Sensitivity Analysis of Multi-Parameter Magnetic Control Indicators for determining the Mechanical Properties of Steel

Alibek Zhakupov
Toraighyrov University, Pavlodar, Kazakhstan
zhakupov.a@tou.edu.kz

Aray Zhakupova
Toraighyrov University, Pavlodar, Kazakhstan
zhakupova.a@tou.edu.kz (corresponding author)

Alexey Bogomolov
Toraighyrov University, Pavlodar, Kazakhstan
bogomolov.a@tou.edu.kz

Received: 14 August 2024 | Revised: 18 September 2024 | Accepted: 22 September 2024

 DOI: https://doi.org/10.48084/etasr.8745

ABSTRACT

This paper presents the results of a steel magnetic property study using a non-destructive method of determination of the mechanical properties of products made from structural steels 20, 09Mn2Si, and 25CrMoV. The influence of tempering temperature on the change of magnetic properties was analyzed and a statistical analysis of the input parameter significance, including coercive force, residual magnetic induction, and maximum magnetic permeability, was carried out. As a result, it was found that the greatest sensitivity for steels at tempering temperatures up to 400 °C is the coercive force and, above 300 °C, the residual magnetic induction. At the same time, the maximum magnetic permeability provides a correlation over the whole range of tempering temperatures, justifying the use of magnetic properties in the determination of mechanical properties.

Keywords-coercive force; residual magnetic induction; maximum magnetic permeability; non-destructive testing

I. INTRODUCTION

Magnetic methods are widely employed non-destructive methods that control the ferromagnetic material structural state after various types of heat treatment [1-5]. These methods are based on the relationship between the structural state of the metal after heat treatment and its magnetic characteristics. It cannot be stated that the control problems in this area have been completely solved, because in most cases the found dependencies have high reliability and information content only for a limited range of materials and their structural-phase states [6]. There are known works [7-10] in which coercive force is utilized as a parameter applied to control the hardness of steel. Despite the positive aspects of using coercive force as a criterion, the applicability of this approach is currently somewhat limited, due to the lack of a general pattern regarding the change in mechanical properties and coercive force for different grades of steel with different processing [11-15]. In [16], the dependencies of coercive force, residual magnetic induction, relaxation magnetization, and other magnetic characteristics of steel on heat treatment, hardening and subsequent aging modes were studied. By replacing one parameter with another, it is impossible to obtain a universal dependence for a large group of steels, the mechanical properties of which depend on a large number of factors (chemical, phase, and structural composition). It is quite expected that by using several different magnetic parameters simultaneously, the reliability of determining the mechanical properties will increase. In this regard, the characteristics of the magnetic hysteresis loop are preferable [17]. Due to the ambiguity of the data presented on the presence of a correlation between certain magnetic characteristics and mechanical properties for different grades of steel, the possibility of utilizing a set of magnetic characteristics for a more accurate determination of mechanical properties has been considered [18-21]. Mechanical stresses caused by various manufacturing processes introduce significant changes in the magnetic properties. Internal stresses can prevent magnetization, leading to an increase in coercive force and a decrease in magnetic permeability [22-26]. Heat treatment, such as tempering, plays an important role in the formation of magnetic properties after machining. This process helps to relieve internal stresses and create an optimal microstructure of the crystal lattice [27-31].

This study is a continuation of [32], which proposed a methodology for the integrated application of coercive force, residual magnetic induction, and maximum magnetic permeability values to determine the mechanical properties of steel products. This technique is applicable to any ferromagnetic material. At the same time, the sensitivity of each magnetic parameter manifests itself differently in different types of heat treatment. Therefore, this paper analyzes the effect of each parameter on the degree of steel hardening or de-hardening [33-36]. The aim of the study is to identify the sensitivity of magnetic parameters in determining mechanical properties by deploying non-destructive methods.

II. STUDY OBJECTS AND RESEARCH METHODS

The study objects were samples from 20, 09Mn2Si, and 25CrMoV steel. The sensitivity and reliability of each indicator of the steel magnetic properties was carried out on the basis of experimental data acquisition and statistical analysis. Magnetic measurements were performed using a KIM-2M coercimeter and a 43205M teslameter. Mechanical tests were conducted on a WDW-200 tensile testing machine (Figure 1).

Fig. 1. Devices for determining magnetic and mechanical properties: (a) KIM-2M coercimeter, (b) 43205M teslameter, (c) WDW-200 tensile testing machine.

III. RESULTS AND DISCUSSION

Since the heat treatment of structural steel products determines their consumer qualities, it is of practical interest to establish relationships between the tempering temperature and the magnetic characteristics of these steel grades in order to establish magnetic parameters that can be used as a basis for the construction of a particular non-destructive testing magnetic method. To determine the sensitivity of magnetic parameters, samples of 20, 09Mn2Si, and 25CrMoV steels were heat treated. The heat treatment consisted of quenching the samples at a temperature of 880 °C and subsequent tempering in the temperature range of 20-700 °C. After that, the magnetic properties were measured and tensile tests were conducted. The results are presented in Table I and Figures 2-4.

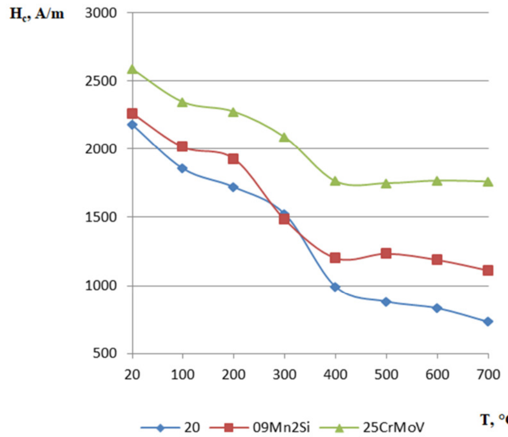

Fig. 2. Dependence of coercive force on tempering temperature.

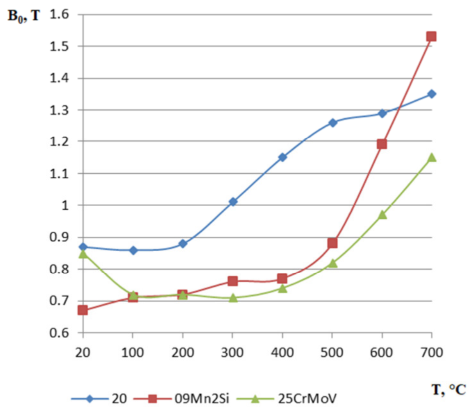

Fig. 3. Dependence of residual magnetic induction on tempering temperature.

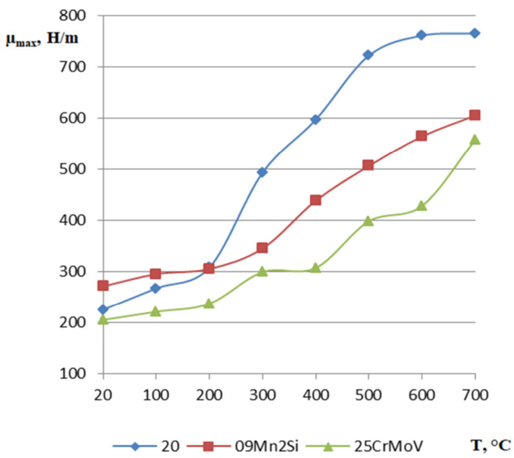

Fig. 4. Dependence of maximum magnetic permeability on tempering temperature.

TABLE I. MAGNETIC AND MECHANICAL PROPERTIES OF STEEL SAMPLES

Steel	Tempering temperature, °C	Mechanical properties		Magnetic properties		
		Tensile strength, MPa	Yield strength, MPa	Coercive force, A/m	Residual magnetic induction, T	Maximum magnetic permeability, H/m
20	20	1172	950	2178	0.87	225
	100	1024	878	1855	0.86	267
	200	992	815	1720	0.88	308
	300	869	719	1522	1.01	493
	400	785	634	991	1.15	597
	500	728	574	882	1.26	722
	600	684	556	833	1.29	761
	700	672	523	732	1.35	765
09Mn2Si	20	1128	850	2261	0.67	271
	100	1085	803	2013	0.71	295
	200	1029	794	1927	0.72	305
	300	972	740	1481	0.76	345
	400	751	697	1201	0.77	438
	500	705	634	1234	0.88	506
	600	684	577	1188	1.19	564
	700	652	530	1111	1.53	605
25CrMoV	20	1276	972	2586	0.85	205
	100	1081	911	2345	0.72	221
	200	976	852	2275	0.72	237
	300	878	784	2086	0.71	299
	400	835	742	1762	0.74	307
	500	772	702	1749	0.82	398
	600	735	660	1768	0.97	428
	700	668	582	1761	1.15	557

As can be seen in Figure 2, the coercive force monotonically decreases only for products made of steel 20. For the other steels, monotonicity is observed only up to the tempering temperature of 400 °C. The decrease of coercive force H_c in the specified interval of tempering temperatures is caused by the reduction of the resulting magnetic anisotropy due to the decomposition of martensite in connection with the release of carbon from it. This leads to a decrease in internal stresses, as well as to the disappearance of magnetic scattering fields as the residual austenite decays. The ambiguous behavior of this magnetic parameter at tempering temperature above 400 °C is related to the amount and dispersion of the weakly magnetic carbide phase, which is observed in 09Mn2Si and 25CrMoV steels alloyed with carbide-forming elements. In addition, the non-monotonicity of the alternating growth and the decline of the coercivity are associated with the increase of carbide particles due to the decrease in the total area of domain boundaries and the increase in the energy required to increase this area. Thus, unlike ordinary quality steels, the coercive force has a correlation with the mechanical properties of alloyed steels only at low-temperature tempering (up to 400 °C).

Figure 3 shows the results of residual magnetic induction measurements. Residual magnetic induction depends mainly on the phase composition of steel, and does not depend on the shape, dispersion, and stress state of the metal. According to the graph, up to the tempering temperature of 300 °C, the residual magnetic induction on all steels has a minimum value associated with the absence of phase redistribution. Further growth of residual magnetic induction at tempering is a consequence of the paramagnetic residual austenite decomposition. Thus, up to the temperature of 300 °C, there is an ambiguity of values (kinks of the curve), which does not allow it to be used as a reliable parameter for determining the mechanical properties. This, in turn, leads to the conclusion that the use of residual magnetic induction as an informative parameter in non-destructive testing is recommended for all types of steels only at medium- and high-temperature tempering.

Figure 4 illustrates the variation of the maximum magnetic permeability. As can be observed in the diagram, for all three steels there is a definite increase in values with increasing tempering temperature, which allows for the assertion that it can be used in the whole interval of tempering temperature variation. This is due to the characteristic of the value itself, which characterizes the relationship between the strength and the magnetization of the material. Thus, the maximum magnetic permeability is the most universal parameter. However, its use as the only parameter for determining the mechanical properties utilizing non-destructive methods increases the measurement error. At the same time, high correlation of coercive force appears at tempering temperature of steel up to 400 °C, and for medium- and high-temperature tempering (300-700 °C) the residual magnetic induction is the best. In this connection, the use of a complex measurement of all three parameters, taking into account all modes of heat treatment, is justified.

After the experimental work, a statistical analysis of the significance of each factor was carried out. The results obtained by the regression analysis of the magnetic and mechanical property value correlation dependence for pipe samples made of 20, 09Mn2Si, and 25CrMoV steels are presented in Tables II-IV.

TABLE II. T-STATISTIC FOR STEEL 20

Parameter	Coefficient	T-statistic	Parameter	Coefficient	T-statistic
T_s	293.8125	1.14835706	Y_s	501.9701	2.763318632
H_c	0.227354	2.908465627	H_c	0.15999	2.882703835
B_0	630.4131	2.346003849	B_0	248.4246	1.302100209
μ_{max}	-0.80373	-2.58590077	μ_{max}	-0.54001	-2.447109177

TABLE III. T-STATISTIC FOR STEEL 09MN2SI

Parameter	Coefficient	T-statistic	Parameter	Coefficient	T-statistic
T_s	1158.364	7.18552258	Y_s	890.2707	11.93692723
H_c	0.111239	1.964457872	H_c	0.063434	2.421386667
B_0	198.5359	2.529996028	B_0	-90.7053	-2.498451122
μ_{max}	-1.52522	-4.981458757	μ_{max}	-0.48932	-3.454431524

TABLE IV. T-STATISTIC FOR STEEL 25CRMOV

Parameter	Coefficient	T-statistic	Parameter	Coefficient	T-statistic
T_s	522.742	1.617396152	Y_s	655.8078	4.681529568
H_c	0.188942	1.179898544	H_c	0.144732	2.085268993
B_0	698.3893	1.90876182	B_0	123.1082	0.776288914
μ_{max}	-1.77677	-2.447545958	μ_{max}	-0.83997	-2.669587975

The following relationships between the magnetic (coercive force H_c, residual magnetic induction B_0, maximum magnetic permeability μ_{max}) and mechanical (tensile strength T_s, yield strength Y_s) properties were obtained by the regression analysis:

- Regression equations for steel 20:

$$T_s = 293.812 + 0.227H_c + 630.413B_0 - 0.804\mu_{max}$$

$$Y_s = 501.970 + 0.160H_c + 248.425B_0 - 0.540\mu_{max}$$

- Regression equations for steel 09Mn2Si:

$$T_s = 1158.364 + 0.111H_c + 198.536B_0 - 1.525\mu_{max}$$

$$Y_s = 890.271 + 0.063H_c - 90.705B_0 - 0.489\mu_{max}$$

- Regression equation for steel 25CrMoV:

$$T_s = 522.742 + 0.189H_c + 698.389B_0 - 1.777\mu_{max}$$

$$Y_s = 655.808 + 0.145H_c + 123.108B_0 - 0.840\mu_{max}$$

Furthermore, through the deployment of regression analysis according to the student criterion, the significance of the input factors, which are coercive force, residual magnetic induction, and maximum magnetic permeability, was checked. The output parameters were the strength properties of steel: tensile strength and yield strength. The student criterion test confirmed the analysis of the curves of the magnetic property dependence on tempering temperature (Figure 2-4) made above. At the same time, the values presented in Tables II-IV were obtained.

Analyzing the results, we can see that for steel 20 (Table II), the value of *t*-statistic when analyzing the parameters of the dependence (t=2.346 for determining tensile strength and t=1.302 for determining yield strength) at B_0 is less than the tabulated 2.447 at k=6 degrees of freedom under the condition k=n–2 (where n=8 is the number of observations) and 0.95 confidence level of.

That confirms the weak dependence of this parameter on determining the strength properties of steel. For steel 09Mn2Si and 25CrMoV, the coefficients of coercive force are insignificant, which also confirms the low correlation. In addition, for 25CrMoV steel, the coefficient of residual magnetic induction is also insignificant.

The statistical analysis of the data obtained after measuring the magnetic properties and mechanical tests confirmed the curve analysis. It has been established that the sensitivity of magnetic parameters depends on the phase composition and the structure of steel, requiring an individual approach to determine diagnostic indicators for each steel grade. It has been identified that the coercive force has the greatest sensitivity for the steels under study at tempering temperatures up to 400 °C, and the residual magnetic induction above 300 °C. At the same time, the maximum magnetic permeability ensures correlation in the entire range of tempering temperatures. Thus, the advantages of the applied complex magnetic method for determining mechanical properties, in addition to the sufficient accuracy of determination, are its versatility, applicability to various grades of steel, and efficiency, because it does not require much time to determine the quantitative indicators of the mechanical properties of steel.

IV. CONCLUSION

As a result of the current work, the relationships between the magnetic and mechanical properties of steels 20, 09Mn2Si, and 25CrMoV were established. According to the data obtained, heat treatment temperatures were determined for each steel grade, in the range of which the magnetic parameters have sufficient sensitivity to changes in mechanical properties. The non-monotonicity of the change in the coercive force and residual magnetic induction at different tempering temperatures of steels was substantiated.

Using mathematical methods, the presence of a regular relationship between the magnetic and mechanical properties of steel was determined, allowing for a non-destructive method to identify the tensile and yield strengths of the studied steels. Regression equations were calculated utilizing the measurements of magnetic characteristics and the tensile test results. By means of variance analysis, a test was made to examine the significance of the input parameters using the student criterion, as a result of which the low significance of magnetic parameters with non-monotonic changes in the coercive force and residual magnetic induction depending on the heat treatment temperature was confirmed. Thus, the results of the present study provide new knowledge and information on the effect of the changes in the composition and structure of steels on their magnetic properties. The current study leads to the conclusion that it is impossible to use one parameter to determine mechanical properties, due to the fact that with a change in the structure and phase composition of steel, during its strengthening, some magnetic indicators lose sensitivity, which in turn reduces the reliability and accuracy of determining mechanical properties. It has been established that the use of complex measurements of coercive force, residual magnetic induction, and maximum magnetic permeability provides maximum accuracy in determining the mechanical properties over the entire range of tempering temperature changes.

ACKNOWLEDGMENT

This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan within the framework of grant funding of young scientists for scientific and (or) scientific and technical projects for 2022-2024 under the IRN AP13268736 project "Non-destructive method for determining the mechanical properties of steel products."

REFERENCES

[1] I. Tomas, O. Stupakov, J. Kadlecova, and O. Perevertov, "Magnetic adaptive testing—low magnetization, high sensitivity assessment of material modifications," *Journal of Magnetism and Magnetic Materials*, vol. 304, no. 2, pp. 168–171, Sep. 2006, https://doi.org/10.1016/j.jmmm.2006.02.126.

[2] A. Zhakupov, A. Bogomolov, A. Zhakupova, S. Abdulina, and V. Salina, "Determination of technological parameters for continiuous casting of a hollow pipe billet," *Metalurgija*, vol. 60, no. 3–4, pp. 329–331, Jul. 2021.

[3] A. Stashkov, A. Nichipuruk, V. Kuleev, and E. Schapova, "Magnetic non-destructive testing of residual stresses in low carbon steels," *Journal of Physics: Conference Series*, vol. 1389, Nov. 2019, Art. no. 012032, https://doi.org/10.1088/1742-6596/1389/1/012032.

[4] I. K. Tsybriy, N. S. Koval, and I. A. Topolskaya, "Coercimeter for non-destructive control of solid alloys," *Journal of Physics: Conference Series*, vol. 2131, no. 5, Dec. 2021, Art. no. 052042, https://doi.org/10.1088/1742-6596/2131/5/052042.

[5] C. Hu, X. Bai, M. Tang, X. Tang, and Z. Zhao, "Non-destructive Measurement of Magnetic Properties of Claw Pole," *Chinese Journal of Mechanical Engineering*, vol. 32, no. 1, Oct. 2019, Art. no. 82, https://doi.org/10.1186/s10033-019-0395-x.

[6] R. Shang-kun, O. Yang-chun, F. Ren-zhen, and F. Yue-wen, "MAGNETIC MEMORY TESTING: Studies on stress-magnetism coupling effect for 35 steel components," *Insight - Non-Destructive Testing and Condition Monitoring*, vol. 52, no. 6, pp. 305–309, Jun. 2010, https://doi.org/10.1784/insi.2010.52.6.305.

[7] D. P. Bulte and R. A. Langman, "Origins of the magnetomechanical effect," *Journal of Magnetism and Magnetic Materials*, vol. 251, no. 2, pp. 229–243, Oct. 2002, https://doi.org/10.1016/S0304-8853(02)00588-7.

[8] A. N. Stashkov, E. A. Schapova, A. P. Nichipuruk, and A. V. Korolev, "Magnetic incremental permeability as indicator of compression stress in low-carbon steel," *NDT & E International*, vol. 118, Mar. 2021, Art. no. 102398, https://doi.org/10.1016/j.ndteint.2020.102398.

[9] J. M. Makar and B. K. Tanner, "The in situ measurement of the effect of plastic deformation on the magnetic properties of steel: Part I – Hysteresis loops and magnetostriction," *Journal of Magnetism and Magnetic Materials*, vol. 184, no. 2, pp. 193–208, Apr. 1998, https://doi.org/10.1016/S0304-8853(97)01129-3.

[10] P. Shi, S. Su, and Z. Chen, "Overview of Researches on the Nondestructive Testing Method of Metal Magnetic Memory: Status and Challenges," *Journal of Nondestructive Evaluation*, vol. 39, no. 2, May 2020, Art. no. 43, https://doi.org/10.1007/s10921-020-00688-z.

[11] R. Rautioaho, P. Karjalainen, and M. Moilanen, "Stress response of Barkhausen noise and coercive force in 9Ni steel," *Journal of Magnetism and Magnetic Materials*, vol. 68, no. 3, pp. 321–327, Sep. 1987, https://doi.org/10.1016/0304-8853(87)90008-4.

[12] C.-G. Stefanita, D. L. Atherton, and L. Clapham, "Plastic versus elastic deformation effects on magnetic Barkhausen noise in steel," *Acta Materialia*, vol. 48, no. 13, pp. 3545–3551, Aug. 2000, https://doi.org/10.1016/S1359-6454(00)00134-8.

[13] T. W. Krause, L. Clapham, A. Pattantyus, and D. L. Atherton, "Investigation of the stress-dependent magnetic easy axis in steel using magnetic Barkhausen noise," *Journal of Applied Physics*, vol. 79, no. 8, pp. 4242–4252, Apr. 1996, https://doi.org/10.1063/1.361878.

[14] T. Inaguma, H. Sakamoto, and M. Hasegawa, "Stress Dependence of Barkhausen Noise in Spheroidized Cementite Carbon Steel," *IEEE Transactions on Magnetics*, vol. 49, no. 4, pp. 1310–1317, Apr. 2013, https://doi.org/10.1109/TMAG.2012.2220856.

[15] O. Kypris, I. C. Nlebedim, and D. C. Jiles, "Measuring stress variation with depth using Barkhausen signals," *Journal of Magnetism and Magnetic Materials*, vol. 407, pp. 377–395, Jun. 2016, https://doi.org/10.1016/j.jmmm.2016.01.072.

[16] D. C. Jiles and W. Kiarie, "An Integrated Model of Magnetic Hysteresis, the Magnetomechanical Effect, and the Barkhausen Effect," *IEEE Transactions on Magnetics*, vol. 57, no. 2, pp. 1–11, Feb. 2021, https://doi.org/10.1109/TMAG.2020.3034208.

[17] C. S. Schneider and J. M. Richardson, "Biaxial magnetoelasticity in steels," *Journal of Applied Physics*, vol. 53, no. 11, pp. 8136–8138, Nov. 1982, https://doi.org/10.1063/1.330341.

[18] M. J. Sablik *et al.*, "Micromagnetic model for biaxial stress effects on magnetic properties," *Journal of Magnetism and Magnetic Materials*, vol. 132, no. 1, pp. 131–148, Apr. 1994, https://doi.org/10.1016/0304-8853(94)90307-7.

[19] V. Maurel, F. Ossart, Y. Marco, and R. Billardon, "Setup to test biaxial stress effect on magnetomechanic coupling," *Journal of Applied Physics*, vol. 93, no. 10, pp. 7115–7117, May 2003, https://doi.org/10.1063/1.1557307.

[20] J. Zeng, L. Su, L. Xu, X. Zhang, and Q. Zhang, "Research on the Stress Measurement of Steel Plate Based on Inverse Magnetostrictive Effect," *Journal of Mechanical Engineering*, vol. 50, no. 8, pp. 17–22, Apr. 2014, https://doi.org/10.3901/JME.2014.08.017.

[21] D. Lihong, X. Binshi, D. Shiyun, C. Qunzhi, and W. Dan, "Variation of stress-induced magnetic signals during tensile testing of ferromagnetic steels," *NDT & E International*, vol. 41, no. 3, pp. 184–189, Apr. 2008, https://doi.org/10.1016/j.ndteint.2007.10.003.

[22] T. Inoue, K. Yamauchi, and F. Fujita, "Effects of Alloying Element Balance and Micro-Alloying Elements on Magnetic Properties and Hot Ductility of PC Permalloy," *Materials Transactions*, vol. 49, no. 3, pp. 650–654, 2008, https://doi.org/10.2320/matertrans.MER2007235.

[23] A. T. Zhakupova, A. V. Bogomolov, and A. N. Zhakupov, "The Influence of the Initial Billet on the Mechanical Properties of Pipes," *IOP Conference Series: Materials Science and Engineering*, vol. 969, no. 1, Nov. 2020, Art. no. 012033, https://doi.org/10.1088/1757-899X/969/1/012033.

[24] A. V. Bogomolov, A. N. Zhakupov, A. T. Kanayev, I. A. Sikach, and K. K. Tugumov, "Comparative Structural Strength Research of Hardened Carbon Steel and Hot-Rolled Alloy Steel," *IOP Conference Series: Materials Science and Engineering*, vol. 142, no. 1, Aug. 2016, Art. no. 012076, https://doi.org/10.1088/1757-899X/142/1/012076.

[25] T. H. Danh and L. H. Ky, "Optimization of Wheel Dressing Technological Parameters when Grinding Hardox 500 Steel," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15854–15859, Aug. 2024, https://doi.org/10.48084/etasr.7986.

[26] C. Sukkam and S. Chaijit, "Investigation of Influencing Factors on Surface Quality during Low-Speed Cutting of Steels with a Hardness exceeding 50 HRC for forging Dies," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14056–14061, Jun. 2024, https://doi.org/10.48084/etasr.7079.

[27] F. H. Fahmi and S. Al-Zaidee, "Strength and Deflection Reliability Estimation of Girder Steel Portal Frames Using the Bayesian Updating Method," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9584–9589, Dec. 2022, https://doi.org/10.48084/etasr.5261.

[28] G. V. Bida and A. P. Nichipuruk, "Multiparameter methods in magnetic structuroscopy and nondestructive testing of mechanical properties of steels," *Russian Journal of Nondestructive Testing*, vol. 43, no. 8, pp. 493–509, Aug. 2007, https://doi.org/10.1134/S1061830907080013.

[29] Q. Gu, X. Huang, J. Xi, and Z. Gao, "The Influence of Magnetic Field on Fatigue and Mechanical Properties of a 35CrMo Steel," *Metals*, vol. 11, no. 4, Apr. 2021, Art. no. 542, https://doi.org/10.3390/met11040542.

[30] J. N. Mohapatra, S. Mohanty, S. K. Dabbiru, and I. Tripathy, "Correlation of Magnetic Properties with Mechanical Properties of a High Tensile Grade Steel in Various Heat Treated Conditions," *Transactions of the Indian Institute of Metals*, vol. 71, no. 10, pp. 2361–2374, Oct. 2018, https://doi.org/10.1007/s12666-018-1367-z.

[31] J. Ge, S. Q. Su, W. Wang, and H. Guo, "Experimental and theoretical research on relation between magnetic and mechanical property of structural I-steel column," *AIP Advances*, vol. 12, no. 2, Feb. 2022, Art. no. 025303, https://doi.org/10.1063/5.0075832.

[32] A. Zhakupov, A. Bogomolov, and A. Zhakupova, "Multiparameter Magnetic Method for Mechanical Properties Determination of Products Made of 13CrV Steel," *International Review of Mechanical Engineering*, vol. 17, no. 12, pp. 599–604, Dec. 2023, https://doi.org/10.15866/ireme.v17i12.23986.

[33] E. M. Akhatar *et al.*, "Non-Destructive Control of Lubricating Oil Degradation by Using Ultrasonic Through Reflection Method," *International Review of Mechanical Engineering*, vol. 16, no. 8, pp. 451–459, Aug. 2022, https://doi.org/10.15866/ireme.v16i8.22584.

[34] B. Irissi, I. Aboudaoud, D. Izbaim, E. H. Ouacha, H. Lotfi, and B. Faiz, "Ultrasonic Based Testing Method for the Symmetry and Dissymmetry Analysis of the Bonding Quality of a Three-Layer Bonded Structure," *International Review on Modelling and Simulations*, vol. 16, no. 3, pp. 155–165, Jun. 2023, https://doi.org/10.15866/iremos.v16i3.23558.

[35] R. Langman, "Magnetic properties of mild steel under conditions of biaxial stress," *IEEE Transactions on Magnetics*, vol. 26, no. 4, pp. 1246–1251, Jul. 1990, https://doi.org/10.1109/20.54015.

[36] H. Kikuchi, H. Murakami, and K. Ara, "Feasibility study for nondestructive evaluation of magnetic properties and hardness of two-layered specimens by magnetic single-yoke probe," *NDT & E International*, vol. 46, pp. 1–6, Mar. 2012, https://doi.org/10.1016/j.ndteint.2011.10.009.