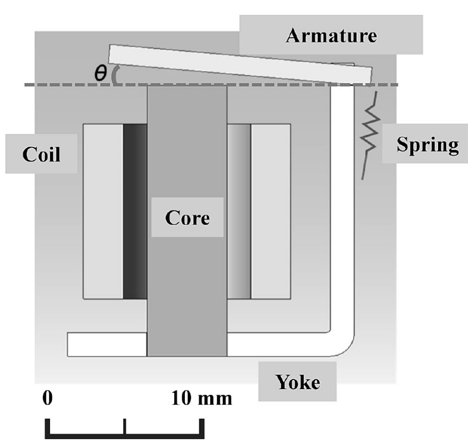

Fig. 7 Calculation model of electromagnetic relay for electromagnetic field analysis

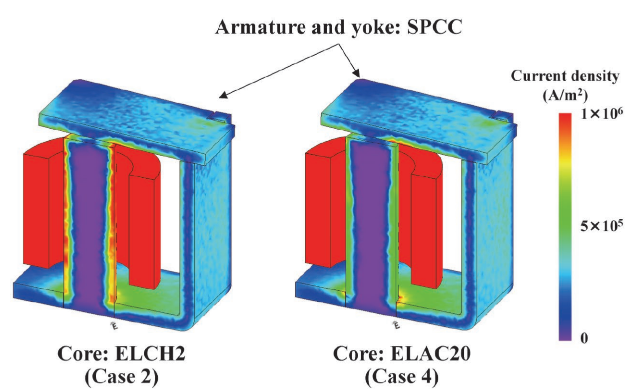

Fig. 8 Eddy current distribution in electromagnetic relays

Table 5 Estimated torque and response time of electromagnetic relay

	Core	Armature	Yoke	Maximum torque (mN·m)	Response time (ms) ON
Case 1	S10C	SPCC	SPCC	90.7	5.094
Case 2	ELCH2	SPCC	SPCC	98.1 (+8.1%)	5.088 (−0.1%)
Case 3	ELCH2	KELMOS	KELMOS	101.9 (+12.4%)	5.088 (−0.1%)
Case 4	ELAC20	SPCC	SPCC	95.8 (+5.6%)	4.998 (−1.9%)
Case 5	ELAC20	KELMOS	KELMOS	99.3 (+9.5%)	5.000 (−1.8%)

ELAC20 core. This is thought to have suppressed the generation of eddy currents that interfere with the magnetization of the material, resulting in a shorter response time. In addition, an excitation coil with fewer turns results in a lower inductance, intensifying the effect of eddy current on response time. As such, the effect of using ELAC20 is further enhanced.

As described above, selecting the material based on the required performance improves the performance of relay components and reduces power consumption.

Conclusions

As the shift toward EVs progresses, electromagnetic components will need to fulfill new requirements in aspects such as compactness, reduced power consumption, and diversity of AC applications. This paper introduces the main characteristics of the ELCH2 series, which features high magnetic flux density and cold forgeability; the ELAC series, which features excellent response time and a high capacity for suppressing eddy current generation; and KELMOS, which applies the findings of ELCH2 to thin sheets. These pure iron-based soft magnetic materials not only meet the required characteristics of electromagnetic components, but also can be used in combination to achieve even higher performance. Kobe Steel will continue to develop and propose pure iron-based soft magnetic materials suitable for various requirements to support higher-performing, more economical electromagnetic components, thereby contributing to the resolution of societal challenges.

References

1) Ministry of Economy, Trade and Industry et al. Mobility Digital Transformation (DX) Strategy. 2024.
2) M. Chiba et al. R&D Kobe Steel Engineering Reports. 2002, Vol.52, No.3, pp.66-69.
3) M. Sakata et al. R&D Kobe Steel Engineering Reports. 2015, Vol.65, No.2, pp.6-11.
4) T. Hoshino et al. KAWASAKI STEEL GIHO. 1991, Vol.23, No.2, pp.21-27.
5) M. Chiba. R&D Kobe Steel Engineering Reports. 2011, Vol.61, No.1, pp.57-61.
6) S. Kasai et al. R&D Kobe Steel Engineering Reports. 2011, Vol.61, No.1, pp.3-6.