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A SYSTEMATIC REVIEW OF COERCIVITY MEASUREMENTS IN THE LIFT OF EFFECT FOR NON-DESTRUCTIVE TESTING METHOD

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ABSTRACT. *Coercivity refers to the intensity of the reverse magnetic field required to demagnetize a material after it has been magnetically saturated. It serves as a crucial indicator of the hardness and stability of magnetic materials. However, the accuracy of coercivity measurements can be compromised by the "lift-off effect," an error caused by air gaps between the sensor and the material surface. This paper proposes a novel method to address this issue by incorporating additional inductance measurements and developing a robust calibration technique. The rationale behind this approach lies in the observation that variations in air gaps influence both coercivity and inductance values. A systematic literature review was conducted following the PRISMA framework to better understand the current state of research and the implementation of such techniques. Searches across ScienceDirect, Scopus, and ProQuest databases yielded 136 documents published between 2014 and 2024 under the keywords: "lift-off effect," "coercivity measurement," "magnetic materials," and "non-destructive testing." Of these, only 17 were original research articles. The review highlights the United Kingdom as the leading contributor to research on reducing the lift-off effect in magnetic plate testing. Collaborations between the United States, Korea, and Poland follow this. The focus of recent studies includes the use of auxiliary inductance data, multi-frequency induction methods, metallic spherical geometry testing, sensor modeling through equivalent parameters, and fibre-optic eddy current sensors for defect detection in magnetic materials. Despite emerging approaches and technological advancements, current research remains fragmented and primarily concentrated on specific sensor designs and material types. There is a notable lack of comprehensive frameworks integrating auxiliary inductance measurements with systematic calibration methods to mitigate the lift-off effect across diverse testing environments. This highlights a critical gap in bridging theoretical insights with practical, scalable applications—an area where further research is urgently needed.*

INTRODUCTION

Coercivity measurements are widely used in industrial applications because they reflect the properties and structural integrity of materials. Coercivity is sensitive to changes in the microstructures of materials and may detect degradation or creep within them (Kikuchi *et al*., 2009; Liu *et al*., 2016; Rumiche *et al*., 2008). Coercivity in stainless steel trends towards Vickers hardness and indicates changes in mechanical properties during the quenching process (Kikuchi *et al*., 2020). The magnetic characteristics of high-carbon steel, such as coercivity and remanence, are connected in three distinct creep stages (Mitra *et al*., 2007), allowing for the non-destructive assessment of interior damage. Coercivity can reflect damage caused by high temperatures and estimate the remaining life of the alloy (Lyu *et al*., 2023).

However, the presence of air gaps between the probe and the test materials negatively impacts the precision and accuracy of coercivity measurement results (lift-off problem) (Stupakov, 2013). This phenomenon poses a serious threat to the coercivity measuring method. Insulation shields, non-standard activities, or abrasive contact surfaces can all contribute to the contact issue. Variations in the gap significantly impact the processes of demagnetization and magnetization (Thomas *et al*., 2012). To accurately estimate the zero-magnetization state, it is also necessary to consider electromagnetic noise effects (Matyuk *et al*., 2003). Many studies aim to minimize or even completely eliminate the lift-off effect. These studies can be divided into two groups: the first aims to reduce the sensitivity of the measuring probe to air gaps (Mazaheri-Tehrani & Faiz, 2022), while the second addresses the lift-off effect on measurement results (Bida, 2010).

This work aims to reduce the lift-off impact on measurement findings. When processing data, it is important to consider factors like magnetic induction and magnetic reluctance, which are very sensitive to fluctuations in the air gap (Balakrishnan *et al*., 1997; Stupakov *et al*., 2010). Conventional coercivity measurements require proximity between the sensor and the sample. However, the sample is always shielded during industrial measurements, and it is expensive to remove and replace the insulating shells. Therefore, using a specially made probe to measure the inductances caused by the air gap would be considerably easier.

The actual coercivity measurement of the sample can be deduced from the measurement result with the air gap by focusing on the relationship between observed coercivity and mutual inductance in the complete magnetic loop when lift-off is present (open-loop measurement). The connection between mutual inductances and coercivity is revealed by measuring the variation tendencies of coercivity and inductances with increasing air gaps for specified samples. The curve can be used to determine a sample's base coercivity from a single coercivity measurement at a random air gap (0 - 15 mm) by extrapolating this connection to subsequent samples. This paper critically evaluates the existing literature and identifies areas for further exploration, clarifying the current research landscape and highlighting promising avenues for future investigation.

LITERATURE REVIEW

Coercivity Measurements Based on Pulse Excitation

Principles and components

Coercivity refers to the strength of the reverse magnetic field required to demagnetize the sample to zero after it has been magnetized to saturation. The coercivity meter created by the University of Manchester's EM sensing group served as the basis for this article. As shown in Figure 1, the coercivity meter consists of a primary device and a measuring probe.

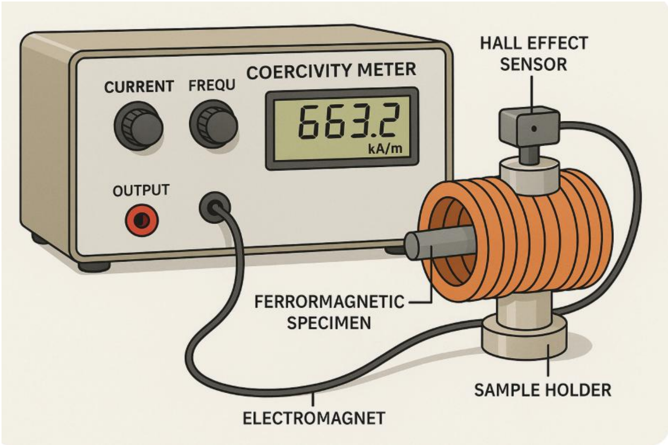

Figure 1. Coercivity meter.

Figure 2 shows the internal structure of the sensor probe, composed of a U-shaped iron core, excitation windings, and Hall-effect sensors. The U-shaped iron core's 25 mm thickness and 64 mm limb allow the magnetic flux to flow through it, greatly minimizing flux leakage. To magnetize the sample being tested to the point of saturation, excitation windings are designed to produce a magnetic field. Numerous magnetic sensors are available to quantify the target sample's magnetic characteristics (Lenz & Edelstein, 2006; Lenz, 1990). Hall-effect sensors are ratiometric devices that can record variations in the strength and direction of magnetic fields. They support wide working bands (10 - 1000 Gauss) (Lenz & Edelstein, 2006; Lenz, 1990; Ramsden, 2011). The iron yoke and the surface of the substance being tested are near the Hall-effect sensors, which are affixed at the tips of each limb. The strength of the magnetic field exerted on the sample is related to the magnitude of the current passing through the sensor.

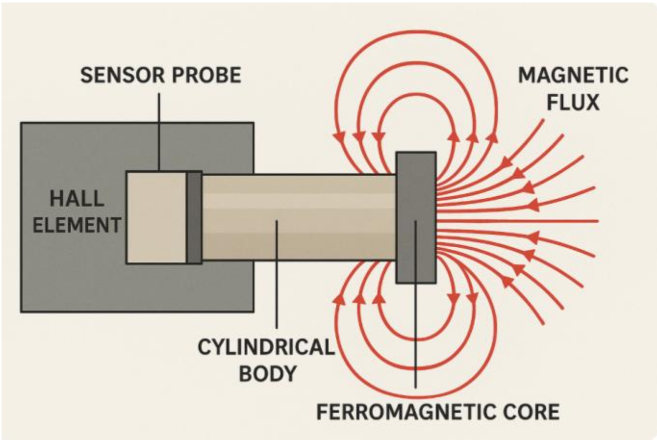

Figure 2. Internal structure of the sensor probe and magnetic flux distribution.

System description

Figure 3 depicts the magnetizing process and the position of the magnetizing stage during the measurement process. The entire measurement process can be divided into the magnetizing process and the coercivity measuring process. During the magnetizing process, the tested samples are subjected to the hysteresis loop. The measurement process starts by triggering the high-voltage excitation module and applying a high-level voltage of up to 350 V to the excitation winding, causing a pulse excitation that magnetizes the sample to reach saturation point 2. The demagnetizing module is turned on after the excitation module is switched off when the voltage output of the Hall sensors reaches its maximum value. The sample is subjected to an opposite-polarity magnetic field by the demagnetizing current, which demagnetizes it to saturation point 3. The entire procedure, applicable to all materials, takes 3.5 seconds. The examined sample returns to retentivity point 4 when the pulse excitation current is turned off, which also causes the externally applied magnetic field to revert to zero. The coercivity measurement procedure starts when the magnetizing process is complete.

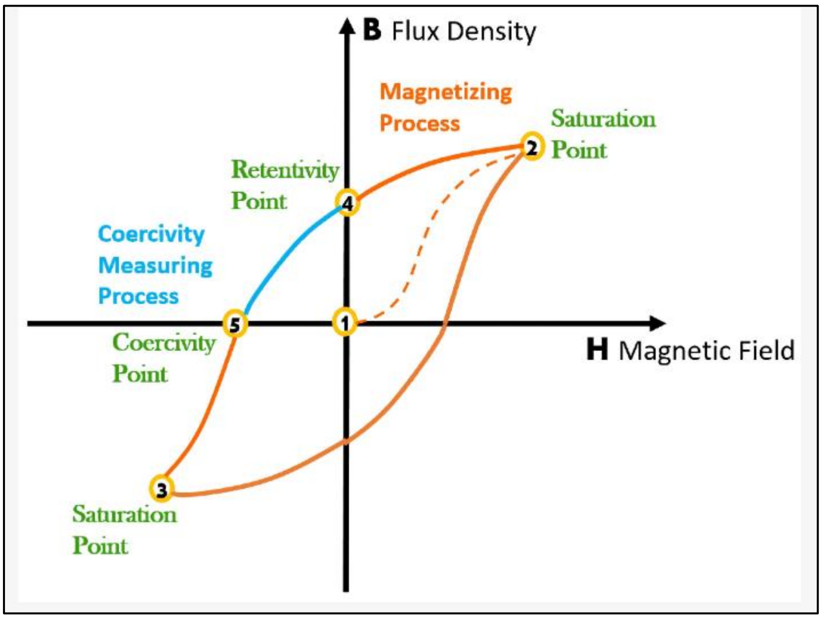

Figure 3. Coercivity meter's magnetizing process.

To measure coercivity, samples are first magnetized to a coercivity point. The coercivity is then calculated by measuring the current flowing through the winding. The material fluctuates near the coercivity point during the measurement procedure, alternating between magnetizing and demagnetizing modes and effectively tracing a very small minor loop. This is accomplished by using Hall sensor feedback to deliver a DC-biased small AC current to the excitation winding. When the sample reaches the coercivity point, the sensor output does not drop to zero. As shown in the internal structure in Figure 4, the non-zero output will be sent to the Hall sensor monitor and used to select the module connected to the windings.

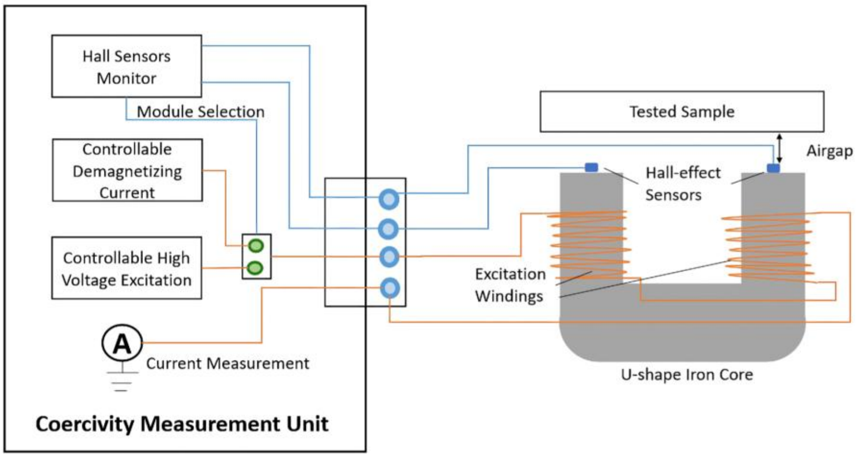

Figure 4. Internal modules of the coercivity meter (Source: Lyu *et al.,* 2023).

Coercivity- Mathematical Approach

The coercivity in magnetic materials is generally defined as the magnetic field intensity (H_C) required to reduce the magnetization (M) of a material to zero after it has been saturated. However, when considering lift-off (i.e., an air gap between the sensor and the material), this introduces a geometric error in measurement, particularly in Eddy current and inductive methods. Therefore, important equations relevant to coercivity and lift-off are given as in equation 1.

$$H_C = H_{M=0} \quad (1)$$

where H_C= coercivity, M = Magnetisation and H= Magnetic field strength.

As for the effect of Lift-Off in Eddy-Current Testing (EC), Lift-Off affects the impedance Z of the sensor due to an increasing air gap (d). The general impedance in Eddy current testing is given as equation 2.

$$Z(d) = R\,(d) + j\omega L(d) \quad (2)$$

where R(d) is the resistance dependent on lift-off distance d; L(d) is the inductance dependent on lift-off, and ω is the angular frequency of the excitation field. As d increases, L(d) decreases, which leads to an incorrect estimation of coercivity if not compensated.

Hence, calibration correction using inductance variation is needed to correct for lift-off in coercivity measurement, which is given as equation 3.

$$H_C^{corrected} = H_C^{measured} + k \cdot \Delta L(d) \quad (3)$$

where k = calibration constant, $\cdot$ $\Delta L(d)$ = change in inductance due to lift-off; $H_C^{measured}$= uncorrected coercivity.

While the sensor signal attenuation due to lift-off is given as equation 4.

$$S(d) = S_0 + e^{-\alpha d} \quad (4)$$

where $S(d)$ = sensor signal at lift-off distance, d; S_0 = signal at zero lift-off; α = decay constant.

Figure 5 shows the sensor signal attenuation due to lift-off. The key takeaway is that lift-off introduces systematic errors that attenuate the magnetic signal and shift the measured coercivity. Compensation can be achieved by analyzing how inductance or signal strength decays with the air gap and using this relationship for calibration.

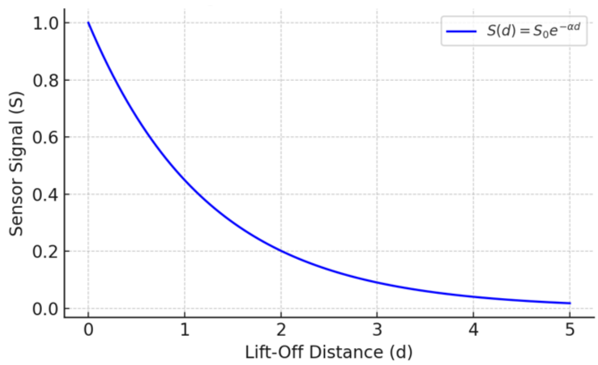

Figure 5. The sensor signal attenuation due to lift-off.

MATERIALS AND METHODS

Article Strategy

The article search for the systematic literature review (SLR) is based on four types of academic databases: Science Direct, Scopus, and ProQuest. These databases were used because they include all journal articles from various sources and are credible. Gusenbauer and Haddaway (2020) stated that the selection of the four base resources includes "search engines," which assist in obtaining appropriate and high-quality studies for systematic research. The search was also implemented with the keyword settings "Lift-off Effect," "Coercivity Measurement," "Magnetic Materials," "Non-Destructive Testing," and "Magnetic Coercivity Measurement" in all three databases. Table 1 shows the keywords used in the article selection process.

Table 1. Article search for SLR database.

Database	Keyword
	"Lift-off Effect"
Science Direct	"Coercivity Measurement"
Scopus	"Magnetic Materials"
ProQuest	"Non-Destructive Testing"
	“Magnetic Coercivity Measurement”
	TITLE-ABS-KEY /Article Title – Abstract - Keywords

Article Selection Criteria

A methodical procedure has been used to filter the search results to obtain accurate and pertinent articles for the research inquiry, as shown in Figure 6. The initial screening stage involves applying acceptance and rejection criteria. The criteria have been meticulously outlined in five steps, encompassing factors such as publication date, reference material, language, methodology, and the field of study of the journal article. This approach ensures that the selected journal article pertains to neuroscience education in the context of online learning, specifically for the SLR objective.

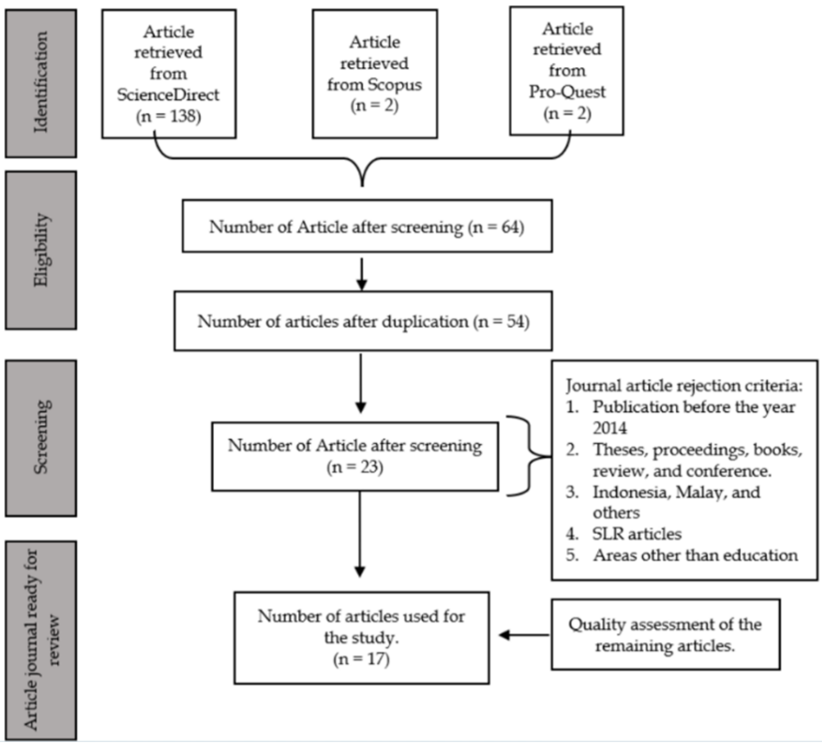

Figure 6. Article Selection Process Flow

The study follows a five-step process to select relevant articles for analysis. The first step involves choosing articles published between 2014 and 2024 to find new information about coercivity measurement and lift-off. The ten-year range is selected to limit the search. In the second step, articles with the same findings or those published repeatedly in different databases are excluded. Only journal articles are selected, while SLR articles, books, proceedings, theses, reviews, and conference papers are excluded. In the third step, only items published in English are selected, and the chosen articles are carefully read for analysis in the fourth step. Any journal article in Indonesian, Malay, or any other language other than English is excluded. The research methods used in each journal article include quantitative, qualitative, and mixed methods. In the fifth step, the study focuses on the areas of "lift-off effect," "coercivity measurement," "magnetic materials," "non-destructive testing," and "magnetic coercivity measurement." Table 2 outlines the acceptance and rejection criteria for journal articles.

Table 2. Article acceptance and rejection criteria.

Database	Acceptance	Rejection
Year of publication	Publication from 2014 - 2024	Publications before 2014
Type of reference material	Journal articles	Theses, proceedings, books, reviews, and conferences
Language	English	Malay, Indonesian, Thailand, and others
Methodology	Quantitative, Qualitative, Mixed method	Systematic Literature Review
Field of study	Non-Destructive Testing	Others
Level	Higher learning Institution Professional Development	

Article Selection Progress

Science Direct, Scopus, and ProQuest are three reputable databases utilized in the study to locate pertinent publications addressing the research topics. Each article's title, abstract, and content were carefully examined to ensure they met the research criteria before selection. The chosen articles were processed and analyzed for data. The PRISMA flow diagram (Moher *et al.,* 2009) is depicted in Figure 6 and describes the steps involved in finding and evaluating publications. In total, 17 papers from various databases were located and used.

RESULTS AND DISCUSSIONS

Out of the 23 publications initially reviewed, 17 met the inclusion criteria following a rigorous screening and quality assessment process. The excluded articles were removed due to insufficient relevance, methodological weaknesses, or duplication. The 17 selected studies, summarized in Table 3, include key details such as publication year, research focus, authorship, and country of origin. These works provide valuable insights into developing non-destructive testing (NDT) methods, particularly in reducing the lift-off effect in coercivity and magnetic property measurements.

The United Kingdom emerged as the leading contributor in this research area, producing six of the 17 selected publications (Figure 7). These studies predominantly focus on advancing sensor technologies, optimizing testing models, and mitigating the lift-off effect through novel techniques. A notable example is the study by Hu (2023), which utilized eddy current techniques for the electromagnetic NDT of metallic spherical geometries. Earlier, Lu *et al*. (2018) explored the reduction of lift-off effects on permeability measurement using multifrequency induction data, setting a precedent for technical innovation in this field. Among the most relevant to this paper is the work by Lyu *et al*. (2023), who proposed a novel approach integrating auxiliary inductance data and a calibration method to reduce lift-off errors in coercivity measurement. Their methodology aligns closely with the objectives of the present study, particularly in addressing how air gap variations impact both inductance and coercivity readings.

Table 3. List of articles analysed in a systematic literature review.

No	Year	Title	Author	Research on	Country
1	2018	Reducing the Lift-Off Effect on Permeability Measurement for Magnetic Plates from Multifrequency Induction Data	Lu *et al.* (2018)	Lift-off variation causes errors in eddy current measurement of nonmagnetic plates as well as magnetic plates. For nonmagnetic plates, previous work has been carried out to address the issue	The United Kingdom
2	2019	Non-destructive testing on creep-degraded 12% Cr-Mo-W-V ferritic test samples using Barkhausen noise	Gupta *et al.* (2019)	The MBNenergy method is employed for evaluating the microstructural changes induced by creep/ageing of high chromium steel subjected to different creep test conditions as stress and temperature.	France & Japan
3	2019	A fast and non-destructive method to evaluate yield strength of cold-rolled steel via incremental permeability	Li *et al.* (2019)	This paper describes the relationship among IP, eddy-current (EC) impedance and microstructure, and discovered a new IP feature that indicates materials' average grain size and lattice friction.	China
4	2022	Magnetic indicators for evaluating plastic strains in electrical steel: Toward non-destructive assessment of the magnetic losses	Zhang *et al.* (2022)	In this study, a setup was designed to stimulate the magnetization mechanisms separately while maintaining the same experimental conditions. The magnetization processes related to the domain wall kinetics were revealed to be more correlated to plastic strain.	France & Japan
5	2022	An evaluation of non-destructive methods for detection of thermally-induced metallurgical machining defects.	Brown *et al.* (2022)	Introduces a recently developed x-ray diffraction method is shown to be capable of detecting thermally induced white layers formed during hard turning, as well the identification of grinding-induced rehardening and tempering.	The United Kingdom
6	2022	Research progress on magnetic memory nondestructive testing.	Xu *et al.* (2022)	This paper systematically reviews the progress of magnetic memory research in the past 20 years in terms of theoretical studies on the coupling of force-magnetic effects, factors influencing weak magnetic signals, defect identification, and quantification studies.	China
7	2023	Non-destructive surface and subsurface characterization of the machined parts by using a fiber optic Eddy current sensor	Kim *et al.* (2023)	Introduces a fiber-optic eddy current sensor (FECS) to enable non-destructive surface and subsurface characterization of the subtractive or additive manufactured metal parts practical way of using the method of evaluating the metrological properties of eddy current sensors.	The United States & Korea

Continue **Table 3.** List of articles analysed in a systematic literature review.

No	Year	Title	Author	Research on	Country
8	2023	Evaluation of the Properties of Eddy Current Sensors Based on Their Equivalent Parameters	Dziczkowski & Tytko (2023)	A practical way of using the method of evaluating the metrological properties of eddy current sensors. The idea of the proposed approach consists of employing a mathematical model of an ideal filamentary coil to determine equivalent parameters of the sensor and sensitivity coefficients of tested physical quantities.	Poland
9 *	2023	A Novel Method for Reducing the Lift-Off Effect in Coercivity Measurement through Auxiliary	Lyu *et al.* (2023)	This paper proposes a new method to address this issue by incorporating additional inductance measurements and formulating a calibration method. The calibration principle is based on the fact that both the coercivity and the inductance measurements change with the variation of air gaps.	The United Kingdom
10	2023	Application of Eddy Current Techniques in Electromagnetic Non-Destructive Testing of Metallic Spherical Geometry	Hu (2023)	Introduces two strategies to counteract the lift-off effect. Firstly, a method leveraging a linear eddy-current characteristic identifies the ball's diameter without contact. A key insight is the peak frequency feature relating to the lift-off spacing between the coil's center and the ball.	The United Kingdom
11	2023	Non-destructive evaluation of magnetic anisotropy associated with crystallographic texture of interstitial free steels	Jolfaei *et al.* (2023)	The findings indicate that the non-destructive technique deployed in this study - a U-shaped electromagnetic (EM) sensor that can be placed onto a sheet specimen - is promising for a rapid assessment of the magnetic anisotropy in IF steels.	The United Kingdom & Netherland
12	2023	Coercivity modulation of FeCoCrMoTi films by artificial magnetic phase defects engineering based on multilayer structure	Liu *et al.* (2023)	Demonstrated an in-plane anisotropic [Ta(20nm)/FeCoCrMoTi(100 nm)]2/Ta(10 nm) multilayer film (M20 sample) with a high coercivity of 945 Oe and a sufficient remanent magnetization of 2890 Oe, which is 92.1% and 63.1% higher than FeCoCrMoTi(200 nm)/Ta(10 nm) film (SL sample), respectively.	China
13	2024	Non-destructive testing of ferromagnetic steel components based on their magnetic response	Ducharne (2024)	Introduces the non-destructive testing (NDT) methods based on the magnetization mechanisms. Then, the targeted properties, that is, the specific information required by the industrials or NDT end-users, are described (internal stress, microstructural properties, to name a few).	France

Continue **Table 3.** List of articles analysed in a systematic literature review.

No	Year	Title	Author	Research on	Country
14	2024	Design of a multi-modal sensor for the in-process measurement of material properties based on inductive spectroscopy	Wendler *et al.* (2024)	This paper proposes a robust contactless multi-modal sensor for the in-process measurement of material magnetic properties composed of a central excitation coil surrounded by eight receiving coils.	Germany
15	2024	Characterization on multiphase microstructures of carbon steels using multi-frequency electromagnetic measurements	Shen *et al.* (2024)	This paper studied responses of electromagnetic signals on carbon steels with different phase compositions using a U-shaped and a cylindrical electromagnetic sensor.	The United Kingdom & China
16	2024	Experimental and theoretical study of the harmonic distortion in a ferromagnetic plate excited by a pair of air-cored coils.	Skarlatos & Poulakis, (2024)	This paper studies the harmonic distortion in a ferromagnetic plate. The electromagnetic field inside the specimen is excited by a couple of air-cored coils, and the field is measured at a specific location using a set of Hall sensors.	Greece & France
17	2024	Parametric design methodology for yoke-magnetization in magnetic flux leakage detection systems	Lam *et al.* (2024)	This paper proposes a systematic design procedure for the yoke-magnetization component in MFL systems utilizing permanent magnets.	Vietnam

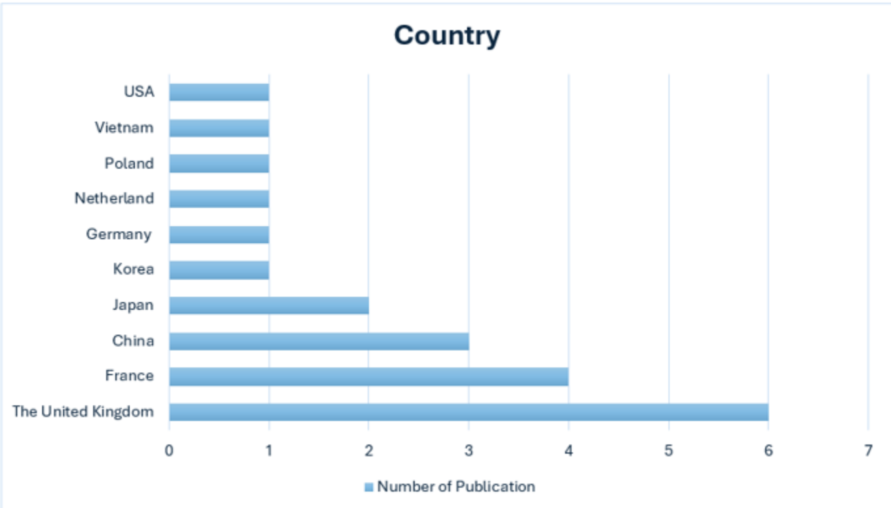

Figure 7. Tendencies of countries in article publications.

Research from France and Japan reflects a different emphasis, often involving experimental designs that isolate specific magnetization mechanisms under controlled conditions. Meanwhile, studies from China tend to centre on the correlation between eddy current impedance, incremental permeability, and material microstructure, highlighting the influence of electromagnetic properties on material evaluation. Poland's contribution introduces a mathematical modelling approach using an ideal filamentary coil to derive equivalent sensor parameters and sensitivity coefficients, indicating a strong theoretical orientation. Conversely, the United States and Korea have collaborated on fibre-optic eddy current sensors for surface and subsurface characterization, showcasing applied sensor innovation in advanced manufacturing contexts. The cumulative literature reflects a global interest in refining NDT techniques; yet gaps remain, particularly in applying these methods to a broader range of magnetic materials. While current studies largely focus on specific alloys or configurations, there is limited empirical work on coercivity measurements across various materials such as cobalt, nickel, iron, and steel. By incorporating these materials, the present study extends the applicability of lift-off mitigation strategies, contributing novel insights to the field.

CONCLUSION

From 2014 to 2024, there were relatively few published studies on the lift-off effect in coercivity measurements of magnetic materials. The United Kingdom dominated in publishing related to coercivity measurement and the lift-off effect compared to other countries. In conclusion, the systematic review of literature on the lift-off effect in coercivity measurement of magnetic materials highlights the significant influence of non-ideal conditions during testing. The lift-off effect, which arises from the separation between the measurement sensor and the material surface, can lead to inaccuracies in coercivity readings, particularly in soft magnetic materials where precise measurements are crucial. Addressing the lift-off effect is vital for improving the accuracy and reliability of coercivity measurements. Future research should focus on enhancing sensor technology, developing standardized protocols to minimize lift-off variation, and creating robust mathematical models to correct for lift-off-induced errors. Additionally, different materials can also be suggested as samples. By doing so, the precision of magnetic material testing can be significantly improved, leading to better material performance in various industrial applications.

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