Benefit Estimation of Soft-magnetic Pure Iron by Magnetic Field Analysis Considering Effect of Forging Strain

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Abstract

The movement toward carbon neutrality is expanding as a result of heightened environmental awareness. For soft-magnetic materials, whose usage is expected to increase as electrification progresses, the omission of the heat treatment step called magnetic annealing is regarded as one of the measures for reducing the amount of CO_2 produced by the manufacturing process. Kobe Steel's soft-magnetic pure iron, the ELCH2 series, has magnetic properties comparable to those of the magnetic-annealed material of low-carbon steel, even without magnetic annealing, and is being looked to as a non-heat-treated material of low-carbon steel. Using forging analysis and magnetic field analysis, a comparison has been made among the component characteristics when a solenoid iron core is changed from magnetic-annealed material of low-carbon steel to as-cold-forged material of ELCH2. This paper introduces the results indicating that the ELCH2, even if the magnetic annealing is omitted, achieves the same electromagnetic force at low current and also achieves higher electromagnetic force at high current than what is achieved by the magnetic-annealed material of low-carbon steel.

Introduction

Heightened environmental awareness, such as global warming countermeasures, is rapidly promoting electrification, mainly in the field of automobiles.[1] Kobe Steel is developing soft-magnetic pure iron, which makes the best use of the magnetic properties of iron, in response to the needs for such electrification, including smaller size, lighter weight, and the higher performance of electromagnetic equipment. **Fig. 1** is an image diagram of the operating frequency range and magnetic flux density of Kobe Steel's soft-magnetic pure iron.

Kobe Steel's products include the soft-magnetic pure iron, "ELCH2 series" (wire/bar) with proven performance mainly in DC applications; and the pure iron-based magnetic iron powder (MAGMEL) with proven performance in magnetic parts of electrical systems for AC applications. In addition,

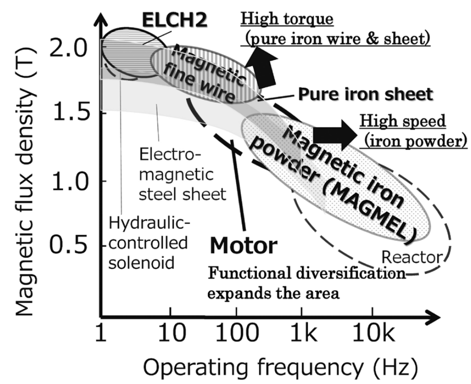


Fig. 1 Examples of operating frequency range and magnetic flux density

the company has developed a "pure-iron magnetic wire" with smaller diameters and "pure-iron sheets" with smaller thicknesses to reduce the eddy current, which lowers the AC magnetic characteristics. Kobe Steel is building a system to propose soft-magnetic pure iron suitable for each application.

This paper describes one such product, the soft-magnetic pure iron ELCH2 series. The ELCH2 series is used as an iron core material for linear solenoids and electromagnetic clutches and is a material that contributes to improving the performance of electromagnetically controlled components. Section 1 describes the advantages of the ELCH2 series (excellent magnetic properties and cold forgeability), and Section 2 describes the magnetic-field analysis results considering the strain due to cold forging to omit magnetic annealing, contemplating the growing need for carbon neutrality.

1. Soft-magnetic pure iron ELCH2 series

1.1 Chemical composition

Table 1 shows the exemplary chemical compositions of the ELCH2 series (ELCH2 and ELCH2S) and the composition standard of JIS soft magnetic irons, SUY.

The ELCH2 series is an ultra-low carbon soft-magnetic iron that increases the magnetic moment, the origin of ferromagnetism, by reducing the factors

Table 1 Example of chemical composition

Priority	Steel grade	C	Si	Mn	P	S
Magnetic properties	ELCH2	0.005	0.004	0.25	0.009	0.008
Machinability	ELCH2S	0.005	0.004	0.26	0.010	0.025
JIS SUY		≦0.03	≦0.2	≦0.5	≦0.03	≦0.03

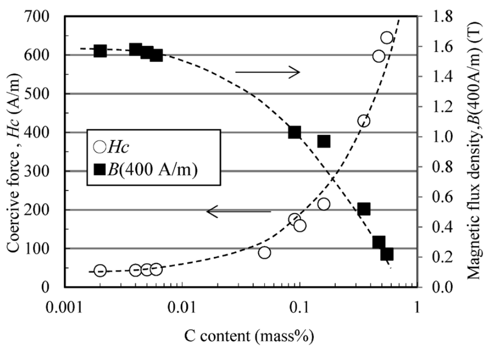


Fig. 2 Carbon content dependence of magnetic properties [2)]

that adversely affect magnetic properties as much as possible. Excellent magnetic properties (high magnetic flux density and low coercive force) are realized in the low to high magnetic field regions. **Fig. 2** shows the effect of carbon content on coercive force and magnetic flux density. The ferrite phase with ferromagnetism increases as carbon content decreases, improving both the magnetic flux density and coercive force.[2)] Another advantage is the improved cold forgeability, a result of reduced Si and additional Mn.[3)]

ELCH2S contains a small amount of S, an element improving the free-cutting property, and is a grade expected to reduce tool wear by half, compared with ELCH2. Excessive addition of S causes FeS to precipitate at the prior austenite grain boundary and lowers the magnetic properties. Hence, the Mn/S ratio is appropriately controlled to prevent the precipitation of FeS.[4)]

1.2 Microstructure

The domain wall motion in a material is a critical factor that influences magnetic properties. The domain wall moves through the material as the external magnetic field changes. It is known, however, that the presence of lattice defects with low magnetic energy, such as grain boundaries, precipitates, and dislocations, hinders the movement and causes a declination in magnetic properties.[5)] Hence, a heat treatment called "magnetic annealing" is applied to remove lattice defects caused by part fabrication processes such as rolling, wire drawing, forging, and cutting, and further coarsen the crystal grains.

Fig. 3 shows the relationship between the average grain size and coercive force before and

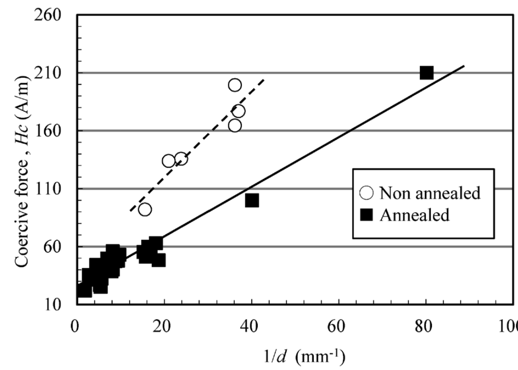
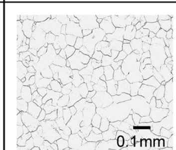
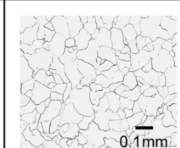


Fig. 3 Relation between grain size and coercive force [2)]

Magnetic annealed	Non-annealed	850℃×3 h
Ferrite grain size number	6.0	4.0
Microstructure		

・Magnetic annealed ⇒ furnace cooling (cooling speed＜100℃/s)

Fig. 4 Microstructure before and after magnetic annealing

after magnetic annealing of ELCH2. **Fig. 4** shows the microstructure and ferrite crystal grain size before and after magnetic annealing of ELCH2 rolled material. It is shown that the grain size is coarsened by magnetic annealing, and the larger the grain size, the smaller the coercive force becomes. The crystal grain grows as the annealing temperature rises, but care must be taken not to overheat because the Ac3 point of the ELCH2 series is at about 910℃. If the annealing temperature is too high, a part of the ferrite begins to transform into austenite, and a temperature exceeding the Ac3 point results in a single-phase austenite which leads to the generation of a fine ferrite phase in the cooling process and deteriorates the magnetic properties. Desirably, the magnetic annealing shall be in the temperature range of the ferrite single-phase region and performed at around 850℃, considering the temperature variation of the heating furnace.

1.3 Magnetic properties

Table 2 shows the initial magnetization characteristics of the ELCH2 series before and after the magnetic annealing and of low-carbon steel S10C. Also included is the property lower limit of JIS SUY-0, the highest grade of JIS soft magnetic irons. The ELCH2 series after magnetic annealing has a magnetic flux density that satisfies the SUY-0 standard and has properties that can contribute to

Table 2 Example of magnetic properties

Steel		Magnetic flux density (T)				Hc
		100 A/m	500 A/m	1,000 A/m	4,000 A/m	(A/m)
Magnetic annealed	ELCH2	1.22	1.58	1.64	1.82	45
	ELCH2S	1.09	1.53	1.59	1.80	56
	S10C	0.45	1.40	1.54	1.74	86
Non annealed	ELCH2	0.32	1.32	1.54	1.76	96
	ELCH2S	0.23	1.29	1.54	1.76	105
JIS	SUY-0	0.90	1.35	1.45	1.60	≦60

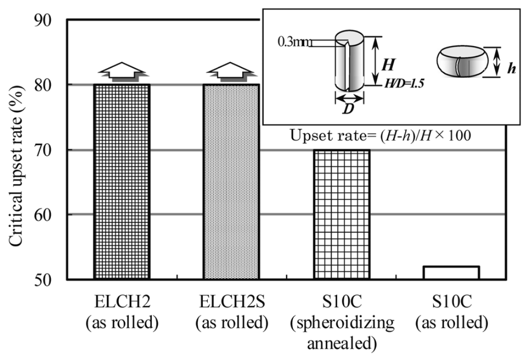


Fig. 5 Comparison of critical upset rate [2)]

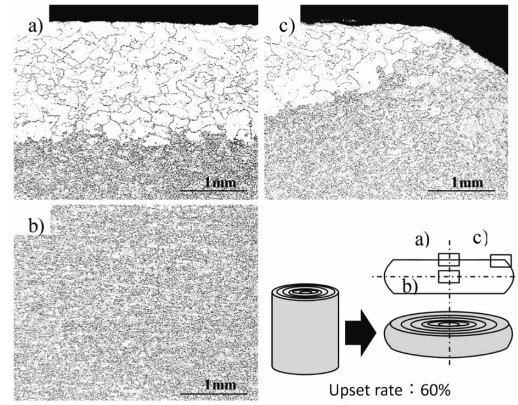


Fig. 6 Microstructure of compressed specimen after magnetic annealing [2)]

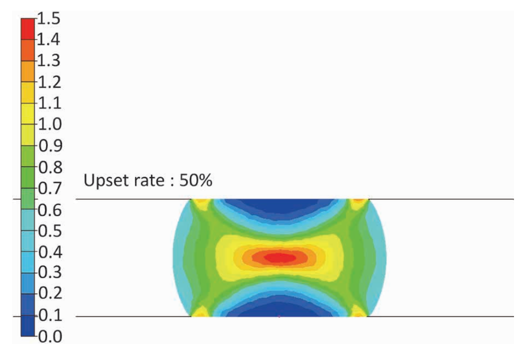


Fig. 7 FEM-analysis of equivalent strain (cold upsetting)

the miniaturization, weight reduction, and enhanced output of electromagnetic components. In addition, even without magnetic annealing, the steel product has properties at the same level as those of S10C after magnetic annealing, allowing the omission of magnetic annealing required by low-carbon steel, which is expected to improve productivity and contribute to carbon neutrality.

1.4 Effect on cold forgeability and post-annealing microstructure

The ELCH2 series has the advantage of high elongation, making cracks unlikely to occur. **Fig. 5** compares the critical upset rate of cracking for ELCH2 and S10C under severe conditions with a notch in each cylindrical test piece. Even as-rolled, the ELCH2 series exhibits a critical upset rate of cracking higher than that of the S10C spheroidize-annealed material, enabling cold forging of complex-shaped parts without soft annealing.

On the other hand, the strain energy due to cold working increases the driving force of grain growth,[6)] and the strain distribution affects the grain size after magnetic annealing. **Fig. 6** shows the cross-sectional microstructure of the sample magnetically annealed after cold upsetting, and **Fig. 7** shows the analysis result for the equivalent strain distribution during cold upsetting. The plastic processing analysis software FORGE (trademark of Transvalor S. A.) was used to analyze the ELCH2 material on the basis of an axisymmetric model. As shown, the crystal grains in the part where the strain is minor, near the fixed end (the upper part of Fig. 6 a and c), have been coarsened. On the other hand, the part with significant strain, in the center (Fig. 6b), has not coarsened, due to the effect of the remaining strain. The improvement of component characteristics requires strain distribution and annealing conditions that maximize the grain size of the part where magnetic properties are critical, such as a magnetic circuit part where magnetic flux concentrates.

1.5 Temperature dependence

Fig. 8 shows the temperature dependence of the coercive force of the ELCH2 series, and **Fig. 9** shows the temperature dependence of its magnetic flux density. Since the detailed measurement conditions are different, the room temperature characteristics are standardized to 100% for the plotting.

There is no significant difference in magnetic flux density, but the coercive force deteriorates on the low-temperature side. The cause of the deterioration of the coercive force on the low-temperature side is thought to be the effect of an increase in the magnetic anisotropy coefficient[7)] and the heat shrinkage of the test piece (an increase in internal strain). It is essential to consider the manufacturing process and usage environment to demonstrate the performance of soft-magnetic material.

Table 3 Examples of magnetic properties of ELCH2 applied work strain by cold upsetting

Steel	Upset rate	Magnetic flux density (T)				*Hc* (A/m)
		100 A/m	500 A/m	800 A/m	5,000 A/m	
ELCH2 non magnetic annealed	0%	0.39	1.24	1.45	1.79	91
	20%	0.04	0.80	1.03	1.74	178
	40%	0.03	0.71	1.01	1.74	218
	60%	0.02	0.61	0.96	1.73	228

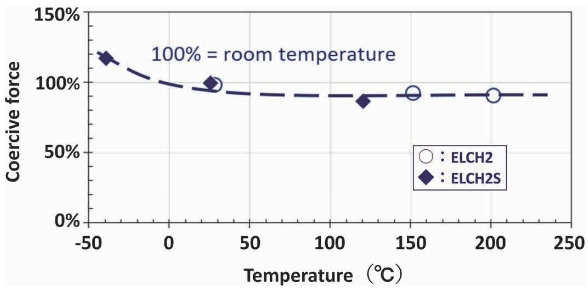


Fig. 8 Temperature dependence of coercive force

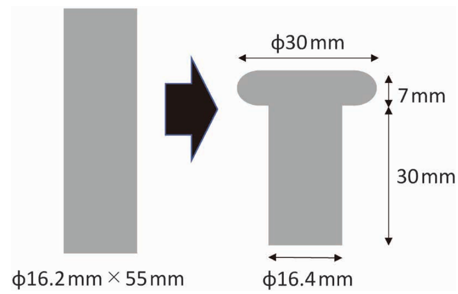


Fig.10 Shape of iron core after cold upsetting process

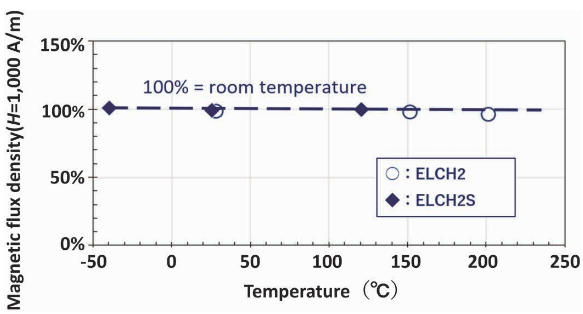


Fig. 9 Temperature dependence of magnetic flux density (H=1,000 A/m)

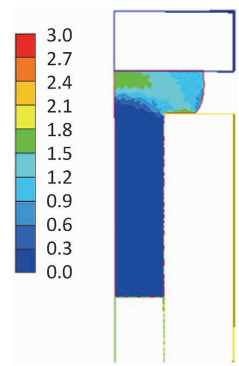


Fig.11 Calculated equivalent strain in cold upsetting

2. Example of applications to electromagnetic components

Maximizing the electromagnetic component's function while maintaining productivity requires setting the processing conditions that best use the magnetic material's characteristics. This section describes an example of magnetic field analysis regarding the effect of cold-forging strain on component characteristics. This example is in response to the fact that energy reduction in heat supply is being studied from the viewpoint of carbon neutrality.[8] The ELCH2 is assumed to be used as cold-forged without magnetic annealing. Electromagnetic field analysis software JMAG was used for the magnetic field analysis.

2.1 Changes in magnetic properties due to cold forging

The strain associated with cold working reduces the magnetic moment and acts as pinning of the domain wall, thus deteriorating the magnetic properties after cold working. **Table 3** shows the magnetic properties measured on a ring-shaped specimen of ϕ38 mm × ϕ30 mm × thickness 4 mm collected from the central part in the axial direction of material after cold-forging (upsetting) a ϕ44 mm × 50 mm ELCH2 rolled sample at room temperature. As the compression rate increases, the strain increases, and the magnetic properties deteriorate.

2.2 Analysis method and results

Fig.10 schematically illustrates the shape of a sample cold forged around the upper side of the ϕ16.2 mm × 55 mm cylindrical iron core, and **Fig.11** shows an equivalent strain contour diagram of the forging analysis. The upper side, with large deformation, shows a significant strain. Three solenoid models were made, each comprising a pair of iron cores of the above dimensions abutting against each other with a coil and an outer cylinder disposed outside the pair of cores. In the first model, the iron cores were made of ELCH2 (without strain consideration, without magnetic annealing). In the second model, the iron cores were made of ELCH2 (with strain consideration, without magnetic annealing). In the third model, the iron cores were made of S10C (without strain consideration, with magnetic annealing). Then the electromagnetic force between each pair of iron cores was analyzed for comparison. The analysis was performed in the following steps: (1) performing axisymmetric forging analysis on FORGE and outputting strain distribution data; (2) passing the strain distribution data to JMAG and interpolating the magnetic properties of each part from the measured data regarding the strain distribution; and (3) performing axisymmetric magnetic field analysis on JMAG and outputting the electromagnetic force. **Fig.12** shows the magnetic flux density contour diagram at a coil current of 0.5 A, and **Fig.13** shows the results of electromagnetic force analysis.

A comparison between the contour diagrams of ELCH2 with and without strain consideration shows that the magnetic flux with strain consideration is concentrated at the root corner of the collar. This is due to the decreased magnetic properties in the top region with high forging strain, and the magnetic saturation due to corner concentration slightly lowers the electromagnetic force. The effect of strain can also be seen from the fact that the contour diagrams of ELCH2 and S10C without strain are similar. The electromagnetic force analysis results show that ELCH2 has a greater electromagnetic force than S10C in the high current region regardless of strain. This is because ELCH2 is superior in magnetic flux density on the high magnetic field side (Table 2). Analysis considering strain clarifies the cause of characteristics change, enabling measures to alleviate saturation, such as rounding the corners. Thus, it is possible to omit annealing for the ELCH2 forged product to achieve the same performance as the S10C annealed product.

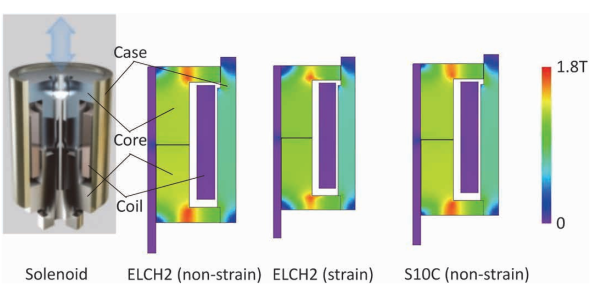


Fig.12 Magnetic flux density distribution in solenoid components

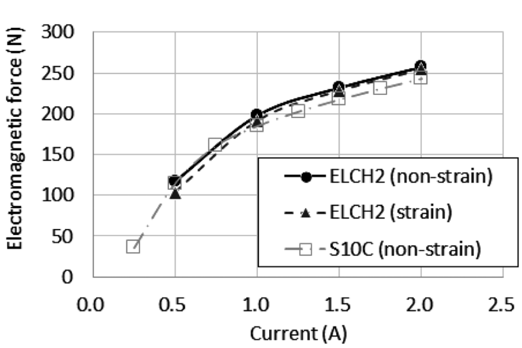


Fig.13 Estimated magnetic force by FEM analysis

The above results demonstrate the possibility that changing from S10C machined products (with magnetic annealing) to ELCH2 forged products (without magnetic annealing) leads to material yield improvement by altering the process from cutting to forging and productivity improvement and energy reduction by omitting magnetic annealing, without sacrificing the component characteristics.

Kobe Steel will continue contributing to the realization of carbon neutrality by proposing solutions while utilizing analysis technology to maximize component functions and improve productivity in the manufacturing process.

Conclusions

This paper has introduced the advantages of the soft-magnetic pure iron ELCH2 series and has demonstrated the possibility of changing from machined products of low-carbon steel (with magnetic annealing) to ELCH2 forged products (without magnetic annealing) and thus omitting heat treatment (soft annealing and magnetic annealing) and improving material yield. Kobe Steel will continue to propose solutions, including optimal conditions taking an extra step into the manufacturing process of components, and contributing to the challenges such as the realization of carbon neutrality.

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