Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume II, 345-349

Influence of Strength Characteristics on the Technological Parameters of the Boroaluminizing Process

Beata Vlahova
dep. "Automotive Engineering and Transport Logistics"
National Military University "V. Levski"
Veliko Tarnovo, Bulgaria
E-mail: beata_mineva@abv.bg

***Abstract*— At present, data on the influence of boroaluminizing on the mechanical properties of steels are scarce and contradictory. This publication presents a mathematical model for determining the strength characteristics of medium-alloyed quality steel and their influence on the technological characteristics of the boroaluminizing process (saturation times, quenching and tempering temperatures). Based on the mathematical model, graphical relationships for Rm, $R_{0.2}$ and A_5 as a function of the technological characteristics of the boroaluminizing process have been developed.**

Keywords— boroaluminizing, diffusion, proportional limit, relative elongation, tensile strength.

I. Introduction

The development of modern mechanical engineering and other branches of industry in the context of Industry 4.0 is inextricably linked to placing high demands on the properties of parts and tools [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

There are increasingly frequent cases when structural and tool materials must have high hardness, strength and resistance in oxidizing and highly aggressive environments. All this can be achieved with the methods of chemical-thermal treatment. In this technological process, diffusion layers with fundamentally new phases are created on the surface, fully satisfying the set requirements. Moreover, the formed diffusion layer, as a result of reducing defects in the structure of the part, brings its working surface closer to the ideal, which increases the durability of the product as a whole [11, 12].

The choice of saturating elements is determined by the desired complex of mechanical properties of the particular part, but in any case it is necessary that the formation of the diffusion layer is accompanied by a decrease in the thermodynamic potential of the surface and an increase in the forces of interaction of atoms. Moreover, the greater the change in the specified characteristics, the higher the physicochemical and mechanical properties of the layer.

Currently, processes related to single-component saturation of parts – carburizing, nitriding, boriding, etc. [13, 14, 15, 16, 17, 18, 19] Saturation with two, three or more elements (with the exception of the nitrocarburizing process) are widely used in practice.

The possibility of simultaneous saturation with boron and aluminum was established in the eighties of the last century [20, 21, 22, 23, 24]. The first results show an exceptional perspective of the obtained diffusion layers for protecting the parts from abrasive impact. Subsequently, it was proven that the properties of the boron-alloyed layers depend on the ratio of diffusing boron and aluminum atoms in the surface of the part, but in all cases they have:

- high microhardness 14÷19000 MPa, and when saturated with high-alloy steels up to 21000 MPa;
- high abrasion resistance exceeding that of heat-treated steels by 3÷18 times;
- resistance to heating in an oxidizing environment up to 950ºC;
- resistance in sulfur-containing and other active gas environments.

However, this method has not found wide application due to insufficient knowledge of the technological processes occurring during saturation [25, 26, 27, 28, 29].

In this regard, the purpose of this publication is to trace the influence of the technological processes of boroalicitation on the main strength characteristics of diffusion-enriched samples of medium-alloyed high-quality structural steels [30, 31].

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol2.34

II. MATERIALS AND METODS

The study used samples of medium-alloyed high-quality structural steel 34CrNiMo6 EN ISO 6892-1:2020, with chemical composition according to Table 1 and mechanical properties in the as-delivered condition Rm=1100MPa, $R_{0.2}$ 900÷1000MPa and HB 229.

TABLE 1 CHEMICAL COMPOSITION

	Chemical composition,%						
	C	Cr	Mn	Si	P	S	Fe
min	0,32	0,80	0,80	1,10	≤0,025	≤0,025	>96,00
max	0,38	1,10	1,10	1,40			

The diffusion enrichment of the samples was carried out in a liquid saturating medium. Borax ($Na_2B_4O_7.10H_2O$), boric anhydride (B_2O_3) and alumina (Al_2O_3) were used as carriers of active atoms in the diffusion medium, and boron carbide (B_4C) was used as a reducing agent.

The saturation temperature is 820÷880 ⁰C, and the duration is 120÷240 min. After saturation, the samples are quenched (from the saturation temperature) in an oil bath and subjected to high-temperature annealing at 500÷600 ⁰C.

The annealing duration of the standard test specimens for tensile strength testing is constant - 1 h.

The strength characteristics test according to EN 1002 was conducted on an automatic hydraulic, universal tensile/compression testing machine with an optical control module with a touch screen display, maximum tensile force 700kN and accuracy of results ± 1% - Fig. 1.

Fig.1. Universal tensile strength testing machine

III. RESULTS AND DISCUSSION

The mechanism of influence of boroaluminizing diffusion coatings on the mechanical properties of the studied samples after saturation and subsequent heat treatment was investigated using mathematical planning of the experiment using a second-degree orthogonal compositional design [40]. On this basis, adequate regression equations modeling the saturation regime and the subsequent heat treatment were derived.

The tensile strength – Y_1 (Rm, MPa), the proportionality limit – Y_2 (R0.2, MPa), and the conditional relative elongation at break – Y_3 (A5, %) were used as control functions.

The input factors (parameters) are the saturation temperature – X_1 (T_1, ⁰C), from which the parts are immediately quenched in oil, the saturation duration – X_2 (t, min), and the tempering temperature – X_3 (T_2, ⁰C).

The main levels of input factors, as well as the variation intervals, are presented in Table 2.

TABLE 2 INPUT FACTORS

	Input factors		
	X_1, T_1, ⁰C	X_2, t, min	X_3, T_2, ⁰C
Basic level	850	180	550
Variation interval	30	60	50
Upper level	880	240	600
Lower level	820	120	500

When implementing the experimental plan, analytical dependencies were established for the control functions on the specified factors 1÷3.

$$Y_1 = 13220 - 35X_1 + 8{,}4X_2 + 10{,}8X_3 + 0{,}025X_1^2 + 0{,}0076X_2^2 - 0{,}0021X_3^2 - 0{,}0073X_1X_2 - 0{,}0124X_1X_3 - 0{,}068X_2X_3 \quad (1)$$

$$Y_2 = 15816 - 38{,}9X_1 - 0{,}7X_2 + 8{,}58X_3 + 0{,}025X_1^2 + 0{,}013X_2^2 - 0{,}0032X_3^2 - 0{,}0027X_1X_2 - 0{,}086X_1X_3 - 0{,}0029X_2X_3 \quad (2)$$

$$Y_3 = 28{,}6 + 0{,}044X_1 + 0{,}017X_2 + 0{,}02X_3 - 0{,}00008X_1^2 - 0{,}00009X_2^2 - 0{,}000009X_3^2 - 0{,}000012X_1X_2 - 0{,}00001X_1X_3 - 0{,}0002X_2X_3 \quad (3)$$

The graphical interpretations of the obtained dependencies are presented in Fig. 1÷3.

Through them, with given values for Rm, R0.2 and A5, the optimal values of the technological parameters of diffusion saturation (temperature and duration of saturation) with boron and aluminium can be determined.

The graphical dependences show a stronger influence of the tempering temperature on the studied mechanical characteristics than the saturation temperature and duration. This indicates that the strengthening during simultaneous diffusion of boron and aluminum into the surface of the samples is a result of an increase in the amount of pinned dislocations on the surface of the strengthened samples [32, 33, 34, 35].

Boron is known to be a surface active element with respect to iron. The absorption of boron along dislocation lines creates an atmosphere analogous to that of Cottrell of carbon atoms. This allows for easier pinning of dislocations and lowers the linear stresses around them. At the same time, their density increases. The latter is stimulated by the effects of stresses arising from the diffusion of boron and aluminium [36, 37, 38, 39].

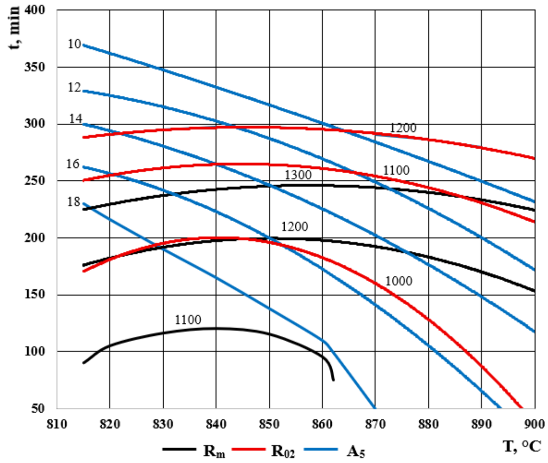

Fig. 1. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 500ºC.

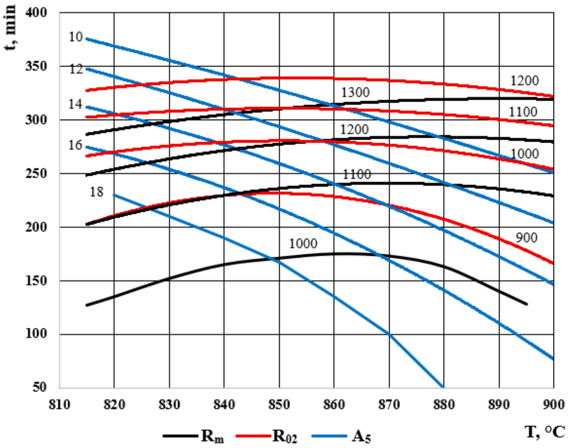

Fig. 2. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 550ºC.

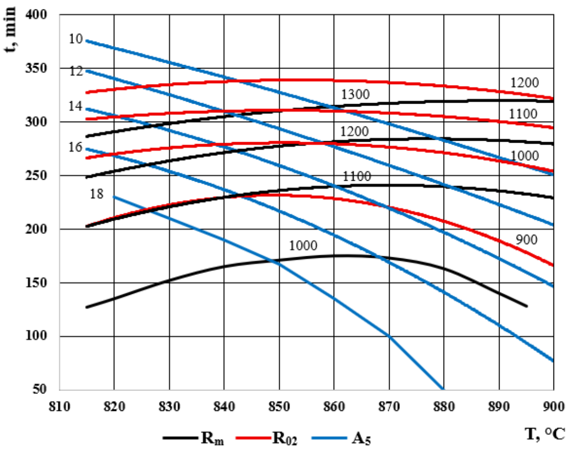

Fig. 3. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 600ºC.

Furthermore, the formation of the borides FeB and Fe_2B with elastic moduli of 350 and 290.10^3 MPa, respectively, significantly exceeding the elastic modulus of steel, increases the elastic modulus on the surface of the product. This increases the resistance to the movement of dislocations and their emergence to the surface.

Therefore, the strength characteristics of steels after simultaneous diffusion enrichment with boron and aluminum are determined by the structural state of the formed diffusion layer and to a lesser extent by its thickness. The diffusion of boron and aluminium and the formation of borides on the surface of the parts change the density and energy of the dislocations (the structural energy state of the saturated surface), which leads to a change in the bulk properties of the product as a whole [40].

IV. Conclusions

From the conducted studies and the results obtained, the following important conclusions can be formulated:

- The mechanism of influence of boroaluminizing diffusion coatings on the strength properties of 34CrNiMo6 steel after saturation in liquid media at 820÷880 ºC, with a duration of 120÷240 min and subsequent heat treatment (quenching from the saturation temperature and high-temperature tempering) was studied.
- Mathematical models of the process were constructed using a second-degree orthogonal compositional design and adequate regression equations were derived.
- Graphical relationships have been developed to determine the technological parameters of the boroaluminizing process (temperature and duration) depending on the desired strength properties (Ra, $R_{0.2}$ and A_5) of the product.
- It has been proven that the influence of the tempering temperature on the studied mechanical characteristics is stronger than the temperature and duration of saturation.

References

[1] V. Toshkov, Nitriding in low-temperature plasma, King, Sofia, 2013.

[2] I. Vinev, I. Miteva, Kinetics of Boride Layer Growth in Semi-Permeable Iron-Carbon-Cupper Powder Materials, UISC "Unitech", 2019, 15-16, November 2019, Gabrovo, Proceeding v.II, pp 235-238, ISSN 1313-230X.

[3] I. Mitev and S. Tsenkulovski, Local Processing of Non-Metal Materials with Concentrated Energy Flow, 14th ISPC "Environment Technology Resources", Rezekne, Latvia, Vol. 3, 2023, pp.183÷186,ISSN 1691-5402 print; ISSN 2256-070X online

[4] I. May and L. Schetky, Cooper in iron and steel, John Wiley and sons. Toronto, 1988, p.307, ISBN 0-471-05913-7.

[5] I. Miteva, I.Vinev and I.Mitev, Features of Alloying Matrix of Water-dispersed Iron Powders, 13th International Scientific and Practical Conference, 15.06.2021, Rezekne Academy of Technologies, Rezekne, Latvia,pp.226÷231.

[6] Lengerov, A., D., Petrova, M., Bozhakov, Technological Assurance Of The Milling Process Of Prismatic Channels In Heat Exchange Aluminum Alloys, Vide. Tehnologija. Resursi - Environment, Technology, Resources, Volume 3, Pages 154 – 157, 2024, 15th International Scientific and Practical Conference on Environment. Technology. Resources, ETR 2024, Rezekne 27 June 2024 through 28 June 2024, ISSN 16915402, ISBN 978-171389957-0, DOI: https://doi.org/10.17770/etr2024vol3.8163, ISSN 0094243X, 15517616.

[7] V. Konnur et al., Analysis of CNC turning parameters and simultaneous optimisation of surface roughness and material removal rate by MOGA for AISI 4340 alloy steel. Advances in Materials and Processing Technologies, 2024, 10 (4), 3885÷3908.

[8] I. Samsonov et al., A. Research on the design features of block-module tooling used on CNC machine tools. Part 1 – Analysis of block-module tooling used on CNC lathes. Volga Scientific Journal, volume 52 (12-3), 2015, 74÷80.

[9] V. Patel and R. Singh, Precision Robotics for CNC Machining. Industrial Automation Today, vol. 25, no. 5, 2020.

[10] T. Kuzmanov and Hr. Metev, Technology of Mechanical Engineering – Part IV, Technological Processes for CNC Machines, EKS-PRESS, Gabrovo, 2007, ISBN 954-485-033-4.

[11] G. Karlovski et al., Selection of Instrumentation Based on Statistical Analysis, XXXII International Scientific Symposium “Metrology and Metrology Assurance 2022”, Sozopol, 2022, 978-1-6654-8569-2/©2022 IEEE, DOI: https://doi.org/10.1109/MMA55579. 2022.9992429.

[12] A. Shah, The Impact of Robotics on Manufacturing Efficiency and Productivity, Frontiers in Robotics and Automation, vol. 1, 73÷84, 2024.

[13] T. Simajaya et al. Workpiece Handling Systemusing 6-DOF Manipulator Robot for CNC Lathe Machine. Cyliinder: Jurnal Ilmiah Teknik Mesin. Vol. 3. No 2. 2017.

[14] B. Stewart, Overcoming Challenges in Six-Axis Robotic CNC Integration, Industrial Robotics Engineering, vol. 28, no. 2, 2020.

[15] K. Chan, Cartesian Robots and Their Role in CNC Operations. Automation & Manufacturing, vol. 29, no. 2, 2021.

[16] M. Javaid et al., Significant Capabilities of Robotics in Enhancing Industry 4.0 Implementation, Materials Today: Proceedings, 2021.

[17] R. James and S. Kumar, Challenges and Opportunities in Robotic CNC Machining. Robotics & Automation, vol. 14, no. 3, 2020.

[18] J. Ribeiro et al. Robotic Process Automation and Artificial Intelligence in Industry 4.0 – A Literature review / Procedia Computer Science 181 (2021). 51÷58.

[19] A. Souza, et al. Industry 4.0: Machine Learning to Monitor the Life Span of Cutting Tools in an Automotive Production Line, January 2021, International Journal of Advanced Engineering Research and Science 8(5):220÷228.

[20] I. Mitev, Materials and blanks – part 1 (Materials), Credo – 3M, Gabrovo, 2021, ISBN 978-619-7100-44-0.

[21] I. Ivanov, K., Petrov, T., Rachovski, D., Petrova, Methodological and Applied Aspects of Artificial Intelligence in Energy Consumption Prediction, Published by RTU PRESS, Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume II, pp. 165-169, Online ISSN 2256-070X, ISSN 16915402, DOI: https://doi.org/10.17770/etr2025vol2.8601.

[22] Hr. Metev, K., Krumov, B., Vlahova, Economic aspects of the modular tools, AIP Conference Proceedings, Open Access, Volume 2980, Issue 124, January 2024, Article number 060001, 11th, International Scientific Conference on Engineering, Technologies and Systems, TechSys 2022, ISSN 0094243X, ISBN 978-073544814-8, DOI: https://doi.org/10.1063/5.0184231.

[23] M. Marinov Jordanov, Vector-Matrix Computer Method for Drafting Circling-Point Curves and Centering-Point Curves of Burmester, Vide. Tehnologija. Resursi - Environment, Technology, Resources, Volume 2, Pages 440 – 443, 2024, 15th International Scientific and Practical Conference on Environment. Technology. Resources, ETR 2024, Rezekne, 27 June 2024 through 28 June 2024, Code 201245, Conference Proceedings, ISSN 16915402, ISBN 978-171389957-0, DOI: https://doi.org/10.17770/etr2024vol2.8072.

[24] Mokhtari Homami, Fadaei, R., Tehrani, A., Mirzadeh, H. et al. Optimization of turning process using artificial intelligence technology. Int J Adv Manuf Technol 70, 1205÷1217 (2014).

[25] D. Petrova, An Alternative Approach to Reducing Aging of Innovative Industrial Products in Terms of Industry 4.0, Environment. Technology. Recourses – Proceeding of the 13-th International Scientific and Practical Conference, Rezekne Academy of Technologies, Rezekne, Latvia, 2021, ISSN 1691-5402, Online ISSN 2256-070X, https://doi.org/10.17770/etr2021vol3.6507 p. 274-280, scopus. SJR=0,113.

[26] D. Petrova, An Approach to Modeling Innovation Obsolescence, Vide. Tehnologija. Resursi - Environment, Technology, Resources, Proceeding of the 14th International Scientific and Practical Conference, 2023, Volume I, pp. 175–179, Print ISSN 1691-5402, Online ISSN 2256-070X, DOI: https://doi.org/10.17770/etr2023vol1.7237 , https://www.scopus.com/authid/detail.uri?authorId=56323816400.

[27] D. Petrova, Application of Alternative Approaches for Innovative Technology Obsolescence in Bulgarian Engineering Companies, Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume IV, pp. 323-327, Online ISSN 2256-070X, ISSN 16915402, DOI: https://doi.org/10.17770/etr2025vol4.8462,

[28] D. Petrova, Classification of Micromechanical Elements and Fabrication of Beam-type Micromechanical Elements, Published by RTU PRESS, Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume IV, pp. 289-296, Online ISSN 2256-070X, ISSN 16915402, DOI: https://doi.org/10.17770/etr2025vol4.8396.

[29] D. Petrova, Zlateva-Petkova, Ts., Lengerov, A., Methodology for Variant and Generative Design of Microcomponents Based on the CAD System "MICROSYS 25", Published by RTU PRESS, Environment. Technology. Resources. Rezekne, Latvia.Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume IV, pp. 315-321, Online ISSN 2256-070X, ISSN 16915402, DOI: https://doi.org/10.17770/etr2025vol4.8442,

[30] D. Petrova, Zlateva-Petkova, Ts., Lengerov, A., Algorithm and Flowchart for Geometric Modeling of Microcomponents Based on the CAD System "MICROSYS 25", Published by RTU PRESS, Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume IV, pp. 309-314, Online ISSN 2256-070X, ISSN 16915402, DOI: https://doi.org/10.17770/etr2025vol4.8441,

[31] N. Dolchinkov, Interconnection of digital, cultural, and strategic transformations on the Balkan Peninsula, Achieving Business Excellence Through Triple TransformationOpen source preview, 2025, pp. 209–240, ISBN13: 9798369394359, ISBN13 Softcover: 9798369394366, EISBN13: 9798369394373, DOI: https://doi.org/10.4018/979-8-3693-9435-9.ch008.

[32] O. Manav, S. Chinchanikar and M. Gadge, Multi-performance optimization in hard turning of AISI 4340 Steel using Swarm Optimization technique, in IConAMMA_2017, Materials Today: Proceedings, vol. 5, 24652÷24663, 2018.

[33] R.Saravanan, G. Sekar and M. Sachithanandam, Optimization of CNC machining operations subject to constraints using genetic algorithm (GA), Proceedings of the International Conference on Intelligent Flexible Autonomous Manufacturing Systems, Coimbatore, India, 472÷479, 2000.

[34] S. Poornima, Optimization of machining parameter in CNC turning of martensitic stainless steel using RSM and GA. International Journal of Modern Engineering Research (IJMER) Vol.2, Issue.2, Mar.-Apr. 2012, 539÷542.

[35] S. Demirova, Turning knowledge into innovation and innovation into an effective product concept, International Conference on Creative Business for Smart and Sustainable Growth, CreBUS

2019Conference Paper2019, DOI: https://doi.org/10.1109/CREBUS.2019.8840107.

[36] S. Mumtaz, A. Alsohaily, Z. Pang, A. Rayes, K. F. Tsang and J. Rodriguez, 'Massive Internet of Things for Industrial Applications: Addressing Wireless IIoT Connectivity Challenges and Ecosystem Fragmentation', IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp. 28-33, March 2017.

[37] S.Tsenkulovski, Mitev, I., Influence of the Parameters of the Laser Marking Process on the Depth of Penetration in Layer-reinforced Composites, Vide. Tehnologija. Resursi - Environment, Technology, Resources, Volume 3, Pages 319 – 324, 2024, 15th International Scientific and Practical Conference on Environment. Technology. Resources, ETR 2024, Rezekne, 27 June 2024 through 28 June 2024, Code 201245, Conference Proceedings, ISSN 16915402, ISBN 978-171389957-0, DOI: https://doi.org/10.17770/etr2024vol3.8147.

[38] T. Kovachev and others, Density Before Sintering Water Dispersed Iron Powders, ISC UNITECH 2020, Volume II, ISSN 1313-230, pp. 46÷49.

[39] T. Kovachev and others, Influence of Pressure Force on Density Before sintering of Iron Powder materials Obtained by Reduction, AJ Industrial Technologies, Issue7/2020, ISSN 1314-9911, pp. 23÷27.

[40] V. Nikolova-Minkova, Bulgarian and Foreign Patent Activity in Bulgaria and Bulgarian Patent Activity Abroad by Technological Areas and Fields for the Period 2010-2021. Economic Studies (Ikonomicheski Izsledvania), 32(5), 2023, pp. 82-114. Available: https://archive.econstudies.iki.bas.bg/2023/2023_05/2023_05_06.pdf [Accessed: Febr. 10, 2025].