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研究員による成果

鉄鋼材料の超多点硬さ測定・残留歪み測定と材料特性に関する研究

材料評価・開発研究室 長江正寛

1. 目的

近年、コストカットへのさらなる要求と材料調達のグローバル化により、同一規格の鋼種であれば可能な限り安価な材料を求めようとする傾向が強まりつつある。しかしながら、それに伴い、歯車等の重要機械部品に関して、材料の品質に起因すると考えられる損傷事故が増えているのも事実であり、購入した鋼材の品質検査の重要性が高まっている。こうした背景から、我々は「超多点自動HV硬さ測定装置」を開発し、超多点のマイクロビッカース硬さ測定は、鋼材の微細組織、合金成分分布などの不均一性を顕在化し、素材や熱処理の良否の判断や、機械部品の損傷原因の推定に対して有益な指針を与えることを明らかにしてきた。また、ポータブル型X線残留応力測定装置(μ -X360s)による残留応力測定時に取得されるデバイ環形状の解析や、非接触硬さムラスキャナ(muraR)を用いた解析を行い、X線回折を利用したデバイ環形状解析が鋼材品質の良否判定に有効であるばかりでなく、歯車寿命予測にも適用できる可能性を見出しつつある。

今年度は昨年に引き続き μ -X360sによるデバイ環形状解析に加え、muraRを用いた解析を行い、歯車材料の寿命予測への適用可能性について検討した。

2. 成果の一例 (異なる数種の歯車材の評価から得られた知見)

図1は耐久試験を行ったSCM420製浸炭焼入れ歯車について、 μ -X360sを用いて歯元のかみ合い限界付近のX線回折の半価幅とデバイ環ピーク強度を測定した結果である。X線は歯先側から

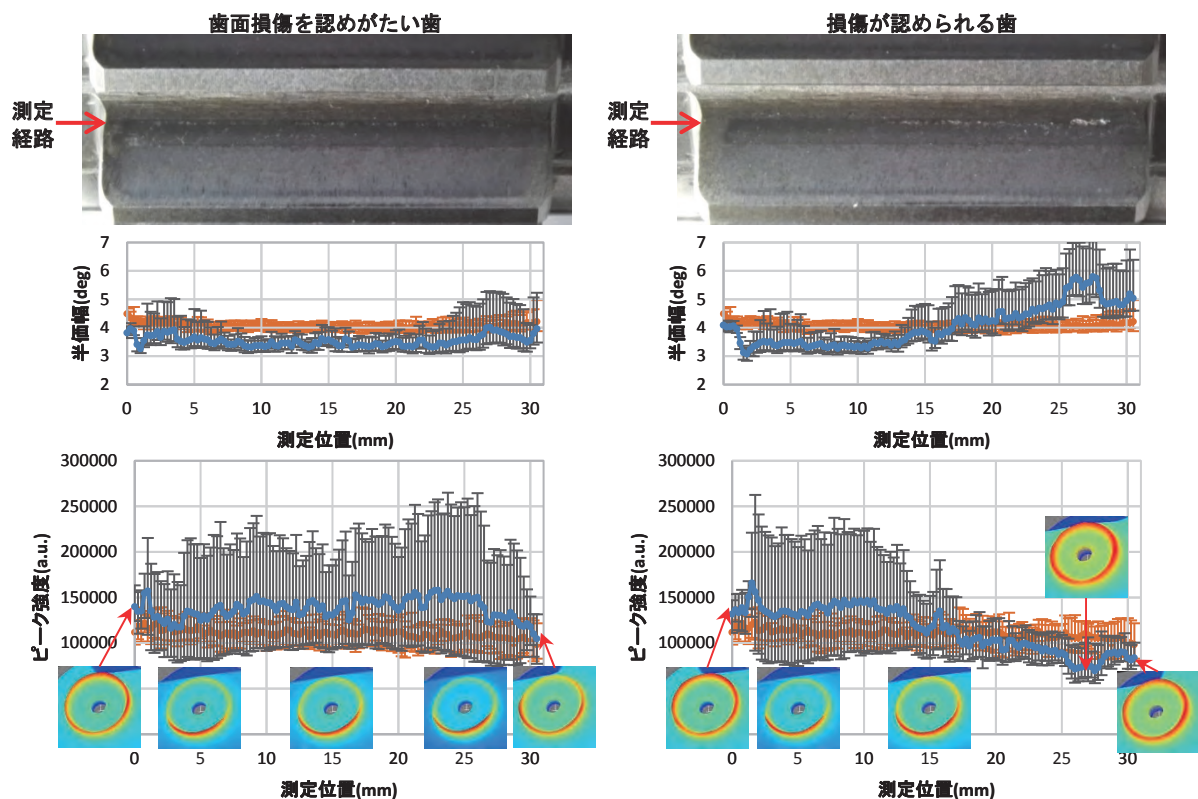


図1 耐久試験を行った浸炭焼入れ歯車のかみ合い限界付近における μ -X360s測定結果

測定経路(歯すじ方向)に対して垂直な方向となるよう入射し、 $\phi 0.4\text{mm}$ のX線照射径を用い、矢印の位置を歯すじ方向に測定した。オレンジ色のデータは裏歯面の測定結果であり、耐久試験前の状態に相当する。歯面損傷を認めがたい歯面(上図左)では、半価幅の低下(硬さの低下に対応)とデバイ環ピーク強度のバラツキ幅(鋼材結晶粒の配向の偏りの激しさの程度に対応)の著しい増加が認められる。半価幅の低下は恐らく歯面接触による温度上昇が原因である。また、左側端部より5、15、25mmの測定位置におけるデバイ環形状から判断して、表面材質に塑性流動によるフェライト結晶の配向化が進んでいると考えられる。一方、損傷が認められる歯面(上図右)では、歯幅中央付近から右側端部にかけて、損傷が激しくなるに従い、半価幅(硬さ)が上昇し、デバイ環ピーク強度の平均値が低下し、バラツキ幅が減少している。この結果は、歯当りが強い箇所では、相手歯車の歯先エッジ・歯末面との接触により歯表面が摩耗し、硬いマルテンサイト層が露出していることを意味する。このような接触歯面の状態変化は、X線回折測定により、損傷の発生時期や、およその発生場所の推定が可能であることを示唆していると考えられる。

図2に動力循環式試験機で耐久試験を行ったSCr420HV浸炭焼入れはすば歯車の歯面について、X線回折により歯面の劣化状態を調査した結果の一例を示す。耐久試験の累積サイクル数は 4.8×10^6 である。歯面損傷は駆動歯車のかみ合い開始部に集中して発生している。非接触硬さムラスキャナ(muraR、X線照射径 $\phi 1\text{mm}$)を用い、全歯にわたり歯面全体の硬さ分布を測定し、経時変

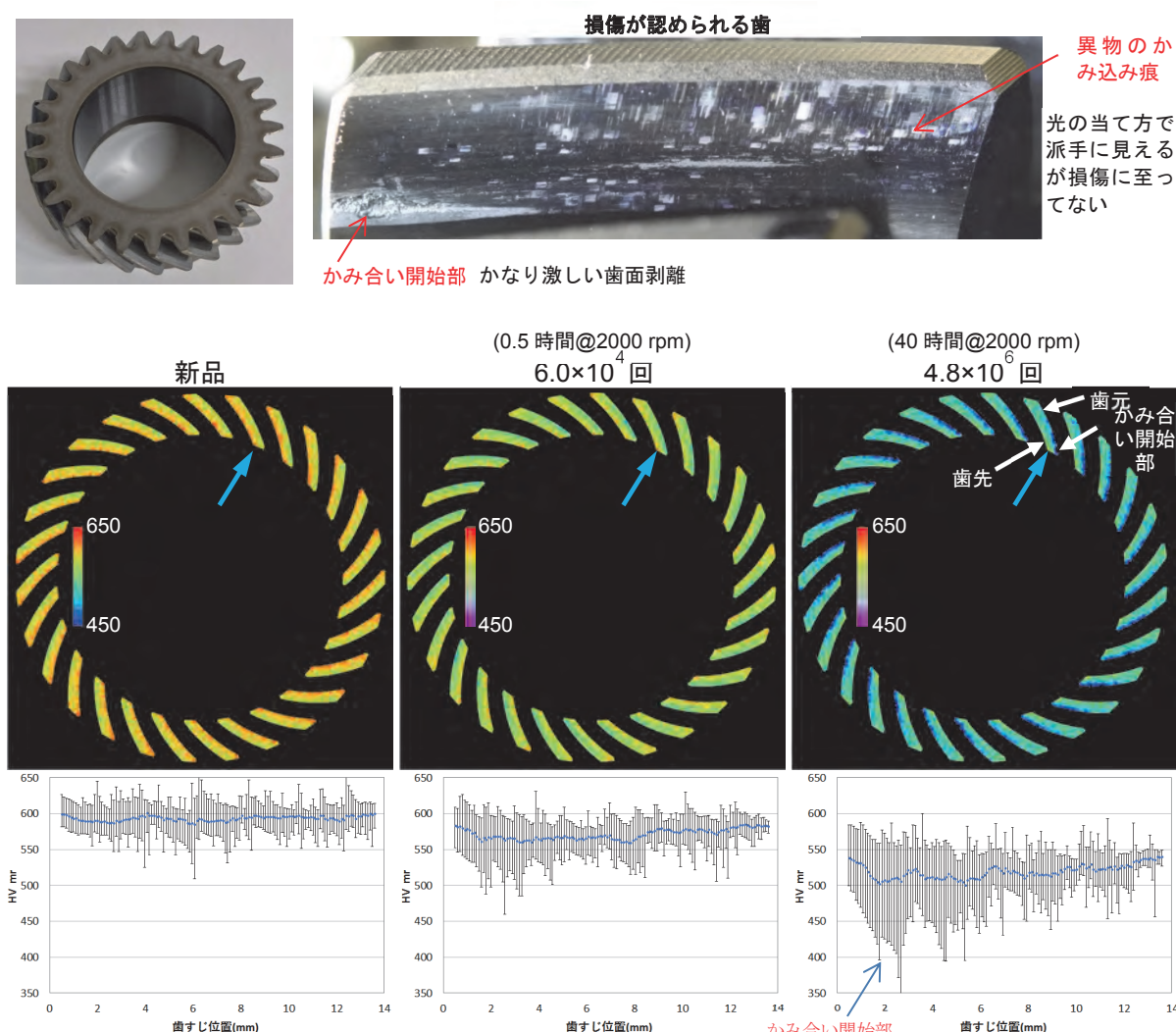


図2 耐久試験を行った浸炭焼入れはすば歯車歯面の muraR 硬さ測定結果
(上部右の写真は損傷が認められた歯のデジカメ写真)

化を検討した。全歯面の硬さは、運転時間の増加に伴う温度上昇のために、全体的に低下して行くことがわかる。剥離が認められなかった図中青矢印の歯について、歯すじ方向の各位置で、縦軸に歯元のかみ合い限界付近から歯先までの硬さの平均値とバラツキ幅をとり、歯すじ位置を横軸にとってグラフ化すると、かみ合い開始部の硬さ低下が著しく、損傷の程度に応じバラツキ幅が大きくなっている。その兆候は運転初期(0.5 時間)の段階で既に現れており、図1の結果と同様に、X線回折測定によって可視化される接触歯面の状態変化は、歯面損傷の発生時期や、およその発生場所の推定が可能であることを示唆していると考えられる。

報告書作成日 令和8年6月30日

大強度粒子加速器標的材として採用可能な超耐熱タン グステン合金の製造法に関する研究

材料評価・開発研究室 長江正寛

1. 目的

宇宙の起源や物質生命科学の解明を目指す大強度高エネルギー陽子加速器では、J-PARC COMET 第二期計画、J-PARC MLF 第二標的計画、米国フェルミ研究所 Mu2e 計画、欧州 ESS 中性子源計画などに代表されるように、中性子発生源である標的材料として高融点金属の一つであるタングステンが期待されている。高エネルギー陽子が標的材料に衝突する際には大きな熱が発生するため、標的材料には耐熱性や熱衝撃耐性も要求される。しかしながら、容易に調達が可能な純タングステンは、高温に曝されると再結晶化による脆化が起こるばかりでなく、高エネルギー陽子の照射による照射脆化の課題も抱えている。

本研究では、東北大の栗下らにより開発され、高エネルギー加速器研究機構に引き継がれた高強度・高靱性 W-TiC 合金の作製法を更に発展させることによって、従来の試作 W-TiC 合金よりも耐熱性に優れ、再結晶脆化・照射脆化の課題を解決し、従来の純タングステンと比較してビーム受入強度を飛躍的に高める W-MC 合金(Mは Ti、Zr、Ta 等)を完成させることを目的とする。本年度は主としてメカニカルアロイングにより調整した合金粉末を焼結して作製した W-Ru-TiC 系合金について種々の組織観察を行った。

2. 成果の一例

図1に W-5Ru-1.2TiC 焼結材の典型的な反射電子像の一例を示す。黒く見える微細な粒子は TiC であり、TiC の結晶粒界ピン止め効果により、母相 W の粒成長が 2 μ m 程度に抑制されていることが分かる。一方、Ru 量を 20%まで高めた焼結体では、TiC によるピン止め効果は失われ、母相 W は 30 μ m 程度まで粒成長する事が分かった。

本研究は株式会社サンリックと高エネルギー加速器研究機構が共同事業管理機関である Go-Tech プロジェクト(次世代パワー半導体産業に貢献する革新的高融点合金及び加工法の開発)へアドバイザーとして参画する中で行った組織観察であり、本事業は令和8年度まで継続されることが確定している。

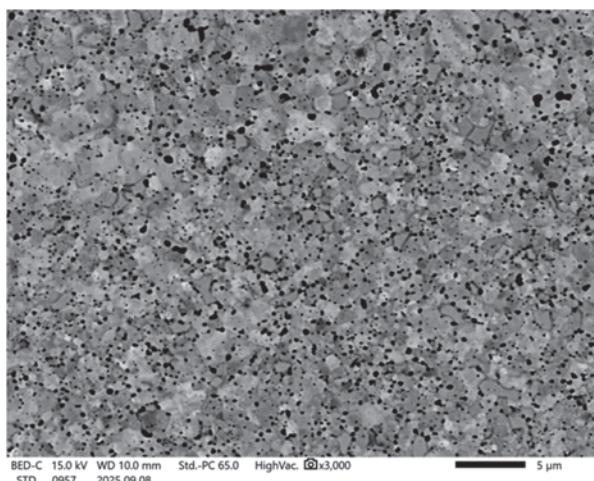


図1 W-5Ru-1.2TiC 焼結材の反射電子像

3. 成果の公表

(1) T. Inoue, S. Makimura, K. Niikura, Y. W. Chai, D. Kondo, M. Onoi, M. Nagae, M. Ishida, H. Kurishita, “Newly developed toughened, fine grained, recrystallized (TFGR) W-1.2%TiC alloy with enhanced room temperature ductility”, Acta Materialia (投稿中)

報告書作成日 令和8年6月30日



6th International Conference on Gear Production 2025

3rd Conference day
Friday, September 12th, 2025



Material quality and heat treatment

Moderation: Dr.-Ing. Joachim Thomas, Managing Director, ZG Hypoid GmbH, Aschheim, Germany

11:00 Form-irregularity of crater-expression of Debye-ring at X-ray diffraction measurement for checking gear steel quality

- Strong correlation exists between the scattering or the standard deviation of Debye-ring crater height and prior-austenite grain size
- Capability of detecting the coarsening of prior-austenite grains with high-speed analog-measurement of successive cross-section of Debye-ring by scanning
- Proposal of Debye-ring shape analysis to substitute the etching method for checking steel quality

Prof. h.c. Dr.-Ing. Aizoh Kubo, President, Dr.-Ing. Masahiro Nagae, Research fellow, Research Institute for Applied Sciences, Kyoto, Japan

Form-irregularity of crater-expression of Debye-ring at X-ray diffraction measurement for checking gear steel quality

A. Kubo, RIAS (Research Institute for Applied Sciences);
M. Nagae, RIAS Kyoto 606-8202 Japan;

Abstract

The state of form-irregularity of Debye-ring of X-ray diffraction measurement was investigated with Debye-ring analyzer DRA for quality checking of gear steels, in terms of the degree of scattering of peak heights of Debye-ring craters, FWHM etc. Strong correlation between Debye-ring shape disorder and the diameter of prior-austenite grains is confirmed. Other inspecting method, with using Hardness Map Maker HMM was tested that scans the shape of a cross-section of Debye-ring at each data sampling point along measuring path with very high speed. Both the measured results show a strong correlation between the standard deviation of measured output curve and the grain size of the objective steel.

1. Introduction

When the measuring head for X-ray diffraction is set on an XY stage, we obtain in-line or map data over the target plane. Those multi-points measured results have dispelled such arguments as that residual stress value obtained from X-ray diffraction is not reliable enough. X-ray diffraction map or measured curve provides us with many new insights into the state of steel materials.

Residual stress can be obtained by analyzing the shape of the Debye-Scherrer ring (refer to Debye-ring), but its shape surely contains more information about the steel characteristics other than residual stress. From our experience of conducting many X-ray diffraction measurements of steels, good, bad and those of experienced failure problem, we have a feeling that the Debye-ring of good steel usually has a symmetric conical smooth crater mountain shape, while problematic steel has large disorder in the shape.

To develop the evaluating method of steel-quality and heat treatment quality using X-ray diffraction, it seems necessary to focus on the rank of form-irregularity of the Debye-ring. This method can also contribute to obtain quantitative values that has strong correlation with the state of the matrix

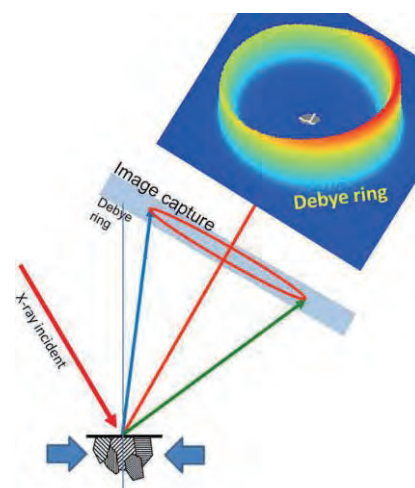


Fig.1 X-ray diffraction and Debye-ring formation

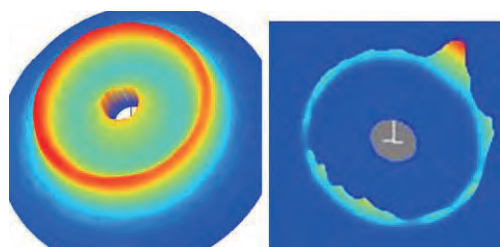


Fig.2 Typical shape of Debye ring crater of normal and problematic steel

of the steel. This is an attempt to find an alternative method to etching that is usually used for checking crystal structure of the steel.

2. Debye-ring

Ferrite in various forms exists in gear steels. For example, if we consider the case where the steel microstructure

undergoes martensitic transformation by quenching, the prior-austenite grains are made up of a structure filled with a set of elongated lath-martensite, as shown schematically in Fig.3. That is, when fcc austenite transforms to bcc, it appears to have a very biased orientation in two directions, i.e. (50-60) deg. and (10-20) deg., as shown in the rightmost column of Table 1 for the 24 variants.

When X-ray diffraction is performed with small irradiation diameter on such a steel surface like Fig.4, the diffraction does not reflect in a uniform conical shape, but is biased stronger in two specific directions. If the steel is polycrystalline and its orientation is random, and if diffraction images are obtained with an X-ray irradiation diameter that is far larger than the diameter of the prior-austenite grains, the diffraction reflection from each crystal is superimposed and the Debye-ring will have a crater shape of uniform height.

However, if the prior-austenite grains coarsen and the number of prior-austenite grains present within the X-ray irradiation diameter decreases, the crater height of the Debye-ring will be partly high and partly low, because the orientation of the reflection from a single prior-austenite grain is limited. In other words, when diffraction images are obtained

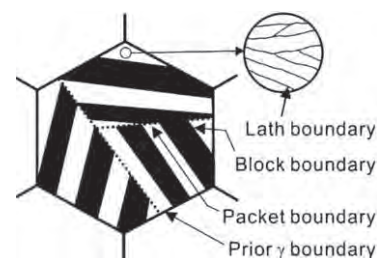


Fig.3 Schema of lath martensite in low carbon steel

Table 1 24 variations in K-S orientation relationship
Kurdjumov-Sachs' relation (K-S relation):

No	Close-packed plane parallel relation	(111)fcc // (011)bcc, [111]fcc // [111]bcc Close-packed direction parallel relation	Bain	Misorientation from V1 (deg)
V1	(111) _f //(011) _a CP1	$[\bar{1}01]_f // [\bar{1}\bar{1}1]_a$	B1	
V2		$[\bar{1}01]_f // [\bar{1}1\bar{1}]_a$	B2	60.0
V3		$[01\bar{1}]_f // [\bar{1}\bar{1}1]_a$	B3	60.0
V4		$[01\bar{1}]_f // [\bar{1}1\bar{1}]_a$	B1	10.5
V5		$[1\bar{1}0]_f // [\bar{1}\bar{1}1]_a$	B2	60.0
V6		$[1\bar{1}0]_f // [\bar{1}1\bar{1}]_a$	B3	49.5
V7	$(\bar{1}\bar{1}1)_f // (011)_a$ CP2	$[\bar{1}\bar{1}0]_f // [\bar{1}\bar{1}1]_a$	B2	49.5
V8		$[\bar{1}\bar{1}0]_f // [\bar{1}1\bar{1}]_a$	B1	10.5
V9		$[\bar{1}\bar{1}0]_f // [\bar{1}\bar{1}1]_a$	B3	50.5
V10		$[\bar{1}\bar{1}0]_f // [\bar{1}1\bar{1}]_a$	B2	50.5
V11		$[011]_f // [\bar{1}\bar{1}1]_a$	B1	14.9
V12		$[011]_f // [\bar{1}1\bar{1}]_a$	B3	57.2
V13	$(\bar{1}1\bar{1})_f // (011)_a$ CP3	$[0\bar{1}1]_f // [\bar{1}\bar{1}1]_a$	B1	14.9
V14		$[0\bar{1}1]_f // [\bar{1}1\bar{1}]_a$	B3	50.5
V15		$[\bar{1}0\bar{1}]_f // [\bar{1}\bar{1}1]_a$	B2	57.2
V16		$[\bar{1}0\bar{1}]_f // [\bar{1}1\bar{1}]_a$	B1	20.6
V17		$[110]_f // [\bar{1}\bar{1}1]_a$	B3	51.7
V18		$[110]_f // [\bar{1}1\bar{1}]_a$	B2	47.1
V19	$(11\bar{1})_f // (011)_a$ CP4	$[\bar{1}\bar{1}0]_f // [\bar{1}\bar{1}1]_a$	B3	50.5
V20		$[\bar{1}\bar{1}0]_f // [\bar{1}1\bar{1}]_a$	B2	57.2
V21		$[0\bar{1}\bar{1}]_f // [\bar{1}\bar{1}1]_a$	B1	20.6
V22		$[0\bar{1}\bar{1}]_f // [\bar{1}1\bar{1}]_a$	B3	47.1
V23		$[101]_f // [\bar{1}\bar{1}1]_a$	B2	57.2
V24		$[101]_f // [\bar{1}1\bar{1}]_a$	B1	21.1

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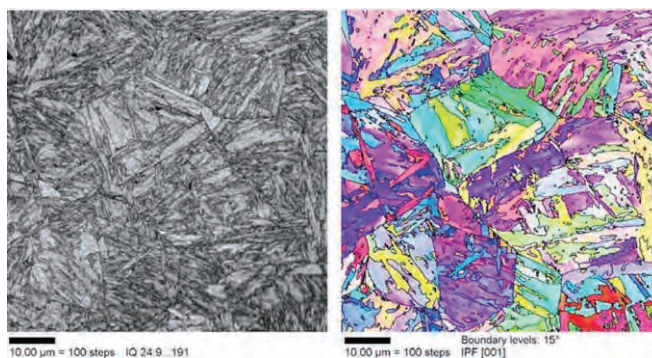


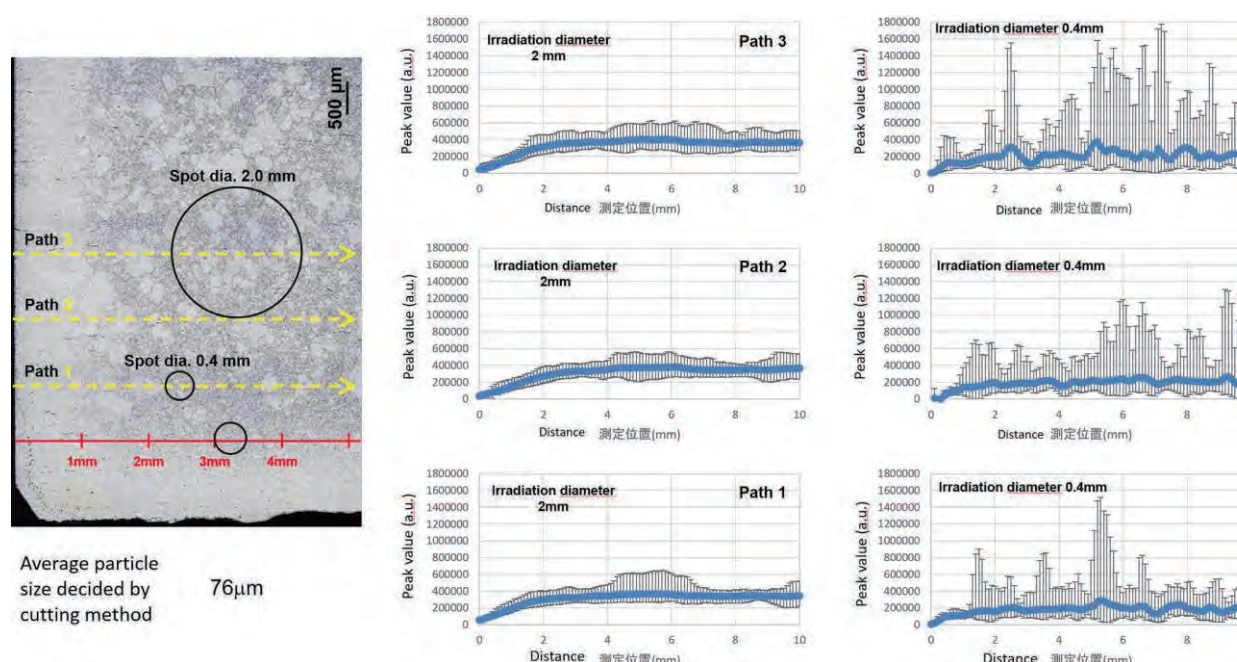
Fig.4 Lath martensite structure、0.2%C-steel.
SEM picture and EBSD orientation

from a certain diameter of X-ray irradiation, the degree of height scattering of the Debye-ring crater may be strongly correlated with the size of the prior-austenite grains. Grain size is very important for the strength of gear steel: As is well known empirically as Hall-Petch's law^[1], the strength of material decreases inversely with the square root of grain size.

We use a detailed analyzer of Debye-ring (refer to DRA). DRA is the improved model of residual stress measuring apparatus to evaluate the deformation of ferrite crystal after $\cos(\alpha)$ method for X-ray diffraction analysis and it is mounted on XY-stage or θ -stage to realize full-automatic measurement in line, in peripheral or over plane. The usability of this apparatus is already reported at the past VDI Int'l Gear Conference ^{[4]-[6]}. The DRA needs ca.1 min. to measure one point with using a X-ray spot diameter ϕ 2mm.

3. X-ray spot diameter and sensitivity

When the diameter of X-ray irradiation beam decreases, the number of prior-austenite grains contained therein decreases. As a result, the X-ray diffraction from that spot is strongly oriented in two definite directions. The height value along the 360-degree peak path of the crater of Debye-ring (refer to peak height) has a considerable difference between the maximum and the minimum value, and the amplitude of scattering becomes large.



The blue curves are calculated from the average shape of the Debye-ring. The vertical lines show the variation of the calculated value along each 360 deg. crater peak path of the Debye-ring.

Fig.5 Difference in measured results as function of irradiating X-ray spot diameter for CCQ SCM822 gear steel of coarse crystal structure from D company

Fig.5 shows an example of peak height scattering to show the difference in measuring sensitivity with X-ray irradiating spot diameter 2.0 mm and 0.4 mm for case carburized and quenched (refer to CCQ) SCM822 gear steel of coarse crystal structure. The results of measured scattering for the spot diameter 0.4mm shows the state of steel matrix construction far clearly in comparing the results with the spot diameter 2.0mm.

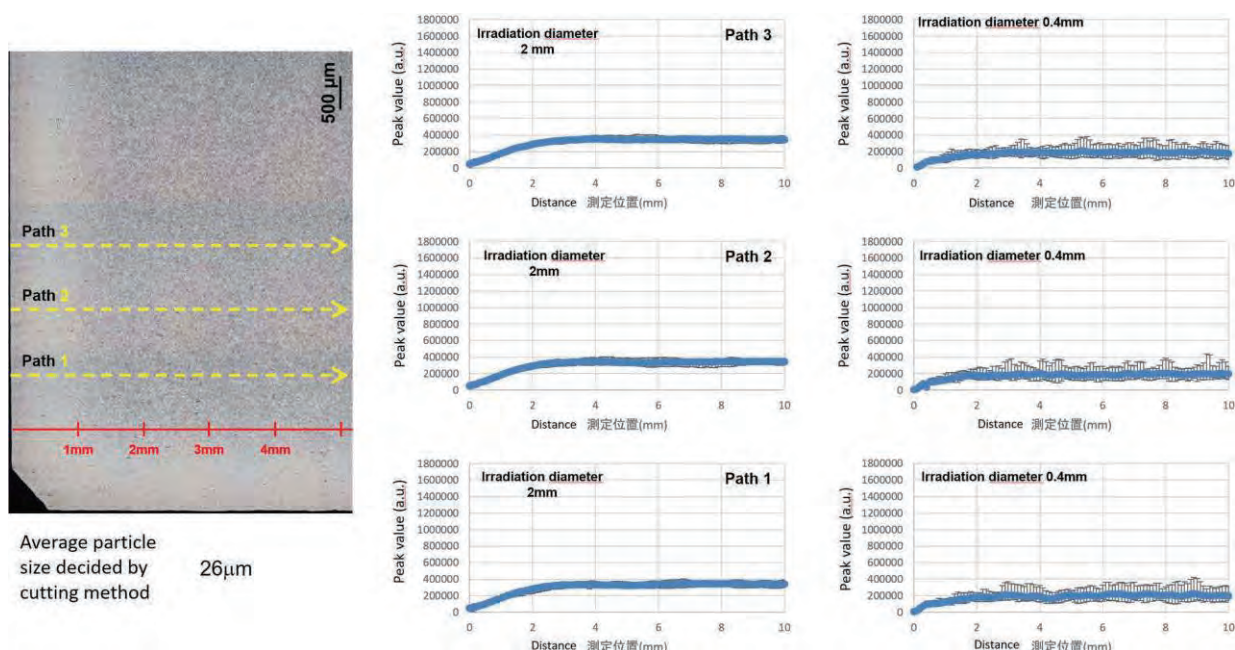


Fig.6 Measured Debye-ring crater height scattering for fine crystal structure steel
(CCQ SCM822 from E company)

Measurement with small spot diameter of X-ray irradiation costs longer measuring time, but the increase of the measuring resolution to catch the state of form irregularity of Debye-ring well compensates the longer time consumption for the measurement.

Fig.6 shows another example for a case of the same CCQ SCM822 gear steel from different steel maker, but its matrix is of finer crystal structure. The results of measured peak height variation show far softer scattering. This state of small amplitude of scattering corresponds to the state of fine and homogeneous steel matrix construction. It is very interesting that the both steels of Fig.5 and of Fig.6 have the same standardized steel name and delivered with good MILL certificate sheet.

4. High speed measurement of Debye-ring shape and data scattering

Hardness map maker HMM is a high speed Debye-ring form measuring machine. It measures the intensity of X-ray diffraction with 4 photo sensors. When the 3D form of objective Debye-ring is not axially symmetric, i.e. when crater mountain height in a definite cross-section at each data sampling runs up and down, FWHM (Full width at half maximum) or peak height fluctuates and the measured output curve shows waviness. When the ferrite percent inside the matrix is not homogeneous along the measuring path, it affects also the output strength. The measuring speed of HMM is more than 1000 times faster than the speed of DRA, but its output is voltage corresponding only to FWHM or Debye-ring crater height in a definite cross-section.

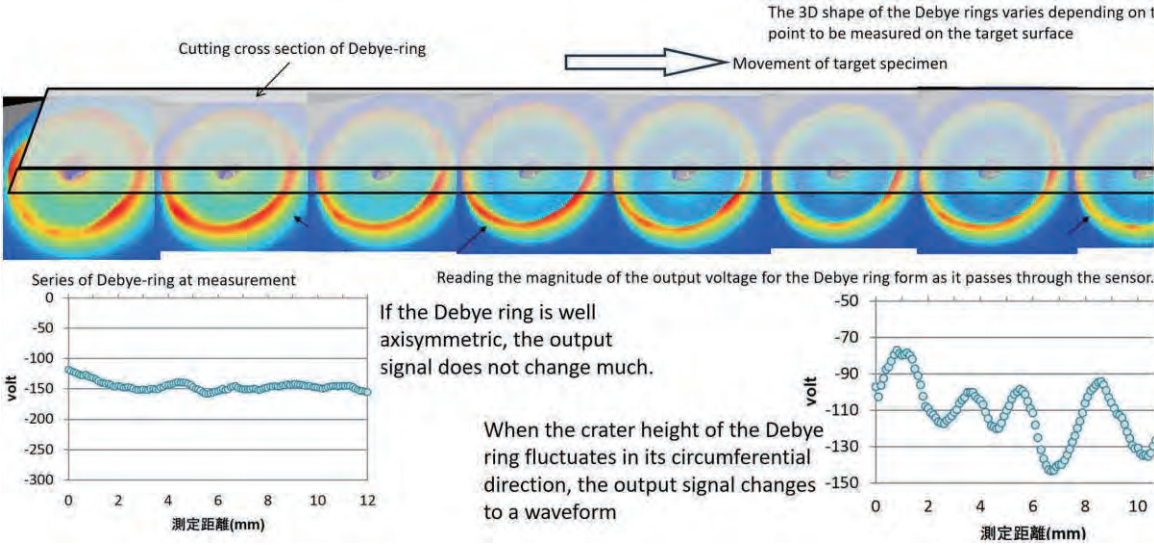


Fig. 7 Measurement with HMM

Fig. 8 compares hardness distribution estimated from the HMM output for 3 different quality steels whose matrix outlook, nital-etched figure, are shown in the uppermost raw of the figure. The scattering of the output signal of HMM and its standard deviation is calculated and shown in the bottom of the figure. On the other hand, the average grain size is calculated from these pictures by line-cutting method. It is interesting that the standard deviation corresponds well to the average grain size of these steels.

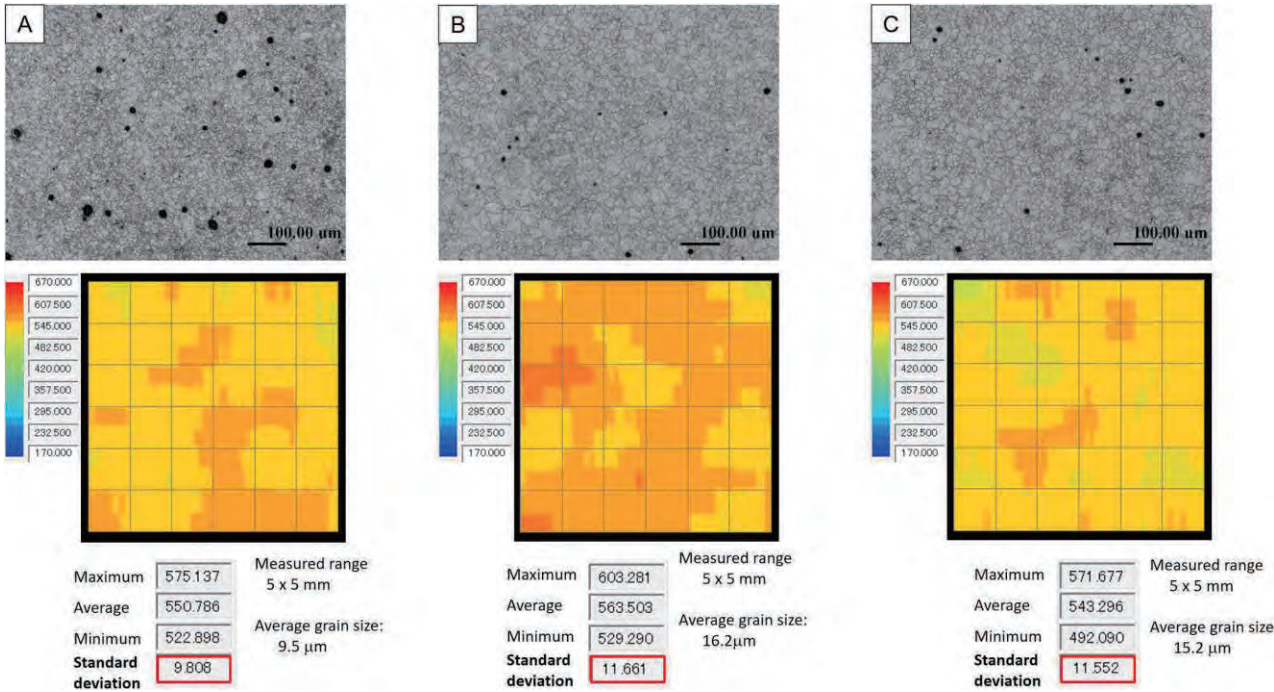


Fig. 8 Hardness distribution for 3 different quality steels and the standard deviation of their scattering, estimated from the HMM measurement

Fig. 9 compares FWHM scattering by DRA with HMM output for the problematic steel of Fig.5 and for the good steel of Fig.6. We can observe the same tendency in the result: it suggests that the HMM can be incorporated as a substitute of DRA for rough measurement i.e. for the estimation of coarse prior-austenite grain existence or of the matrix uniformity of gear steel.

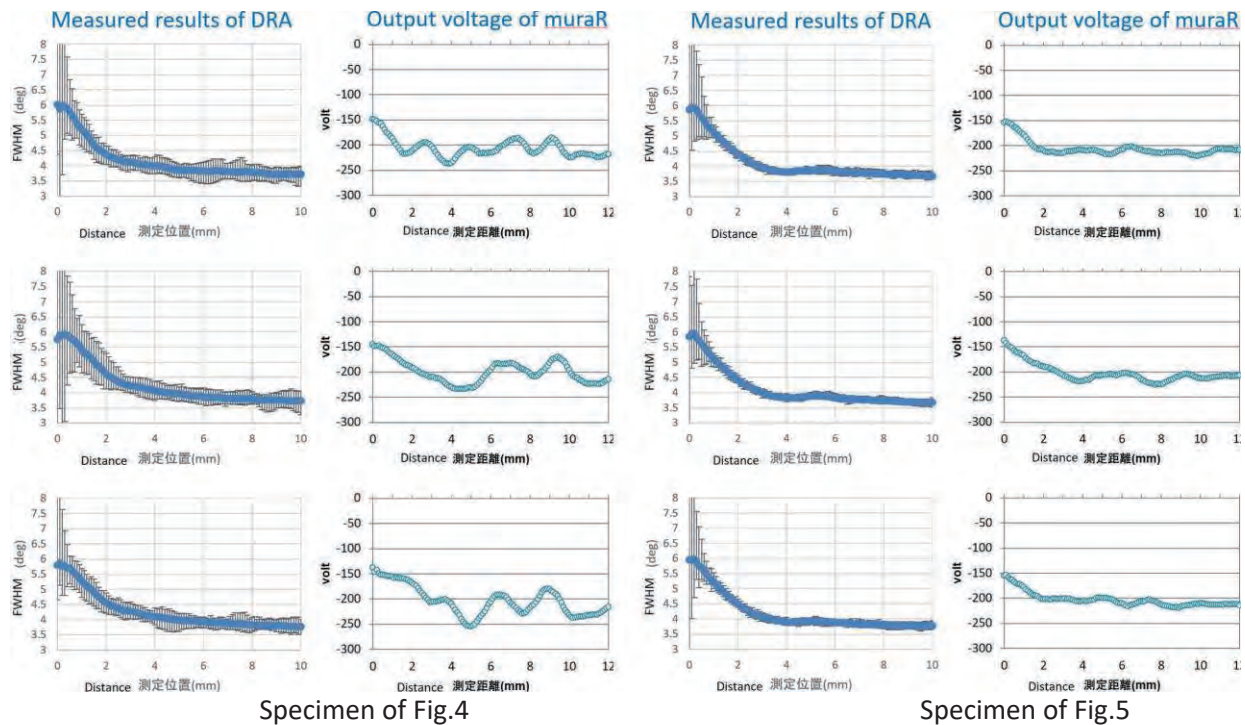


Fig. 9 Comparison between FWHM by DRA and HMM output

5. Finding the deterioration of steel quality in long production years

A Japanese machine company uses V-added carbon steel for machine construction since 2008. Recently though, some trouble has occurred on the machines using this steel, cf. Table 2.

Investigation shows, the actual quality of this steel deteriorates in some extent, though it was

delivered with the same standardized steel name and OK Mill certificate sheet as in old time.

Fig.10 shows some example of Debye-ring shapes for the recent problematic steels No.1 to No.4, together with reference steel No.5 of good old days and alloy steel No.6. The waving of peak heights for No.1 to No.4 looks somewhat stronger than that of No.5. The fluctuation of peak heights for alloy steel No.6 is small.

Table-2 Field used carbon steels used for this investigation

	Target steel No.	Status
Steel with problem	No.1 2018 made	no failure
	No.2 2019 made	no breakage at bench test
	No.3 2021 made	tooth breakage during operation
	No.4 2022 made	tooth breakage during operation
Steel of good old days	No.5 2008 made	not used(fresh) material
Alloy ateel	No.6 2022 made	no failure at bench test
Candidates: Countermeasure steel proposed by steel maker	No.7-1	countermeasure article
	No.7-2	countermeasure article
	No.7-3	countermeasure article

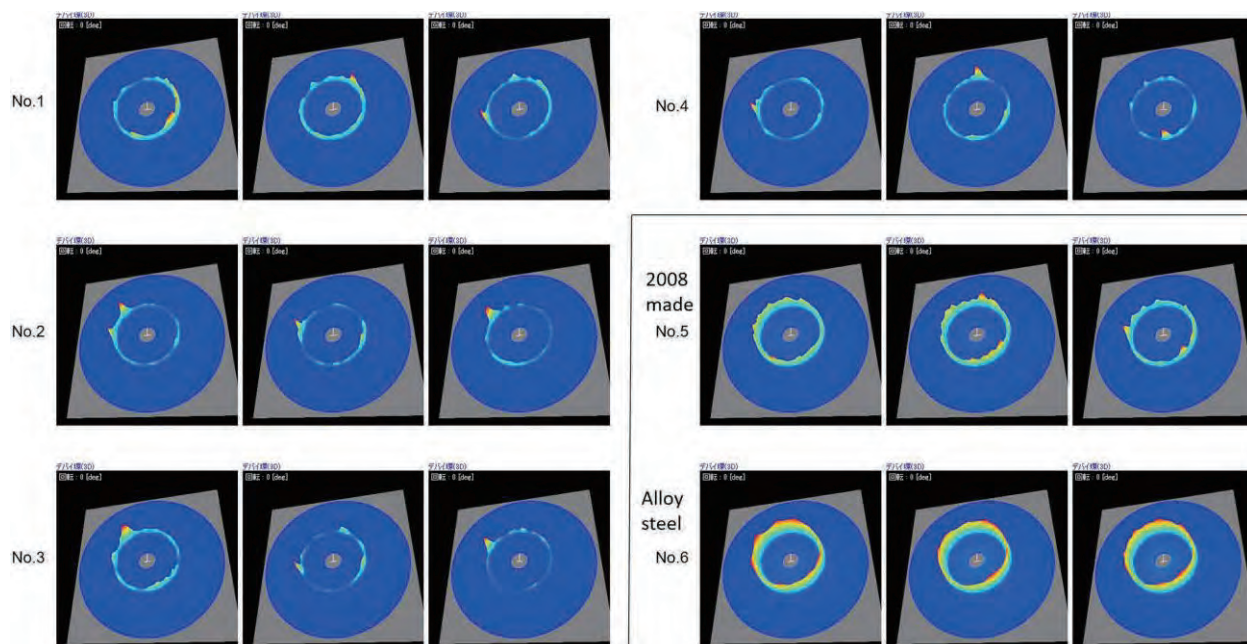


Fig.10 Debye-ring shapes of the target specimen

Typical outputs of DRA are residual compressive/tensile stress, residual shear stress, FWHM and peak heights of crater mountain. Fig.11 compares these objective issues to be evaluated. The point of evaluation is their amplitude of the scattering. Comparing the figure of the recent steel No.4 with that of reference steel No.5, all objective issues show, that the amplitude of scattering for No.4 is somewhat larger than that of No.5. That suggests, the steel quality of No.4 is somewhat worse in crystal structure in comparison with that of No.5. Among those issues for the evaluation, the scattering of crater peak height shows most clearly the difference in steel quality.

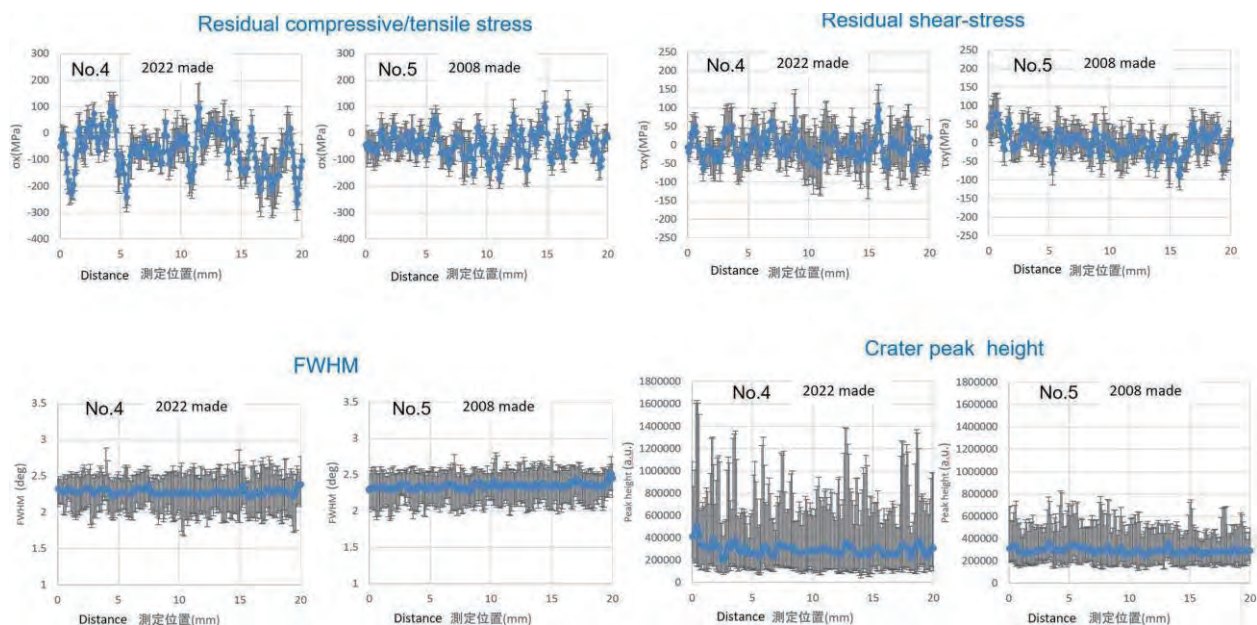


Fig.11 Objective issues to be evaluated, that is derived from Debye-ring shape analysis, measured with X-ray spot diameter 0.4mm.

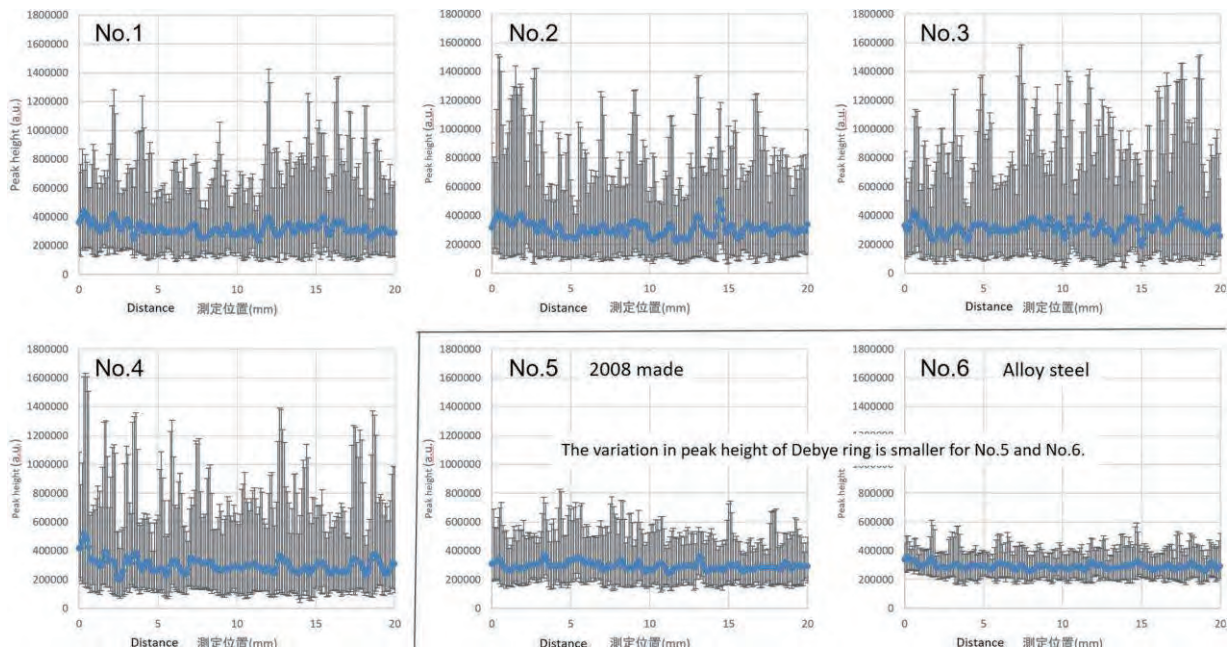


Fig.12 Peak height fluctuation of the craters of Debye-rings

The states of peak height scattering for the recent problematic steels No.1 to No.4 and reference good steel No.5 are compared in Fig.12. It is clearly observed, that the amplitude of the scattering for all the recent steels No.1 to No.4 is far wider than that of the reference steel No.5. This fact indicate that there is a quality deterioration of the steel since last 15 years, although the steel name was kept as written in the National and/or ISO Standard and the Mill certificate sheet was attached to the purchased steel. Mill certificate sheet did not work effectively to keep the steel quality.

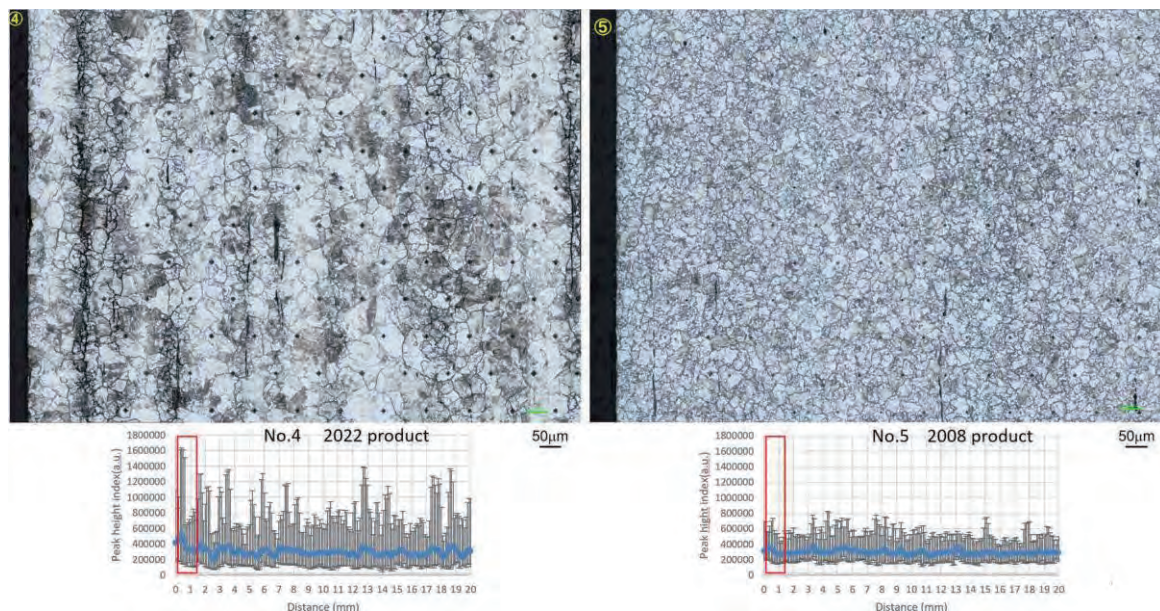


Fig.13 Picric acid etched crystal structure and scattering of crater height of Debye-ring

Fig.13 shows, what difference exists in the metallurgical structure between No.4 steel and No.5 steel. Picric acid etched crystal structure is shown together with the scattering of the peak heights. The picture shows that the texture of the recent problematic steel is considerably coarse comparing with that of the steel of good old days. We can find many

vertical black lines in the left figure for No.4 steel. They are surely Mangan sulfide, typical sign of poor steel quality, and this indicates also that the quality of No.4 steel is of problem.

Measuring Debye-rings with DRA to prepare such data as Fig.12 costs considerably long working time. If we can get the comparable information from HMM measurement, the evaluation work becomes easier with considerably less time consumption. Fig.14 comparers the result of HMM output signals between investigated steels like Fig.12. The measurement was carried out to make hardness map like Fig.8. It is recognized that the magnitude of measured curves for No.1 to No.4 steels are fluctuated much stronger in comparison with that of No.5. The standard deviations of these data well express this state of steel quality difference.

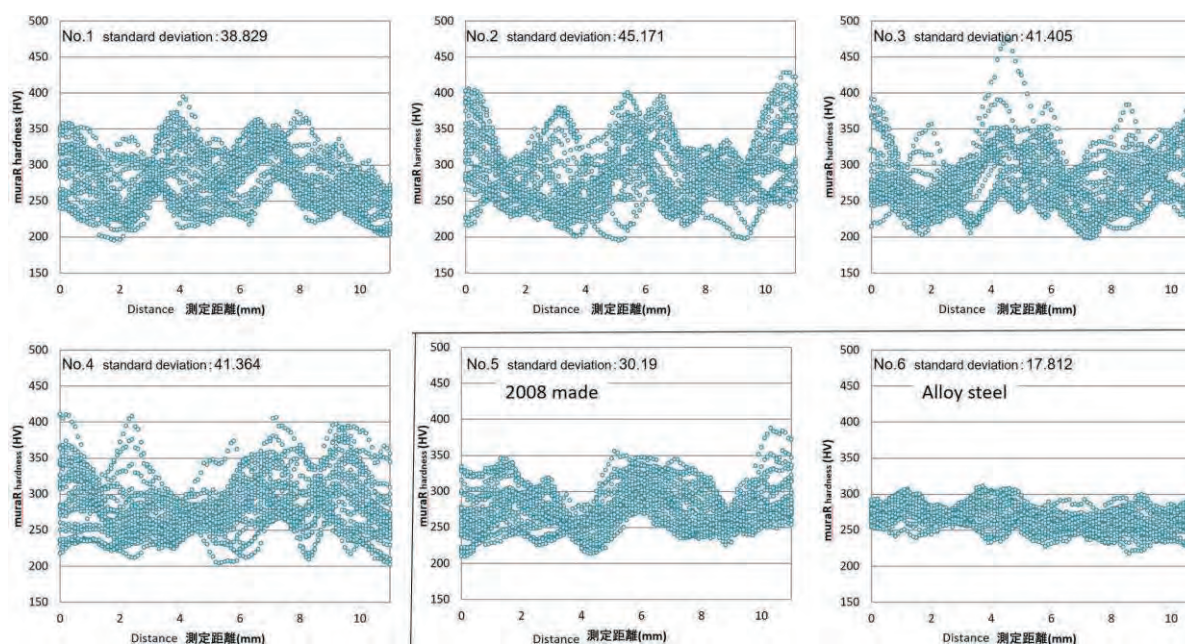


Fig.14 Comparison of HMM output signals between investigated steels

6. Countermeasure products

In response to the user's claim concerning this steel quality problem, the steel maker develops countermeasure steels No.7's of the same standardized steel name. The rough history is listed on the Table-2. The nital etched metallurgical structure is shown in Fig.15. Comparing those problematic steel with that of the countermeasure steels, the state of the grain diameters of the countermeasure steels are well improved to be small, but not fine enough as the steel of good old days. The vertical lines between layers in the matrix of countermeasure steels show that the production procedure/condition of recent steels differs considerably from that of good old days. Such outlook characteristics is though inevitable: when we consider the current economical situation where we need to cut back on energy costs and to consider on CO₂ problem in the manufacturing of steel, compared to the past.

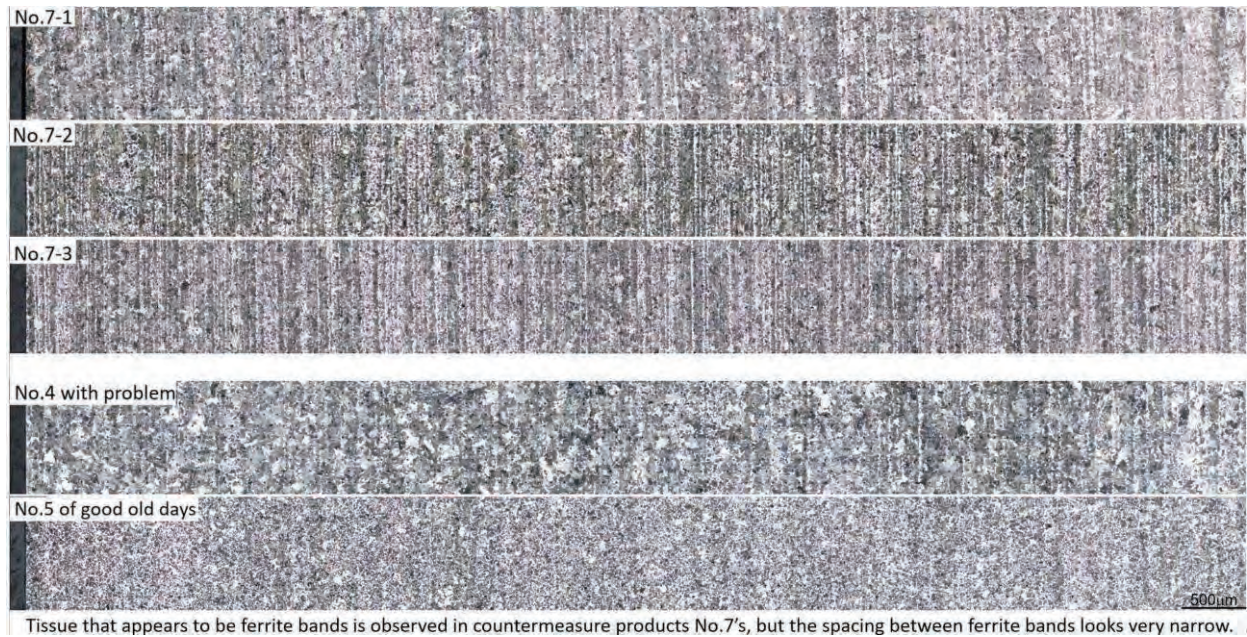


Fig.15 Nital etched crystal construction of countermeasure products and of reference steels

Fig.16 compares the scattering of peak heights of Debye-ring for countermeasure steels No.7-1 to No.7-3 with that of today's problematic steel No.4 and with that of good old days No.5. It is recognized that the magnitude of scattering for the countermeasure steels is somewhat less than that of the today's steel, but not the level of the reference steel No.5. We appreciate the steel maker's effort to improve the steel quality, but it does not reach the level of the reference steel. Simultaneous understanding of Fig.15 and Fig.16 suggests, the evaluation of scattering of the peak heights can be an alternative method to the observation of the etched surface of the steels. The merit is, such X-ray diffraction measurement is

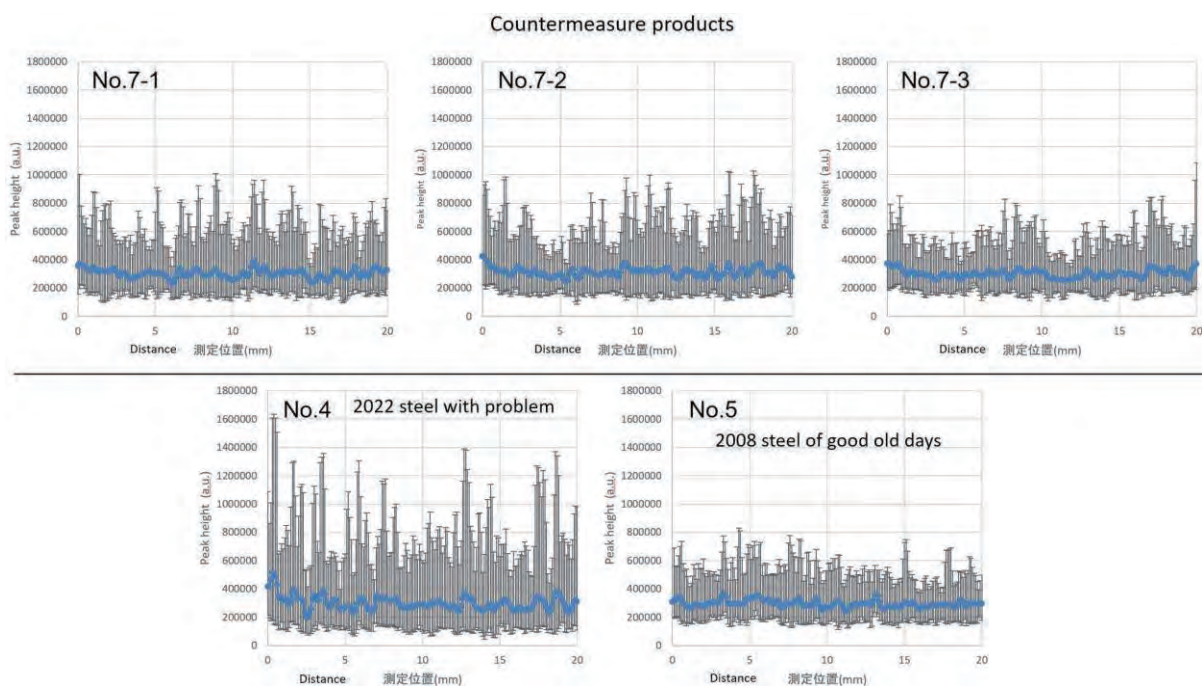


Fig.16 Scattering of crater height of Debye-rings of countermeasure products, compared with today's steel and with steel of good old days.

considerably easier compared to the work for etching process.

Observation of etched surface to judge the steel quality needs very high skilled metallurgical knowledge and the experience where the evaluation is worked out by pattern recognition; it is difficult to transfer the result to other people. On contrary, the output of such X-ray diffraction measurement is expressed with digital values, that makes the treatment of the results far easier. In addition, almost the same results can be obtained no matter who makes the measurement.

7. Standard deviation of peak height scattering of Debye-ring crater

The scattering amplitude of peak height for all the steels listed in Table 2 is summarized in Fig.17 left figure. The standard deviation of these data is also shown in Fig.17 right figure. Both figures show the same result of the evaluation: problematic steel No.1 to No.4 show considerably higher scattering amplitude and higher value of the standard deviation in comparison with that of steel No.5 of good old days. Those values for the countermeasure steel No.7's exist between the level of the two. This fact appeals that the scattering amplitude of Debye-ring crater heights or the standard deviation of these data is a good candidate index for steel quality checking.

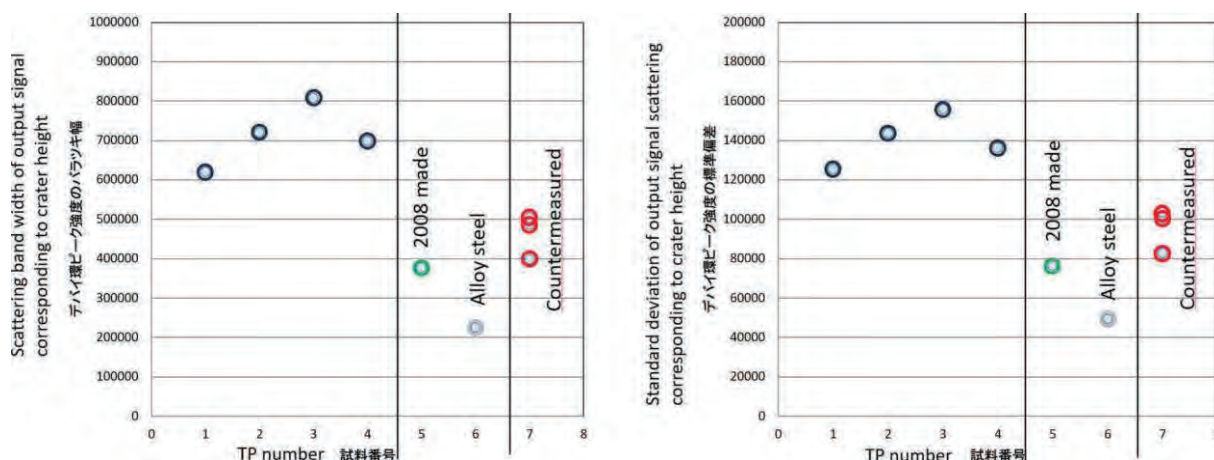


Fig.17 Comparison between scattering of Debye-ring crater height for steels of problem, that of good old days and countermeasure products

Fig.18 compares the standard deviation of HMM output data fluctuation. This result is very similar to the result of DRA analysis shown in Fig.17. It suggests that the HMM measurement can substitute the DRA analysis: The standard deviation of the output data fluctuation is good candidate for the index of steel quality checking, that can substitute the etching technique for steel quality evaluation.

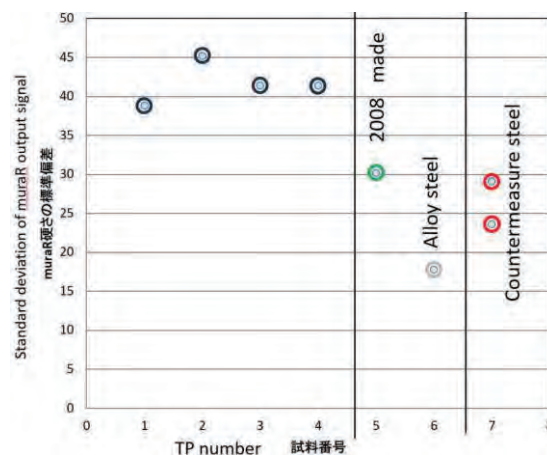


Fig.18 HMM results between good old steel, new steels and countermeasure

8. Conclusions

1. The degree of irregularity in the shape of Debye-ring correlates closely to the grain size of prior-austenite. The amplitude scattering of peak height variation over the 360-deg.path of Debye-ring crater is the most sensitive output item of this measurement for steel quality checking. Incorporation of X-ray irradiation of small diameter raises the sensitivity of the measurement.
2. The standard deviation of the measured scattering of the peak heights of Debye-ring crater is a good candidate for this steel quality evaluating method. It has a possibility to substitute the etching method to check the metallurgical status of steel. Comparing with the etching method whose evaluation must be carried out with analog pattern recognition of skilled specialist, numerical expression of the results of this method is a big merit in industrial usage.
3. The amplitude or the standard deviation of the waviness of the output signal of high-speed Debye-ring shape measuring apparatus HMM roughly indicates the situation of prior-austenite grain size.

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特別研究員による成果

(Sm, Ce)₂(Co, Fe, Cu, Zr)₁₇ 磁石の磁気測定および軟 X 線 磁気円二色性顕微鏡観察から導かれる磁化反転過程

松浦 裕* (公益財団法人 応用科学研究所)

Demagnetization Processes of (Sm, Ce)₂(Co, Fe, Cu, Zr)₁₇ magnets based on magnetic measurement
and soft X-ray magnetic circular dichroism microscopy analysis
Yutaka Matsuura* (Research Institute for Applied Sciences)

Observations of the demagnetization process for (Sm, Ce)₂(Co, Fe, Cu, Zr)₁₇ magnets using soft X-ray magnetic circular dichroism confirmed that the demagnetization process begins with magnetization reversal at the grain boundaries and around oxides existing inside the grains. Subsequently, magnetization reversal progresses from the grain boundaries and oxide peripheries into the crystalline grains via domain wall movement, eventually reaching coercivity. The reason for the larger slope in the linear portion of the demagnetization curve for this magnet compared with that of Nd-Fe-B sintered magnets is thought to be the relatively large grain boundary thickness of several hundred nanometers. After H_k , (i.e., the magnetic field corresponding to 90% of the residual magnetization), the magnetization reversal area, which had penetrated the grains from the grain boundaries and oxide peripheries, gradually reaches coercivity owing to pinning and de-pinning in the intragrain microstructure. The slow demagnetization between H_k and the coercivity is estimated to be attributed to the large crystal grains, $\sim 100\ \mu\text{m}$. By accounting for the demagnetization field and the magnetic after-effect, the average demagnetization curve of soft X-ray magnetic circular dichroism microscopy can be reproduced numerically, verifying that the results reflect the magnetization reversal process within the bulk magnet. Furthermore, when the average demagnetization curve is corrected using the demagnetization factor, the magnetic field at which magnetization reversal proceeds inside the crystal grains is found to be $-0.98\ \text{Tesla}$, a value close to H_k ($-1.066\ \text{Tesla}$). To date, discussions on the coercivity mechanism for Sm₂Co₁₇ type magnets have mainly considered the angular dependence of coercivity, but the angular dependence of coercivity of this magnet exhibits a similar behavior to ferrite magnets and Ga-doped Nd-Fe-B sintered magnets. Therefore, it may be insufficient to discuss the coercive force mechanism based solely on the angular dependence of coercivity.

キーワード：磁石, SmCo 磁石 2, 減磁過程 3, 保磁力メカニズム 4, 磁気余効 5, XMCD6,
(magnet, SmCo magnet 2, demagnetization process 3, coercivity mechanism 4, magnetic after effect 5, XMCD 6)

1. はじめに

Sm-Co 磁石、特に Sm₂Co₁₇ (以下 2-17 型磁石) 系磁石は高いキュリー温度を持っていることから磁石特性 (残留磁束密度(B_r)および保磁力(H_{co})) の温度依存性に優れており、信頼性が要求される航空機用モータや高温に晒される可能性がある足回りの自動車用アンチロックブレーキングセンサーに使われている。2-17 型磁石は (Sm, Ce)(Co, Fe, Cu)₇ 近傍で優れた特性が得られることが発見されたことに始まる。⁽¹⁾ この磁石の磁石特性は、その後 Zr 添加により 1977 年には 240kJ/m^3 (30MGOe) を越えた。^{(2),(3)} 近年、堀内らは 282kJ/m^3 ($> 35\text{MGOe}$) の磁石特性を報告しており、2-17 型磁石の磁石特性改良は今なお続いている。⁽⁴⁾

2-17 型磁石の保磁力は、焼結後の溶体化熱処理に続く熱

処理により主相結晶粒内の SmCo₇ 相が Sm₂Co₁₇ 相 (2-17 相) とそれを取り囲む SmCo₅ 相 (1-5 相) へ分離した 100nm 程度の微細なセル構造により、磁壁がピンニングされることにより発現すると言われている。このセル組織については透過電子顕微鏡を用いて調べられており、磁壁は 1-5 相内もしくは 2-17 相と 1-5 相の境界で止められていると推定されている。^{(5),(6)}

2-17 型磁石の保磁力(H_{co})は、セル組織の 1-5 相にピンニングされた磁壁が動き出すことで決定されと考えられている。したがってこの磁石は典型的なピンニング型磁石とされている。しかし、2-17 型磁石の 2-17 相および 1-5 相の異方性エネルギーの温度変化や H_{co} の角度依存性の測定から、この磁石の保磁力メカニズムについてはピンニングとニュークリエーションの両面から様々な議論が行われてい

る。(7)・(12)

町田らは2-17型磁石の光学顕微鏡による磁化反転過程の観察から、磁化反転は最初に主相結晶粒の境界で起こり、その後、主相結晶粒内に磁化反転が進展することを報告している。(13) 同様の磁化反転過程は軟X線磁気円二色性顕微鏡観察(XMCD)を用いた磁化反転過程の観察により報告されている。(14)

本報告では $(\text{Sm, Ce})_2(\text{Co, Fe, Cu, Zr})_{17}$ のXMCDによる減磁過程の観察およびXMCDから得られた平均減磁曲線と磁気測定から得られた減磁曲線について比較検討した結果から得られた磁化反転プロセスについて議論を行う。

2. 実験方法

実験に使った試料は信越化学工業(株)より提供を受けた磁石組成 $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Cu}_{0.05}\text{Zr}_{0.02})_{7.2}$ を用いた。

磁石特性は上記組成の試料を $7\times7\times7\text{mm}$ に切り出した後、最大磁界8 Teslaの東英工業製パルス磁気測定装置(TMP-2-08S25VT-C)を用い測定を行った。 H_{cJ} の角度依存性は $\phi4\text{mm}\times4\text{mm}$ (磁化容易方向径方向)を8 Teslaで着磁した後、東英工業製振動試料型磁力計(VSM-5, 最大磁界1.8 Tesla)を用い測定した。

XMCD観察はSpring-8ビームラインBL25SUを用い行った。用いた磁石は $0.6\text{mm}\times0.6\text{mm}\times\text{Lmm}$ (磁化容易方向:Lmm)に切り出し、予備室で $\sim4.89\times10^{-6}\text{Pa}$ の高真空中で磁化容易方向と垂直方向に破断した後、 $\sim4.6\times10^{-7}\text{Pa}$ の測定室に移送された。測定は最大磁界 $\pm5\text{ Tesla}$ の磁界を用い室温中で行われた。入射X線と磁界はc面に垂直方向にかけられた。測定領域は $55.95\mu\text{m}\times60\mu\text{m}$ 、測定は 150nm 間隔で行われた。

X線吸収強度はCo L_3 プレエッジ(774.0 eV)、Co L_3 エッジ(774.0 eV)、Sm M_5 プレエッジ(1066.0 eV)およびSm M_5 エッジ(1078.6 eV)を用い、全電子収量にて測定を行った。これらのエネルギー領域において、X線は $100\text{nm}\times100\text{nm}$ に集光され、焦点深度は 1.5nm である。XMCD測定の詳細はDavid Billingtonらの論文を参考にされたい。(15)

3. 結果と考察

図1(a),(b)は $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Cu}_{0.05}\text{Zr}_{0.02})_{7.2}$ (以下Sm, Ce系2-17磁石と表記する。)と $\text{Nd}_{15}\text{Co}_{1.0}\text{B}_{6.0}\text{Fe}_{\text{bal.}}$ の減磁曲線を示している。図から分かるようにSm, Ce系2-17磁石はNd-Fe-B焼結磁石に比べ、減磁カーブの直線部の傾きが大きく、 H_k から H_{cJ} までの磁化減少も緩やかに減少する。このことは減磁カーブの角形性を表す指標である H_k/H_{cJ} (ここで H_k は磁化の値が残留磁束密度(B_r)の90%となる磁界を示す。)がSm, Ce系2-17磁石で0.72に対しNd-Fe-B焼結磁石では0.89であることから、減磁曲線の角形性

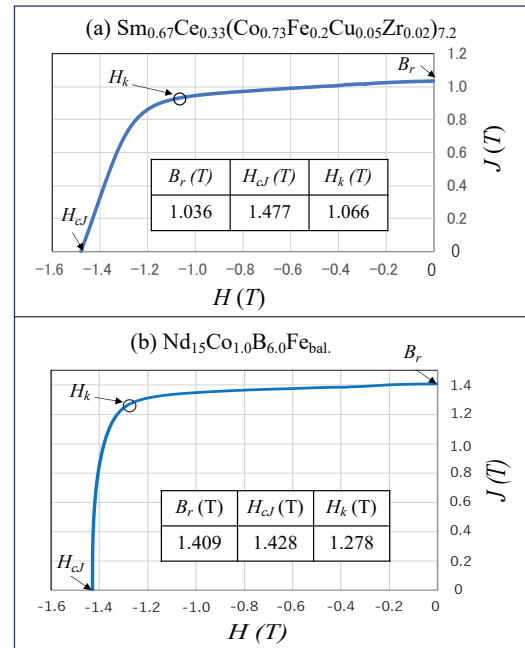


図1 $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Cu}_{0.05}\text{Zr}_{0.02})_{7.2}$ とNd-Fe-B焼結磁石の減磁曲線比較

Fig. 1. Demagnetization curve of $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Cu}_{0.05}\text{Zr}_{0.02})_{7.2}$ and Nd-Fe-B sintered magnet

が悪いことは明らかである。

この角形性はSm, Ce系2-17磁石に限らず2-17磁石全般に当てはまる現象であるが、その原因が何処にあるのかについて詳細な議論はされていない。

図2(a)~(e)はXMCDによるSm, Ce系2-17磁石の磁化反転過程を5.0 Teslaの着磁状態から、 -5.0 Tesla まで観察した結果を示している。(14) 図の中で赤く表示されている領域は着磁状態を表しており、青で示されている領域は磁化反転している領域を表している。図の中で白く示された領域は非磁性の希土類酸化物である。図2(a)では非磁性領域を除いて着磁されているが、2(b)の -0.4 Tesla では粒界が磁化反転していることが分かる。この磁化反転は町田らによる2-17型磁石のKirk効果による観察結果と一致している。また酸化物周囲でも減磁が起こっていることが明らかとなった。XMCD観察からSm, Ce系2-17磁石の粒界幅は数百 μm と推定されNd-Fe-B焼結磁石の粒界相幅の数 nm と比べ遥かに大きな粒界相である事がわかる。この磁石の減磁曲線の B_r からの直線部の傾きがNd-Fe-B焼結磁石より大きい原因はこの粒界相幅の大きさと関係しているものと推定される。図2(c)および2(c)の四角に囲った部分を拡大した図から -0.5 Tesla で磁化反転は粒界および酸化物周辺か

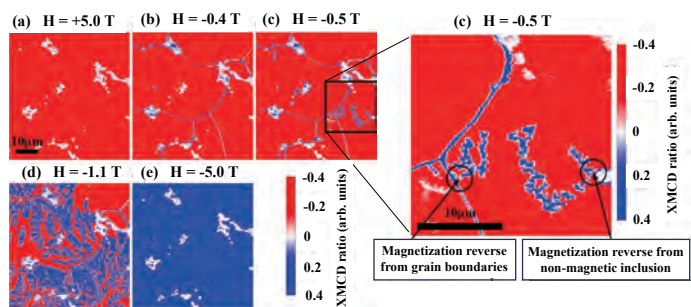


図2 XMCDによる磁化反転プロセス(赤部分は着磁領域、青い部分は減磁領域を示している。)

Fig. 2. Demagnetization process by XMCD (red area: Magnetized area, blue area: Demagnetized Area)

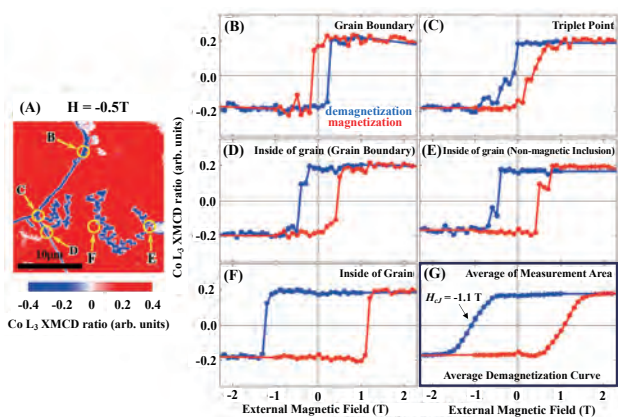


図3 $H = -0.5$ TeslaでのXMCD画像と各点での磁化曲線および画面全体の平均磁化曲線

Fig. 3. (A) XMCD Image at $H = -0.5$ Tesla, (B)-(F) Magnetization curves at various point and (G) Average magnetization curve of $59.5 \mu\text{m} \times 60 \mu\text{m}$

ら結晶粒内に入ることが分かった。その後、粒内で磁化反転が進み2(d)の-1.1 Tesla 辺りで H_{cJ} に達し、2(e)の-5.0 Tesla で磁化反転は完了していることが分かる。

図3は2(c)の四角に囲った部分AのB点からF点の各点について、磁化曲線を調べたものである。またGはXMCDマッピング全体の平均磁化曲線を示している。図から粒界三重点および粒界の磁化曲線の保磁力が低くなっていることが分かる。また平均磁化曲線からXMCD観察から得られる保磁力が1.1 Tesla であることが分かる。

図4に磁気測定から得られた減磁曲線とXMCDの平均減磁曲線を比較して示している。XMCDの平均減磁曲線は磁気測定の減磁曲線に比べ、カーブの角形性が悪くなってお

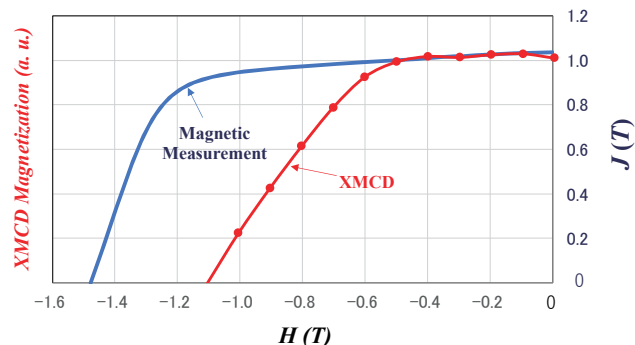


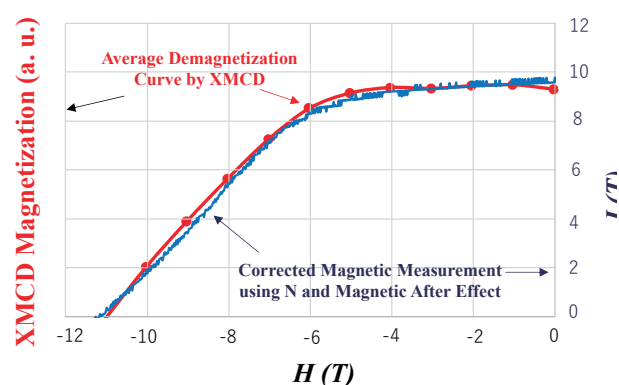
図4 磁気測定減磁曲線とXMCD平均減磁曲線の比較

Fig. 4. Demagnetization curve by the magnetic measurement and XMCD average demagnetization curve

り、磁気測定の H_k (1.066 Tesla) より低い 0.5 Tesla 以上の磁界で磁化の急激な減少が見られる。更に、磁気測定の減磁曲線では H_{cJ} は 1.477 Tesla に対し、XMCDの平均減磁曲線では、 H_{cJ} の値は 1.1 Tesla とかなり低い値になっている。

この現象は Ce, Sm 系 2-17 磁石だけではなく、Nd-Fe-B 焼結磁石やフェライト磁石の XMCD 平均減磁曲線でも観測されている。⁽¹⁶⁾ ここでは Nd-Fe-B 焼結磁石およびフェライト磁石で用いられたのと同じ手法を Sm, Ce 系 2-17 磁石に適用した場合、両者の関係について検討する。

XMCD 観察時に Nd-Fe-B 焼結磁石は真空中で破断されるが、その際の破断面は粒界破断が起り、粒界は結晶粒表面に残る。この破断面と研磨した磁石表面を XMCD で観察すると研磨面の表面に比べ、破断面の XMCD はきれいな磁



$N=0.5$, Magnetic After Effect $(\Delta J)_{\text{max}} = 0.5 \text{ T}$ at $(\chi_{\text{irr}})_{\text{max}}$

図5 XMCD平均減磁曲線と反磁界および磁気余効を考慮した磁気測定減磁曲線

Fig. 5. XMCD average demagnetization curve and demagnetization curve of the magnetization measurement taken into account of the demagnetization factor and the magnetic after effect.

区模様をしていることから破断面は磁氣的に内部情報を反映していると定性的に判断されるとしている。⁽¹⁵⁾しかし、破断面が内部情報を反映していると反磁界補正されている磁気測定減磁曲線から、XMCD 減磁曲線は再現される必要がある。XMCD 測定では表面を観察する事から、表面の大きな反磁界がかかっていることが推定される。しかし、反磁界は減磁カーブの角形性の低下を説明できるが、XMCD 平均減磁曲線の H_{cJ} が磁気測定と比べ低くなっている原因にはなり得ない。

この原因を考えるためにはXMCDの測定方法を検証する必要がある。XMCD 測定は一定のスweep速度でした後、測定磁界付近に近づいた時点でオーバーシュートを防ぐためスweep速度を落とし、目的の磁界に到達させる。測定に入るまでに数分間、磁界が安定するまで置いた後、測定を開始する。この測定方法を考えると、測定が始まるまでに磁気余効が起こっていることを考慮する必要がある。⁽¹⁶⁾

永久磁石の磁気余効は以下の式で表される。

$$\Delta J = J_t - J_1 = \chi_{irr} S_v \ln t \dots\dots\dots(1)$$

ここで ΔJ は磁気余効による磁化の変化、 J_t は t 秒後の磁化の値、 J_1 は測定開始時の磁化、 χ_{irr} は不可逆帯磁率、 t は測定時間を表している。磁気粘性係数 S_v は次式で表される。

$$S_v = k_B T / \mu_0 v_a J_s \dots\dots\dots(2)$$

ここで k_B はボルツマン定数、 T は温度、 μ_0 は真空中の透磁率、 v_a は活性化体積、 J_s は飽和磁化を表している。

減磁曲線の磁界での帯磁は

$$\chi_{total} = \chi_{rev} + \chi_{irr} \dots\dots\dots(3)$$

で表される。ここで χ_{total} は全帯磁率で磁気測定減磁曲線の各点での帯磁率、 χ_{rev} は可逆帯磁率、 χ_{irr} は不可逆帯磁率を表している。一般に可逆帯磁率と不可逆帯磁率を分離するのは難しいとされているが、Nd-Fe-B 焼結磁石や SmCo 磁石では χ_{rev} の値は小さく、 $\chi_{total} \approx \chi_{irr}$ で表すことができる。⁽¹⁷⁾

したがって、磁気測定減磁曲線に横軸（磁界 H ）に色々な反磁界係数を入れ、縦軸（磁化 J ）に磁気余効を入れた場合、XMCD 平均減磁曲線を再現できるのかが問題となる。再現できれば XMCD 減磁曲線は内部情報を反映していると言えるが、再現できなければ XMCD 測定は磁石内部情報を反映していないか、この解析手法が成り立たないことが推定される。

図5は磁気測定減磁曲線に反磁界係数($N = 0.5$)と磁気余効 (ΔJ)_{max} = 0.5 Tesla の補正を入れた減磁曲線と XMCD 平均減磁曲線を重ねて書いた図を示している。Nd-Fe-B 焼結磁石およびフェライト磁石と同様に、色々な反磁界係数および磁気余効を入れて行くと、磁気測定減磁曲線は XMCD 平均減磁曲線に収束して行くことが分かった。このことは XMCD 観察から得られた平均減磁曲線は磁石の内部情報を反映していることを示している。

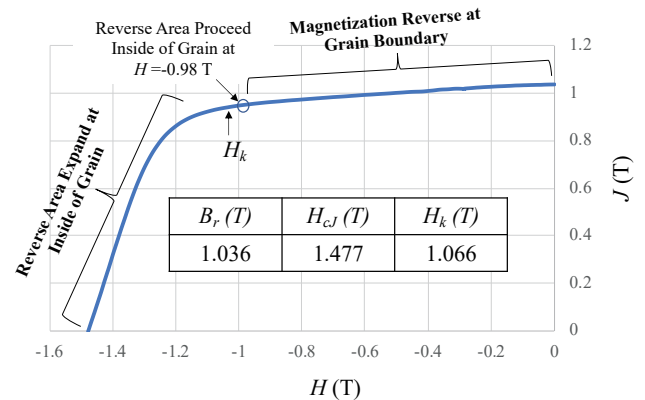


図6 磁気測定減磁曲線と XMCD 観察および反磁界補正後の XMCD 平均減磁曲線から得られた磁化反転プロセス

Fig. 6. Demagnetization curve by magnetization measurement, the XMCD average demagnetization curve after the demagnetization correction and the magnetization reverse process of Sm_{0.67}Ce_{0.33}(Co_{0.73}Fe_{0.2}Cu_{0.05}Zr_{0.02})_{7.2}

図6は、この解析から得られた N を用い、XMCD 観察から得られた磁化反転が粒界から粒内に進む磁界 ($H = -0.5$ Tesla) の位置を磁気測定減磁曲線上に示した。図から分かる通り、反磁界補正後の磁界は -0.98 Tesla となり、この値は磁気測定から得られた減磁曲線の H_k の磁界 -1.066 Tesla に近い値になっていることが分かった。

XMCD による磁化反転の観察から Sm_{0.67}Ce_{0.33}(Co_{0.73}Fe_{0.2}Cu_{0.05}Zr_{0.02})_{7.2} はまず粒界および希土類酸化物周辺から磁化反転が起こり、 H_k 近傍で磁化反転は粒内に進むことが分かった。その後、粒内で磁化反転は進み H_{cJ} に達する。

この磁化反転過程は、これまで言われていた粒内のセル組織にある磁壁を止めていると考えられている 1-5 相から磁壁が動くことにより H_{cJ} が決定される、というメカニズムとは異なっている。しかし、XMCD の結果は、この磁石では磁壁移動により H_{cJ} は決定されていることを強く示唆しておりニュークリエーションは起こっていないように思われる。

ところで、2-17 磁石の保磁力角度依存性に関する報告では、これら磁石の保磁力角度依存性は磁壁移動 ($1/\cos \theta$)⁽¹⁸⁾ および磁化一斉回転 ($1/((\cos \theta)^{2/3} + (\sin \theta)^{2/3})^{2/3}$)⁽¹⁹⁾ で予想される曲線の間で変化することが知られており、これら磁石の保磁力メカニズムがどちらであるのかについて議論がされている。^{[7]-[12]} 図7は高い配向度を持つ Sm_{0.67}Ce_{0.33}(Co_{0.73}Fe_{0.2}Cu_{0.05}Zr_{0.02})_{7.2}、SrO・6Fe₂O₃ および Ga 添加 Nd-Fe-B 焼結磁石の保磁力角度依存性を示している。これら磁石の保磁力角度依存性は 0° から減少し、 40° 以

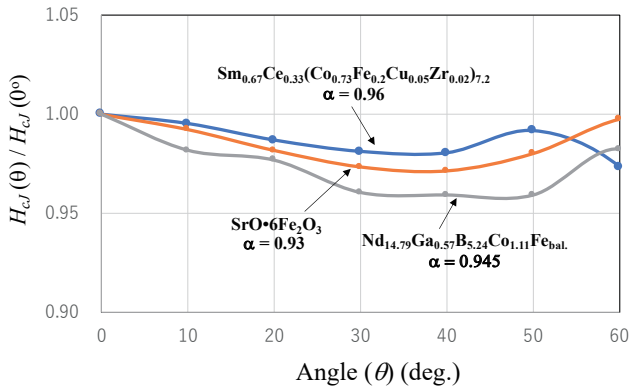


図7 $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Co}_{0.05}\text{Zr}_{0.02})_{7.2}$, $\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$ および $\text{Nd}_{14.79}\text{Ga}_{0.57}\text{B}_{5.24}\text{Co}_{1.11}\text{Fe}_{\text{bal.}}$ 高配向度磁石の保磁力角度依存性
Fig. 7. Angular dependence of coercivity for $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Co}_{0.05}\text{Zr}_{0.02})_{7.2}$, $\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$ and $\text{Nd}_{14.79}\text{Ga}_{0.57}\text{B}_{5.24}\text{Co}_{1.11}\text{Fe}_{\text{bal.}}$ with high alignment (α)

降の高い角度で増加するという、一見したところ磁化一斉回転に見られる角度依存性を示す。^[20]しかし、同じく図7に示している通り磁壁移動で保磁力が決定され则认为されるフェライト磁石 ($\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$) や Ga 添加 Nd-Fe-B 焼結磁石^{[21], [22], [23]}と同一ような変化を示している。

フェライト磁石や Ga 添加 Nd-Fe-B 焼結磁石の保磁力角度依存性の議論からは、これら磁石の角度依存性がニュークリエーションの証拠とは言えず、磁壁移動から説明できると考えられる。^{[21], [22], [23]}

図8に等方性磁石の保磁力角度依存性測定値と全ての粒子が独立に磁壁移動で磁化反転するとして計算した保磁力角度依存性^[23]を比較した図を載せている。破線は磁化一斉回転の場合の等方性磁石の保磁力角度依存性を示してい

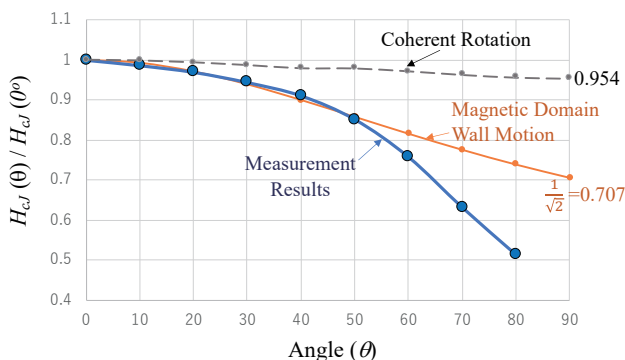


図8 $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Co}_{0.05}\text{Zr}_{0.02})_{7.2}$ 等方性磁石の保磁力角度依存性

Fig. 8. Angular dependence of $\text{Sm}_{0.67}\text{Ce}_{0.33}(\text{Co}_{0.73}\text{Fe}_{0.2}\text{Co}_{0.05}\text{Zr}_{0.02})_{7.2}$ isotropy magnet

る。等方性磁石の保磁力角度依存性は Nd-Fe-B 焼結磁石やフェライト磁石と同じ変化を示しており、50°まで磁壁移動で磁化反転が起こるとして計算した値とほぼ一致している。

このように考えると 2-17 磁石および Sm, Ce 系 2-17 磁石について角度依存性を用いた保磁力メカニズムあるいは磁化反転過程についての議論について、今後詳細な検討が必要であると思われる。

3. 結論

XMCD による Sm, Ce 系 2-17 磁石の減磁過程の観察結果から、この磁石の減磁は粒界および酸化物周囲で磁化反転が始まることが確認された。その後、磁化反転は粒界および酸化物周辺から結晶粒内に進行し、 H_{cJ} に達する。Sm, Ce 系 2-17 磁石減磁曲線直線部で傾きが Nd-Fe-B 焼結磁石に比べ大きい原因は、数百 nm 程度もある粒界の厚さに起因しているものと考えられる。また H_k からの減磁過程では粒界から粒内に侵入した磁化反転領域が粒内マイクロ組織による、ピンニング、デ・ピンニングにより徐々に H_{cJ} に到達する様子が観察されており、 H_k 以降の減磁曲線の悪さは Sm, Ce 系磁石の~100μm 近い大きな結晶粒に起因していることが推定される。

磁気測定の減磁曲線に反磁界と磁気余効を考慮すると XMCD の平均減磁曲線を再現できることから、XMCD の観察結果はバルク磁石内部の磁化反転過程を反映していることが分かった。

更に XMCD 平均減磁曲線を反磁界補正すると、磁壁が結晶粒内に侵入する磁界(-0.5 Tesla)は-0.98 Tesla となり H_k (-1.066 Tesla)に近い値であることが分かった。

これまで 2-17 型磁石でも保磁力メカニズムの議論は保磁力角度依存性が用いられて来た。しかし、XMCD 観察から、Sm, Ce 系 2-17 磁石での磁化反転は磁壁移動で進むことが確認されており、ニュークリエーションは起こっていない。また、この磁石の保磁力角度依存性は 0°から低下し 40°から増加するものの、この現象はフェライト磁石や Ga 添加 Nd-Fe-B 焼結磁石でも同じような傾向は観察されており、この保磁力の角度依存性をもってニュークリエーションとは言えない。保磁力角度依存性だけを使って保磁力メカニズムの議論をすることは出来ないように思われる。今後、Sm, Ce 系 2-17 型磁石だけでなく、2-17 型磁石全般に亘る保磁力メカニズムの研究が進むことが望まれる。

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Demagnetization Process of Nd-Fe-B Sintered and Ferrite Magnets

Yutaka Matsuura* Non-member

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The magnetization reversal mechanism for Nd-Fe-B sintered and ferrite magnets was investigated using magnetic measurements and soft X-ray magnetic circular dichroism microscopy. In magnetization reversal, discrete reversals of crystal grains occurred first in the demagnetized field region, which was lower than the coercivity. In the next step, clusters of reversed grains were formed by reversals in crystal grains around the discrete reversed grains. For highly aligned magnets, the cluster sizes at the coercivity increased with decreasing temperature, and also varied with composition. The alignment and angular dependences of the coercivity varied with cluster size, which depended on the number of discrete magnetization reversal grains that occurred in the demagnetizing field that was lower than the coercivity. Hence, if the number of discrete reversal grains was large, the cluster size was small; conversely, if the number of discrete reversal grains was small, the cluster size was significant.

Keywords: Nd-Fe-B magnet, ferrite magnet, demagnetization process, coercivity mechanism, alignment, angular dependence

1. Introduction

More than 40 years have passed since the invention of the Nd-Fe-B sintered magnet. ⁽¹⁾ Its characteristics have since improved, and its production has grown significantly. In particular, the application of Nd-Fe-B magnets to drive electric vehicles (EVs), hybrid electric vehicles (HEVs), and auxiliary motors for automobiles has been expanding recently to reduce CO₂ greenhouse gas. Demand for energy-saving home appliances, especially compressor motors for air conditioners, is also increasing. Ferrite magnets are widely used in automotive auxiliaries because they use abundant oxides raw materials and straightforward manufacturing processes in contrast to rare-earth magnets. Demand is expected to grow as crucial materials support modern society.

Expectations for improving their properties, especially the coercivity (H_{cJ}), are increasing. However, this requires many heavy rare-earth elements (HREs), such as Tb and Dy, when used in EV and HEV motors, which causes resource constraints. Therefore, high H_{cJ} and high residual flux density (B_r) via HRE diffusion into the magnets after sintering has been performed. ⁽²⁾

However, it will be essential to elucidate the magnetization reversal process and the H_{cJ} mechanism to improve Nd-Fe-B magnet properties and save resources by not using HREs.

Two H_{cJ} theories have been proposed. One is based on the Stoner-Wohlfarth model in which magnetization reversal occurs when the entire magnetization of the Nd₂Fe₁₄B grains rotates simultaneously. This is coherent rotation of magnetization. ⁽³⁾ The other theory is where magnetization reversal of the entire crystal proceeds by the formation of magnetic domain walls after the magnetization reversal appears at the grain boundary, and the entire magnetization of grains reverses by magnetic domain wall motion. ⁽⁴⁾ This debate continued until the beginning of the 2010s.

The angular dependence of H_{cJ} (ANDC) has been used to examine these coercivity models. It is still unclear which mechanism is at work.

We have reported on the magnetization reversal of these magnets based on the alignment dependence of H_{cJ} (ALDC) and have discussed the ANDC using the results of ALDC. ⁽⁵⁻¹⁵⁾ We also reported the minor demagnetization in lower demagnetization field than H_{cJ} using the recoil curve properties ⁽⁹⁾. Results obtained from microscopic observations via soft X-ray magnetic circular dichroism (XMCD) were compared with the demagnetization process speculated from magnetic measurements. ⁽¹⁶⁾ This paper aims to synthesize and discuss with the demagnetization process using the magnetization reversal of Nd-Fe-B sintered and ferrite magnets using magnetic measurements and XMCD.

2. Experiment

In section 3.2, Nd_{14.1}B_{6.1}Co_{1.0}Fe_{bal.}, Nd_{12.1}Dy_{2.1}B_{6.1}Co_{1.0}Fe_{bal.}, Nd_{10.2}Dy_{4.1}B_{6.1}Co_{1.0}Fe_{bal.}, Sr_{0.76}La_{0.24}Fe_{11.5}O₁₉ (Sr_{0.76}La_{0.24}O•6Fe₂O₃) and Nd_{12.37}B_{5.76}Fe_{bal.} are used. In section 3.3, Nd_{13.48}B_{5.76}Co_{0.55}Fe_{bal.} is used for the temperature dependence of the alignment dependence of H_{cJ} (ALDC), and Nd_{14.2}B_{6.3}Co_{1.0}Fe_{bal.} is used for the temperature dependence of the angular dependence of H_{cJ} . In section 3.4, Nd_{14.2}B_{6.2}Co_{1.0}Fe_{bal.}, Nd_{14.2}Dy_{0.3}B_{6.2}Co_{1.0}Fe_{bal.}, SrO•6Fe₂O₃ and Nd_{14.79}B_{5.24}Co_{1.11}Ga_{0.54}Fe_{bal.} are used for the measurement of the ALDC, and Nd_{14.2}B_{6.2}Co_{1.0}Fe_{bal.}, Nd_{14.2}Dy_{0.3}B_{6.2}Co_{1.0}Fe_{bal.}, SrO•6Fe₂O₃ and Nd_{14.79}B_{5.26}Co_{1.11}Ga_{0.54}Fe_{bal.} are investigated for the ANDC. In section 3.5, the recoil properties are investigated using Nd_{14.5}B_{6.3}Co_{1.0}Fe_{bal.}, Nd_{13.4}Dy_{0.97}B_{6.7}Fe_{bal.} and Nd_{11.5}Dy_{2.9}B_{6.3}Co_{1.0}Fe_{bal.}. In section 3.6, the demagnetization process by XMCD is observed using Nd_{15.0}B_{6.0}Co_{1.0}Fe_{bal.}, SrO•6Fe₂O₃.

Table 1 shows sample shapes and their dimensions.

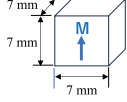
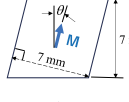
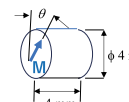
For the ALDC, these magnets are cut in 7mm x 7mm x 7mm and

a) Correspondence to: Yutaka Matsuura. E-mail: yutaka.matsuura@rias.or.jp

* Research Institute for Applied Sciences

49 Tanaka Ohi-cho, Sakyo-ku, Kyoto, Japan 606-08202

Table 1. Sample shape and dimension

	Alignment Dependence of H_{cJ} (ALDC)	Temperature Dependence of Angular Dependence of H_{cJ} (ANDC)	Angular Dependence of H_{cJ} (ANDC)
Measurement Method	Flux Meter, Pulse Field Flux Meter	Flux Meter	VSM, High-Temperature Conductivity VSM
Sample Shape and Dimension	 Cross Section Area Perpendicular to M: 49 mm ²	 Cross Section Area Perpendicular to M: 49 mm ²	

measured by the D.C. recording flux-meter (BH tracer) with maximum field 2 Tesla and the pulse high-field flux meter (maximum field: 8 Tesla) after fully magnetized by 8 Tesla magnetic fields for Nd-Fe-B magnets and 2 Tesla magnetic fields for ferrite magnets.

We measured the ANDC using two different shapes of magnets. Magnets are cut in parallelepiped with different easy magnetization angles to measure the temperature dependence of ANDC by the flux meter θ . In the parallelepiped magnets, the cross-section perpendicular to the M direction was 49 mm² (7mm $\times$ 7mm) for magnets with various θ . To measure the ANDC by VSM (maximum field: 2Tesla) and VSM using the high-temperature superconducting coil (maximum field: 5 Tesla), cylinder magnets with Dia. 4 mm, length 4 mm, where easy magnetization direction is in Dia. 4mm, are used. These magnets used for the ANDC are fully magnetized by 8 Tesla magnetic fields for Nd-Fe-B sintered magnets and 2 Tesla for ferrite magnets.

The detail measurement method of XMCD is mentioned in another paper.⁽¹⁶⁾

3. Results and Discussion

3.1 Conventional demagnetization theories and derived angular dependence of H_{cJ} (ANDC) The microstructure of Nd-Fe-B sintered magnets has a Nd-rich phase surrounding the main Nd₂Fe₁₄B phase grains, a Nd-rich phase, a B-rich phase, and

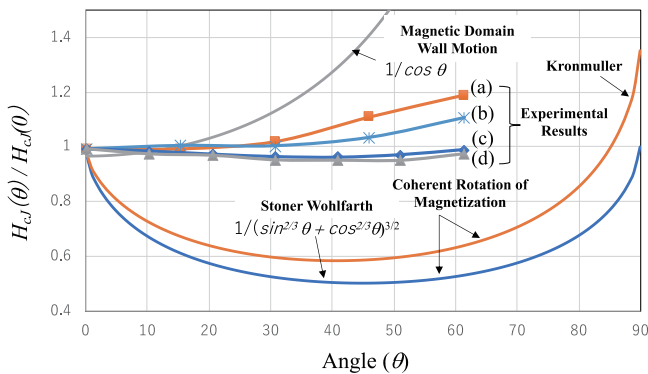


Fig. 1. Angular dependence of coercivity derived from the conventional theories of coherent rotation of magnetism theories, which are Stoner-Wohlfarth and Kronmüller⁽³⁾, and magnetic domain wall motion. Also shown are experimental results of (a) Nd_{14.2}B_{6.2}Co_{1.0}Fe_{bal.}, (b) Nd_{14.2}Dy_{0.3}B_{6.2}Co_{1.0}Fe_{bal.}, (c) SrO $\cdot$ 6Fe₂O₃ and (d) Nd_{14.79}B_{5.24}Co_{1.11}Ga_{0.54}Fe_{bal.}

Nd oxides at the grain boundary triple point.^{(1), (17), (18)} In the discussions of the coercivity mechanism between Kronmüller and Givord, the Nd-rich phase has been regarded as non-magnetic from the Nd-Fe-B ternary phase diagram⁽¹⁹⁾, the main phase grain has been considered magnetically isolated by the Nd-rich boundary phase and magnetically disconnected from surrounding main phase grains. On the basis of this idea, magnetization reversal has been discussed in terms of demagnetization in a single main phase grain.^{(3), (4)} These discussions have centered on whether the magnetization of the main phase grain undergoes magnetization reversal by coherent rotation of magnetization or by magnetic domain wall motion. In both theories, magnetization reversal begins at grain boundaries with a weak anisotropy in the main phase grain boundaries. The coherent rotation of magnetization occurs when a bud of magnetization reversal nucleates at a weak anisotropic point, such as a defect in the grain boundary. This has been considered to have low anisotropy, and the entire magnetization of the grain rotates simultaneously, similar to the Stoner-Wohlfarth model.⁽²⁰⁾

In the magnetic domain wall motion model, magnetic walls are also generated in a similar area with weak anisotropy. However, the activation volume that appears in the thermal fluctuation magnetic after-effect equation grows from some process (passage) into a magnetization reversal magnetic domain.⁽²¹⁾ The magnetic walls generated at the grain boundary penetrate the grain and cause magnetization reversal. ANDC has been used to show which of these is occurring.

As shown in Figure 1, the angular dependence of the H_{cJ} of the actual magnet lay between magnetic domain wall motion, which is shown as $1/\cos\theta$ in Fig. 1, and the coherent rotation of magnetization. This makes it difficult to determine which model is correct.

3.2 H_{cJ} mechanism derived from alignment dependence of H_{cJ} (ALDC)

Increasing the B_r or the saturation magnetization (J_s) of permanent magnets is vital to reducing the size of devices such as motors. It is therefore essential to synthesize (i) the composition of Nd-Fe-B sintered magnets as close as possible to the stoichiometric composition of Nd₂Fe₁₄B, and (ii) improvement on the alignment ($\alpha = B_r / J_s$) of the main phase crystal grains (Nd₂Fe₁₄B). The easy magnetization direction for this crystal structure is the c-axis of Nd₂Fe₁₄B, and the alignment must

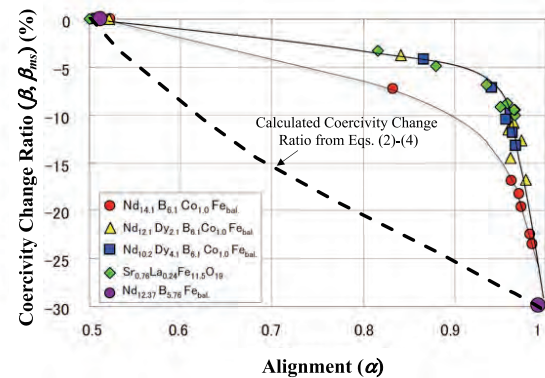


Fig. 2. Alignment dependence of coercivity change ratio (β_{ms}) of various magnets calculated from Eq. (1) and calculation results from Eq. (3) and (4)

be close to $\alpha = 1$. In the case of (i), H_{cJ} vanishes in the region where the Nd-rich phase disappears. When we used methods (i) and (ii), we produced the highest energy product with 474 kJ/m³ (59.5 MGOe).^{(5), (22)}

However, we found that H_{cJ} decreased with increasing α from the isotropic magnet.^{(5), (6)} We defined the measured H_{cJ} change ratio (β_{ms}) as follows:

$$\beta_{ms} (\%) = \frac{H_{cJ} - H_{cJ}^{\text{isotropy}}}{H_{cJ}^{\text{isotropy}}} \times 100 \quad (1)$$

H_{cJ} is the coercivity of aligned magnets, while H_{cJ}^{isotropy} represents the coercivity of the isotropic magnets.

The ALDCs of Nd-Fe-B sintered and ferrite magnets are shown in Figure 2. In the high region ($\alpha > 0.95$), H_{cJ} decreased rapidly, and the extrapolated value to perfect alignment ($\alpha = 1$) was 70% of that for isotropic magnets. A similar ALDC was experimentally observed in Nd-Fe-B sintered and ferrite magnets.^{(6), (12)} The Stoner-Wohlfarth model for the ALDC indicated that the coercive force increased with the improved α from the isotropic magnet.^{(7), (8), (10)} Similar results were obtained using the modified Stoner-Wohlfarth model of Kronmüller et al.⁽³⁾ However, if the magnetic domain wall motion reversed the magnetization, the H_{cJ} at perfect alignment ($\alpha = 1$) was $1/\sqrt{2} \approx 0.7$ of isotropic magnets, which agreed well with the ALDC experimental value.⁽⁷⁻¹⁰⁾ Therefore, it strongly suggested that the H_{cJ} was not determined by coherent rotation of magnetization, but instead by magnetic domain wall motion.

The wall motion determined the ALDC, but it needed to be confirmed whether the alignment dependence obtained could be reproduced if it was assumed that every particle was independently reversed by the wall motion ($1/\cos \theta$).

Calculations were used to determine the coercivity change ratio (β) at various α via the following equations and compared with measured β_{ms} values.⁽¹⁰⁾

$$\alpha = B_r / J_s = \frac{1}{2} \int_0^{\frac{\pi}{2}} P(\theta) \sin 2\theta d\theta \quad (2)$$

$$J = \frac{1}{2} J_s \left(\int_{\theta_1}^{\frac{\pi}{2}} P(\theta) \sin 2\theta d\theta - \int_0^{\theta_1} P(\theta) \sin 2\theta d\theta \right) = 0 \quad (3)$$

$$\beta (\%) = \left(\frac{1/\cos \theta_1}{1/\cos 45^\circ} - 1 \right) \times 100 = \left(\frac{1}{\sqrt{2} \cos \theta_1} - 1 \right) \times 100 \quad (4)$$

$P(\theta)$ denotes the alignment distribution, which was confirmed to be almost the same as Gaussian distributions from electron back-scattered diffraction.⁽¹⁰⁾ The magnetization component of the magnetization direction of a particle tilted θ from the easy magnetization direction ($\theta = 0$) can be expressed as $J_s \times \cos \theta$, where J_s is the saturation magnetization of magnets. B_r in Eq. (2) represents the sum of the easy magnetization direction components of magnetization of the grains in the magnet. There is good agreement between α obtained from Eq. (2) and the experimental data.⁽⁹⁾

In Eq. (3), assuming that the magnetic domain wall motion ($1/\cos \theta$) determines H_{cJ} and every grain reverses by $1/\cos \theta$ without any interactions, the H_{cJ} of grain tilted θ from the easy direction of magnetization is larger by $1/\cos \theta$ than those of grains with 0° .

Therefore, the magnetization reversal starts from grains along with the easy magnetization direction (0°), and after reversing the grains

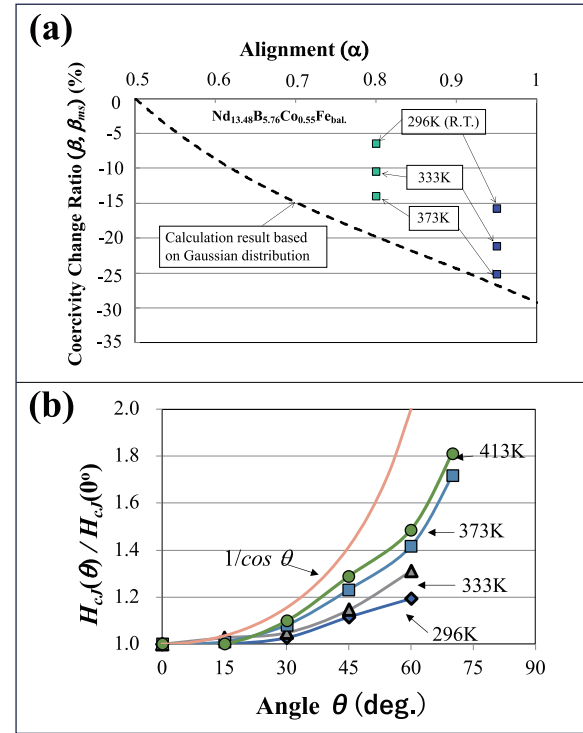


Fig. 3. Comparison of the temperature dependence of ALDC and ANDC for Nd-Fe-B sintered magnets. (a) Temperature dependence of ALDC for Nd_{13.48}B_{5.76}Co_{0.55}Fe_{bal.} and that calculated from Eqs. (3,4). (b) Temperature dependence of ANDC for Nd_{14.2}B_{6.2}Co_{1.0}Fe_{bal.} and $1/\cos \theta$

with a tilted angle θ , the magnetization becomes zero, and H_{cJ} is reached. From equation (3), we see that θ_i in the isotropic magnet ($P(\theta) = 1$) is 45° . For an aligned magnet with $P(\theta)$, θ_i is smaller than 45° ($\theta_i < 45^\circ$).

In Eq. (3), H_{cJ} is defined as the de-magnetization field at $J = 0$. The first term in Eq. (3) shows the magnetization state and the second term shows the magnetization reversed state by $1/\cos \theta$.

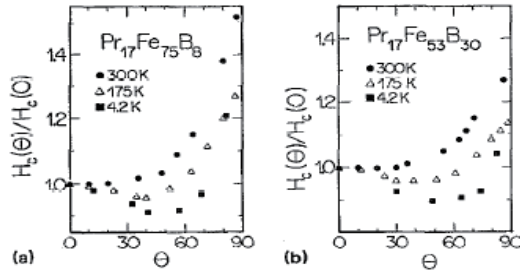
In Eq. (3), J is the magnetization, and H_{cJ} is defined as $J = 0$, where the first term in Eq. (3) denotes the magnetized state and the second term represents the demagnetized region. θ_i is defined as the angle of the magnetization reversed area, where $J = 0$.

β is derived from equation (4) using θ_i .

The broken line in Figure 2 shows calculation results from Eqs. (2-4). In figure 2, the calculated ALDC shows a significant deviation from measurements.⁽⁹⁾ This suggested that every particle in the magnets were not independently reversed by magnetic domain wall motion, but instead formed a cluster of magnetization-reversed particles at H_{cJ} .

3.3 Temperature dependence of ALDC and ANDC of Nd-Fe-B and Pr-Fe-B sintered magnets

Discussions of the coercivity mechanism are used for the ANDC at room temperature. The ALDC does not use the coercivity mechanism. The temperature dependence of the ANDC of PrFeB sintered magnets at low temperatures was reported by Elvas et al.⁽²³⁾ There are no reports of the ALDC and the ANDC of Nd-Fe-B sintered and ferrite magnets at the temperature above room temperature. This section



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Fig. 4. Angular dependence of H_{cJ} of Pr-Fe-B sintered magnets at several temperatures by Elvaz et al. ⁽²³⁾, (a) $\text{Pr}_{17}\text{Fe}_{75}\text{B}_8$, (b) $\text{Pr}_{17}\text{Fe}_{53}\text{B}_{30}$

discusses the temperature dependence of the ALDC and ANDC and their relations.

The temperature dependences of ALDC and ANDC were investigated, as shown in Figure 3(a,b) for Nd-Fe-B sintered magnets. The broken line in Fig. 3(a) shows the ALDC obtained from Eqs. (2-4). ⁽¹¹⁾ With increasing temperature, the ALDC approached the dashed line, which was calculated assuming that all particles had magnetization reversed independently via magnetic domain wall motion. Similarly, the ANDC approached $1/\cos\theta$, as shown in Fig. 3(b). The changes in the ALDC and ANDC temperature dependences appeared correlated. This suggested that the cluster sizes at H_{cJ} decreased with increasing temperature. The ALDC and the ANDC correlation for various temperatures was also reported for ferrite magnets. ⁽¹²⁾

Elvas et al. reported the ANDC for Pr-Fe-B sintered magnets at below room temperature, as shown in Figure 4. ⁽²³⁾ The room temperature results were similar to those of Nd-Fe-B sintered magnets. At 175 K and 4.3 K, it decreased from 0° and increased at angles above 50° , consistent with coherent rotation of magnetization. However, they did not discuss the H_{cJ} mechanism. The ANDC of Pr-Fe-B magnets at low temperatures was studied because, unlike the Nd-Fe-B magnet, they did not undergo spin re-orientation. ⁽²⁴⁾ The ALDC and the ANDC temperature dependences for Nd-Fe-B sintered magnets indicated that the H_{cJ} was determined by magnetic domain wall motion, and the cluster sizes at H_{cJ} decreased with increasing temperature.

3.4 Relationship between ALDCs and ANDCs in Nd-Fe-B sintered and ferrite magnets The temperature dependences of ALDC and ANDC for Nd-Fe-B sintered magnets indicated a correlation and cluster sizes at the H_{cJ} decreased with increasing temperature. ⁽¹¹⁾ In this section, ALDC and ANDC for Nd-Fe-B sintered and ferrite magnets having different compositions were studied to further investigate the correlation. And the experiment of ANDC and the calculated ANDC from θ_I , which is obtained from the ALDC with various compositions, are compared.

Figure 5(a,b) showed that the ALDC and the ANDC differed according to composition, but were clearly correlated. ⁽¹³⁾⁻⁽¹⁵⁾ In the ALDC, the H_{cJ} change ratio from isotropic magnets was smaller in the order of Nd-Fe-Co-B, Nd-Dy-Fe-Co-B, ferrite, and Ga-doped Nd-Fe-B. The change in the ANDC also was smaller in this order, especially for ferrite magnets, and the ANDC of Ga-doped Nd-Fe-

B sintered and ferrite magnets decreased from 0° and then increases from approximately 50° . These ANDCs appeared to exhibit coherent magnetization rotation. However, in the ALDC, H_{cJ} s decreased relative to those for the isotropic magnets. Thus, H_{cJ} was also determined by magnetic domain wall motion. As with the ALDC and ANDC temperature dependences in Sections 3.3, the cluster size increased from Nd-Fe-Co-B to Ga-doped Nd-Fe-B. To use this ALDC to obtain θ_{Ims} aligned magnets, Eq. (4) was transformed as follows:

$$\theta_{1ms} = \frac{1}{\sqrt{2}(\frac{\beta_{ms}}{100} - 1)} \quad (5)$$

The experimental β_{ms} was input into Eq. (5) to obtain the magnetization reversed area (θ_{Ims}). A comparison of θ_{Ims} with θ_I in Eq. (3) is shown in Figure 6.

In Fig. 6, the θ_{Ims} obtained from the measured β_{ms} was larger than the θ_I value obtained by assuming that all particles were independently reversed by magnetic domain wall motion ($1/\cos\theta$). The figure shows that θ_I and θ_{Ims} were 45° for isotropic magnets,

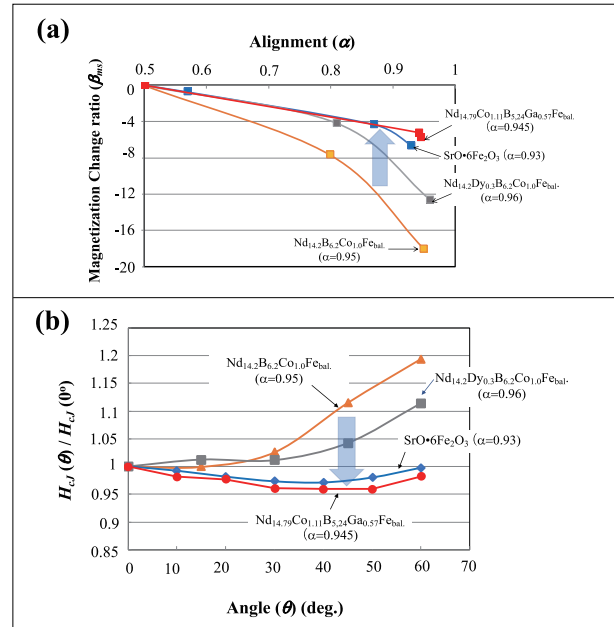


Fig. 5. The relation of ALDC and ANDC of various magnets. (a) ALDC and (b) ANDC of various Nd-Fe-B sintered magnets and ferrite magnets

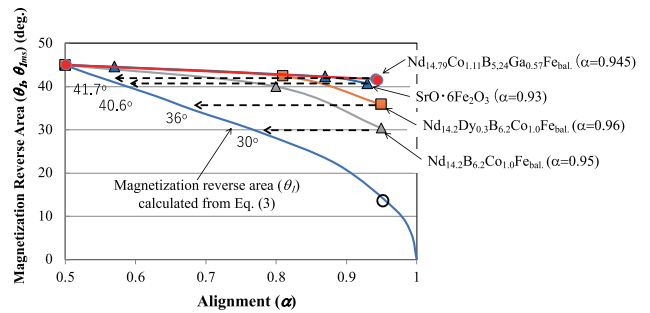
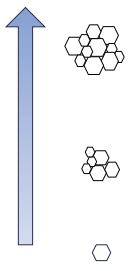


Fig. 6. θ_{Ims} for various magnets calculated from Eq. (5), and θ_I calculated from Eqs. (3,4).

Table 2. Composition and θ_l for Aligned Magnets

	Magnetization Reverse Area (θ_h, θ_{lm})	
(Ultimate Magnet)	(45°)	
Nd _{14.79} Ga _{0.57} B _{5.24} Co _{1.11} Fe _{bal.} ($\alpha = 0.945$)	41.7°	
SrO•6Fe ₂ O ₃ ($\alpha = 0.93$)	40.6°	
Nd _{14.2} Dy _{0.3} B _{6.2} Co _{1.0} Fe _{bal.} ($\alpha = 0.96$)	36°	
Nd _{14.79} Ga _{0.57} B _{5.24} Co _{1.11} Fe _{bal.} ($\alpha = 0.95$)	30°	
Calculation using Eq. (3) ($\alpha = 0.95$)	14°	

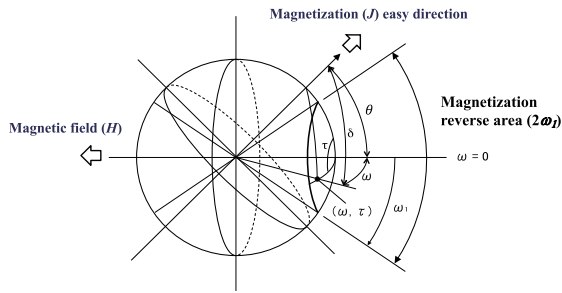


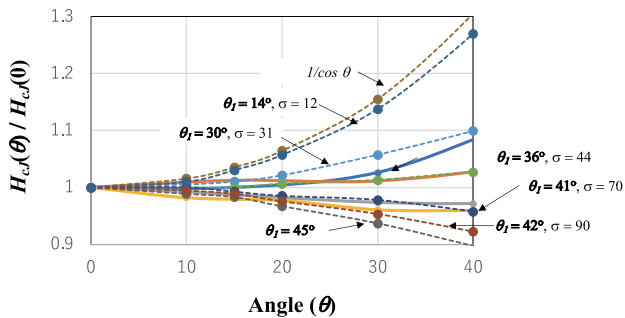
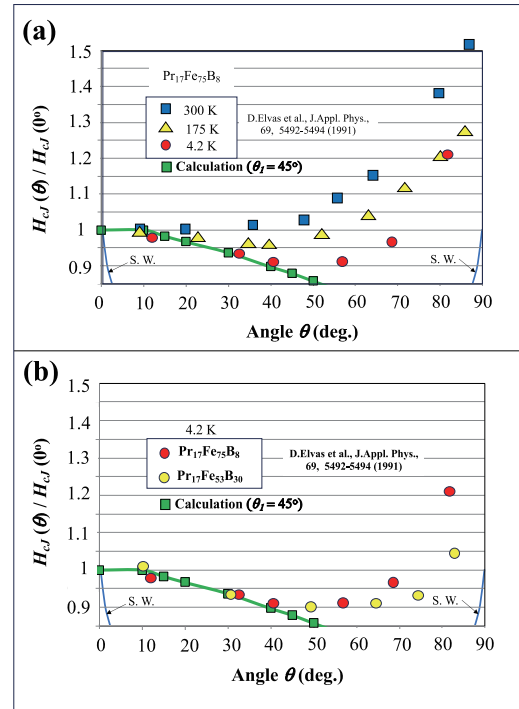
Fig. 7. Spherical trigonometry using for the calculation of ANDC

regardless of composition.

Table 2 shows θ_{lms} of the aligned magnets and the calculated θ_l . The measured θ_{lms} of the highly aligned magnets was related to cluster size, indicating that the size increased with θ_{lms} , as shown in Table 2. If H_{cJ} was also determined by magnetic domain wall motion, then the ultimate value of θ_{lms} for highly aligned magnets would be estimated to be 45°, and the H_{cJ} of the aligned magnet should be the same as isotropy magnets.

Using the low alignment with θ_l with respect to matching θ_{lms} obtained from Fig. 6, the ANDC was calculated from the following equation using spherical trigonometry shown in Fig. 7: ⁽¹³⁾

$$\frac{1}{8\pi} \int_{\omega_1}^{\pi} \int_0^{2\pi} Q(\omega, \tau) \sin 2\omega \, d\tau d\omega - \frac{1}{8\pi} \int_0^{\omega_1} \int_0^{2\pi} Q(\omega, \tau) \sin 2\omega$$

Fig. 8. Angular dependence of H_{cJ} (ANDC) of various magnets and the calculated ANDC using Eqs. (6,7).Fig. 9. Temperature dependence of ANDC for Pr-Fe-B sintered magnets. ⁽²³⁾ (a) Pr₁₇Fe₇₅B₈ at several temperature, (b) Pr₁₇Fe₇₅B₈ and Pr₁₇Fe₅₃B₃₀ at 4.2K and the calculated ANDC with $\theta_l = 45^\circ$ using Eqs. (6,7)

$$d\tau d\omega = 0 \quad (6)$$

$Q(\omega, \tau)$ is the alignment distribution, which has the Gaussian distribution, and ω_l is the angle of the reversed magnetization area, which was similar to θ_l in Eq. (3).

The ANDC was determined using Eq. (7):

$$\frac{H_{cJ}(\theta \geq 0)}{H_{cJ}(\theta = 0)} = \frac{\cos \omega_1(\theta = 0)}{\cos \omega_1(\theta \geq 0)} \quad (7)$$

θ is the angle between the magnetic field and the magnetization.

In Figure 8, the ANDC calculated from Eq. (7) was used θ_{lms} of the ALDC in Fig. 6. In measurements of the ALDC, the magnetic field and magnetization were parallel. Therefore, it was considered

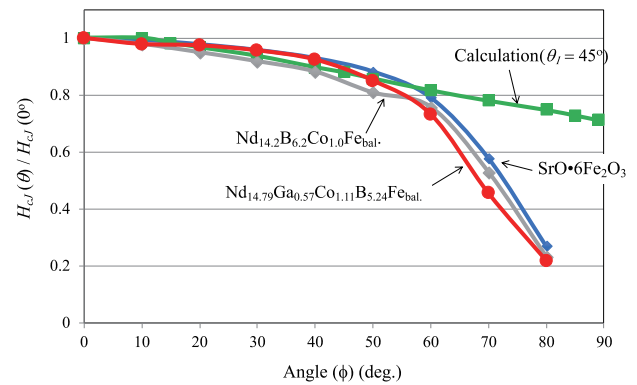


Fig. 10. ANDC of isotropy magnets of Nd-Fe-B sintered magnets and ferrite magnets with various composition.

to give correct information on the ANDC in the low angle area around 0° . σ in Fig. 8 represents the standard deviation of the orientation distribution ($Q(\tau, \omega)$) in Eq. (6).

The calculated ANDC at low angles reproduced the tendency of the measured ANDC. In particular, when it was postulated that ferrite magnets and Ga-doped Nd-Fe-B sintered magnets with large θ_l behaved like low-aligned magnets by forming larger clusters, it was strongly assumed that H_{cJ} was determined by magnetic domain wall motion, even if the ANDC of these magnets decreased from 0° .

It was thus of interest whether the ANDC at low temperatures, especially 4.2 K, for Pr-Fe-B magnets reported by Elvas et al., behaved more like coherent rotation of magnetization⁽²³⁾ than the angular dependence expected at $\theta_l = 45^\circ$, which was the upper limit of magnetic domain wall motion.

Figure 9(a) shows the temperature dependence of the $\text{Pr}_{17}\text{Fe}_{75}\text{B}_8$ ANDC, and Fig. 9(b) shows the ANDC at 4.2 K for $\text{Pr}_{17}\text{Fe}_{75}\text{B}_8$ and $\text{Pr}_{17}\text{Fe}_{53}\text{B}_{30}$ reported by Elvas et al.⁽²³⁾ These were compared with that at $\theta_l = 45^\circ$ calculated from Eq. (7) and with Stoner-Wohlfarth shown by the blue line. In Fig. 9(a), $\text{Pr}_{17}\text{Fe}_{75}\text{B}_8$ exhibited an ANDC similar to that of Nd-Fe-B sintered magnets at room temperature. However, at 175 K and 4.2 K, H_{cJ} decreased from 0° and exhibited a behavior similar to that of coherent rotation of magnetization. However, the ANDC at 4.2 K varied in line with the calculated ANDC with $\theta_l = 45^\circ$ up to 40° . Figure 9(b) shows the ANDC for $\text{Pr}_{17}\text{Fe}_{75}\text{B}_8$ and $\text{Pr}_{17}\text{Fe}_{53}\text{B}_{30}$ at 4.2 K that follow the calculated ANDC with $\theta_l = 45^\circ$ until 40° . Compared with the ANDC of the Stoner Wohlfarth model shown in Fig. 9(a, b), the ANDC of Pr-Fe-B sintered magnets at 4.2 K was close to the ANDC of $\theta_l = 45^\circ$ and did not go lower than this line. This indicated that even for Pr-Fe-B sintered magnets with nearly 9T of H_{cJ} at 4.2 K, magnetic domain wall motion still determined the H_{cJ} .

Similarly, for isotropic magnets, $\theta_l = \theta_{ms} = 45^\circ$ was expected. Figure 10 shows the ANDC of isotropic Nd-Fe-B sintered magnets, ferrite magnets, Ga doped Nd-Fe-B sintered magnets, and the calculated ANDC with $\theta_l = 45^\circ$.^{(14), (15), (25)} The coercive force angle dependence of isotropic magnets agreed with the calculations up to around 60° .

These accumulated facts and considerations strongly supported the presence of clusters of magnetization-reversed grains at the H_{cJ} in highly aligned magnets.

3.5 Recoil Curve Properties Until now, the conventional theory considered that the magnetization of $\text{Nd}_2\text{Fe}_{14}\text{B}$

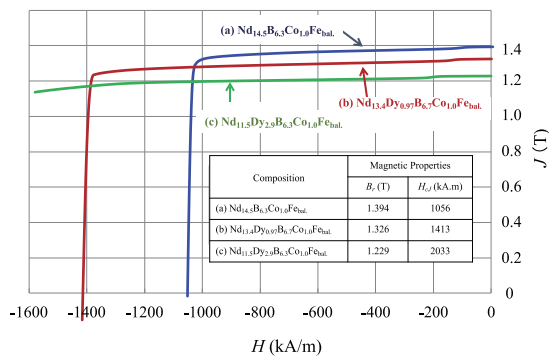


Fig. 11. Demagnetization curves of Nd-(Dy)-Fe-B sintered magnets measured with recoil properties

grains in sintered magnets was simultaneously reversed by coherent rotation of magnetization, or magnetic domain wall motion, when the nucleation near H_{cJ} generated magnetization reversal. The reversal in the demagnetizing field region lower than H_{cJ} had not been considered.^{(3), (4), (23)} This image of the demagnetization process comes from the excellent rectangularity of demagnetization curves in Nd-Fe-B sintered and ferrite magnets. Therefore, the following questions are generated. If H_{cJ} was determined by magnetic domain wall motion, where are the magnetic domain walls? Where in the demagnetization field does the magnetic wall or magnetization reversal occur? Does demagnetization not occur until the vicinity of H_{cJ} ? The magnetic domain wall may not exist in magnets until the vicinity of H_{cJ} , according to the precise rectangularity of the demagnetization curve in Nd-Fe-B sintered and ferrite magnets. It is essential to investigate whether there is demagnetization in magnetic fields lower than the coercive force to study the demagnetization process of Nd-Fe-B sintered magnets, which can be quickly confirmed by examining the recoil properties as a method.

Figure 11 shows the demagnetization curves of Nd-(Dy)-Fe-B sintered magnets with different H_{cJ} measured with the D. C. recording flux-meter (BH Tracer).⁽⁹⁾ They exhibit excellent rectangularity despite bending in the demagnetization curves caused by the mirror-image effect at demagnetization fields above 1200 kA/m.

Figure 12 indicated that the recoil curves of various Nd-(Dy)-Fe-B sintered magnets in the magnetic field region were lower than H_{cJ} . Slight demagnetization continuously occurred in the demagnetization field region lower than H_{cJ} for all the magnets having different grades of H_{cJ} . This demagnetization in the recoil curves was different from that occurring on the magnet surface.

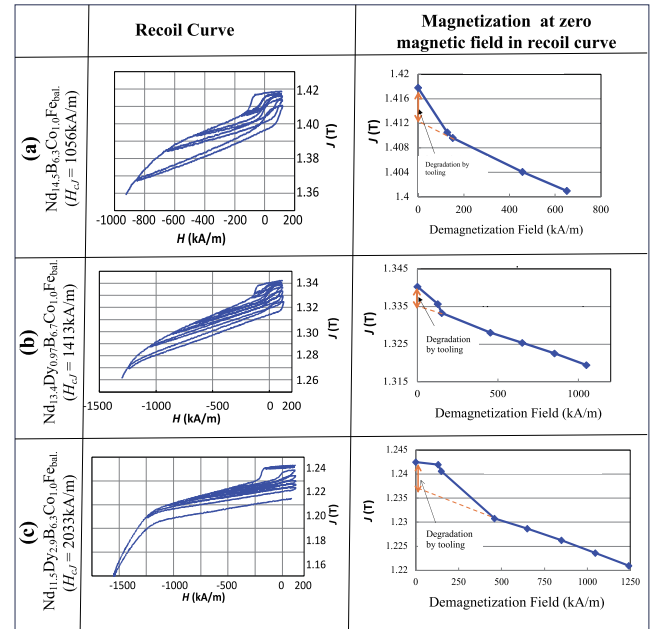


Fig. 12. Recoil curve and magnetization at zero magnetic fields after various demagnetization fields added to (a) $\text{Nd}_{14.5}\text{B}_{6.3}\text{Co}_{1.0}\text{Fe}_{\text{Bal}}$, (b) $\text{Nd}_{13.4}\text{Dy}_{0.97}\text{B}_{6.7}\text{Co}_{1.0}\text{Fe}_{\text{Bal}}$, and (c) $\text{Nd}_{11.5}\text{Dy}_{2.5}\text{Co}_{1.0}\text{Fe}_{\text{Bal}}$.

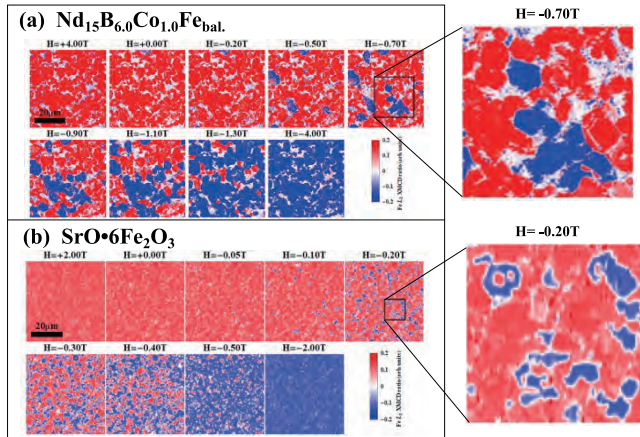


Fig. 13. X-ray magnetic circular dichroism image of (a) $\text{Nd}_{15}\text{B}_{6.0}\text{Co}_{1.0}\text{Fe}_{\text{bal.}}$ sintered magnet and (b) $\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$ in various magnetic fields. Enlarged images are -0.7T for the Nd-Fe-B sintered magnet and -0.2T for the ferrite magnet.

This was from degradation by surface tooling, cutting, or grinding, and was expected to occur throughout the entire magnet.⁽⁹⁾

Observations of demagnetization of Nd-Fe-B sintered magnets via XMCD revealed that it occurred initially in discrete grains in the weak demagnetization field region, which may have corresponded to demagnetization seen in the recoil curves.⁽¹⁶⁾

3.6 Observation of demagnetization of Nd-Fe-B sintered magnets and Ferrite magnets with XMCD

The demagnetization of Nd-Fe-B sintered magnets and ferrite magnets have been investigated with magnetic measurements. Small demagnetizations occurred continuously in magnetic fields lower than H_{cJ} . It was possible that clusters were formed at H_{cJ} and that their sizes varied with composition and measurement temperature.

It was crucial to visually verify the results obtained from magnetic

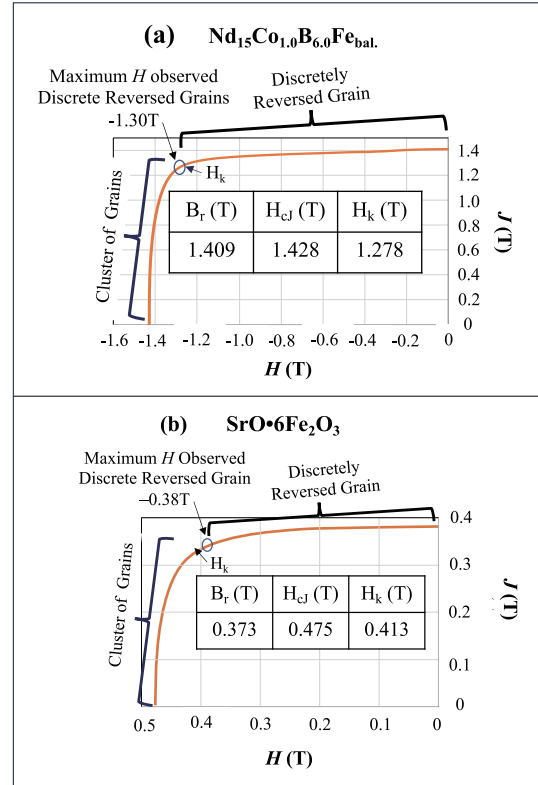
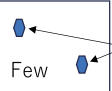
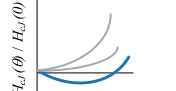


Fig. 14. Demagnetization curves of a Nd-Fe-B sintered magnet and a ferrite magnet. The maximum magnetic field observed in discrete reverse grains was that after demagnetization field correction.⁽²⁶⁾

measurements. It was then possible to create a consistent picture of the demagnetization process by examining them together with visual data.

XMCD was used to observe demagnetization of Nd-Fe-B sintered

Table 3. Summary of demagnetization process of Nd-Fe-B sintered and ferrite magnets.

Temperature	Low → High				
Composition	$(\text{Pr}_{17}\text{Fe}_{75}\text{B}_8)$ $(\text{Pr}_{17}\text{Fe}_{53}\text{B}_{30})$ at 4.2K	$\text{Nd}_{14.79}\text{Ga}_{0.57}\text{B}_{5.24}\text{Co}_{1.11}\text{Fe}_{\text{bal.}}$ at R.T.	$\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$ at R.T.	$\text{Nd}_{14.2}\text{Dy}_{0.3}\text{B}_{6.2}\text{Co}_{1.0}\text{Fe}_{\text{bal.}}$ at R.T.	$\text{Nd}_{14.2}\text{B}_{6.2}\text{Co}_{1.0}\text{Fe}_{\text{bal.}}$ at R.T.
Magnetization Reverse Area (θ_{ms})	($\sim 45^\circ$)	41.7°	40.6°	36°	30°
Cluster size of reversed grains at H_{cJ}	Large → Small				
Number of discretely reverse grains before cluster formation)	Few 				
Alignment dependence (β) of H_{cJ}					
Angular dependence of H_{cJ} ($H_{cJ}(\theta) / H_{cJ}(0)$)					

and ferrite magnets.⁽¹⁶⁾ Figure 13(a, b) shows demagnetization of Nd₁₅Co_{1.0}B_{6.0}Fe_{bal.} and SrO6Fe₂O₃ observed via XMCD. Discrete magnetization reversals of the crystal grains initially occurred in the demagnetization field region lower than H_{cJ} in Nd-Fe-B sintered and ferrite magnets.⁽¹⁶⁾ Subsequently, magnetization reversal of the crystals around discrete grains occurred at -0.7 T for Nd-Fe-B sintered magnets and at -0.20 T for ferrite magnets, indicating that clusters were generated. As the demagnetization field increased, the clusters grew and reached H_{cJ} .

When the average demagnetization curve of the XMCD was compared with that of the magnetic measurement, the squareness of the curve and H_{cJ} of XMCD were lower than that of the magnetic measurement. The reduced squareness of the demagnetization curve was caused by the self-demagnetization field at the surface and the low H_{cJ} derived from the magnetic after-effect during the XMCD measurement.⁽¹⁶⁾

The magnetic after-effect was proportional to the irreversible magnetic-susceptibility (χ_{irr}) in the demagnetization curve obtained from magnetic measurements.⁽²⁶⁾ When the various magnetic after-effects were corrected, after the maximum irreversible magnetic-susceptibility ($(\chi_{irr})_{max}$) and the demagnetization factors (N) were put into the demagnetization curve, the curve was consistent with the average demagnetization curve of the XMCD.⁽¹⁶⁾ Using the demagnetization field coefficients obtained from this result, reversed particles demagnetized and formed clusters, and the magnetic field was close to the H_k of the demagnetization curve.

Figure 14(a, b) shows the demagnetization curve for Nd-Fe-B sintered and ferrite magnets. The magnetic field area observed in the discrete reversed grains, as well as cluster formation and growth, are shown.

When these factors were corrected, the average demagnetization curve agreed with that of the magnetic measurement corrected for the demagnetization field. Thus, the XMCD measurement was expected to reflect information within the magnet.

4. Conclusion

The ALDC and ANDC results of Nd-Fe-B sintered and ferrite magnets, magnetic measurements of recoil curve properties, and XMCD observations are summarized in Table 3. Magnetization reversal in highly aligned Nd-Fe-B sintered and ferrite magnets with approximately $\alpha = 0.93\sim 0.96$ was characterized by discrete magnetization reversals of crystal grains in the demagnetization field region below H_{cJ} . This was followed by clustering of reversed particles near H_k , at which B_r reached $0.9B_r$. The clusters grew as the demagnetization field increased and approached H_{cJ} . The clusters sizes at H_{cJ} varied with temperature, increasing at lower temperatures. The size at room temperature also varied with composition, increasing in the order of Nd-Fe-B, (Nd, Dy)-Fe-B, SrO · 6Fe₂O₃, and Ga-doped Nd-Fe-B. That for Pr-Fe-B was measured at 4.2K. As shown in Table 3, the ALDC and the ANDC varied with cluster size. The size was likely determined by the number per unit volume of discretely reversed particles created in the demagnetization field region below H_{cJ} .

Recently, it was reported that the grain boundary phase exists in ferrite magnets.⁽²⁷⁾ The main phase grains of ferrite magnets are magnetically separated by the grain boundary phase, similar to the Nd-Fe-B sintered magnets. A similar discussion as the

demagnetization process in Nd-Fe-B sintered magnets seems valid in ferrite magnets.

Acknowledgments

This work was supported by the Japan Science and Technology Agency (JST), in part by the Collaborative Research based on Industrial Demand under Grant No. JPMJSK 1617, and in part by the Japan Society for the Promotion of Sciences (JSPS) Grant-Aid for Scientific Research (KAKENHI) under Grant No. 17K06781. The synchrotron radiation experiments were performed at the BL25SU of SPring-8 with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) (Proposal No. 2017A1008, 2018A1010, and 2019B1153). The XMCD mapping technique used in this work was developed by the Elements Strategy Initiative Center for Magnetic Materials (ESICMM) project with Grant No. JPMXP0112101004 through the Ministry of Education, Culture, Sports, Science, and Technology (MEXT).

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Yutaka Matsuura (member) was born in Shimane, Japan, on September 14, 1952. He graduated with a master's degree in physics at Okayama University in 1977 and received a Doctor of Engineering from Kyoto University in 1987. He worked in R&D of permanent magnet materials in Ex-Sumitomo Special and Ex Hitachi Metals. Currently, he works at the Research Institute for Applied Sciences.



K Osamura and S Machiya, “BENDING STRAIN DEPENDENCE of CRITICAL CURRENT in BSCCO and REBCO TAPES”, IEEE Transactions on Applied Superconductivity vol 35 (2025) pages:1-11

Abstract

Applying BSCCO and REBCO tapes to various engineering purposes, three modes of tensile and edgewise- and flatwise- bending are essential to deform the tape in pancake and spiral windings as well as twisting. Both kinds of tape consist of brittle superconducting (SC) oxide and several metallic components. Fine SC filaments are embedded in Ag matrix in BSCCO tape while single SC layer is put on the well oriented metallic sheet in REBCO one. These texture difference influences clearly on the bending dependence of critical current (I_c). The I_c of BSCCO tape decreased up to 95% of I_{c0}/I_{c00} when the tape is bent to ~ 53 mm diameter by flatwise bending and 1325 $\sim$ 1682 mm by edgewise one. The equivalent flatwise bending strain was 0.29~0.39% when the critical current degradation starts, while the critical edgewise strain was 0.29 $\sim$ 0.31%. In the case of REBCO tape, the I_c did not decrease up to 10 mm flatwise bending while it decreased by 405 mm edgewise bending. The degradation was observed to start from 1.04% edgewise bending strain while the flatwise bending did not give degradation up to 0.92%. The fracture behavior induced in BSCCO and REBCO tapes was discussed. The degradation starts from fracture of BSCCO filaments, while it originates to a delamination between the oxide and the metal interface in REBCO tape.

S Shin, M A Diaz, K Osamura, Y Zhao, Y Zhang, I Falorio, N Bagrets and X Zhang, “International round-robin test for electromechanical properties of HTS wires under uniaxial tension at liquid nitrogen temperature”, Supercond. Sci. Technol. 38 (2025) 065001

Abstract

As superconducting wires have become more prevalent, it has become increasingly important to establish reliable and standardized methods for evaluating their electromechanical properties (EMPs) at cryogenic temperatures. An international round-robin test (RRT) was conducted to assess the EMPs of four commercially available high-temperature superconducting (HTS) tapes as an activity to establish a standard for the EMP test method. Six laboratories participated in the RRT, adhering to the guidelines. During tensile testing of the HTS wires at 77 K, critical current (I_c) measurements were performed using a stress-based test method. This method streamlined the testing procedure by changing stress intervals from broad to narrow as the applied stress approached the I_c degradation point while eliminating the need for dedicated extensometers. The EMPs of the reversible stress limit (R_{rev}) and retention stress limit (R_{ret}) for I_c degradation were defined based on specific criteria for 99% I_{c0} recovery and 95% I_{c0} retention. Once the RRT participants reported their test results, statistical analysis tools such as ANOVA were employed to identify sources of variation and assess their magnitude in the results. The primary source of the relative standard uncertainty was the effect of inter-laboratory scattering. The RRT results are utilized to develop an international standard for evaluating EMPs of HTS wires through I_c measurements under uniaxial tension at liquid nitrogen temperature. These RRT analysis results offer valuable insights into potential sources and magnitudes of measurement uncertainties, ultimately contributing to standardized test procedures for accurate and reliable EMP characterization of HTS wires.

EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive

Hajime Takayama^{1*}, Kazuki Matsumoto¹, Shiu Mochiyama², Shuhei Fukunaga³,
Michihiro Shintani¹, Takashi hikihara²

¹ Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan

² Department of Electrical Engineering, Kyoto University, Kyoto, Japan

³ Graduate School of Engineering, The University of Osaka, Suita, Japan

*hajime-takayama@kit.ac.jp

Abstract—The application of silicon carbide (SiC) power devices in switched reluctance motor (SRM) drives enhances their operation speed and power density at the cost of increased electromagnetic interference (EMI) and device stress. This work implements a digitally controlled active gate driver (AGD) to mitigate these undesired byproducts while maintaining the benefits of SiC devices. An internally developed AGD is integrated into a hysteresis-controlled asymmetric H-bridge drive for SRM. The experimental results confirm the effectiveness of AGD in suppressing high-frequency ringings caused by switching operations by precisely controlling the switching transients of the power devices. Furthermore, the measurement of the conducted emission confirms the reduction of conducted noise spectra at 10-50 MHz frequency band, validating the applicability of AGD as a promising approach to mitigate EMI for high-density SiC-based SRM drives.

Index Terms—Switched reluctance motor, active gate drive, electromagnetic interference, SiC MOSFET, conducted emission

I. INTRODUCTION

Switched reluctance motors (SRMs) have gained increased attention for multiple industrial and commercial applications in recent years. Their simple, efficient, and rare-earth-free configurations offer practical advantages compared to the conventional induction and synchronous motors [1]–[3]. The recent development of silicon carbide (SiC) power devices further enhances its advantage by increasing operation frequency and power density, which are particularly favorable for demanding applications such as electric vehicles (EVs) [4].

Despite the above benefits, adopting SiC devices poses several challenges for the motor drive system [4]. One of the significant issues is the electromagnetic interference (EMI), which is primarily caused by the switching operation in the power converter for motor drives. To protect control, communication, and other peripheral circuitry from malfunction, several standards provide limits on allowable conducted emissions, such as those defined in CISPR 25 [5]. In particular, emissions in the 2–30 MHz frequency band play a major role in common-mode noise, affecting the reliability of the system [6]. The increased switching speed of SiC devices, combined with their reduced output capacitance, contributes to large overshoots and ringing at elevated frequencies, making it even more challenging to meet EMI regulations. The increased

number of integrated sensors in EV systems makes EMI issues an even more critical concern.

The EMI issue can be addressed by two circuitual approaches: applying noise filters and/or reducing the noise source itself [4]. EMI filters are regarded as crucial components in the EV traction system. However, the attenuation performance can be severely degraded at a frequency range of 10 MHz or higher due to the resonance of circuit parasitics and filtering components, making it challenging to meet the EMI regulations [7]. The use of additional filters may reduce emissions, but it suffers from the increased size and loss of the overall system. Therefore, removing or reducing the noise source is a preferable approach to leveraging the potential of SiC devices to achieve high power density [6].

The use of large gate resistors is a common practice for reducing the switching speed of power devices and the resulting ringings, thus attenuating the noise emission. However, this approach severely degrades the excellent characteristics of SiC devices. Recently, the technique called active gate driver (AGD) has attracted considerable attention as a measure to improve the switching characteristics of power devices, particularly for fast-switching SiC devices [8], [9]. AGDs dynamically control the switching transient of power devices by precisely adjusting the gate-voltage waveform, resulting in reduced ringing without sacrificing their fast-switching performance. Adaptive or programmable AGDs have also been proposed to achieve optimal operation under varying operating conditions, which is particularly beneficial for motor drive applications [10]–[12]. By reducing the EMI source flexibly, AGD could ease the requirement for bulky and lossy filtering components of motors, thereby contributing to the miniaturization of the system [13].

This work investigates the applicability of AGD in SiC-based SRM drives. To the best of the authors' knowledge, no report has applied AGD to SRM drives. The square-wave excitation current of the SRM drive is found to be suitable for implementing load-adaptive control of AGD. An internally developed digital AGD is incorporated into a three-phase SRM drive circuit, where the effectiveness of AGD in suppressing EMI is experimentally analyzed in both time-domain and frequency-domain.

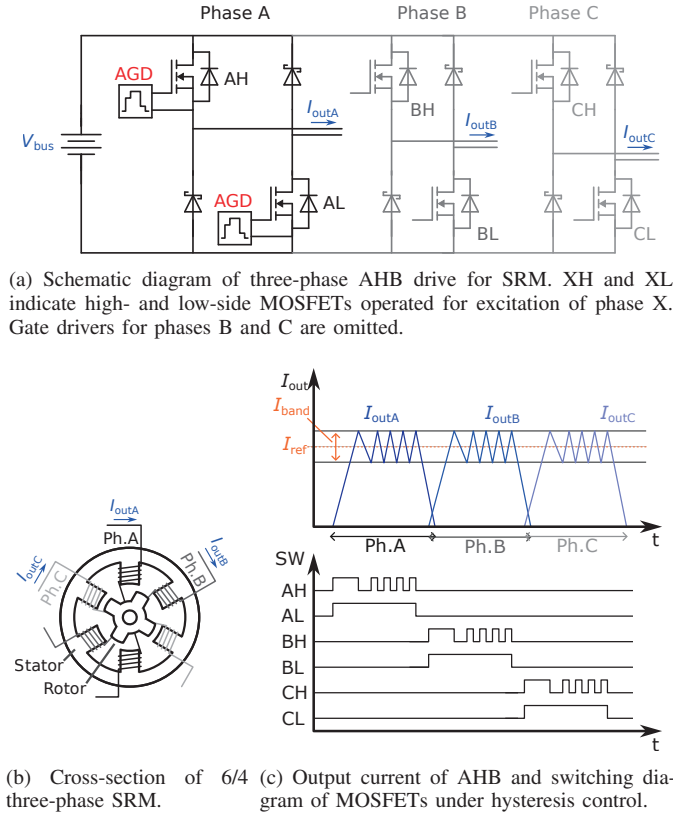


Fig. 1. System overview of AHB SRM drive.

II. DRIVE CIRCUIT FOR SRM

A driver for a three-phase 6/4 SRM [3] is developed, integrating control algorithms and AGD hardware. Brief descriptions of the driver circuit and control algorithm are given in this section.

A. Asymmetric H-bridge Circuit

SRMs require a constant current throughout each phase for the excitation of their stator coils. This work adopts the asymmetric H-bridge (AHB) topology, which is one of the simplest and fundamental configurations of SRM drives [1], [2]. Fig. 1(a) shows the schematic of the three-phase AHB circuit, where each phase deploys two SiC MOSFETs and two SiC SBDs. Switching of these MOSFETs generates three patterns of the output current (I_{out}), namely the magnetization, demagnetization, and freewheeling. The three-phase excitation currents are supplied to the SRM as shown in Fig. 1(b), which energize the stator coils sequentially to generate a rotating magnetic field that pulls the rotor.

B. Hysteresis Control

The three-phase output current of the AHB drive is controlled by hysteresis control [2]. The representative current waveforms and corresponding switching patterns of MOSFETs are shown in Fig. 1(c), where the reference current and the hysteresis band are denoted by I_{ref} and I_{band} , respectively. At the beginning of a phase, both the high-side and low-side

MOSFETs are turned on, injecting output current I_{out} from the DC power supply into the windings. Once I_{out} reaches $I_{ref} + I_{band}/2$, the high-side MOSFET is switched off and I_{out} freewheels through the low-side SBD and the low-side MOSFET. The high-side MOSFET is turned on again when I_{out} reaches $I_{ref} - I_{band}/2$. With this hysteresis control, I_{out} is maintained at the reference current value within the range of I_{band} . At the end of the phase, both high- and low-side MOSFETs are turned off. The same sequence is repeated for the other two phases, generating a three-phase excitation current.

III. ACTIVE GATE DRIVER

An AGD is introduced to mitigate unwanted overshoot and ringing during the switching transients of SiC MOSFETs. By employing a digitally controlled multi-level topology, this AGD enables precise shaping of the gate-voltage profile alongside online programmability, which is beneficial for motor drive applications.

A. Schematic Configuration and Operation

Fig. 2 details the developed three-voltage-level (3-L) AGD [14]. It employs the modular multi-level topology [15]–[17], which primarily consists of a series connection of three submodules with bootstrap power supplies. With this configuration, the gate-source voltage V_{gs} is generated as the sum of the outputs of submodules as formulated in (1).

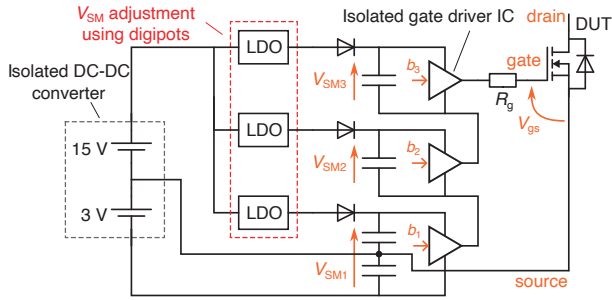
$$V_{gs}(t) = b_1(t) \cdot V_{SM1} + b_2(t) \cdot V_{SM2} + b_3(t) \cdot V_{SM3} \quad (1)$$

Here, $b_i \in \{0, 1\}$ denotes the i -th bit gate signal required for its operation. By having delays among the three gate signals, the AGD generates a step-wise V_{gs} waveform as illustrated in Fig. 2(b). It is noted that if we toggle all three gate signals simultaneously, we obtain a standard two-level gate-driving waveform (without AGD).

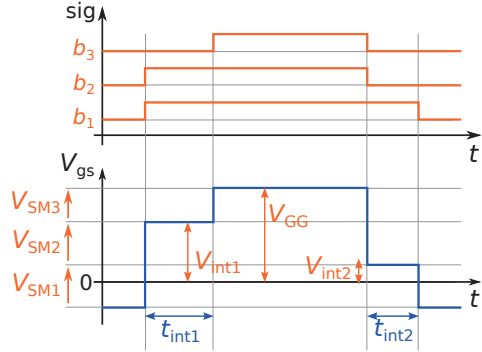
A single isolated DC-DC converter is employed to power the AGD board. Each of the three submodule voltages V_{SMi} is supplied by the DC-DC converter through a low-dropout (LDO) regulator. A digital potentiometer (digipot) is adopted as the variable resistor in the feedback voltage divider of the LDO, enabling digital adjustment of V_{SMi} .

The operation of this 3-L AGD is determined by the three voltage levels (V_{GG} , V_{int1} , V_{int2}) and the signal delay at each switching transition (t_{int1} , t_{int2}). These parameters are easily accessible using standard DSPs or FPGA-based controllers by interacting with digipot ICs through serial communication and adjusting the delays among the three gate signals, providing online programmability of the AGD.

The photograph of the fabricated 3-L AGD board is shown in Fig. 3. Utilized components are listed in Table I. Commercial isolated gate driver ICs are utilized as submodules to achieve their floating operation. The minimum value of V_{SMi} is imposed by the under-voltage lockout threshold of the IC, which is around 4 V. A digital signal isolator IC is used to transfer serial communication signals to the IC. The external gate resistor R_g is set at 1 Ω .



(a) Schematic diagram of 3-L digital AGD.



(b) Timing diagram of gate signals and generated V_{gs} waveform of 3-L AGD.

Fig. 2. Configuration and operation of 3-L AGD.

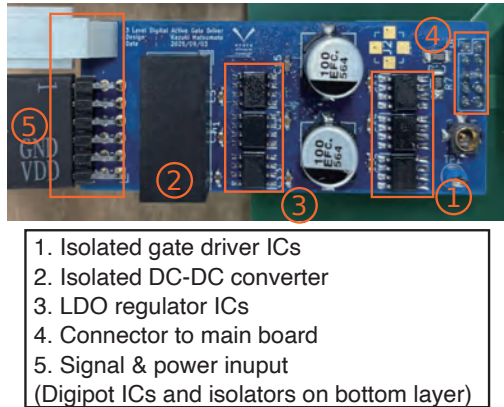


Fig. 3. Photograph of 3-L AGD fabricated on PCB.

TABLE I
LIST OF PRIMARY COMPONENTS USED IN AGD.

Component	Part number	Manufacturer
Isolated gate driver	1EDB7275FXUMA1	Infineon
Isolated DC-DC converter	MGJ2D051802SC	Murata
LDO regulator	LP2951DR	Texas Instruments
Digital potentiometer	AD5292BRUZ-50	Analog Devices
Digital signal isolator	Si8660BC-B-IS1	Skyworks

B. AGD Strategy in AHB SRM Drive

One of the practical challenges of AGD is load-adaptive operation, as the effective AGD patterns strongly depend on the load current [10], [11]. Inverter applications, for example, require a sinusoidal current waveform. To obtain maximum

performance from AGD, one needs to always feed back the instantaneous current value and select the appropriate AGD pattern from the lookup table at each switching event. This increases system complexity and the cost of sensing circuitry especially at high rotation speed, undermining the benefits of AGDs.

In this regard, conveniently, typical SRM drive circuits require a constant excitation current for each phase, which implies that the MOSFET is always turned on or off at a known, fixed current. Therefore, the AGD pattern does not need to be modified across the phase and only needs to be updated if I_{ref} is changed. The update can be performed when the other phases are excited, which is long enough (in the order of 10 ms) for the digipots to be programmed and for the submodule voltages to settle to a new value. This characteristic of the SRM drive circuit makes it easy to implement AGD as a countermeasure to the increased EMI caused by the fast switching of SiC MOSFETs.

IV. EXPERIMENTAL VERIFICATION

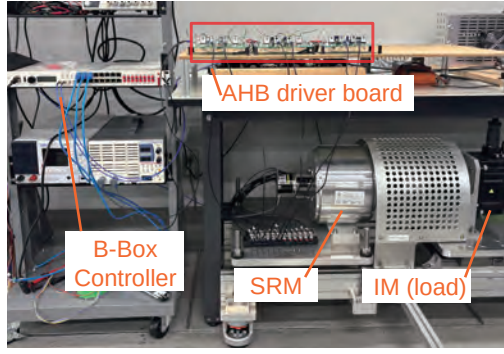
We developed an experimental setup to verify the applicability of AGD for the SRM drives. Particularly, its effect on the reduction of conducted emission is analyzed based on the time-domain switching waveforms and the frequency-domain noise measurement.

A. Experimental Setup

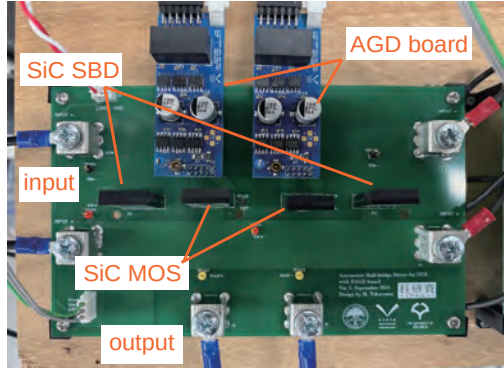
Fig. 4 shows the experimental setup. An internally developed SRM is placed at the bottom, with its shaft interconnecting to an induction motor (IM) that controls the load torque of the SRM. The three-phase AHB drive circuits are placed above the SRM. SiC MOSFETs (SCT2160KE, ROHM) and SiC Schottky barrier diodes (SBDs) (SCS220AE, ROHM) are selected as the power devices in the AHB circuit, in which each MOSFET is driven by an AGD. The hysteresis control is implemented in a DSP-FPGA integrated controller (B-BOX-RCP3.0, Imperix), which samples the output currents through current sensor ICs (T430-HSWF20DR, Allegro MicroSystems) and generates pulse-width modulation (PWM) signals, each of which contains three-bit gate signals for AGD operation. The controller also sets V_{SMi} of AGDs via serial peripheral interface (SPI) communication. The SRM is operated in a single condition. The target rotation speed is 200 rpm, while the load torque is set at 0.89 Nm and $V_{bus} = 200$ V is supplied, resulting in $I_{ref} = 5$ A.

B. Measurement Setup

The effectiveness of AGD is evaluated based on the time-domain switching waveforms and the frequency-domain spectra of conducted emissions. Since the three-phase legs operate symmetrically, it is satisfactory to focus on a single-phase operation for detailed measurement of the switching waveform and analysis. Fig. 5 shows the measurement points of voltages and currents in the phase-C drive circuit, where the subscripts H and L denote high- and low-side. The utilized oscilloscope and probes are listed in Table II. Gate voltages are measured



(a) System overview.



(b) AHB driver board (single phase).

Fig. 4. Photograph of experimental setup.

with optical isolation probes, while the other voltages are measured with high-voltage differential probes. The source currents of the two MOSFETs and the output current are measured using Hall-effect current probes.

For the frequency-domain analysis, we evaluate the conducted emission at the input terminals of the AHB circuit. Fig. 6 shows the measurement setup. The utilized instruments are also listed in Table II. The line impedance stabilization network (LISN) is placed between the power supply and the equipment under test (EUT), which is composed of the AHB circuit and SRM. The positive and negative nodes of the input terminals are referred to as Line A and Line B, respectively. The conducted emission signals from the two LISNs are routed through a measurement-mode switch before entering the spectrum analyzer. This configuration allows independent measurement of the raw signal on Line A and Line B, as well as the separated common-mode (CM) and differential-mode (DM) spectra.

C. Operation of AHB Drive Circuit Without AGD

Firstly, the AHB drive circuit is operated without AGD to verify its operation and to identify the EMI-related issues. Fig. 7 shows the measured waveforms of gate-source voltages (V_{gsH} , V_{gsL}), drain-source voltages (V_{dsH} , V_{dsL}), and source currents (I_{sH} , I_{sL}) of high- and low-side MOSFETs, as well as I_{out} and V_{bus} , during the excitation of phase C. It is confirmed I_{out} is successfully maintained near I_{ref} by the hysteresis control. On the other hand, the waveform of V_{bus} exhibits large

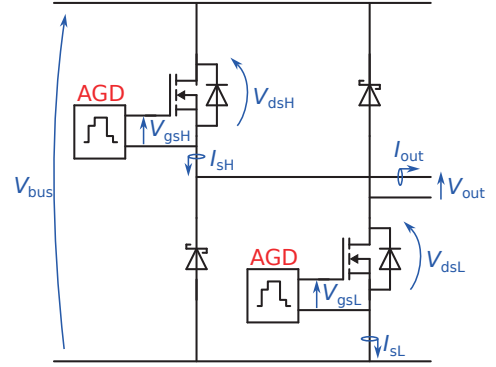


Fig. 5. Measurement points in phase-C AHB drive circuit.

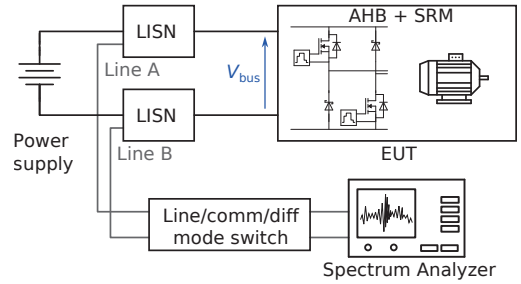


Fig. 6. Schematic diagram of conducted emission measurement.

TABLE II
LIST OF MEASUREMENT INSTRUMENTS UTILIZED IN EXPERIMENT.

Instrument	Part number	Manufacturer
Oscilloscope	MSO68B	Tektronix
Isolated voltage probe	TIVP1	Tektronix
Differential voltage probe	THDP0200	Tektronix
Current probe	TCP0030A	Tektronix
Spectrum analyzer	E4420B	Agilent
LISN	9117-5-PJ-50-N	Solar Electronics
Measurement mode switch	CMDM 8700 B	Schwarzbeck

overshoots and ringings at every switching event of the high-side MOSFET, which would lead to an elevated conducted noise.

D. Switching Waveforms under AGD

We applied several AGD patterns to mitigate the ringings. We performed preliminary tests to apply multiple AGD patterns to select two patterns, namely AGD mid. and AGD max., based on the noise-suppression capability.

Fig. 8(a) shows the enlarged switching waveforms of V_{gsH} , V_{dsH} , I_{sH} , I_{out} , and V_{bus} at turn-on of the high-side arm, where three different gate driving conditions of without AGD, AGD mid., and AGD max. are utilized. Table III compares the switching performance of each gate driving condition using the peaks of the voltage/current overshoots and the turn-on switching loss E_{on} of the high-side MOSFET calculated from the waveforms of V_{dsH} and I_{sH} . It is confirmed that the application of AGD helps reduce the dV_{ds}/dt stress present in V_{dsH} and the resulting overshoot seen in V_{bus} waveforms, while increasing

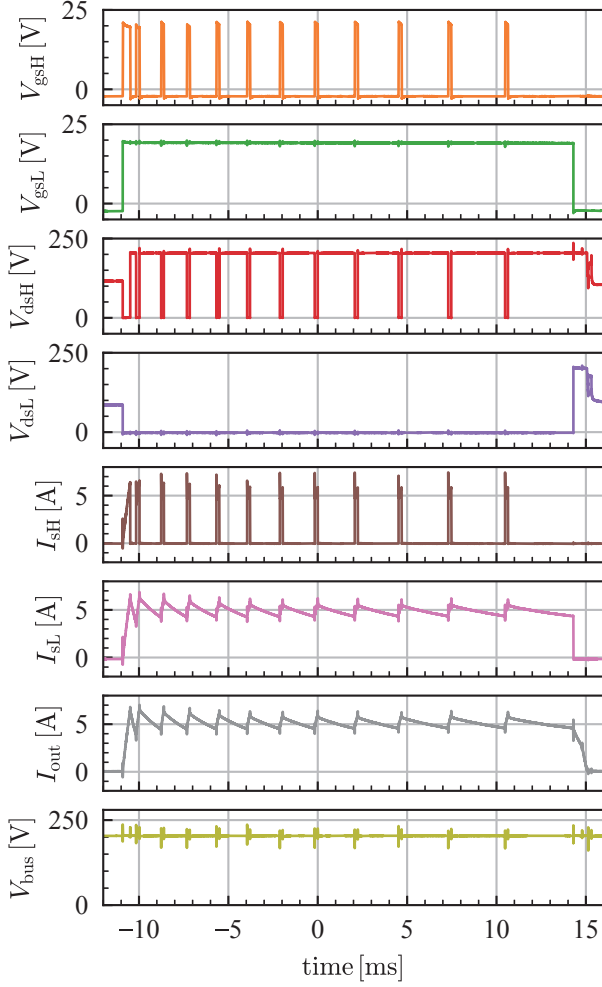


Fig. 7. Measured operational waveforms during Phase C.

TABLE III
COMPARISON OF SWITCHING PERFORMANCE AT TURN-ON.

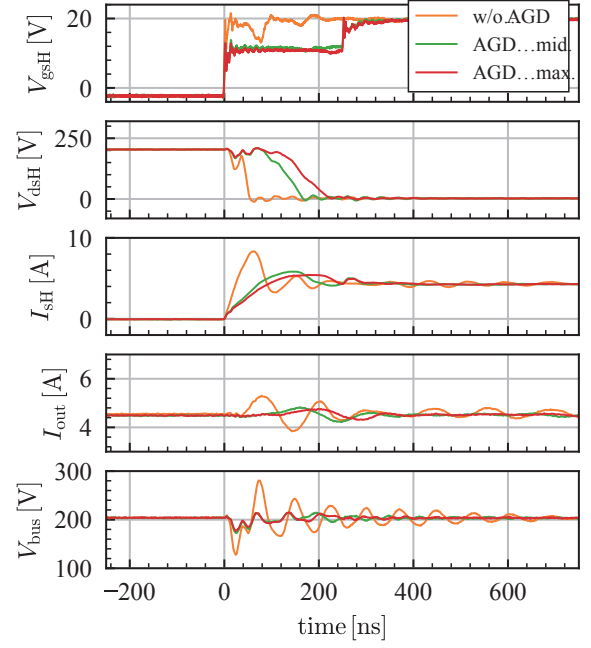
AGD Pattern	V_{dsH} peak	I_{sH} peak	V_{bus} peak	E_{on}
w/o AGD	208 V	8.35 A	281 V	31.5 μ J
AGD mid.	210 V	5.85 A	215 V	94.5 μ J
AGD max.	210 V	5.45 A	215 V	122 μ J

the switching loss as a trade-off. The overshoot and oscillation seen in the waveforms of I_{sH} and I_{out} are also mitigated by the AGD, with AGD max. suppressing the ringing better than AGD mid.

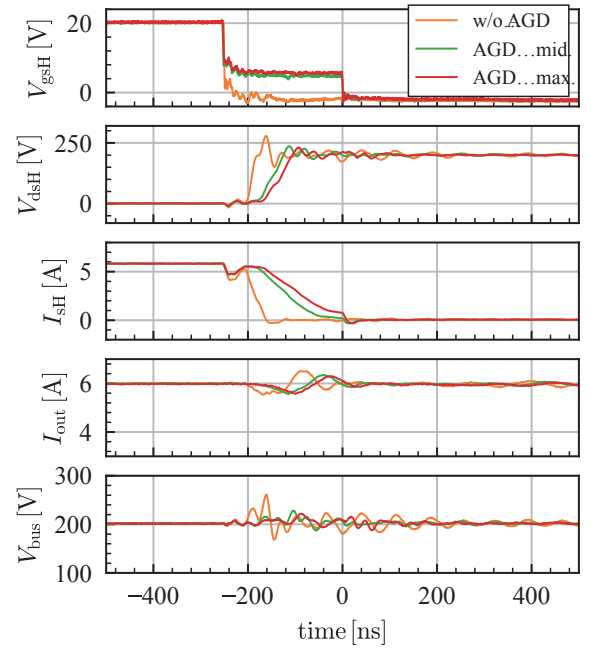
Fig. 8(b) shows the switching waveforms under three AGD conditions at turn-off, and Table IV lists their performance. Similarly to turn-on, the application of AGD is effective in suppressing the overshoots and ringings present in the waveform of V_{bus} .

E. Evaluation of Conducted Emission

The effect of AGD on the EMI suppression is quantitatively analyzed in the frequency domain based on the measurement of conducted emission. Due to the limitation in the mea-



(a) Turn-on.

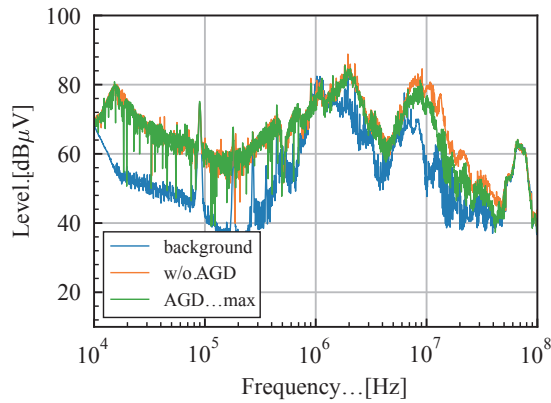


(b) Turn-off.

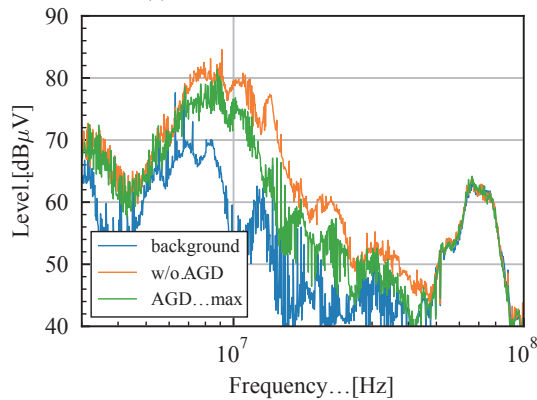
Fig. 8. Switching waveforms of V_{gsH} , V_{dsH} , I_{out} , and V_{bus} .TABLE IV
COMPARISON OF SWITCHING PERFORMANCE AT TURN-OFF.

AGD Pattern	V_{dsH} peak	I_{sH} peak	V_{bus} peak	E_{off}
w/o AGD	279 V	5.87 A	261 V	12.9 μ J
AGD mid.	237 V	5.87 A	228 V	49.3 μ J
AGD max.	232 V	5.84 A	222 V	63.9 μ J

surement environment, this evaluation focuses on the relative



(a) From 10 kHz to 100 MHz



(b) Enlarged view from 3 MHz to 100 MHz.

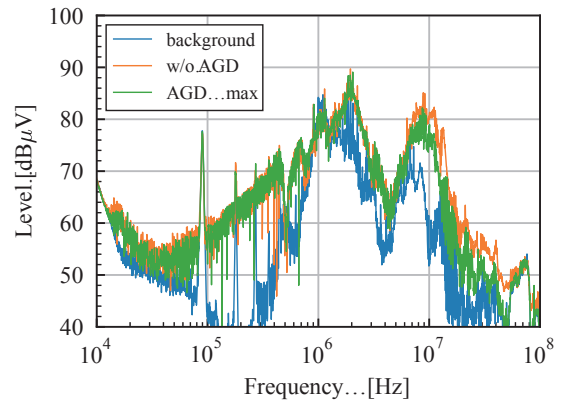
Fig. 9. Measured spectra of conducted emission at Line A.

comparison among the different gate drive conditions rather than the analysis of the absolute magnitude of the spectrum.

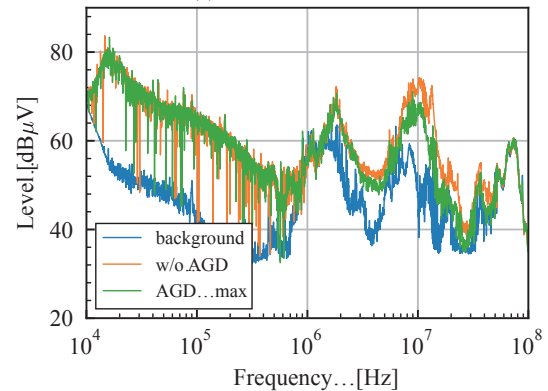
Fig. 9 compares the spectrum of total conducted emission at Line A without AGD and with AGD max. The background noise spectrum is also plotted for reference. It is clearly seen that the application of AGD reduces the noise spectrum by up to 10 dB in the frequency range from around 10 MHz to 50 MHz, which corresponds to that of ringings suppressed by the AGD. Fig. 10 shows the extracted common-mode and differential-mode spectra of the conducted emission. The effectiveness of applying AGD is also present in these results in the same frequency range from around 10 MHz to 50 MHz. These results confirm the applicability of AGD in suppressing EMI for SRM drives in the critical frequency band often specified by EMI standards, such as for automotive applications governed by CISPR 25, without adding any filtering components.

V. CONCLUSION

This work demonstrated the applicability of digital AGD to AHB SRM drives for suppressing EMI. The hysteresis-controlled rectangular excitation current makes it possible to apply an identical AGD pattern throughout a phase, easing its application compared to other motor drive applications requiring sinusoidal currents. Experimental results confirmed that



(a) Common-mode.



(b) Differential-mode.

Fig. 10. Measured common- and differential-mode conducted emission spectra extracted from Line A-B.

the adopted AGD reduces the overshoots and ringings of the DC bus voltage in the time-domain switching waveforms. The measurement results of the conducted emission also confirmed the effectiveness of AGD in the frequency domain, particularly in the critical frequency range of 10-50 MHz targeted in the standards for EMI regulation. Ultimately, this approach offers a viable solution with minimized filtering for managing SiC-induced EMI in high-density SRM drives.

ACKNOWLEDGMENT

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EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive

Hajime Takayama^{1*}, Kazuki Matsumoto¹, Shiu Mochiyama²,
Shuhe, Fukunaga³, Michihiro Shintani¹, Takashi Hikiyama²

¹Kyoto Institute of Technology, Japan
²Kyoto University, Japan
³The University of Osaka, Japan
e-mail*: hajime-takayama@kit.ac.jp

Outline

- Introduction
- Drive Circuit for SRM
- Active Gate Driver for SRM Drive
- Experimental Verification of EMI Supression
- Conclusion

Prospects of SiC-based SRM Drives

- Switched Reluctance Motor (SRM) offers practical advantages
 - Simple structure, low-cost, excellent mechanical and thermal robustness
 - No rare-earth magnets required
- SiC-based SRM drive further enhances SRM's advantage
 - Increased operation frequency and power density due to fast switching speed
 - Candidate for demanding applications (e.g. EV, propulsion, use in extreme condition) [2]

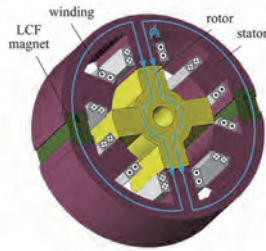


Fig: Structure of 6-stator / 4-rotor SRM [1].

- [1] K. Fuat and T. Nakamura, IEEJ Trans. Electrical and Electron. Eng., 17(5), 732-738 (2022).
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Challenge: Increased EMI

- Fast-switching of SiC devices increases **electromagnetic interference (EMI)**
 - Elevated ringing frequency due to reduced C_{oss} → 2-30MHz is crucial for CM noise [3]
 - Challenging to meet limits defined by standards (e.g., CISPR 25)
 - Conventional approach: passive EMI filters
 - Attenuation performance degrades above 10 MHz due to self-resonance [4]
 - Additional filters increase weight and volume of the powertrain
- Suppression of high-frequency noise at the source is demanded

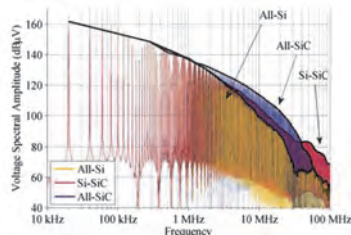
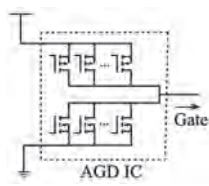


Fig: Spectra of SiC-based vs Si-based converter [5].

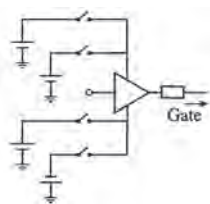
- [3] D. Jiang et. al., IEEE Trans. Power Electron., 26 (12), 3823-3831 (2021).
 [4] F. Stella et. al., Proc. ECCE 2022.
 [5] C. Li et. al., IET Power Electron., 16 (13), 2121-2137(2023).

EMI Mitigation via Active Gate Drive

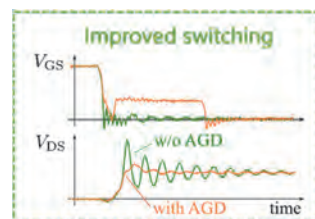
- Active gate drive (AGD) to mitigate ringings and EMI issues
 - Dynamically control the switching transient of power devices
 - Adaptive/programmable AGDs for optimal performance under varying load: beneficial for motor drives
- Potentially a good solution for SRM drives, but no report exist



Current-controlled AGD



Multi-voltage-level AGD



Objective of This Work

- Applicability of AGDs in SiC-based SRM drives is investigated
- Experimentally verified using an internally developed AGD and a three-phase 6/4 SRM drive
- Measurement of conducted emission is performed to assess EMI quantitatively

Outline

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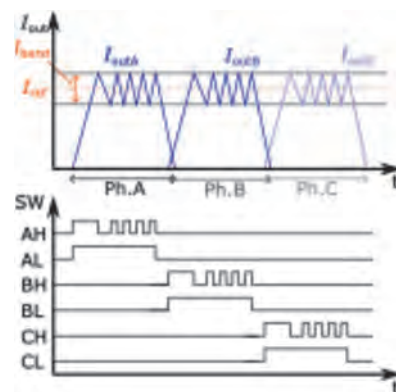
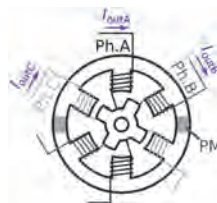
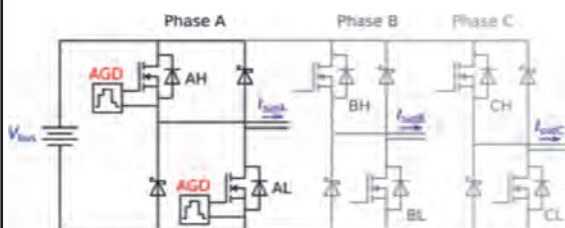


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Assymetric H-bridge Drive

- SRM drive requires a constant exitation current throughout each phase
- Assymetric H-bridge (AHB) is adopted: fundamental topology for SRM drive
 - Consists of two SiC MOSFETs and two SiC SBDs
 - AH=1, AL=1: Magnetization
 - AH=0, AL=1: Free-wheeling
 - AH=0, AL=0: Demagnetization

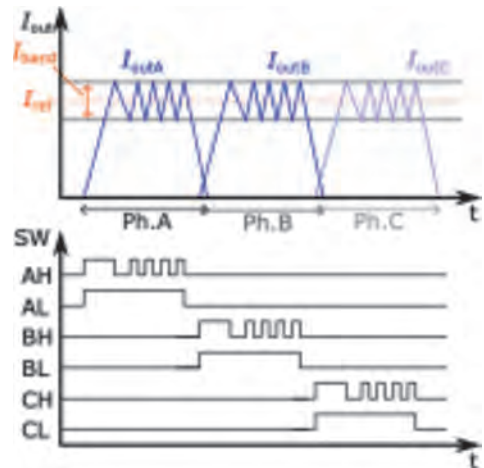
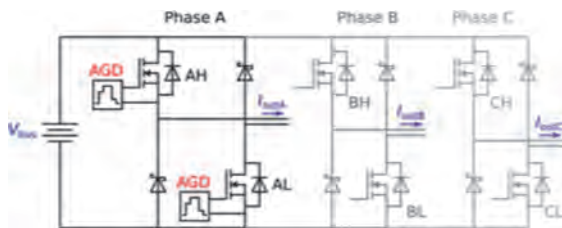


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Hysteresis Control

- Fundamental control approach for SRM drive
- Output current I_{out} is maintained at I_{ref} within hysteresis band (I_{band})
 - AH switches off at $I_D = I_{ref} + \frac{1}{2} I_{band}$
 - AH switches on at $I_D = I_{ref} - \frac{1}{2} I_{band}$

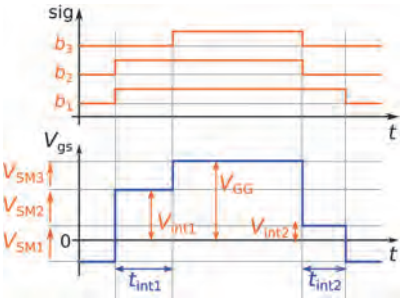
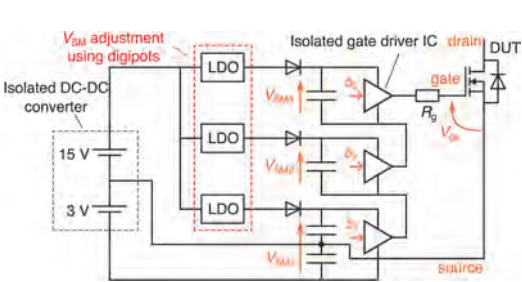


Outline

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Schematic Configuration and Operation of AGD

- Three-voltage-level (3-L) AGD based on modular multi-level topology
 - Gate-source voltage (V_{gs}) is sum of submodule (mini-gate driver) outputs:
$$V_{gs(t)} = b_1(t) \cdot V_{SM1} + b_2(t) \cdot V_{SM2} + b_3(t) \cdot V_{SM3} - 3 \text{ [V]}$$
 - V_{SMi} generated by LDO, adjusted by digital potentiometers with serial interface
 - Requires three-bit gate signals (b_1, b_2, b_3) with delays (t_{int1}, t_{int2}) generated by controllers



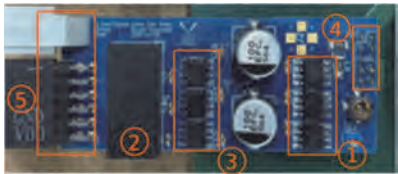
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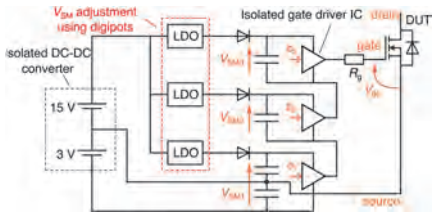
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Fabricated AGD Board

- Commercial isolated gate-driver ICs are utilized as submodules
- Single DC-DC converter and bootstrap circuits supply power to all the submodules



1. Isolated gate driver ICs
2. Isolated DC-DC converter
3. LDO regulator ICs
4. Connector to main board
5. Signal & power input (Digipot ICs and isolators on bottom layer)



LIST OF PRIMARY COMPONENTS USED IN AGD.

Component	Part number	Manufacturer
Isolated gate driver	1EDB7275FXUMA1	Infineon
Isolated DC-DC converter	MGJ2D051802SC	Murata
LDO regulator	LP2951DR	Texas Instruments
Digital potentiometer	AD5292BRUZ-50	Analog Devices
Digital signal isolator	Si8660BC-B-IS1	Skyworks

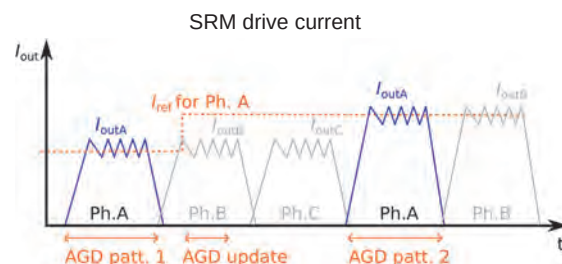
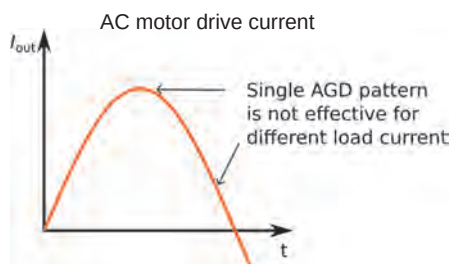


EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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AGD Strategy in SRM Drive

- Effective AGD pattern strongly depends on load (drain) current
- Challenge in AGD for AC motor drives: constantly changing drain current
- In SRM drive, MOSFETs switches at a known, fixed current throughout a phase
→ AGD pattern only updated if I_{ref} is changed, during idle phases (ms order)
- AGD is a good fit for SRM drive

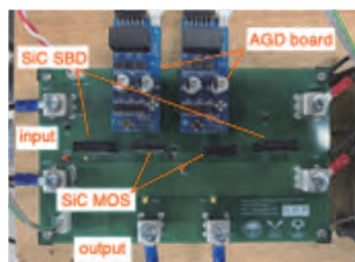
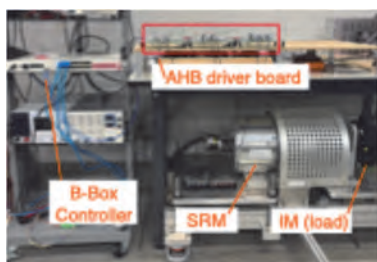


Outline

- Introduction
- Drive Circuit for SRM
- Active Gate Driver for SRM Drive
- Experimental Verification of EMI Supression
- Conclusion

Experimental Setup

- Internally developed 6/4 SRM with shaft interconnected to a PMSM (load)
- AHB driver
 - Power devices: SCT2160 KE SiC MOSFETs and SCS220AE SiC SBDs (ROHM)
 - Controller: B-BOX-RCP3.0 controller (Imperix)
 - Current sensor IC for I_{out} : T430-HSWF20DR (Allegro MicroSystems)
 - No filtering components
- Target rotation speed: 200 rpm, load torque: 0.89 Nm $\rightarrow I_{ref} = 5A @ V_{bus} = 200V$



Measurement Setup

- Time-domain (single phase)
 - Switching waveforms of MOSFETs are measured under different AGD patterns
 - Peak of overshoots and switching loss are used as indices
- Frequency-domain spectra of conducted emission (detailed later)

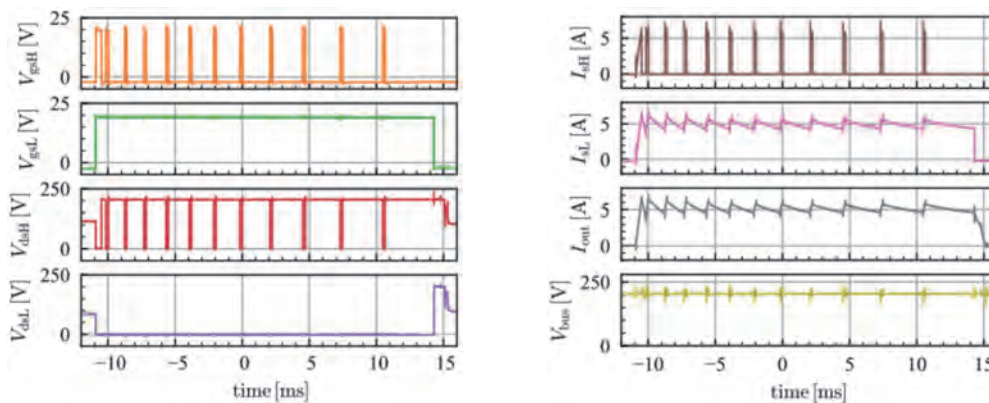


LIST OF MEASUREMENT INSTRUMENTS UTILIZED IN EXPERIMENT

Instrument	Part number	Manufacturer
Oscilloscope	MSO68B	Tektronix
Isolated voltage probe	TIVP1	Tektronix
Differential voltage probe	THDP0200	Tektronix
Current probe	TCP0030A	Tektronix

Operation Without AGD (Phase C)

- Hysteresis control of I_{out} is confirmed, ~ 70 W output
- Large ringing present in V_{bus} waveform at every HS switching event



EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

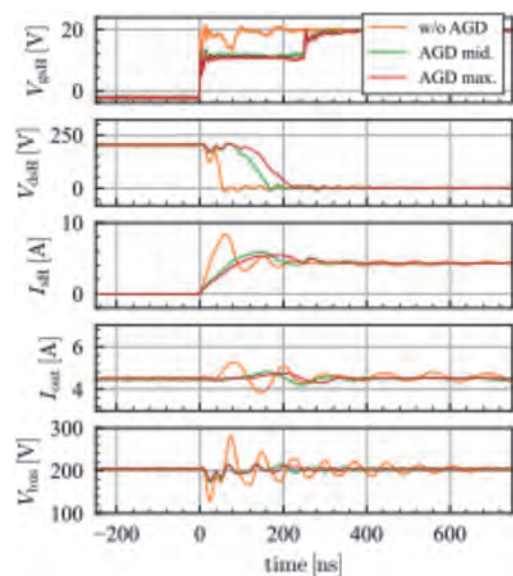
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AGD at Turn-on

- Two AGD patterns (AGD mid. & max.) are selected based on preliminary testing
- AGD helps reducing dV_{ds}/dt stress and resulting ringing at V_{bus}
- Increase of switching loss as trade-off

COMPARISON OF SWITCHING PERFORMANCE AT TURN-ON.

AGD Pattern	V_{dsH} peak	I_{eH} peak	V_{bus} peak	E_{on}
w/o AGD	208 V	8.35 A	281 V	31.5 μ J
AGD mid.	210 V	5.85 A	215 V	94.5 μ J
AGD max.	210 V	5.45 A	215 V	122 μ J



EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

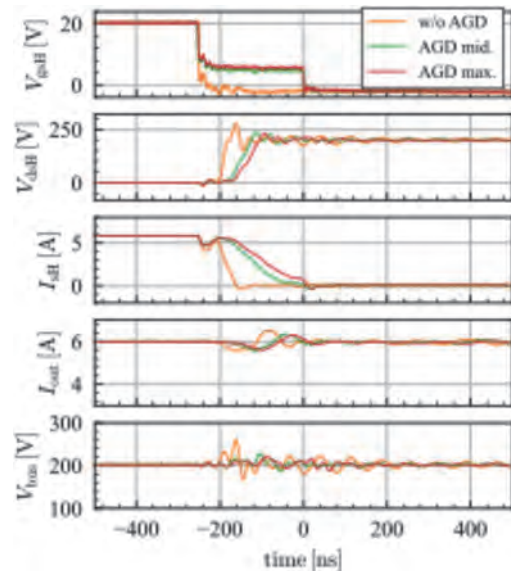
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AGD at Turn-off

- Similar to turn-on, AGD suppresses ringing on V_{bus} at the cost of increased switching loss

COMPARISON OF SWITCHING PERFORMANCE AT TURN-OFF.

AGD Pattern	V_{dsH} peak	I_{sH} peak	V_{bus} peak	E_{off}
w/o AGD	279 V	5.87 A	261 V	12.9 μ J
AGD mid.	237 V	5.87 A	228 V	49.3 μ J
AGD max.	232 V	5.84 A	222 V	63.9 μ J



EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

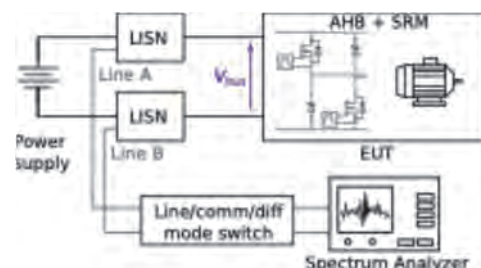
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Frequency-domain Analysis of Conducted Emission

- Conducted emission is measured at input terminals of AHB circuit
 - EUT: AHB + SRM drives
 - Line impedance stabilization networks (LISN) is placed b/w power supply and EUT
 - Line/ common-mode (CM) and differential-mode (DM) spectrum are measured
- Relative comparison with/without AGD is performed
 - Absolute magnitude evaluation is not possible due to environment limitation

LIST OF MEASUREMENT INSTRUMENTS UTILIZED IN EXPERIMENT.

Instrument	Part number	Manufacturer
Spectrum analyzer	E4420B	Agilent
LISN	9117-5-PJ-50-N	Solar Electronics
Measurement mode switch	CMDM 8700 B	Schwarzbeck

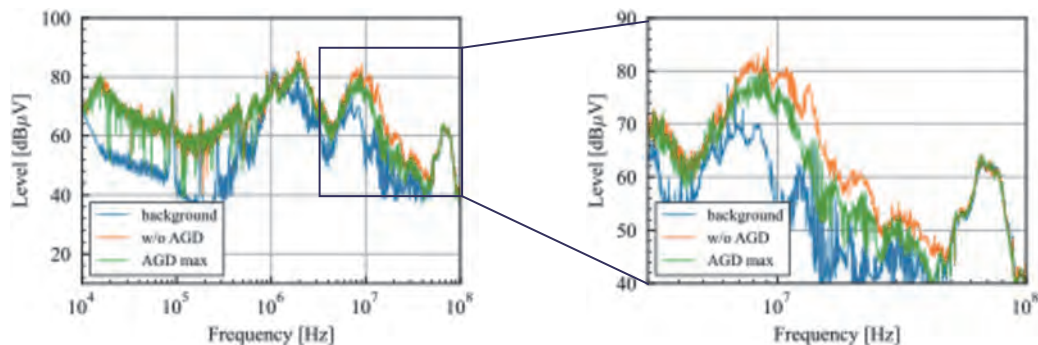


EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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Measured Conducted Emission at Line A

- Noise spectrum @ 10-50 MHz reduced by up to 10 dB by AGD
→ Corresponds to the reduction of ringing in V_{bus} waveform



Spectrum at Line A

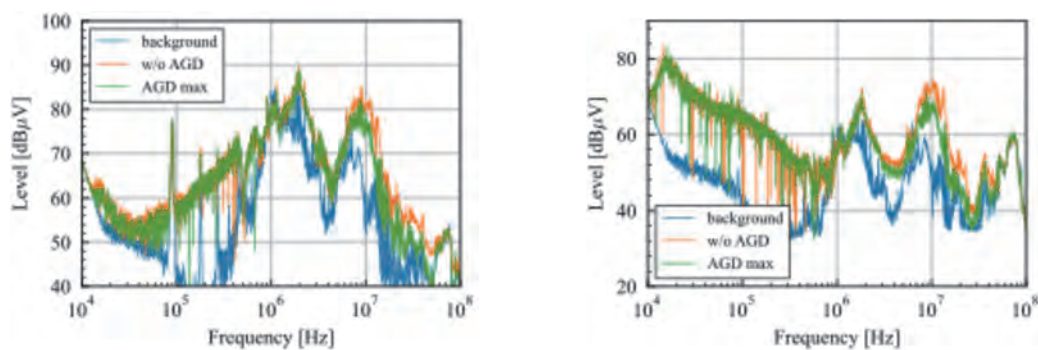


EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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Extracted CM/DM Emission

- Noise spectrum @ 10-50 MHz reduced by AGD
→ critical frequency range targeted by standards (e.g., CISPR25)
- Results confirm the applicability of AGD to EMI suppression in SRM-drive



CM spectrum

DM spectrum



EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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Outline

- Introduction
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EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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Conclusion

Summary

- We demonstrated applicability of AGD to SRM drives for EMI suppression
- Conducted emission was measured and analyzed in frequency domain
- AGD is effective in mitigating emission in 10-50 MHz range targeted in EMI/EMC standards

Future works

- Optimization of AGD pattern considering switching loss
- Adaptive AGD pattern selection for the whole operating range
- Comparison with other approach, combination with minimum filtering



EMI Suppression in Asymmetric H-Bridge SRM Drives Using Active Gate Drive, H. Takayama, O12-3-03

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共同研究員による成果

多端子直流系統に対する潮流計算法 -電源(負荷)の母線電圧垂下特性の適用-

共同研究員 舟木 剛
大阪大学大学院工学研究科教授

受託先名：株式会社ダイヘン

1. 目的

マイクログリッドや洋上風力発電などで直流系統が検討されている。[1]このような系統では電源や負荷が複数接続され多端子系統となる。太陽光や風力などの再エネ電源が接続された系統では、変動する電源出力に対して蓄電池やデマンドレスポンスなどで需給を一致させるが、その際にどのような電力潮流が発生し、制御するのが重要となり、潮流計算が求められる。これまで交流系統における潮流計算は議論されてきたが[2,3]、直流系統については十分議論がされていないようである。本研究では多端子直流系統に焦点をあて、その潮流計算法について報告する。

2. 成果

自励式直流送電では、各端子の有効電力を協調制御する方法として電力マージン方式、電圧マージン方式が提案されている。[4]電力マージン方式では電圧決定端子の有効電力指令値を電力マージン分だけ大きくするとともに、定出力端子の直流電圧指令値に電圧マージンを設定することで動作点を決めている。電圧マージン方式では、端子の直流電圧設定値の間に差を設けることで電圧設定端子の出力が決まる。多端子に拡張する場合は、電圧マージンの設定を多段にすることで、一つの端子を電圧決定端子とし、他の端子がすべて有効電力決定端子となる。マージンを用いる方式では、変動する電源出力に対してシームレスに動作点を移動させることは難しい。以下では電圧垂下特性をノード(端子)に与えることで対応することを考え、これに対応した潮流計算法について述べる。

交流系統の潮流計算では、電力ネットワークを送電線や接続機器のインピーダンスもしくはアドミタンスで表す。直流系統では電力ネットワークを送電線のレジスタンスもしくはコンダクタンスで表すことになる。 n ノードの直流ネットワークにおけるノード電圧 V_i ($i = 1 \sim n$)と電流 I_i ($i = 1 \sim n$)の関係はコンダクタンス行列を用いて(1)式で表される。

$$\begin{bmatrix} I_1 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} G_{11} & \cdots & G_{1n} \\ \vdots & \ddots & \vdots \\ G_{n1} & \cdots & G_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix} \quad (1)$$

ただしノードからネットワークに流入する電流を正とし、 G_{kk} はノード k の駆動点コンダクタンス、 G_{lk} はノード $k-l$ 間の伝達コンダクタンスである。

直流系統では有効電力のみとなるため、ノード k の電力方程式は有効電力 P_k に対して(2)式で表される。

$$P_k = V_k I_k = V_k \sum_{l=1}^n G_{kl} V_l \quad (2)$$

潮流計算における拘束条件は、交流系統ではノードの有効電力と無効電力または有効電力と電圧

であるが、直流系統では有効電力と電圧となる。基準ノードは交流系統と同様に電圧を拘束条件とする。太陽光発電などの分散電源が接続されたノードは有効電力を指定する。また負荷ノードも有効電力を指定する。系統における需要と供給の差を調整するための蓄電池が接続されたノードは電圧を指定する。これらの n 個の変数を指定した拘束条件をもちいて電力方程式を解いて残りの n 個の変数を求めるのが直流多端子系統の潮流計算となる。

交流系統の潮流計算において、簡易法として用いられる直流法はノード間の相差角を用いた近似計算であるため、直流系統の潮流計算に用いることはできないため交流法に相当する厳密計算が必要となる。厳密な潮流計算では非線形方程式である電力方程式を、初期値と反復計算により近似解として求める。ここではニュートンラプソン法により直流多端子系統の潮流計算を行う。

有効電力を指定したノード $1 \sim m$ のうちノード k の q 回目の反復計算における有効電力の計算値 $P_k(V_1^q, \dots, V_m^q)$ と設定値 P_{kref} の差 ΔP_k^q は(3)式で表される。

$$\Delta P_k^q = P_{kref} - P_k(V_1^q, \dots, V_m^q) \quad (3)$$

これより反復計算 $q+1$ 回目におけるノード k の電圧の近似値 V_k^{q+1} は、(7)式に示すヤコビ行列による修正方程式を用いて(4)式で与えられる。

$$\begin{bmatrix} \Delta P_1^n \\ \vdots \\ \Delta P_m^n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial V_1} & \dots & \frac{\partial P_1}{\partial V_m} \\ \vdots & & \vdots \\ \frac{\partial P_m}{\partial V_1} & \dots & \frac{\partial P_m}{\partial V_m} \end{bmatrix} \begin{bmatrix} \Delta V_1^n \\ \vdots \\ \Delta V_m^n \end{bmatrix} \quad (4)$$

ただしヤコビ行列の非対角要素($k \neq l$)、対角要素($k = l$)はそれぞれ次式となる。

$$\left(\frac{\partial P_k}{\partial V_l} \right)^q = \frac{\partial}{\partial V_l} V_k^q \sum_{l=1}^m V_l^q = V_k^1 G_{kl} \quad (5)$$

$$\left(\frac{\partial P_k}{\partial V_k} \right)^q = \frac{\partial}{\partial V_k} V_k^q \sum_{l=1}^m V_l^n = I_k^q + V_k^q G_{kk} \quad (6)$$

$$V_k^{q+1} = V_k^q + \Delta V_k^q \quad (7)$$

つぎに母線の電圧垂下特性を考慮した潮流計算について述べる。ここでは蓄電池などを想定した、出力電流に対して電圧垂下特性を与えた直流端子を含む潮流計算について考える。入出力電流の上下限の範囲の中では、電流に対して一定の傾きで端子電圧を決める。

垂下特性の電圧・電流上下限をそれぞれ V_{max} , V_{min} , I_{max} , I_{min} とすると、垂下特性の傾きは(8)式で与えられる。

$$a = \frac{V_{max} - V_{min}}{I_{max} - I_{min}} \quad (8)$$

ここで P 指定もしくは V 指定のノード x と、電圧垂下特性を持つノード y で構成される(9)式のネットワーク行列を考える。

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{yx} \\ G_{xy} & G_{yy} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (9)$$

ノード y の部分の垂下特性は(10)式で表される。

$$[V_y] = [A_y][I_y] + [V_{0y}] \quad (10)$$

ただし A_y は(8)式で求めた垂下特性の傾き、 V_{0y} は0出力時の電圧である。ネットワーク行列に電圧垂下特性ノードを組み込んで縮約すると(11)式となる。

$$[I_x] = \left([G_{xx}] + [G_{yx}][A_y]\{[E] - [G_{yy}][A_y]\}^{-1}[G_{xy}] \right) [V_x] \\ + \left([G_{yx}][A_y]\{[E] - [G_{yy}][A_y]\}^{-1}[G_{yy}] + [G_{yx}] \right) [V_{0y}] \quad (11)$$

なお(10)式は電圧源に直列に内部抵抗が接続されたテブナン回路と等価であるため、ノートン回路に変換し、内部抵抗をネットワーク行列に組み込み、電圧源を等価電流源として表してもよい。ここでは図1に示す4母線系統を例に、直流系統の潮流計算結果を示す。直流系統のアドミタンスで表したネットワーク行列は(12)式のように与えた。

$$G = \begin{bmatrix} 9 & 0 & 4 & -5 \\ 0 & 7.5 & -2.5 & -5 \\ -4 & -2.5 & 14.5 & -8 \\ -2.5 & -5 & -9 & 18 \end{bmatrix} \quad (12)$$

ノード1をV指定($V_1 = 1\text{p.u.}$)、ノード3,4をP指定($P_3 = 1\text{p.u.}$, $P_4 = 0\text{p.u.}$)、ノード2を電圧垂下特性(垂下特性5%、ゼロ出力時電圧1p.u.)とした。全てのノードに対して電圧初期値を1p.u.として反復計算を行った結果は表1のようになった。垂下特性であるノード2において、電流 $I_2 = 0.34\text{p.u.}$ に対して5%の垂下特性により0出力電圧から0.017p.u.上昇しており、垂下特性を正確に表すことができている。

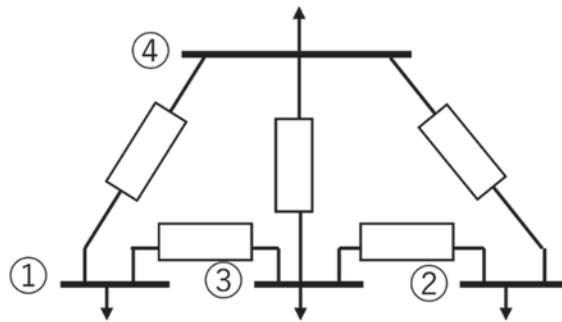


図1 直流4母線系統

表1 潮流計算結果

bus	1	2	3	4
V(p.u.)	1	1.0170098343	1.03608185010	0.93943448911
I(p.u.)	0.158500154000	0.340196686663	0.96518632785	3.4981367917e-05
P(p.u.)	0.158500154000	0.345983375944	1.00001203626	3.2862703498e-05

参考文献

- [1]泉井、「マイクログリッドにおける直流技術の適用と実証実験事例」、電学論B、vol.140、no.9、pp.658-681、2020.
- [2]新田目、電力系統の潮流計算、電気書院、2001.
- [3]深尾、豊田、電力系統へのコンピュータの応用、産業図書、昭47.
- [4]町田、直流送電工学、東京電機大出版局、1999.

3. 成果の公表

「多端子直流系統に対する潮流計算法-電源(負荷)の母線電圧垂下特性の適用」、電気学会 令和7年 電力・エネルギー部門大会、125、琉球大学 千原キャンパス、2025年9月17日-19日.

報告書作成日 令和8年6月9日

自律分散協調エネルギーマネジメントの開発

共同研究員 平田研二¹ 太田快人²

¹富山大学 学術研究部 工学系 教授

²京都大学 名誉教授

受託先名：株式会社ダイヘン

1. 目的

太陽光発電システムの連系容量の増加や電力取引の自由化などを背景に、電力系統の安定運用を担保するための発電設備や蓄電池設備の制御、電力需要群に対する消費電力の制御、加えて卸電力取引市場や需給調整市場への入札方針などまでを対象とした、自律分散協調制御方策に関する研究推進を目的としている。

2. 成果

太陽光発電システムの連系容量の増加や電力取引の自由化などを背景に、電力系統の安定運用を担保するための発電設備や蓄電池設備の制御、電力需要群に対する消費電力の制御、すなわち仮想発電所を実現するための分散協調制御方策に関する研究を推進している。これらの制御問題に加え、卸電力取引市場、需給調整市場での一次および三次調整力の複合約定を可能とする蓄電拠点の分散型運用などを考察、提案し、その有効性を数値実験ならびに実機実験によって検証している。なおこの時、この蓄電拠点への入力となる目標充放電量は、市場での約定により決定される。このため、適切な目標値を獲得するための市場入札手順を検討しておく事は重要である。今年度は、卸電力取引市場、需給調整市場における実績約定データを活用した約定価格推定方策の検討、ならびに推定価格を利用した入札目標量決定のための最適化問題の定式化などの検討を進めた。

報告書作成日 2026 年 7 月 2 日

電力取引市場の最適運用に関する研究

共同研究員 阿久津 彗（富山県立大学工学部助教）

受託先名：株式会社ダイヘン

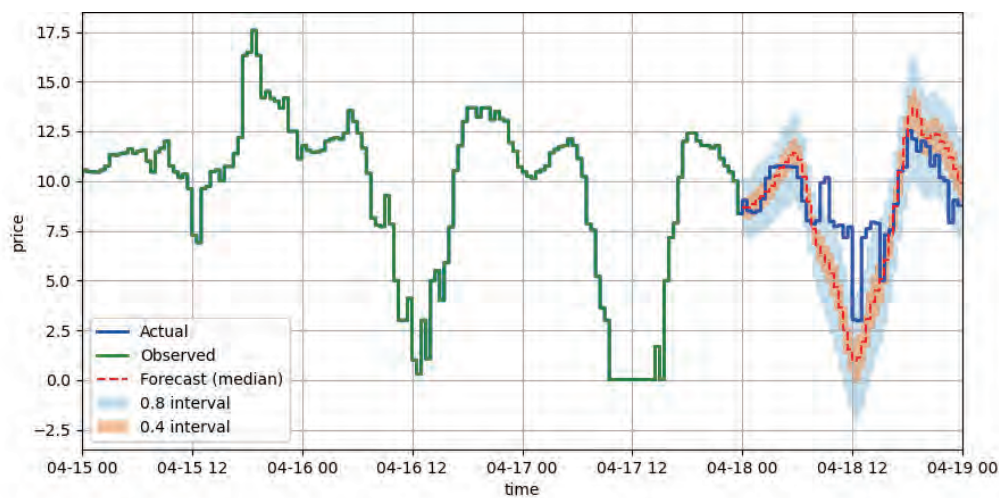
1. 目的

需要家が保有する蓄電池などの運用にあたり、電力取引市場を考慮した計画の作成が必要である。計画作成方策の検討に向けて今年度は、一日前市場の価格予測値および分布を得るため、時系列基盤モデルを活用し、精度比較をおこなう。

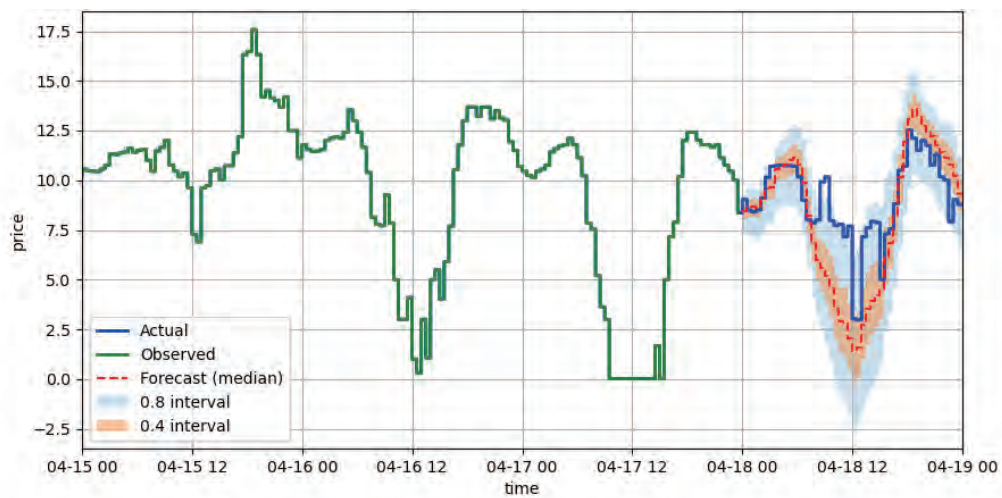
2. 成果

4つの時系列基盤モデル（モデルAは3モード）をもちいて、市場価格の予測をおこなう、簡易的な精度比較を実施した。

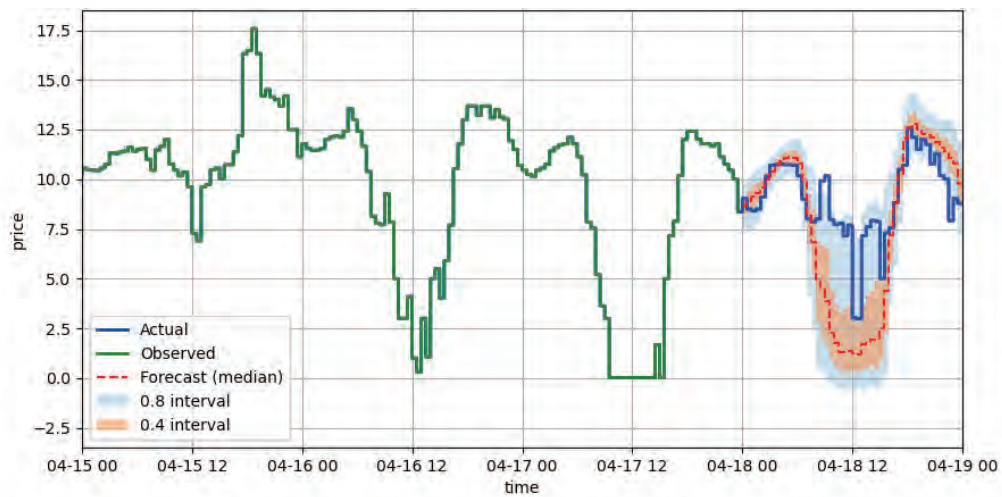
【予測結果】



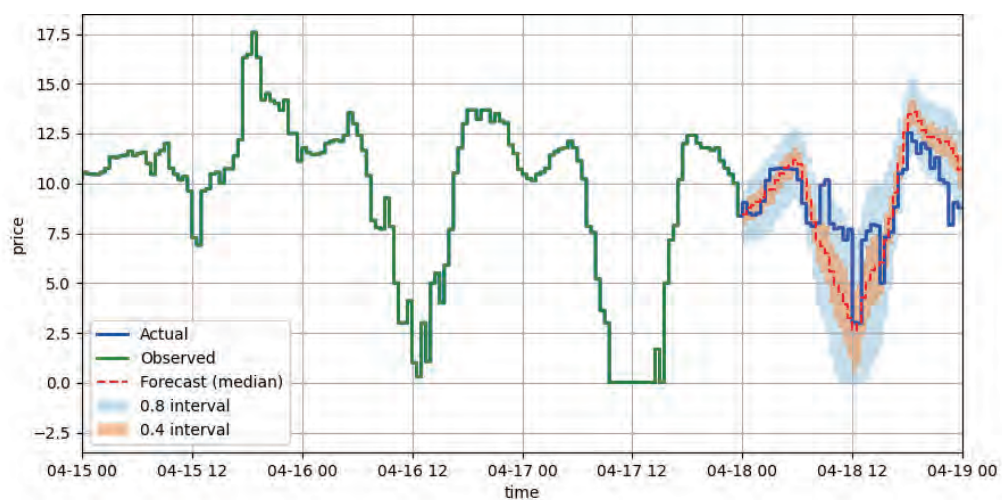
結果：時系列基盤モデル A－モード 1



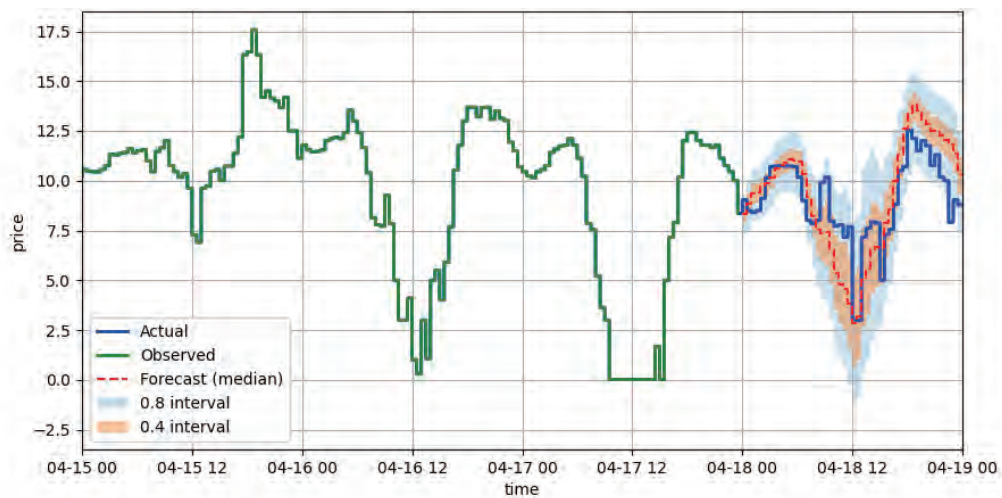
結果：時系列基盤モデル A - モード 2



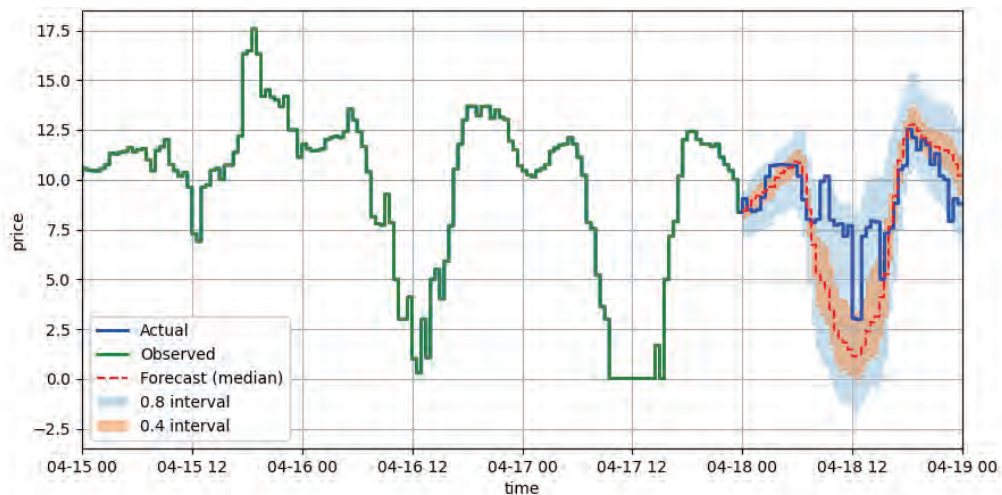
結果：時系列基盤モデル A - モード 3



結果：時系列基盤モデル B



結果：時系列基盤モデル C



結果：時系列基盤モデル D

【結果のまとめ】

今年度は、80%予測区間の精度のみを確認し、時系列基盤モデル A から D のすべてでほぼ同様の予測結果が得られた。一方で、平均値や 40%予測区間の精度比較、入力データ長に関する比較検証、多変量データにもとづく予測への改良などが今後の課題としてあげられる。

3. 成果の公表

- [1] 阿久津慧、仮想的な価格をもちいた大規模な分散型電源群の制理論と実装、第 69 回システム制御情報学会研究発表講演会 (SCI'25)、33E-1、TS09 社会システムの制御・計画・検証 招待講演、2025 (口頭発表)

報告書作成日 令和8年7月8日

理事長寄稿

退潮期に入った国の問題

久保愛三 2026.03.01

我々が謳歌してきた豊かな生活を支えてきた経済体制の「付け」と人間の Nature の関係

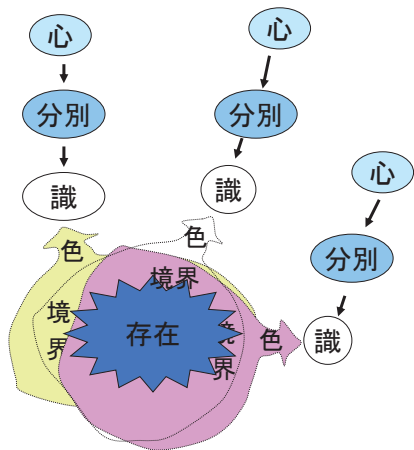
私が本論中で用いている「**神**」と言う表現は、人間ではどうしようもなく、宇宙の摂理として物事が起こってしまう状況を意味しています。

空

色

COGITO ERGO SUM
デカルト

認識と存在



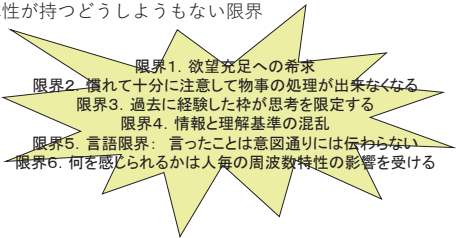
カント、ヘーゲル、近くはソシュールとかの認識論を
2300年も前に若き日の釈尊は言っているようだ。

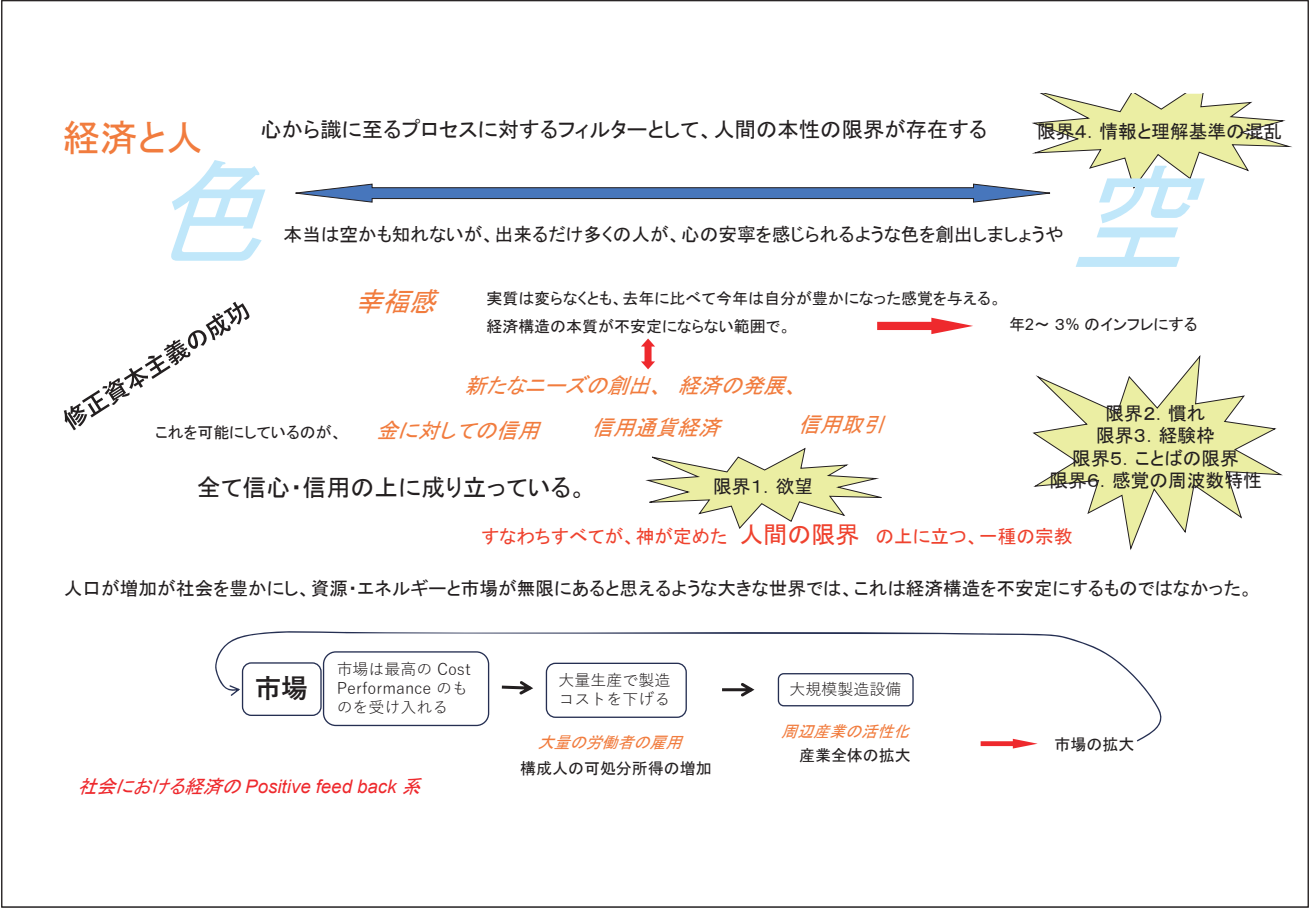
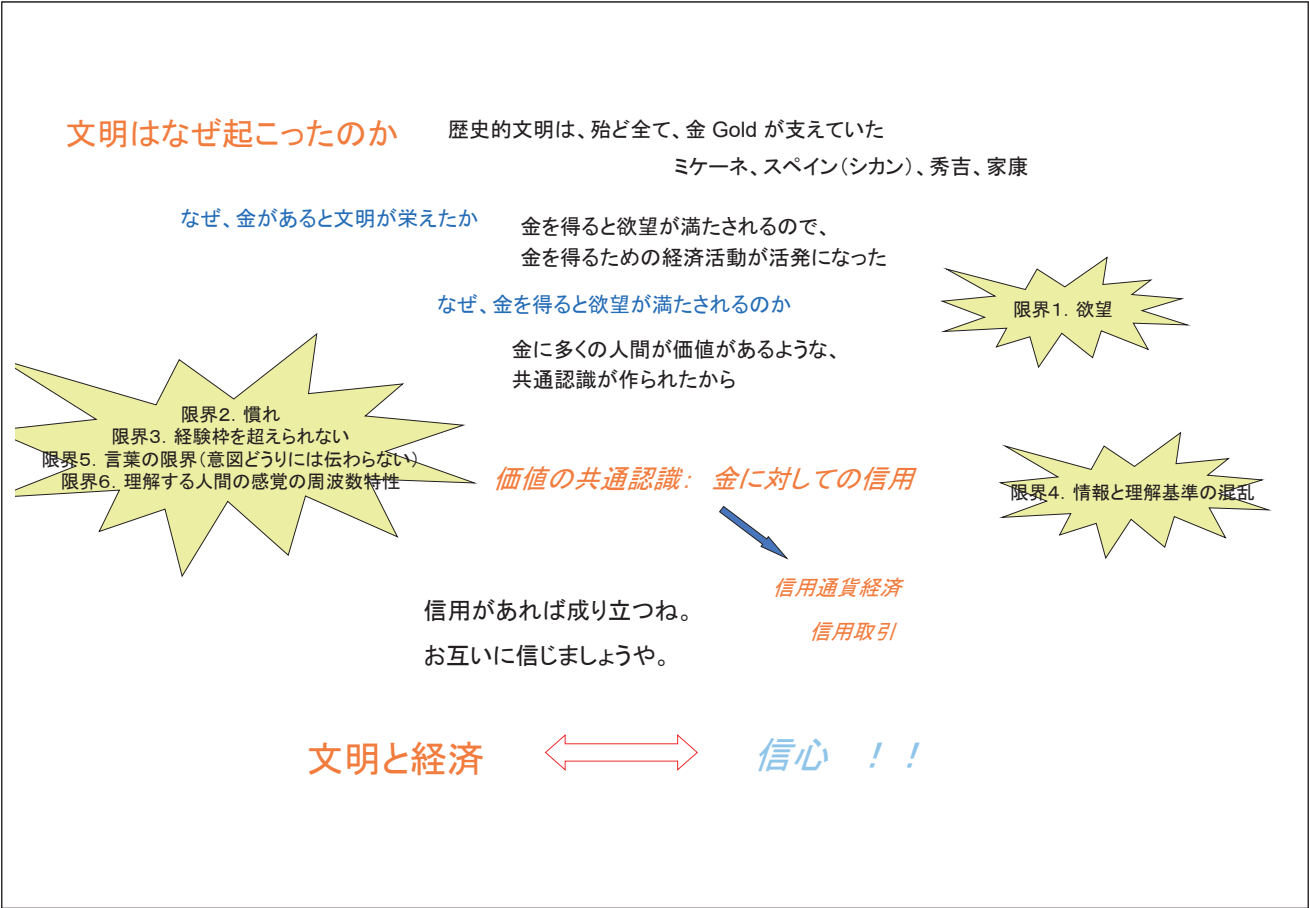
(原始仏典的理解)

色ハ 境界ノ観ナリ
境界ハ 識ニ存シ
識ハ 分別ヨリ発ス
分別ハ 心ヨリ生ジルニ
心ハ 個々ニ偏シ汎タル実ハ無シ
故二色ハ 空ニ等シ

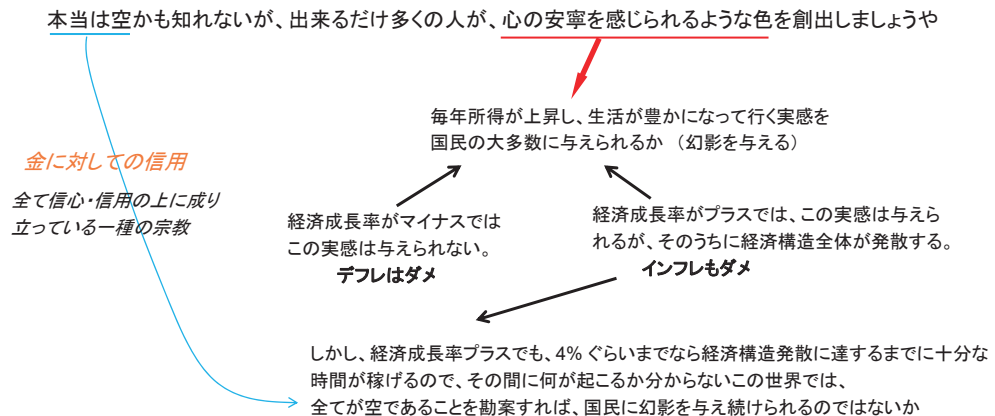
色 即 是 空

人間の本性が持つどうしようもない限界





現在まで、可成りうまく機能している修整資本主義の基本



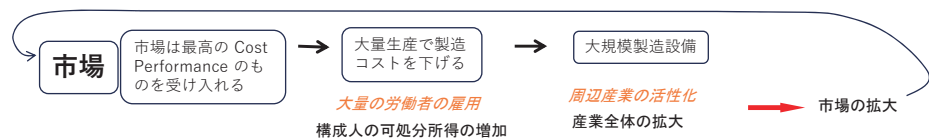
現在の修整資本主義の世界では、全て年率 2~4% 弱のインフレになる様に景気を調整して政治が動いている。

しかし現在、経済構造全体の発散以前に別のシステム不安定の問題が起こってきている

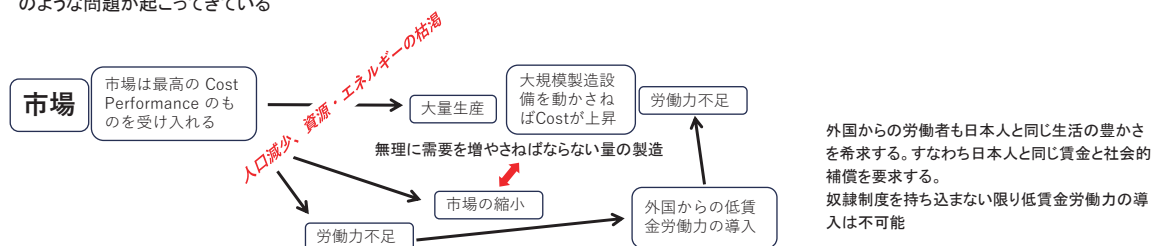
本来、国家の経済はその国の人民を豊にする様に動くべきものであるが、これが脅かされる状態が出てきている。

人口が増加が社会を豊かにし、資源・エネルギーと市場が無限にあると思えるような大きな世界では、これは経済構造を不安定にするものではなかった。

社会における経済の
Positive feed back 系



しかし、人口が減少し出し、資源・エネルギーの枯渇が喫緊の問題と感じられるようになり、市場が縮小が感じられるようになってきた世界で、以下のような問題が起こってきている

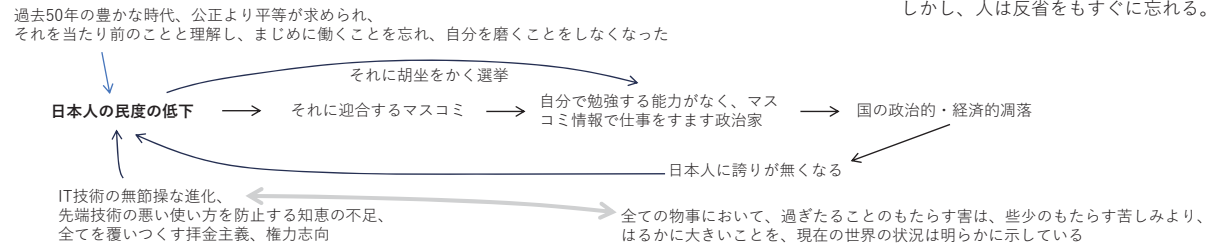


国家の経済が従来の大規模生産システムに基づく構造を維持することが目的となってしまうと、その国の人民を豊にする様に動くことが出来なくなってきた。

3000年の歴史を見てみても、外国からの低賃金労働力を導入して栄えた国はない。人口減少、資源・エネルギーの枯渇に面した国家がその国の人民を豊にする様に経済を持って行くには、従来の経済構造にとらわれることなく、新たなパラダイムを作って行かねばならない。

日本凋落のポジティブ・フィードバック系

第2次世界大戦 WW II のもたらした大きな災害に対する反省が、民主主義、自由・平等などの考えを育み、人々を豊かな生に導いた。



現在の日本の報道は全く信用できない。 YouTube等のSNSは80%以上 Hate-speech や嘘八百。 NHKや大手新聞などの Old media の報道も、昔はなかったほど嘘や公表内容の恣意的選択が多い。

誰が黒幕で日本人を洗脳しようとしているのか？

現在の世界

人間の3000年以上にわたる歴史のほとんどは戦乱に明け暮れていた。平和な時なんてものは権力者の欲望に押しつぶされて殆ど無かった。

WW II 以降、戦争の被害の甚大さにショックを受けた人たちは平和を求め、たまたま80年に及ぶ歴史上稀な長い平和の時が続いた。**平和教育がなされ、この間に生まれ育った人たちは平和・人権・平等が価値判断の基準になった。** 人間の nature と3000年以上にわたる歴史を顧みることなしに。

ところが人間に本性なんてものは変るはずがなく、権力者の中に権力指向・金銭欲・領土欲・人種主義に満ちたものが再び現れてきた。ブーチン、トランプ、習近平、ネタニエフetc. である。

その結果、**現在の世界**からは、民主主義やの理想的社会主義は消え去り、**昔の帝国主義・皇帝支配の帝国に里帰り**してしまった。

WW II 以降に生まれ育った人たちは物事の価値判断基準が全く狂ってしまっているのに、それに気づくことすら出来ない状態にあり、それを指摘する人もないことであり、大きな誤りを犯す可能性がある。

(80年/3000年 = 0.027 の精度の判断基準)

結 言

人口減少に陥り、経済が悪くなり、日本の将来を危ぶんでいるが、この解決に、今までと同じ経済モデルを保持したままで、より一層の経済的發展を求めようとしている。

1. 労働力不足

2. 人材難

3. 大量生産、大量消費（旧アメリカモデルを肯定）

4. 過剰生産

外国人労働者の安い価格での導入

大学等の国際化で、優秀な外国人材も作ろうとしている

何も深く洞察することはなく、過去の成功体験を良しとしている

資源・エネルギーの無駄遣い。廃棄物による地球汚染

外国人問題

生活が貧しくなる問題

水・空気・地域景観の悪化

ジャパン・ファースト主張

外国排斥的主張

日本の孤立化問題

ドイツ、フランス等のヨーロッパ先進国が外国人を招き入れることによりこの問題を解決しようとして、大きな困難に陥ったことに何も学んでいない。

日本人口が減ってきているのに、今までと同じ以上の経済規模を維持・発展して行こうとしているところに 根本的誤りがある。経済規模は人口に比例的でなくてはならない。

ジャパン・ファーストを主張するならば、経済は日本人を豊かにするだけの規模にとどめ、安価な外国人労働者の取り込みやGDP至上主義を排すべきである。

しかし、信用の上に成り立つ貨幣経済で、人民に満足感を与え続けなければならない現在の世界安定の基礎としての経済構造に、これは矛盾することであり、現在走っている経済構造を、減少して行く人口に合わせて縮小して行くことは不可能と言って良いほど、困難である。解決が可能であるかどうか、に、智慧を集めなくてはならない。

これを抜け出るには、日本人が精神的に謙虚になり、まじめに働き、清廉な生き方に価値を見出すようにならないといけないのであるが、世界を揺るがす権力志向、拝金主義、日本人の自尊心の喪失がこれを難しくし、上のシステムから脱却できなくしている。

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発行：公益財団法人応用科学研究所

〒606-8202 京都市左京区田中大堰町49

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