SCIENTIFIC AND TECHNICAL JOURNAL
"Voprosy Materialovedeniya"

2018, № 1(93)

CONTENTS

UDC 669.14.018.295:539.2

UNIFYING CHEMICAL COMPOSITIONS OF HIGH-STRENGTH STEELS IN SHIPBUILDING

M.V. KOVALCHUK[1], Corresponding Member of the RAS, A.S. ORYSHCHENKO[2], Dr Sc. (Eng), V.A. MALYSHEVSKY[2], Dr Sc. (Eng), S. N. PETROV[2], Cand. Sc. (Chem), E. A. Shumilov[2]

[1] *National Research Center "Kurchatov Institute", 1, Akademika Kurchatova Sq. 123182 Moscow, Russian Federation. E-mail: nrcki@nrcki.ru*

[2] *NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015, St Petersburg, Russian Federation. E-mail: mail@crism.ru*

Received December 12, 2017

The problems of creation of structural high-strength steels of unified chemical composition and production technologies ensuring the yield point in the range of 590–950 MPa have been considered. The possibility of obtaining such materials appeared after extensive studies on the Gleeble 3800 thermomechanical simulator and Quarto 800 laboratory mill confirming the possibility of unifying chemical compositions of high-strength steels with adjustable yield strength within the specified limits. Given the identity of the results of steel treatment on the mentioned equipment and Quarto 5000 industrial mill, the results achieved in the present work could be realized in industry.

Keywords: thermomechanical treatment, nanostructuring, fragmentation, unification of chemical composition

ACKNOWLEDGEMENTS

Experimental studies were carried out on the equipment of the Center for the Collective Use of scientific equipment "Composition, structure and properties of structural and functional materials" of the National Research Center "Kurchatov Institute" – CRISM Prometey with the financial support of the Ministry of Education and Science under the agreement No. 14.595.21.0004, the unique identifier RFMEFI59517X0004.

DOI: 10.22349/1994-6716-2018-93-1-07-14

REFERENCES

1. Kovalchuk, M.V., Oryshchenko, A.S., Malyshevsky, V.A., Petrov, S.N., Shumilov, E.A., Problemy sozdaniya tekhnologichnykh ekonomnolegirovannykh vysokoprochnykh staley dlya arkticheskikh konstruktsiy [Problems of creation of technological economically alloyed high-strength steels for arctic constructions], *Voprosy Materialovedeniya*, 2017, No 2 (90), pp. 7–14.

2. Gorynin, I.V., Malyshevsky, V.A., Rybin, V.V., Vysokoprochnye svarivaemye korpusnye stali dlya nadvodnogo korablestroyeniya: vchera, segodnya, zavtra [High-strength welded hull steels for surface shipbuilding: yesterday, today, tomorrow], *Rol rossiyskoy nauki v sozdanii otechestvennogo podvodnogo flota*, Moscow: Nauka, 2008, pp. 281–288.

3. Gorynin, I.V., Khlusova E.I., Nanostrukturirovannye stali dlya osvoeniya mestorozhdeniy shelfa Severnogo Ledovitogo okeana [Nanostructured steels for the development of the deposits of the shelf of the Arctic Ocean], *Vestnik RAN* [Bulletin of the Russian Academy of Sciences], 2010, No 2, pp.1069–1075.

4. Hanlon, D.N., Sietsma, J., Van der Zwaag, S., The effect of plastic deformation of austenite on the kinetics of subsequent ferrite formation, *ISIJ International*, 2001, V. 41, Issue 9, pp. 1028–1036

5. Zisman, A.A., Petrov, S.N., Ptashnik, A.V., Kolichestvennaya attestatsiya beynitno-martensitnykh struktur vysokoprochnykh staley metodami skaniruyushchey elektronnoy mikroskopii [Quantitative attestation of bainitic-martensitic structures of high-strength steels by scanning electron microscopy methods], *Metallurg*, 2014, No 11, pp. 91–95.

UDC 669.14.018.295:621.785.72

STRUCTURE CHANGES OF HIGH-STRENGTH ECONOMICALLY ALLOYED STEEL 09KhGN2MD (09CrMnNi2MoCu) WHEN TEMPERING

M.V. GOLUBEVA[1], O.V. SYCH[1], Cand. Sc. (Eng), E.I. KHLUSOVA[1], Dr Sc. (Eng), G.D. MOTOVILINA[1], Cand. Sc. (Eng), E.V. SVIATYSHEVA[1], S.V. ROGOZHKIN[2,3], Dr Sc. (Phys-Math), A.A. LUKYANCHUK[2]

[1] NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

[2] NRC "Kurchatov Institute" – Institute for Theoretical and Experimental Physics, 25, Bolshaya Cheremushkinskaya St, 117218, Moscow, Russian Federation

[3]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31, Kashirskoe shosse, 115409, Moscow, Russian Federation

Received December 28, 2017

Abstract—Purpose of the present investigation is to determine the optimal heat treatment parameters that ensure yield strength over 690 MPa in combination with toughness of at least 35 J/cm^2 at temperature –70°C in new economically alloyed cold-resistant steel. The effect of various quenching and tempering parameters on mechanical properties, structure of steel and fracture mode of samples after impact tests at temperature –70°C has been studied. The relationship between the properties, structure and fracture mode of steel samples is shown. The optimal heat treatment parameters of new economically alloyed cold-resistant steel are deter-mined.

Keywords: economically alloyed high-strength steel, cold resistance, reduction of carbon equivalent, scanning electron microscopy, transmission electron microscopy, mechanical properties, structure, bainite, martensite, quenching, tempering.

ACKNOWLEDGEMENTS

Experimental studies were performed on the equipment of the laboratory of the Test and Technical Complex of Irradiated and Radionuclide Materials and the Center for Collective Use "Composition, Structure and Properties of Structural and Functional Materials" of the NRC "Kurchatov Institute" – CRISM "Prometey" with financial support of the Ministry of Education and Science of Russian Federation within the framework of the agreement 14.595.21.0004.

DOI: 10.22349/1994-6716-2018-93-1-15-26

REFERENCES

1. Nastich, S.Yu., Morozov, Yu.D., Marchenko, V.N., Stepashin, A.M., Zyryanov, V.V., Sorokolet, O.V., Novaya iznosostoykaya stal 17KhGN2MFBT dlya kuzovov karyernykh samosvalov [New wear-resistant steel 17KhGN2MFBT for bodies of quarry dump trucks], *Stal*, 2005, No 3, pp. 82–85.

2. Nastich, S.Yu., Morozov, Yu.D., Marchenko, V.N., Stepashin, A.M., Zyryanov, V.V., Sorokolet, O.V., Razrabotka i promyshlennoe oprobovanie vysokoprochnoy svarivayemoy stali s vysokoy khladostoykostyu dlya nesushchikh konstruktsiy v transportnom mashinostroenii [Development and industrial testing of high-strength welded steel with high cold resistance for bearing structures in transport engineering], *Metallurg*, 2005, No 5, pp. 55–58.

3. Rybin, V.V., Malyshevsky, V.A., Khlusova, E.I., Vysokoprochnye svarivaemye stali [High-strength welded steels], St Petersburg: Publishing house of Polytechnic University, 2014.

4. Semicheva, T.G., Khlusova, E.I., Sherokhina, L.G., Protsessy karbidoobrazovaniya i khrupkost pri otpuske sudostroitelnoy stali [Processes of carbide formation and brittleness during the release of shipbuilding steel], *Voprosy Materialovedeniya*, 2005, No 2 (42), pp. 69–78.

5. Golosienko, S.A., Motovilina, G.D., Khlusova, E.I., Vozmozhnosti povysheniya prochnostnykh kharakteristik ekonomnolegirovannykh vysokoprochnykh staley za schet obrazovaniya nanorazmernykh karbidov [Possibilities of increasing the strength characteristics of economically alloyed high-strength steels due to the formation of nanoscale carbides], *Voprosy Materialovedeniya*, 2010, No 3 (59), pp. 52–64.

6. Khlusova, E.I., Orlov, V.V., Motovilina, G.D., Korchagin, A.M., Matrosov, M.Yu., Vliyanie otpuska na izmenenie struktury i svoystv vysokoprochnoy shtripsovoy stali kategorii prochnosti Kh90 i Kh100 posle termomekhanicheskoy obrabotki [Effect of tempering on the change in the structure and properties of high-strength steel strips of strength category X90 and X100 after thermomechanical treatment], *Metallurg*, 2010, No 11, pp. 68–73.

7. Rogozhkin, S.V., Aleev, A.A., Lukyanchuk, A.A., Shutov, A.S., Raznitsyn, O.A., Kirillov, S.E., Prototip atomnogo zonda s lazernym ispareniyem [Prototype of an atomic probe with laser evaporation], *Pribory i tekhnika eksperimenta*, 2017, No 3, pp. 129–134.

8. Raznitsyn, O.A., Lukyanchuk, A.A., Shutov, A.S., Rogozhkin, S.V., Aleev, A.A., Optimizatsiya parametrov analiza materialov metodami atomno-zondovoy tomografii s lazernym ispareniyem atomov [Optimization of parameters of material analysis by atomic-probe tomography with laser evaporation of atoms], *Mass-spectrometria*, 2017, V. 14, No 1, pp. 33–39.

9. Golubeva, M.V., Sych, O.V., Khlusova, E.I., Motovilina, G.D., Issledovanie mekhanicheskikh svoystv i kharaktera razrusheniya novoy ekonomnolegirovannoy khladostoykoy stali s garantirovannym pre-delom tekuchesti 690 MPa [Investigation of the mechanical properties and character of the destruction of a new economically alloyed cold-resistant steel with a guaranteed yield point of 690 MPa], *Aviatsionnye materialy i tekhnologii*, 2017, No 4 (49), pp. 19–24.

UDC 669.721:539.374

HIGH DUCTILITY OF MAGNESIUM AT DIFFERENT STRAIN RATES UNDER PRESSURE

R.V. CHURBAEV[1], Cand. Sc. (Phys.-Math), V.P. FEDOTOV[†2], Dr Sc. (Eng), E.R. CHEREMITSYNA[2]

[1]*Federal State Budgetary Institution of Science “Institute of Physics of Metals of Ural Branch of the Russian Academy of Sciences, 18, S. Kovalevskoi St, 620137, Yekaterinburg, Russian Federation, E-mail: churbaevravil@gmail.com*

[2]*Federal State Budgetary Institution of Science “Institute of Engineering Science of Ural Branch of the Russian Academy of Sciences”, 34, Komsomolskaya St., 620049 Yekaterinburg, Russian Federation, E-mail: elviera1@rambler.ru*

Received August 31, 2017, in final form, January 17, 2017

Abstract—The influence of the strain rate in the range of $3.3 \cdot 10^{-5}$ to 332 sec^{-1} on the ductility of pure magnesium under hydrostatic pressure varying since 0.1 to 800 MPa and room temperature (293 K) has been researched. High plasticity of magnesium with small and large deformation speed under pressure was found. At pressure pure magnesium ductility reduces while strain rate increases; reduced plasticity is observed only when strain rate is equal to 0.17 sec^{-1}, and above this rate, on the contrary, the ductility of magnesium increases. It is shown that the pressure at ductile-brittle transition increases from 142.2 to 241.5 MPa with strain rate increasing from $3.3 \cdot 10^{-4}$ up to 332 sec^{-1}.

Keywords: ductility of magnesium, pressure, deformation under pressure, strain rate, pressure at ductile-brittle transition, destruction, magnesium.

ACKNOWLEDGEMENTS

The work was carried out for The Federal Agency for Scientific Organizations (FASO Russia) (“Pressure”, No. AAAA-A18118020190104-3) with partial support of the Ural Branch of the Russian Academy of Sciences (Project No. 18-10-1-40).

DOI: 10.22349/1994-6716-2018-93-1-27-34

REFERENCES

1. Busalov, Yu.E., Guriev, I.I., Elkin, F.M., Kopiev, I.M., Vliyanie skorosti deformirovaniya na prochnost’ i plastichnost’ magniya i magnievykh splavov, soderzhashchikh litii [The influence of deformation rate on strength and ductility of magnesium and magnesium alloys containing lithium], *Fizika i khimiya obrabotki materialov*, 1972, No 3, pp.145–148.

2. Toaz, M.W., Ripling, E.J., Correlation of the tensile properties of pure magnesium and four commercial alloys with their mode of fracturing, *Transactions AIME*, 1956, V. 206, pp. 936–946.

3. Pugh, H.L.D., *Mechanical behavior of materials under pressure*, Amsterdam; London; New York: Elsevier, 1970.

4. Sturges, J.L., Col, B.N., Parsons, B., High-rate deformation in a high pressure environment, *Proc. Int. Symp. Intense Dyn. Load and Eff.*, Beijing, June 3–7, 1986, Oxford, 1988, pp. 765–770.

5. Churbaev, R.V., Dobromyslov, A.V., Kolmogorov, V.L., Taluts, G.G., Vliyanie skorosti deformatsii na plastichnost metallov pod davleniem [The influence of strain rate on ductility of metals under pressure], *Fizika metallov i metallovedenie*, 1990, No 6, pp.178–183.

6. Davidson, T.E., Uy, J.C., Lee, A.P., The tensile fracture characteristics of metals under hydrostatic pressures to 23 kilobars, *Acta metallurgica*, 1966, V. 14, No 8, pp. 937–948.

7. Korta, R., Chokshi, A.H., Strain-rate sensitivity and microstructural evolution in a Mg-Al-Zn, *Scr. Mater.*, 2010, V. 63, No 9, pp. 913–916.

8. Song, W.Q., Beggs, P., Easton, M., Compressive strain rate sensitivity of magnesium-aluminium die casting alloys, *Mater. and Des.*, 2009, V. 30, No 3, pp. 642–648.

9. Stanford, N., Sabirov, I., Sha, G., La Fontaine, A., Ringer, S.P., Barnett, M.R., Effect of Al and Gd solutes on the strain rate sensitivity of magnesium alloys, *Met. and Mater. Trans. A*., 2010, V. 41, No 3, pp. 734–743.

10. Wan, G., Wu, B.L., Zhao, Y.H., Zhang, Y.D., Esling, C., Strain-rate sensitivity of textured Mg-3Al-1Zn alloy (AZ31) under impact deformation, *Scr. Mater*., 2011, V. 65, No 6, pp. 461–464.

11. Wang B.S., Xin R.L., Huang G.J., Liu Q. Strain rate and texture effects on microctructural characteristics of Mg-3Al-1Zn alloy during compression], *Scr. Mater*., 2012, V. 66, No 5, pp. 239–242.

12. Kolmogorov, V.L., Spevak, L.F., Churbaev R.V., On the technique used to determine plasticity margin in high-speed deformation under high pressure, *International Journal of Mechanical Sciences*, 2008, V. 50, No 4. pp. 676–682.

13. Tork, B.N., Pardis, N., Ebrahimi, R., Opredelenie resursa plastichnosti metallov pri vysokoskorostnom deformirovanii v usloviyakh vysokogo davleniya [Investigation on the feasibility of room temperature plastic deformation of pure magnesium by simple shear extrusion process], *Mater. Sci. and Eng. A*., 2013, V. 560, pp. 34–39.

14. Churbaev, R.V., Kolmogorov, V.L., Burkin, S.P., Taluts, G.G., Ustanovka slozhnogo nagruzheniya dlya issledovaniya materialov pri vysokikh reguliruemykh davleniyakh [The mechanism of complicated loading for research of materials under high controlled pressure], *Zavodskaya Laboratoriya*, 1989, V. 55, No 9, pp. 98–99.

UDC 669.017.165

STRUCTURE AND PROPERTIES OF THE INTERMETALLIDE BASED ON NICKEL ALUMINIDE MICROALLOYED BY RARE-EARTH METALS

O. A. BAZYLEVA, Cand. Sc. (Eng), E. G. ARGINBAEVA, Cand. Sc. (Eng), A. V. SHESTAKOV, T. V. FESENKO

Federal State Unitary Enterprise “All-Russian Scientific Research Institute of Aviation Materials” (FSUE VIAM), 17, Radio St, 105005 Moscow, Russian Federation. E-mail: admin@viam.ru

Received May 3, 2017, in the final form December 13, 2017

Abstract—The paper studies the combined effects of rare earth metals such as praseodymium, neodymium and erbium, melting technologies on intermetallic alloy based on nickel aluminide and pure charge materials using 25, 50 and 75 wt. % of waste, the technology of casting single-crystals of crystallographic orientation [001] and their heat treatment combined with hot isostatic pressing (HIP), on mechanical properties and long-term strength at the level of passport data.

Keywords: nickel intermetallide, nickel aluminide, single crystal, heat resistance, structure, crystallographic orientation, heat treatment, hot isostatic pressing

ACKNOWLEDGEMENTS

The work was carried out within the framework of the “Strategic directions of materials development and processing technologies for the period until 2030”: 7.3: Creation of intermetallic nickel alloys and composite materials based on them.

The authors are grateful to VIAM’s specialists, who took an active part in the work: Yu.A. Bondarenko, Dr. Sc., E. M. Visik, Cand. Sc., E.V. Kolyadov, M. Yu. Kolodyazhny, P.G. Min.

DOI: 10.22349/1994-6716-2018-93-1-35-49

REFERENCES

1. Kablov, E.N., Innovatsionnye razrabotki FGUP VIAM GNTS RF po realizatsii “Strategicheskikh napravleniy razvitiya materialov i tekhnologiy ikh pererabotki na period do 2030 goda” [Innovative devel-

opments of FSUE “VIAM” for the implementation of “Strategic Directions for the Development of Materials and Technologies for Their Processing until 2030”], *Aviatsionnye materialy i tekhnologii*, 2015, No 1, pp. 3–33. DOI: 10.18577 / 2071-9140-2015-0-1-3-33

2. Kablov, E.N., Strategicheskie napravleniya razvitiya materialov i tekhnologiy ikh pererabotki na period do 2030 goda [Strategic directions of development of materials and technologies of their processing for the period up to 2030], *Aviatsionnye materialy i tekhnologii*, 2012, No S, pp. 7–17.

3. Inozemtsev, A.A., Nikhamkin, M.A., Sandratsky, V.L., *Osnovy konstruirovaniya aviatsionnykh dvigateley i energeticheskikh ustanovok* [Fundamentals of the design of aircraft engines and power plants], Textbook. Moscow: Mashinostroenie, 2008.

4. Sidorov, V.V., Rigin, V.Ye., Kablov, D.E., *Metallurgiya liteynykh zharoprochnykh splavov: tekhnologiya i oborudovanie* [Metallurgy of casting heat-resistant alloys: technology and equipment], Moscow: VIAM, 2016.

5. Shmotin, Yu.N., Starkov R.Yu., Danilov, D.V., Ospennikova, O.G., Lomberg, B.S., Novye materialy dlya perspektivnogo dvigatelya OAO NPO “Saturn” [New materials for the perspective engine of JSC NPO Saturn], *Aviatsionnye materialy i tekhnologii*, 2012, No 2, pp. 6–8.

6. Sidorov, V.V., Rigin, V.E., Goryunov, A.V., Min P.G., Resursosberegayushchaya tekhnologiya pererabotki konditsionnykh otkhodov liteynykh zharoprochnykh splavov [Resource-saving technology of processing of conditional waste of foundry heat-resistant alloys], *Metallurg*, 2014, No 5, pp. 35–39.

7. Povarova, K.B., Buntushkin, V.P., Kazanskaya, N.K., Drozdov, A.A., Bazyleva, O.A., Osobolegkie zharoprochnye nanostrukturirovannye splavy na osnove Ni_3Al dlya aviatsionnogo dvigatelestroeniya i energeticheskogo mashinostroeniya [Light-weight, heat-resistant nanostructured Ni_3Al-based alloys for aircraft engine building and power engineering], *Voprosy Materialovedeniya*, 2008, No 2, pp. 85–93.

8. Guo, J.T., Sheng, L.Y., Xie, Y. et al. Microstructure and mechanical properties of Ni_3Al and Ni_3Al-1B base alloys fabricated by SHS, *Intermetallics*, 2011, No 19, pp. 137–142.

9. Li, P., Li, Sh., Han, Ya., Influence of solution heat treatment on microstructure and stress rupture properties of a Ni_3Al base single crystal superalloy IC6SX, *Intermetallics*, 2011, No 19, pp. 182–186.

10. Bazyleva, O.A., Arginbaeva E.G., Turenko, E.Yu., Vysokotemperaturnye intermetallidnye splavy dlya detaley GTD [High-temperature intermetallic alloys for GTE parts], *Aviatsionnye materialy i tekhnologii*, 2013, No 3, pp. 26–31.

11. Jozwik, P., Polkowski, W., Bojar Z., Applications of Ni_3Al based intermetallic alloyscurrent stage and potential perceptivities, *Materials*, 2015, No 8(5), pp. 2537–2568. DOI: 10.3390/ma8052537.

12. Tikhomirova, E.A., Budinovsky, S.A., Zhivushkin, A.A., Sidokhin, E.F., Osobennosti razvitiya termicheskoy ustalosti v detalyakh iz zharoprochnykh splavov s pokrytiyem [Features of development of thermal fatigue in details from heat-resistant alloys with coating], *Aviatsionnye materialy i tekhnologii*, 2017, No 3, pp. 20–25.

13. Bazyleva, O.A., Kablov, E.N., Arginbaeva, E.G., Turenko, E.Yu., Shestakov, A.V., Patent of the Russian Federation No RU(11) 2 434 068(13) C1: *Alloy on base of intermetallide Ni_3Al*, Date of publication: 20.11.2011, Bull. 32.

14. Shishkareva, L.M., Kuzmina, N.A., Obzor metodik opredeleniya kachestva struktury monokristallicheskikh otlivok zharoprochnykh splavov [A review of methods for determining the quality of the structure of single-crystal castings of high-temperature alloys], *Proceedings of VIAM*, 2014, No 1, Art. 06 URL: http://www.viam-works.ru (reference date: 02/03/2017). DOI: 10.18577/2307-6046-2014-0-1-6-6.

15. Bazyleva, O.A., Unchikova, M.V., Turenko, E.Yu., Bagetov, V.V., Shestakov, A.V., Issledovanie vliyaniya termicheskoy obrabotki na mikrostrukturu, parametry dendritnoy likvatsii i vremya do razrusheniya intermetallidnogo reniysoderzhashchego splava na osnove Ni_3Al [Investigation of the effect of heat treatment on the microstructure, parameters of dendritic liquation and time to failure of intermetallic rhenium-containing alloy based on Ni_3Al], *Proceedings of VIAM*, 2016, No 10, Art. 04 URL: http://www.viam-works.ru (reference date: 02/03/2017). DOI: 10.18577/2307-6046-2016-0-10-4-4.

16. Ospennikova, O.G., Evgenov, A.G., Bazyleva, O.A., Arginbaeva, E.G., Turenko, E.Yu., Mikrostrukturnye i fazovye prevrashcheniya v intermetallidnom splave na osnove Ni_3Al posle vozdeystviya termicheskoy obrabotki i goryachego izostaticheskogo pressovaniya [Microstructural and phase transformations in an intermetallic alloy based on Ni_3Al after the effect of heat treatment and hot isostatic pressing], *Proceedings of VIAM*, 2016, No S (43), pp. 36–43 (viam-works.ru).

17. Povarova, K.B., Kazanskaya, N.K., Drozdov, A.A., Bazyleva, O.A., Izuchenie vliyaniya redkozemelnykh metallov (RZM) na zharoprochnost splavov na osnove Ni_3Al [Study of the effect of rare-earth metals (REM) on the heat resistance of Ni_3Al-based alloys], *Metally*, 2011, No 1, pp. 55–63.

18. Sidorov, V.V., Timofeeva, O.B., Kalitsev, V.A., Goryunov, A.V., Vliyanie mikrolegirovaniya RZM na svoystva i strukturno-fazovye prevrashcheniya v intermetallidnom splave VKNA-25-VI [Influence of micro-alloying of REM on properties and structural-phase transformations in the intermetallic VKNA-25-VI alloy], *Aviatsionnye materialy i tekhnologii*, 2012, No S, pp. 97–105.

19. Kablov, E.N., Sidorov, V.V., Kablov, D.E., Min, P.G., Rigin, V.E., Resursosberegayushchie tekhnologii vyplavki perspektivnykh liteynykh i deformiruyemykh superzharoprochnykh splavov s uchetom pererabotki vsekh vidov otkhodov [Resource-saving technologies of smelting of promising casting and deformable super-high-strength alloys taking into account processing of all kinds of a waste], *Elektrometallurgiya*, 2016, No 9, pp. 30–41.

20. Sidorov, V.V., Rigin, V.E., Goryunov, A.V., Min, P.G., Resursosberegayushchiye tekhnologii pererabotki nekonditsionnykh otkhodov liteynykh zharoprochnykh splavov [Resource-saving technologies of processing substandard waste of foundry heat-resistant alloys], *Metallurg*, 2014, No 5, pp. 35–39.

21. Povarova, K.B., Drozdov, A.A., Bondarenko, Yu.A., Bazyleva, O.A., Vliyanie napravlennoy kristallizatsii na strukturu i svoystva monokristallov splava na osnove Ni_3Al, legirovannogo W, Mo, Cr i redkozemelnymi elementami [Effect of Directional Crystallization on the Structure and Properties of Single Crystals of an Alloy Based on Ni_3Al Doped with W, Mo, Cr, and REE], *Metals*, 2014, No 4, pp. 35–40.

22. Kablov, E.N., Bondarenko, Yu.A., Echin, A.B., Surova, V.A., Kablov, D.E., Razvitie protsessa napravlennoy kristallizatsii lopatok GTD iz zharoprochnykh i intermetallidnykh splavov s monokristallicheskoy strukturoy [Development of directional crystallization of gas turbine blades from heat-resistant and intermetallic alloys with a single-crystal structure], *Vestnik Moskovskogo gosudarstvennogo tekhnicheskogo universiteta im. N.E. Baumana. Seriya: Mashinostroenie*, 2011, No SP2, pp. 20–25.

23. Bondarenko, Yu.A., Yechin, A.B., Napravlennaya kristallizatsiya zharoprochnogo splava s peremennym upravlyayemym gradiyentom [Directional crystallization of a heat-resistant alloy with a variable controlled gradient], *Voprosy Materialovedeniya*, 2016, No 3, pp. 50–58.

24. Gerasimov, V.V., Visik, E.M., Tekhnologicheskie aspekty litya detaley goryachego trakta GTD iz intermetalldnykh nikelevykh splavov tipa VKNA splavov s monokristallicheskoy strukturoy [Technological aspects of casting details of the hot GTE traction from intermetallic nickel alloys of the VKNA type of alloys with a single crystal structure], *Liteyshchik Rossii*, 2012, No 2, p. 19.

25. Kablov, E.N., Bondarenko, Yu.A., Yechin, A.B., Issledovanie vliyaniya peremennogo upravlyaemogo temperaturnogo gradienta na osobennosti struktury, fazovy sostav, svoystva vysokotemperaturnykh zharoprochnykh splavov pri ikh napravlennoy kristallizatsii [Investigation of the influence of a variable temperature gradient on the structural features, phase composition, properties of high-temperature heat-resistant alloys with their directional crystallization], *Vestnik Moskovskogo gosudarstvennogo tekhnicheskogo universiteta im. N.E. Baumana. Seriya: Mashinostroenie*, 2016, No 6, pp.43–61.

26. Bazyleva, O.A., Shestakov, A.V., Arginbaeva, E.G., Turenko, E.Yu., Vozmozhnost povysheniya kharakteristik zharoprochnosti i zharostoykosti konstruktsionnogo intermetallidnogo splava na osnove alyuminida nikelya [Possibility of increasing the characteristics of heat resistance and heat resistance of a structural intermetallic alloy based on nickel aluminide], *Metally*, 2016, No 1. pp. 93–101.

27. Kablov, E.N., Bazyleva, O.A., Shestakov, A.V., Arginbaeva, E.G., Turenko, E.Yu., Patent of the Russian Federation No RU (11) 2 588 949(13) C1: *Alloy based on intermetallic compound Ni_3Al and article made therefrom*; Date of publication: 07.10.2016, Bull.19.

UDC 621.763:621.452.3

ON THE PROSPECTS OF APPLICATION OF NANOSTRUCTURED HETEROPHASE POLYFUNCTIONAL COMPOSITE MATERIALS IN BUILDING INDUSTRY

O.B.SILCHENKO[1], Dr Sc. (Eng), M.V. SILUYANOVA[1], Dr Sc. (Eng), V.E.NIZOVTSEV[2], Cand. Sc. (Eng), D. A. KLIMOV[2], A. A. KORNILOV[2]

[1]*Moscow Aviation Institute (National Research University), 4, Volokolamskoeshosse, 125993, Moscow, Russian Federation*

[2]*Baranov Central Institute of Aviation Motors (CIAM), 2, Aviamotornaya St, 111116, Moscow, Russian Federation*

Received June 9, 2017, in final form, November 17, 2017

Abstract—The paper gives a brief review of properties and applications of developed extra-hard nanostructured composite materials and coatings based on them. The presentresearch suggestsaerospace applications of nanostructured composite materials based on carbides, carbonitrides and diboridesof transition and refractory metals. To improve the technical and economic performance of gas turbine engines, it is advisable to use new composite structural materials whose basicphysicomechanical properties are several times superior to traditional ones. The greatest progress in developing new composites should be expectedin the area ofmaterials created on the basis of polymer, metal, intermetallic and ceramic matrices. Currently components and assemblies of gas turbine engines and multiple lighting power units with long operation life and durabilitywill vigorously develop. Next-generation composites are studied in all developed countries, primarily in the United States and Japan.

Keywords: nanostructured materials, nanostructured coatings; refractory carbide; carbonitride; diboride; coefficient of friction

DOI: 10.22349/1994-6716-2018-93-1-50-57

REFERENCES

1. Klimov, A.K., Klimov, D.A., Krylov, E.A., Kompozitsionnye materialy dlya dvigatelestroeniya [Composite materials for engine building], *Avtomobilnaya promyshlennost*, 2003, No 3, pp. 27–30.

2. Granov, V.I., Glazkov, A.V., Effektivnost primeneniya nanostrukturnykh kompozitsionnykh materialov i izdeliy iz nikh v aviatsionnoy promyshlennosti [Efficiency of application of nanostructured composite materials and products from them in the aviation industry], *Neorganicheskie materialy*, 1975, V. 11, No 2, pp. 226–229.

3. Klimov, D.A., Shkarupa, I.L., Plyasunkova, L.A., Issledovanie svoistv materialov na osnove karbida kremniya [Investigation of the properties of materials based on silicon carbide], *Novye ogneupory*, 2009, No 6, pp. 305–307.

4. Gnesin, G.G., *Karbidokremnievye materialy* [Carbide silicon materials], Moscow: Metallurgiya, 1977.

5. Nizovtsev, V.Ye., Klimov, D.A., Effektivnost primeneniya nanostrukturnykh sverkhtverdykh kompozitsionnykh materialov dlya antifriktsionnykh pokrytiy podshipnikov skolzheniya [Efficiency of application of nanostructured superhard composite materials for antifriction coatings of sliding bearings], *Novye tekhnologicheskie protsessy i nadezhnost GTD*, Moscow: TsIAM, 2015, Issue 9, pp. 144–145.

6. Klimov, A.K., Klimov, D.A., Nizovtsev, V. Ye., Ukhov, P.A., Effektivnost primeneniya nanostrukturnykh kompozitsionnykh materialov i izdeliy iz nikh v aviatsionnoy promyshlennosti [Efficiency of application of nanostructured composite materials and products from them in the aviation industry], *Proceedings of the MAI*, 2013, No 67.

UDC 621.891

IMPROVING THE SERVICE LIFE OF COATINGS DURING RUNNING-IN

I. R. ASLANYAN, Dr Sc. (Eng)

Federal State Unitary Enterprise “All-Russian Scientific Research Institute of Aviation Materials” (FSUE VIAM), 17, Radio St, 105005 Moscow, Russian Federation. E-mail: as-irina@rambler.ru

Received September 22, 2017, in final form, December 27, 2017

Abstract—In work researches of phosphate coatings are conducted. By means of methods of mathematical modeling of contact interaction it is established that on wear of phosphate coatings the greatest influence renders their roughness. For decrease in wear of the running-in coverings applied to protection of steel products, the way on increase in service life of phosphate coatings is offered.

Keywords: coatings, wear, roughness, running-in process

ACKNOWLEDGEMENTS

The work was carried out within the framework of the implementation of the integrated direction 17.1: “Directional crystallization (with variable controlled gradient) of high-temperature alloys” (“Strategic directions for the development of materials and technologies of their processing until 2030”).

DOI: 10.22349/1994-6716-2018-93-1-58-64

REFERENCES

1. Kablov, E.N., Innovatsionnye razrabotki FGUP "VIAM" GNTS RF po realizatsii "Strategicheskikh napravleniy razvitiya materialov i tekhnologiy ikh pererabotki na period do 2030 goda [Innovative developments of FSUE "VIAM" of the NSC RF for the implementation of *Strategic Directions for the Development of Materials and Technologies for Their Processing for the Period up to 2030*], *Aviatsionnye materialy i tekhnologii*, 2015, No. 1 (34), pp. 3–33. DOI: 10.18577/2071-9140-2015-0-1-3-33.

2. Kablov, E.N., Muboyadzhyan, S.A., Heat-resistant coatings for the high-pressure turbine blades of promising GTES, *Russian metallurgy (Metally)*, 2012, V. 2012, No 1, pp. 1–7.

3. Kablov, E.N., Korroziya ili zhizn [Corrosion or life], *Nauka i zhizn*, 2012, No 11, pp. 16–21.

4. Kablov, E.N., Muboyadzhyan, S.A., Zharostoykie i teplozashchitnye pokrytiya dlya lopatok turbiny vysokogo davleniya perspektivnykh GTD [Heat-resistant and heat-shielding coatings for high-pressure turbine blades of advanced GTE], *Aviatsionnye materialy i tekhnologii*, 2012, No S, pp. 60–70.

5. Alexandrov, D.A., Muboyadzhyan, S.A., Gayamov, A.M., Gorlov, D.S., Issledovanie zharostoykosti i kinetiki izmeneniya elementnogo sostava kompozitsii iz titanovogo splava VT41 s zharostoykimi pokrytiyami [Investigation of the heat resistance and kinetics of the change in the elemental composition of a composition of a titanium alloy VT41 with heat-resistant coatings], *Aviatsionnye materialy i tekhnologii*, 2014, No. S5, pp. 61–66. DOI: 10.18577 / 2071-9140-2014-0-s5-61-66.

6. Kablov, E.N., Ospennikova, O.G., Lomberg, B.S., Strategicheskie napravleniya razvitiya konstruktsionnykh materialov i tekhnologiy ikh pererabotki dlya aviatsionnykh dvigateley nastoyashchego i budushchego [Strategic directions of the development of structural materials and technologies for their processing for aircraft engines of the present and future], *Avtomaticheskaya svarka*, 2013, No 10, pp. 23–32.

7. Aslanyan, I.R., Shuster, L.Sh., Iznashivanie elektroliticheskikh NiP pokrytiy pri fretting-korrozii [Wear electrolytic NiP coatings during fretting corrosion], *Aviatsionnye materialy i tekhnologii*, 2015, No 2 (35), pp. 26–31. DOI: 10.18577 / 2071-9140-2015-0-2-26-31.

8. Shuster, L.Sh., Krioni, N.K., Aslanyan, I.R., Emaev, I.I., Otsenka iznashivaniya pokrytiy v razlichnykh usloviyakh treniya [Evaluation of wear of coatings under various friction conditions], *Uprochnyayushchie tekhnologii i pokrytiya*, 2015, No 2 (122), pp. 10–13.

9. Grudev, A.P., Zilberg, Yu.V., Tilik, V.T., *Trenie i smazki pri obrabotke metallov davleniem* [Friction and lubrication in the treatment of metals by pressure]: Handbook, Moscow: Metallurguiya, 1982.

10. *Trenie, iznashivanie i smazka* [Friction, wear and lubrication]: Handbook, Kragelsky, I.V., Alisin, V.V. (Eds.), Moscow: Mashinostroenie. 1979. Book 2.

11. Wenzel, S.V., *Primenenie smazochnykh masel v dvigatelyakh vnutrennego sgoraniya* [Application of lubricating oils in internal combustion engines], Moscow: Khimiya, 1979.

12. Barykin, N.P., Aslanian, I.R., Matematicheskoe modelirovanie rezhimov poverkhnostnogo plasticheskogo deformirovaniya dlya povysheniya iznosostoykosti podshipnikov skolzheniya [Mathematical modeling of surface plastic deformation modes for increasing wear resistance of sliding bearings], *Trenie i iznos*, 2001, V. 22, No 5, pp. 496–501.

13. Goryacheva, I.G., Development of Galin's Research in Contact Mechanics, *Contact Problems*, Galin, L.A., Gladwell, G.M.L. (Eds.), Springer, 2008, pp. 207–237.

14. Johnson, K.L. *Contact Mechanics*, Cambridge University Press, 1985.

15. Goryacheva, I.G., *Mekhanika friktsionnogo vzaimodeistviya* [Mechanics of friction interaction], Moscow: Nauka, 2001.

UDC 621.793.7

EFFECT OF GAS PHASE COMPOSITION ON FUNCTIONAL-GRADIENT COATINGS FORMATION BY SUPERSONIC COLD GAS DYNAMIC SPRAYING

A. M. MAKAROV, T. I. BOBKOVA, Cand. Sc. (Eng), A.F. VASILIEV,
D.A. GERASCHENKOV, Cand. Sc. (Eng), I.S. PRUDNIKOV, B.V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC “Kurchatov Institute” – CRISM “Prometey”, 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received October 26, 2017

Abstract—The paper develops method for manufacturing wear and corrosion-resistant gradient coating. A special feature of the proposed method is the creation of chemical composition gradient due to controlled variation of the gas phase composition when applying supersonic cold gas-dynamic spraying. This ensures high adhesive strength of the composite coatings of the metal-non-metal system in combination with high microhardness of the peripheral layers. Such functional gradient coatings have wide practical applications.

Keywords: supersonic cold gas-dynamic spraying, functional gradient coating, adhesive strength, microhardness.

DOI: 10.22349/1994-6716-2018-93-1-65-69

REFERENCES

1. Gorynin, I.V., *Razmyshleniya s optimizmom* [Reflections with optimism], St Petersburg: Polytechnic University Publishing House, 2014.

2. *Perspektivnye napravleniya razvitiya nauki v Peterburge* [Promising directions of the development of science in St Petersburg], Alferov Zh. et al. (Eds), St Petersburg: Permyakov, 2015, pp. 137–163.

3. Grachev, V.I., Margolin, V.I., Zhabrev, V.A., Tupik, V.A., Osnovy sinteza nanorazmernykh chastits i plenok [Basics of synthesis of nanoscale particles and films], Izhevsk: Udmurtia, 2014.

4. Gerashchenkov, D.A., Farmakovsky, B.V., Samodelkin, E.A., Gerashchenkova, E.Yu., Issledovanie adgezionnoy prochnosti kompozitsionnykh armirovannykh pokrytiy sistemy metall–nemetall, poluchennykh metodom kholodnogo gazodinamicheskogo napyleniya [Investigation of the adhesion strength of composite reinforced coatings of the metal–nonmetal system obtained by the method of cold gas-dynamic spraying], *Voprosy Materialovedeniya*, 2014, No 2(78), pp. 103–117.

5. Gorynin, I., Malyshevsky, V., Farmakovsky, B., Projects of Federal State Unitary Enterprise Central Research Institute of Structural Materials “Prometey”, *Russia; Innovations and Nanotechnologies of Russia*, 2012, No 1(2), April, pp. 64–68.

6. Margolin, V.I., Potapov, A.A., Farmakovsky, B.V., Kuznetsov, P.A., Razvitie tekhnologiy na osnove nanokompozitov [Development of technologies on the basis of nanocomposites], St Petersburg: LETI, 2016.

7. Gorynin, I.V., Oryshchenko, A.S., Farmakovsky, B.V., Kuznetsov, P.A., Perspektivnye issledovaniya i razrabotki nauchnogo nanotekhnologicheskogo tsentra FGUP TSNII KM Prometey v oblasti novykh nanomaterialov [Prospective studies and developments of the scientific nanotechnology center of the Federal State Unitary Enterprise Prometey in the field of new nanomaterials], *Voprosy Materialovedeniya*, 2014, No 2(78), pp. 118–127.

8. Gerashchenkov, D.A., Farmakovsky, B.V.,Vasilyev, A.F., Gorynin, I.V., Patent RU (11) 2 354 749(13) C2: *Method for making nanostructured functional-gradient wear-resistant coating*, Publ. 10.05.2009, Bull. 13.

9. Somkova, E.A., Vasilyev, A.F., Kuznetsov, P.A, Sergeeva, O.S., Farmakovsky, B.V., Samodelkin, E.A., Patent RU (11) 2 367 701(13) C2: *Noncorrosive alloy on basis of germanium*, Publ.: 20.09.2009, Bull. No 26.

UDC 621.793.7

DEVELOPING TECHNOLOGY OF FABRICATION OF FUNCTIONAL NANOSTRUCTURED COATINGS ON WEAR- AND CORROSION-RESISTANT ALLOY BASED ON THE Cu–Ni SYSTEM

A. M. MAKAROV, A. V. KOSULNIKOVA, T. I. BOBKOVA, Cand. Sc. (Eng), A.F. VASILIEV, D.A. GERASCHENKOV, Cand. Sc. (Eng), V.N. KLIMOV, E.A. SAMODELKIN, B.V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC “Kurchatov Institute” – CRISM “Prometey”, 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received October 26, 2017

Abstract—The paper presents complex studies of nanostructured powder of Cu-Hf-BN alloy system and functional wear and corrosion-resistant coatings based on it are presented. A technology for applying a composite nanostructured coating of the Cu-Ni-Zr-Cr-Hf-BN system onto a steel substrate (steel Kh18Yu5S) was developed using supersonic cold and microplasma deposition techniques. The coatings have elevated level of microhardness (up to 32 GPa), adhesive strength (more than 13 MPa), resistance to stress-corrosion crackingand a wide range of operating temperatures from 850 to –196°C.

Keywords: composite nanostructured powder, wear and corrosion-resistant coating, supersonic cold and microplasma spraying.

DOI: 10.22349/1994-6716-2018-93-1-70-75

REFERENCES

1. Gerashchenkov, D.A., Razrabotka tekhnologicheskogo protsessa naneseniya pokrytiy metodom kholodnogo gazodinamicheskogo napyleniya na osnove armirovannykh poroshkov sistemy Al–Sn + Al_2O_3 [Development of the technological process of coating deposition by the method of cold gas-dynamic spraying based on reinforced powders of the Al–Sn + Al_2O_3 system], Abstract of thesis for the degree of candidate of sciences, St Petersburg, 2015.

2. Margolin, V. I., Zhabrev, V.A., Lukianov, G.N., Tupik, V.A, *Vvedenie v nanotekhnologiyu* [Introduction to nanotechnology]: Textbook, St Petersburg: Lan, 2012.

3. *Perspektivnye napravleniya razvitiya nauki v Peterburge* [Promising directions of the development of science in St Petersburg], Alferov Zh. et al. (Eds), St Petersburg: Permyakov, 2015, pp. 137–163.

4. Glezer A.M., Permyakova I.E., *Nanokristally, zakalennye iz rasplava* [Nanocrystals hardened from the melt], Moscow: Fizmatlit, 2012.

5. Kogan, B.I., Sukhovolsky, A.A., Tekhnologicheskoe obespechenie kachestva remonta kovshey ekskavatorov [Technological support of quality of repair of buckets of excavators], *Vestnik KuzGTU*, 2010.

6. Garshin, A. P., Shumyacher, V. M., Pushkarev, O. I., Sposob polucheniya i svoystva abrazivnogo materiala na osnove karbida kremniya i korunda [Method of obtaining and properties of abrasive material based on silicon carbide and corundum], Collection of materials for the 8th International Symposium “Powder Metallurgy: Surface Engineering, New Powder Composite Materials, Welding”, Minsk, 2013, pp. 124–129.

7. Geraschenkov, D.A., Farmakovsky, B.V., Samodelkin, E.A., Geraschenkova, E. Yu., Issledovanie adgezionnoy prochnosti kompozitsionnykh armirovannykh pokrytiy sistemy metal–nemetall, poluchennykh metodom kholodnogo gazodinamicheskogo napyleniya [Investigation of the adhesive strength of composite reinforced coatings of the metal-nonmetal system obtained by the method of cold gas-dynamic spraying], *Voprosy Materialovedeniya*, 2014, No. 2(78), pp. 103–117.

8. Burkanova, E. Yu., Farmakovsky, B.V., Vysokoskorostnoy mekhanosintez s i ispolzovaniem dezintegratornykh ustanovok dlya polucheniya nanostrukturirovannykh poroshkovykh materialov sistemy metall – keramika iznosostoykogo klassa [High-speed mechanosynthesis using disintegrator plants for obtaining nanostructured powder materials of the metal-ceramic system of wear-resistant class], *Voprosy Materialovedeniya*, 2012, V. 1 (69), pp. 80–85.

UDC 621.793.7:621.791.3

OBTAINING THE COMPOSITE CATHODE FOR MAGNETIC SPRAYING OF FUNCTIONAL COATINGS

R. Yu. BYSTROV, A. N. BELYAKOV, A. F. VASILIEV, D. A. GERASCHENKOV, Cand. Sc. (Eng), E. Yu. GERASCHENKOVA, E. N. ESHMEMETIEVA, M. A. KORKINA, E. A. SAMODELKIN, B. V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC “Kurchatov Institute” – CRISM “Prometey”, 49, Shpalernaya St, 191015, St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received October 26, 2017

Abstract—The technology of obtaining composite cathodes for vacuum magnetron deposition of functional coatings has been developed and mastered in the Scientific Nanotechnological Center of the NRC "Kurchatov Institute" – CRISM "Prometey". The example of the Ti–Ru system shows the prospects for creating composite cathodes from expensive and hard-deforming materials by means of activated soldering with amorphous solders.

Keywords: activated soldering, amorphous solder, cold gas dynamic spraying, functional gradient coating, composite cathode.

DOI: 10.22349/1994-6716-2017-92-4-76-81

REFERENCES

1. Grachev, V.I., Margolin, V.I., Zhabrev, V.A., Tupik, V.A., Osnovy sinteza nanorazmernykh chastits i plenok [Basics of synthesis of nanoscale particles and films], Izhevsk: Udmurtia, 2014.

2. Berlin, E.V., Seidman, L.A.,*Poluchenie tonkikh plenok reaktivnym magnetronnym napyleniem* [Production of thin films by reactive magnetron sputtering], Moscow: Tekhnosfera, 2014.

3. Raoelison, R.N., Verdy, Ch.,Liao, H.,Cold gas dynamic spray additive manufacturing today: Deposit possibilities, technological solutions and viable applications,*Materials & Design*, 2017, V. 133, pp. 266–287.

4. Geraschenkov, D.A., Farmakovsky, B.V., Samodelkin, E.A., Geraschenkova, E. Yu., Issledovanie adgezionnoy prochnosti kompozitsionnykh armirovannykh pokrytiy sistemy metal–nemetall, poluchennykh metodom kholodnogo gazodinamicheskogo napyleniya [Investigation of the adhesive strength of composite reinforced coatings of the metal-nonmetal system obtained by the method of cold gas-dynamic deposition], *Voprosy Materialovedeniya*, 2014, No. 2(78), pp. 103–117.

5. Gorynin, I.V., Farmakovsky, B.V., Vasiliev, A.F., Vinogradova, T.S., Samodelkin, E.A., Aktivirovannaya payka raznorodnykh materialov amorfnymi pripoyami [Activated soldering of dissimilar materials by amorphous solders], *Voprosy Materialovedeniya*, 2016, No 2(86), pp. 111–119.

6. Geraschenkov, D.A., Vasiliev, A.F., Farmakovsky, B.V., Mashek, I.I., Issledovanie temperatury potoka v protsesse kholodnogo gazodinamicheskogo napyleniya funktsionalnykh pokrytiy [Investigation of the flow temperature in the process of cold gas-dynamic spraying of functional coatings], *Voprosy Materialovedeniya*, 2014, No 1(77), pp. 87–96.

7. Burkanova, E. Yu., Samodelkin, E. A., Farmakovsky, B. V., Geraschenkov, D. A., Vasiliev, A. F., Korkina, M. A., Patent RU 2486995 C1: *Method of making composite cathode*, Bulletin No 19, Publ. 10.07.2013.

8. Eshmemetieva, E.N., Beliakov, A.N., Bystrov, R. Yu., Vasiliev, A.F., Kuznetsov, P.A., Farmakovsky, B.V., Osobennosti formirovaniya pokrytiy sistemy Ti-Ru-O metodom vakuumnogo magnetronnogo napyleniya na postoyannom toke [Features of formation of coatings of the Ti-Ru-O system by the vacuum magnetron sputtering method on direct current], *Voprosy Materialovedeniya*, 2017, No 1 (89), pp.115–122.

UDC 621.74:621.315.3:669.24

HIGH-RESISTIVE NICKEL-BASED ALLOYS FOR THERMO-STABLE MICROWIRES MANUFACTURED BY HIGH-SPEED MELT QUENCHING

O.V. VASILIEVA, Cand. Sc. (Eng), P.A. KUZNETSOV, Dr. Sc. (Eng),
B.V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received October 27, 2017

Abstract—The paper presents results of a development study of optimal alloy composition based on Ni–Cr–Si–B system for the casting of microwires in glass insulation by high-speed quenching. High-resistant microwires manufactured for the developed alloy have low temperature coefficient of resistance (less than 5 10^{-6} K^{-1}) and high linear resistance (more than 1000 kOhm/m) in a wide range of positive and negative temperatures (from –196 to 250°C).

Keywords: cast microwire in glass insulation, high-resistive alloy, linear resistance, temperature coefficient of resistance.

ACKNOWLEDGEMENTS

The authors express their respect for the memory of V.V. Smirnov† (JSC "Central Research Institute of Materials"), whichmade valuable contribution intothe development of casting technology.

DOI: 10.22349/1994-6716-2017-92-4-82-87

REFERENCES

1. *Perspektivnye napravleniya razvitiya nauki v Peterburge* [Promising directions of the development of science in St Petersburg], Alferov Zh. et al. (Eds), St Petersburg: Permyakov, 2015, pp. 137–163.

2. Masaylo, D.V., Smelov, A.I., Peskov, T.V., Farmakovsky, B.V., Razrabotka tenzo- i termorezistivnykh splavov dlya litya mikroprovodov [Development of strain and thermoresistant alloys for casting microwires], *Voprosy Materialovedeniya*, 2014, No 3(79), pp. 73–78.

3. Badinter, E.Ya. et al., *Litoy mikroprovod i ego svoystva* [The cast microwire and its properties], Kishinev: Shtiintsa, 1973.

4. Gorynin, I.V., Farmakovsky, B.V., Dlinnomernye litye mikroprovoda v steklyannoy izolyatsii s zhiloy iz intermetallicheskikh soyedineniy [Long-length cast microwires in glass insulation with a vein of intermetallic compounds], *Voprosy Materialovedeniya*, 2015, No 4(84), pp. 58–61.

5. *Litoy mikroprovod i ego primenenie v nauke i tekhnike* [Molded microwire and its application in science and technology], Gitsu, D.V. (Ed.), Kishinev: Shtiintsa, 1988.

6. Farmakovsky, B.V., Struktura i svoystva mikroprovodov iz dvoynykh splavov [Structure and properties of microwires from binary alloys], *Metallovedenie i termicheskaya obrabotka metallov*, 1977, No 3, pp. 33–38.

7. Farmakovsky, B.V., et al., Author's certificate No 480773 USSR, MKI C22C19/00: *Nickel based alloy*, Publ. 15.08.75. Bull. No 30.

8. Farmakovsky, B.V., Somkova, E.A., Yurkov, M.A., Tochenyuk, D.A., Bystrov, R.Yu., Semenov, A.S., Patent RU (11) 2 351 672(13) C2: *Amorphous resistive alloy on basis of nickel*, Publ. 10.04.2009, Bull. 10.

9. Farmakovsky, B.V., Vasilyev, A.F., Korkina, M.A., Kuzmin, K.A., Tarakanova, T.A., Zemlyanitsyn, E.Yu., Patent RU(11) 2 424 349(13) C2: *Amorphous alloy on base of nickel for mucro-wires casting*, Publ. 20.07.2011, Bull. 20.

10. Glezer A.M., Permyakova I.E., *Nanokristally, zakalennyye iz rasplava* [Nanocrystals hardened from the melt], Moscow: Fizmatlit, 2012.

11. Zhabrev V.A., Kalinnikov V.T., Margolin V.I., Nikolaev A.I., Tupik V.A., *Fiziko-khimicheskie protsessy sinteza nanorazmernykh obyektov* [Physicochemical processes of synthesis of nanoscale objects], St Petersburg: Elmor, 2012.

12. Bolbochan, V.F., et al., Sposob opredeleniya malykh znacheniy soprotivleniya [The method for determining low values of resistance], *Theses of the Republican Scientific and Technical Conference "Pribory soprotivleniya i rezistivnaya elementnaya baza elektroizmeritelnykh priborov"* [Devices of resistance and resistive element base of electrical measuring instruments], Kishinev, 1982.

13. Masaylo, D.V., Kuznetsov, P.A., Farmakovsky, B.V., Vysokoprochnye litye mikroprovoda dlya armirovaniya konstruktsionnykh kompozitov [High-strength cast microwires for reinforcing structural composites], *Metalloobrabotka*, 2012, No 4, pp. 23–27.

UDC 621.791.92:621.762.2

SYNTHESIS AND ELECTRON BEAM FACING OF TITANIUM MONOBORIDE – TITANIUM MATRIX COMPOSITE POWDERS

G.A. PRIBYTKOV, Dr Sc. (Eng), V.V. KORZHOVA, , Cand Sc. (Eng), M.G. KRINITSYN, I.A. FIRSINA, Cand Sc. (Eng)

Institute of Strength Physics and Materials Science of the Siberian Branch of the Russian Academy of Sciences (ISPMS SB RAS), 2/4 Akademichesky Ave.,634055 Tomsk. E-mail: root@ispms.tomsk.ru

Received November 21, 2017

Abstract—Titanium monoboride – titanium matrix composite powders have been synthesized by self-propagating high temperature synthesis (SHS) in titanium and boron reactive powder mixtures. Titanium matrix (binder) content varied from 20 to 60%. The SHS powders were cladded on VT1-0 titanium sheet by electron beam facing. Cladded coatings' thickness varied from 1 to 3 mm depending on the pass number. Phase composition and structure of powders and coatings were investigated by X-ray diffraction, optical and scanning electron microscopy. According to structure investigation and hardness profiles view in the "coating – titanium base plate" transition zone an adhesion of the coating to the base is high. The hardness and abrasive wear resistance tests of the cladded coatings were carried out depending on the powder used for cladding. The maximum hardness of the coatings strengthened by eagle-like titanium monoboride inclusions as compared with VT1-0 base increases 2.2 times and abrasive wear resistance 3.7 times. According to previously obtained results hardening and abrasive wear resistance of titanium monoboride is much weaker than that of titanium carbide: hardness increases 1.7 times, wear resistance 5.8 times.

Keywords: self-propagating high-temperature synthesis, metal-matrix composites, titanium monoboride, titanium, surfacing, microstructure, hardness, abrasive wear resistance.

ACKNOWLEDGEMENTS

The authors thank V.P. Krivopalov for assistance in the synthesis of powders and carrying out wear tests.

The work was supported by the Russian Science Foundation (grant No. 17-19-01425).

DOI: 10.22349/1994-6716-2018-93-1-88-102

REFERENCES

1. Qi, J.Q., Wang, H.W., Zou, C.M., Wei, W.Q., Wei, Z.J., Temperature dependence of fracture behavior of in situ synthesized TiC/Ti-alloy matrix composite, *Materials Science and Engineering: A*, 2011, V. 528, Issues 25–26, pp. 7669–7673.

2. Rasool, G., Mridha, S., Stack, M.M., Mapping wear mechanisms of TiC/Ti composite coatings, Wear, 2015, V. 328–329, pp. 498–508.

3. Tjong, S.C., Ma, Z.Y., Microstructural and mechanical characteristics of in situ metal matrix composites, *Materials Science and Engineering: R: Reports*, 2000, V. 29, Issues 3–4, pp. 49–113.

4. Zhang, J., Ke, W., Ji, W., Fan, Z., Wang, W., Fu, Z., Microstructure and properties of in situ titanium boride (TiB) /titanium (Ti) composites, *Materials Science and Engineering: A*, 2015, V. 648, pp. 158–163.

5. Attar, H., Löber, L., Funk, A., Calin, M., Zhang, L.C., Prashanth, K.G., Scudino, S., Zhang, Y.S., Eckert, J., Mechanical behavior of porous commercially pure Ti and Ti–TiB composite materials manufactured by selective laser melting, *Materials Science & Engineering: A*, 2015, V. 625, pp. 350–356

6. Sahay, S.S., Ravichandran, K.S., Atri, R., Evolution of microstructure and phases in *in situ* processed Ti–TiB composites containing high volume fractions of TiB whiskers, *Journal of Materials Research*, 1999, V. 14, No 11, pp. 4214–4223.

7. Ma, F., Wang, T., Liu, P., Li, W., Liu, X., Chen, X., Pan, D., Lu, W., Mechanical properties and strengthening effects of in situ (TiB+TiC)/Ti-1100 composite at elevated temperatures, *Materials Science & Engineering: A*, 2016, V. 654, pp. 352–358

8. Li, S., Kondoh, K., Imai, H., Chen, B., Jia, L., Umeda, J., Fu, Y., Strengthening behavior of in situ-synthesized (TiC–TiB)/Ti composites by powder metallurgy and hot extrusion, *Materials and Design*, 2016, V. 95, pp. 127–132.

9. Imayev, V., Gaisin, R., Gaisina, E., Imayev, R., Fecht, H.-J., Pyczak, F., Effect of hot forging on microstructure and tensile properties of Ti–TiB based composites produced by casting, *Materials Science and Engineering: A*, 2014, V. 609, pp. 34–41.

10. Imayev, V.M., Gaisin, R.A., Imayev, R.M., Effect of boron additions and processing on microstructure and mechanical properties of a titanium alloy Ti–6.5Al–3.3Mo–0.3Si, *Materials Science and Engineering: A*, 2015, V. 641, pp. 71–83.

11. Shen, X., Zhang, Z., Wei, S., Wang, F., Lee, S., Microstructures and mechanical properties of the in situ TiB–Ti metal–matrix composites synthesized by spark plasma sintering process, *Journal of Alloys and Compounds*, 2011, V. 509, Issue 29, pp. 7692–7696.

12. Cheloui, H., Zhang, Z., Shen, X., Wang, F., Lee, S., Microstructure and mechanical properties of TiB–TiB_2 ceramic matrix composites fabricated by spark plasma sintering, *Materials Science and Engineering: A*, 2011, V. 528, pp. 3849–3853.

13. Wang, F., Zhang, Z., Luo, J., Huang, Ch., Lee, S., A novel rapid route for in situ synthesizing TiB–TiB_2 composites, *Composites Science and Technology*, 2009, V. 69, pp. 2682–2687.

14. Wei, S., Zhang, Z., Wang, F., Shen, X., Cai, H., Lee, S., Wang, L., Effect of Ti content and sintering temperature on the microstructures and mechanical properties of TiB reinforced titanium composites synthesized by SPS process, *Materials Science and Engineering: A*, 2013, V. 560, pp. 249–255.

15. Chaudhari, R., Bauri, R., Reaction mechanism, microstructure and properties of Ti–TiB in situ composite processed by spark plasma sintering, *Materials Science and Engineering: A*, 2013, V. 587, pp. 161–167.

16. Eriksson, M. Salamon, D., Nygren, D. M., Shen, Z., Spark plasma sintering and deformation of Ti–TiB_2 composites, *Materials Science and Engineering: A*, 2008, V. 475, pp. 101–104.

17. Jia, L. Wang, X., Chen, B., Imai, H., Li, S., Lu, Z., Kondoh, K., Microstructural evolution and competitive reaction behavior of Ti-B4C system under solid-state sintering, *Journal of Alloys and Compounds*, 2016, V. 687, pp. 1004–1011.

18. *Diagrammy sostoyaniya dvoynykh metallicheskikh system* [Diagrams of the state of double metal systems]: Reference book, N.P. Liakishev (Ed.), Moscow: Mashinostroenie, 1996, V. 1.

19. Miklaszewski, A., Effect of starting material character and its sintering temperature on microstructure and mechanical properties of super hard Ti/TiB metal matrix composites, *International Journal of Refractory Metals and Hard Materials*, 2015, V. 53, Part A, pp. 56–60.

20. Yan, Z. Chen, F., Cai, Y., Zheng, Y., Microstructure and mechanical properties of in-situ synthesized TiB whiskers reinforced titanium matrix composites by high-velocity compaction, *Powder Technology*, 2014, V. 267, pp. 309–314.

21. Quast, J.P., Boehlert, C.J., Gardner, R., Tuegel, E., Wyen, T., A microstructure and sonic fatigue investigation of Ti–TiB functionally graded materials, *Materials Science and Engineering: A*, 2008, V. 497, pp. 1–9.

22. Fu, B., Wang, H., Zou, Ch., Wei, Z., Microstructural characterization of in situ synthesized TiB in cast Ti-1100-0.10B alloy, *Trans. Nonferrous Met. Soc. China*, 2015, V. 25, pp. 2206–2213.

23. Akopyan, A.G., Dolukhanyan, S.K., Borovinskaya, I.P., Vzaimodeistvie titana, bora i ugleroda [The interaction of titanium, boron and carbon], *Fizika goreniya i vzryva*, 1978, No 3, pp.70–79.

24. Azatyan, T.S., Maltsev, V.M., Merzhanov, A.G., Seleznev, V.A., O mekhanizme rasprostraneniya volny goreniya v smesyakh titana s borom [On the Mechanism of Propagation of the Combustion Wave in Mixtures of Titanium with Boron], *Fizika goreniya i vzryva*, 1980, V. 16, No 2, pp. 37–42.

25. Zwikker, U., *Titan und Titanlegirungen*, Springer-Verlag, 1974.

26. Gorynin, I.V., Chechulin, B.B., *Titan v mashinostroenii* [Titanium in engineering], Moscow: Mashinostroenie, 1990.

27. Lin, Y., Lei, Y., Li, X., Zhi, X., Fu, H., A study of TiB_2/TiB gradient coating by laser cladding on titanium alloy, *Optics and Lasers in Engineering*, 2016, V. 82, pp. 48–55.

28. Genç, A., Banerjee, R., Hill, D., Fraser, H.L., Structure of TiB precipitates in laser deposited in situ, Ti-6Al-4V–TiB composites, *Materials Letters*, 2006, V. 60, pp. 859–863.

29. Attar, H., Ehtemam-Haghighi, S., Kent, D., Okulov, I.V., Wendrock, H., Bönisch, M., Volegov, A.S., Calin, M., Eckert, J., Dargusch, M.S., Nanoindentation and wear properties of Ti and Ti-TiB composite materials produced by selective laser melting, *Materials Science and Engineering: A*, 2017, V. 688, pp. 20–26.

30. Attar, H., Bönisch, M., Calin, M., Zhang, L., Scudino, S., Eckert, J., Selective laser melting of in sutu titanium-titanium boride composites: Processing, microstructure, and mechanical properties, *Acta materialia*, 2014, V. 76, pp. 13–22.

31. Attar, H., Prashanth, K.G., Zhang, L., Calin, M., Okulov, I.V., Scudino, S., Yang, Ch., Eckert, J., Effect of Powder Particle Shape on the Properties of In Situ Ti–TiB Composite Materials Produced by Selective Laser Melting, *Journal of Materials Science and Technology*, 2015, V. 31, pp. 1001–1005.

32. Hu, Y., Cong, W., Wang, X., Li, Y., Ning, F., Wang H., Laser deposition-additive manufacturing of TiB-Ti composites with novel three-dimensional quasi-continuous network microstructure: Effects on strengthening and toughening, *Composites. Part B*, 2018, V. 133, pp. 91–100.

33. Panin, V.E., Belyuk, S.I., Durakov, V.G., Pribytkov, G.A., Rempe, N.G., Elektronno-luchevaya naplavka v vakuume: oborudovaniye, tekhnologiya, svoistva pokryty [Electron beam surfacing in vacuum: equipment, technology, coating properties], *Svarochnoe proizvodstvo*, 2000, No 2, pp. 34–38.

34. Rogachev, A.S., Mukasyan, A.S., Gorenie dlya sinteza materialov: vvedenie v strukturnuyu makrokinetiku [Combustion for the synthesis of materials: introduction to structural macrokinetics], Moscow: Fizmatlit, 2012.

35. Pribytkov, G.A., Krinitsyn, M.G., Korzhova, V.V., Issledovanie produktov SV-sinteza v poroshkovykh smesyakh titana i ugleroda, soderzhashchikh izbytok titana [Investigation of products of SV synthesis in powder mixtures of titanium and carbon containing an excess of titanium], *Perspektivnye materialy*, 2016, No 5, pp. 59–68.

36. Pribytkov, G.A., Korzhova, V.V., Baranovsky, A.V., Krinitsyn, M.G., Fazovy sostav i struktura SVS-kompozitsionnykh poroshkov “karbid titana – svyazka iz stali R6M5” [Phase composition and structure of SHS composite powders: titanium carbide as a binding for steel R6M5], *Izvestiya vuzov. Poroshkovaya metallurgiya i funktsionalnye pokrytiya*, 2016, No 2, pp. 64–71.

37. Pribytkov, G.A., Krinitsyn, M.G., Firsina, I.A., Durakov, V.G., Tverdost i abrazivnaya iznosostoykost elektronnoluchevykh pokrytiy karbid titana – titanovaya svyazka, naplavlennykh SVS kompozitsionnymi poroshkami [Hardness and abrasive wear resistance of electron-beam coatings of titanium carbide as a titanium binder, built-up by SAF composite powders], *Voprosy Materialovedeniya*, 2017, No 4 (92), pp. 52–61.

38. Svoystva, poluchenie i primenenie tugoplavkikh soedineniy [Properties, production and application of refractory compounds]: Handbook, Kosolapova T.Ya. (Ed.), Moscow: Metallurgiya, 1986.

UDC 621.793.7

CORROSION-RESISTANT COMPOSITE GERMANIUM-BASED ALLOYS COATINGS

A.F. VASILIEV, E.A. SAMODELKIN, E.Yu. GERASCHENKOVA,
B.V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC “Kurchatov Institute” – CRISM “Prometey”, 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received December 4, 2017

Abstract—The results of complex studies on the development of a powder composition Ge–Cr–Zr–Ce–WC, promising for the production of functional cold-resistant coatings by microplasma sputtering, are presented. The coating has high adhesive strength (more than 40 MPa) and microhardness (up to 10–12 GPa) and withstands repeated thermal cycling in the temperature range from –60 to 20°C.

Keywords: powder composition, functional cold-resistant coating, microplasma spraying, corrosion resistance, adhesive strength.

DOI: 10.22349/1994-6716-2018-93-1-103-108

REFERENCES

1. Margolin, V.I., Potapov, A.A., Farmakovsky, B.V., Kuznetsov, P.A., Razvitie tekhnologiy na osnove nanokompozitov [Development of technologies on the basis of nanocomposites], St Petersburg: LETI, 2016.

2. Margolin, V. I., Zhabrev, V.A., Lukianov, G.N., Tupik, V.A, *Vvedenie v nanotekhnologiyu* [Introduction to nanotechnology]: Textbook, St Petersburg: Lan, 2012.

3. Syrkov, A.G., Nanotekhnologii i nanomaterialy. Rol neravnovesnykh protsessov [Nanotechnologies and nanomaterials. The role of nonequilibrium processes]: Textbook, St Petersburg: Publishing house of Polytechnic University, 2016.

4. Gorynin, I.V., Oryshchenko, A.S., Farmakovsky, B.V., Kuznetsov, P.A., Perspektivnye issledovaniya i razrabotki nauchnogo nanotekhnologicheskogo tsentra FGUP TSNII KM Prometey v oblasti novykh nanomaterialov [Prospective studies and developments of the scientific nanotechnology center of the Federal State Unitary Enterprise "Prometey" in the field of new nanomaterials], *Voprosy Materialovedeniya*, 2014, No 2(78), pp. 118–127.

5. Bobkova, T.I., Farmakovsky, B.V., Bogdanov, S.P., Sozdanie kompozitsionnykh nanostrukturirovannykh poverkhnostno-armirovannykh poroshkovykh materialov na osnove sistem Ti/WC i Ti/TiCN dlya napyleniya pokrytiy povyshennoy tverdosti [Creation of composite nanostructured surface-reinforced powder materials on the basis of Ti / WC and Ti / TiCN systems for deposition of coatings of increased hardness], *Voprosy Materialovedeniya*, 2015, No 3 (83), pp. 80–90.

6. Dzhurinsky, D.V., Farmakovsky, B.V., Issledovanie protsessa naneseniya pokrytiy iz raznorodnykh materialov na metallicheskie podlozhki metodom kholodnogo gazodinamicheskogo napyleniya, *Voprosy Materialovedeniya*, 2003, No 2, pp. 38–44.

7. Somkova, E.A., Vasilyev, A.F., Kuznetsov, P.A, Sergeeva, O.S., Farmakovsky, B.V., Samodelkin, E.A., Patent RU (11) 2 367 701(13) C2: *Noncorrosive alloy on basis of germanium*, Publ.: 20.09.2009, Bull. No 26.

8. Gerashchenkov, D.A., Farmakovsky, B.V., Samodelkin, E.A., Gerashchenkova, E.Yu., Issledovanie adgezionnoy prochnosti kompozitsionnykh armirovannykh pokrytiy sistemy metall-nemetall, poluchennykh metodom kholodnogo gazodinamicheskogo napyleniya [Investigation of the adhesion strength of composite reinforced coatings of the metal-nonmetal system obtained by the method of cold gas-dynamic spraying], *Voprosy Materialovedeniya*, 2014, No 2(78), pp. 103–117.

9. Abriata, J.P., Bolcich, J.C., Arias, D., The Ge−Zr (Germanium-Zirconium) system, *Journal of Phase Equilibria*, 1986, Issue 7(1), February, pp. 43–47.

10. *Perspektivnye napravleniya razvitiya nauki v Peterburge* [Promising directions of the development of science in St Petersburg], Alferov Zh. et al. (Eds), St Petersburg: Permyakov, 2015, pp. 137–163.

11. Grachev, V.I., Margolin, V.I., Zhabrev, V.A., Tupik, V.A., *Osnovy sinteza nanorazmernykh chastits i plionok* [Fundamentals of the synthesis of nanosized particles and films], Izhevsk: Udmurtiya, 2014, p. 480.

12. Kuznetsov, N.T., Novotortsev, V.M., Zhabrev, V.A., Margolin, V.I., Osnovy nanotekhnologii [Fundamentals of nanotechnology]: Textbook, Moscow: Laboratoriya znaniy, 2014, p. 397.

UDC 621.793.7

FUNCTIONAL PROTECTIVE COATINGS OF NICKEL-BASED ALLOYS

D.A. GERASHCHENKOV, Cand. Sc. (Eng), T.I. BOBKOVA, Cand. Sc. (Eng), A.F. VASILIEV,
P.A. KUZNETSOV, Dr Sc. (Eng), E.A. SAMODELKIN, B.V. FARMAKOVSKY, Cand. Sc. (Eng)

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received December 19, 2017

Abstract—A composition of a precision alloy based on the Ni–Cr–Mo system for wear and corrosion-resistant coatings by supersonic cold gas dynamic spraying has been developed. The optimum coatings composition provides high level of operational properties; its application is very promising for protection of structural and functional elements of marine equipment from aggressive environmental influence.

Keywords: spraying, microhardness, adhesive strength

DOI: 10.22349/1994-6716-2018-93-1-110-114

REFERENCES

1. *Perspektivnye napravleniya razvitiya nauki v Peterburge* [Perspective directions of science development in St Petersburg], Alferov, Zh.I., (Ed.), St Petersburg: Permiakov Publishing, 2015.

2. Farmakovsky, B.V., Izgotovlenie tonkikh metallicheskikh nitey iz khrupkikh vysokoprochnykh materialov [Manufacturing of thin metal threads from brittle high-strength materials], *Proceedings of the Academy of Sciences of the USSR. Metals*, 1977, No 2, pp. 239–245.

3. Suzuki, H., Mekhanizm uprochneniya i poslednie dostizheniya v oblasti vysokoprochnykh materialov [The mechanism of hardening and recent advances in high-strength materials], *Elektronika*, 1970, pp. 12–16.

4. Geraschenkov, D.A., Farmakovsky, B.V., Samodelkin, E.A., Geraschenkova, E.Yu., Issledovanie adgezionnoy prochnosti kompozitsionnykh armirovannykh pokrytiy sistemy metall – nemetall, poluchennykh metodom kholodnogo gazodinamicheskogo napyleniya [Investigation of the adhesion strength of composite reinforced coatings of the metal-nonmetal system obtained by the method of cold gas-dynamic spraying], *Voprosy Materialovedeniya*, 2014, No 2(78), pp. 103–117.

5. Bobkova, T.I., Buryan, M.A., Geraschenkova, E.Yu., Farmakovsky, B.V., Vasiliev, A.F., Deev A.A., Patent RU 2 527 543 C1: *Nickel-based alloy for application of wear and corrosion resistance by microplasma or cold supersonic spraying*, Bulletin No 25, Publ. 10.09.2014.

6. Farmakovsky, B.V., Ulin, I. V., Funktsionalnye materialy i pokrytija – puti i nadezhdy [Functional materials and coatings – ways end hopes] // *Po puti sozidaniya* [By the way of creation], St Petersburg: FSUE CRISM Prometey, 2009, V. 2.

7. Gorynin, I.V., *Razmyshleniya s optimizmom* [Reflections with optimism], St Petersburg: Polytechnic University Publishing House, 2014.

UDC 621.762.5:669.017.165

PARTICULARITY OF PRODUCING HIGH-TEMPERATURE CARBIDE HARDENED Ni–Al–Ta–C INTERMETALLIC ALLOY POWDER COMPOSITIONS BY GAS ATOMIZATION METHOD FOR FURTHER SELECTIVE LASER MELTING

A.M. ROGALEV, A.N. RAEVSKYKH, E.G. ARGINBAEVA, Cand. Sc. (Eng), S.M. PRAGER

Federal State Unitary Enterprise “All-Russian Scientific Research Institute of Aviation Materials” (FSUE VIAM), 17, Radio St, 105005 Moscow, Russian Federation. E-mail: admin@viam.ru

Received December 22, 2017

Abstract—The paper presents first results of studying samples of high-temperature carbide hardened intermetallic Ni–Al–Ta–C alloys manufactured by selective laser melting. It is shown that the right technological parameters of atomization ensure correct metallurgical processes. The parameters of selective laser melting were determined, which made it possible to obtain a dense structure of the synthesized material.

Key words: metal-powder composition, melt atomization, selective laser melting, microstructure, carbide hardened intermetallic alloys, granulometric composition

ACKNOWLEDGEMENTS

The work was carried out within the implementation of complex scientific “Strategic directions for the development of materials and technologies for their processing for the period until 2030”: 7.3: Creation of intermetallic nickel alloys and composite materials based on them”; and “10.4: Technologies for obtaining bi-and polymetallic naturally reinforced metallic materials by the method of direct laser synthesis from metal powders.

The work was carried out within the framework of the grant of the President of the Russian Federation for state support of leading scientific schools No NSh-9831.2016.8 “Development of the principles for creating heat-resistant materials obtained by the selective laser fusion method using the example of intermetallic alloys with carbide hardening of the Ni-Al-Ta-C system”.

DOI: 10.22349/1994-6716-2018-93-1-115-125

REFERENCES

1. Kablov, E.N., Innovatsionnye razrabotki FGUP “VIAM” GNTS RF po realizatsii “Strategicheskikh napravleniy razvitiya materialov i tekhnologiy ikh pererabotki na period do 2030 goda [Innovative developments of FSUE “VIAM” of the NSC RF for the implementation of *Strategic Directions for the Development of Materials and Technologies for Their Processing for the Period up to 2030*], *Aviatsionnye materialy i tekhnologii*, 2015, No. 1 (34), pp. 3–33. DOI: 10.18577/2071-9140-2015-0-1-3-33.

2. Kablov, E.N., Ospennikova, O.G., Lomberg, B.S., Strategicheskie napravleniya razvitiya konstruktsionnykh materialov i tekhnologiy ikh pererabotki dlya aviatsionnykh dvigateley nastoyashchego i budushchego [Strategic directions of the development of structural materials and technologies for their processing for aircraft engines of the present and future], *Avtomaticheskaya svarka*, 2013, No. 10, pp. 23–32.

3. Kablov, E.N., Ospennikova, O.G., Lomberg, B.S., Sidorov, V.V., Prioritetnye napravleniya razvitiya tekhnologiy proizvodstva zharoprochnykh materialov dlya aviatsionnogo dvigatelestroeniya [Priority directions of the development of technologies for heat-resistant materials for aircraft engine production], *Problemy chernoy metallurgii i materialovedeniya*, 2013, No 3, pp. 47–54.

4. Kablov, E.N., Petrushin, N.V., Svetlov, I.L., Demonis, I.M., Nikelevye liteinye zharoprochnye splavy novogo pokoleniya [Nickel casting heat-resistant alloys of the new generation], *Aviatsionnye materialy i tekhnologii*, 2012, No S, pp. 36–51.

5. Shmotin, Yu.N., Starkov, R.Yu., Danilov, D.V., Ospennikova, O.G., Lomberg, B.S., Novye materialy dlya perspektivnogo dvigatelya OAO NPO “Saturn” [New materials for the perspective engine of NPO Saturn, JSC], *Aviatsionnye materialy i tekhnologii*, 2012, No 2, pp. 6–8.

6. Ospennikova, O., Strategiya razvitiya zharoprochnykh splavov i staley spetsialnogo naznacheniya, zashchitnykh i tekhnologicheskikh pokrytiy [Development strategy for high-temperature alloys and special steels, protective and technological coatings], *Aviatsionnye materialy i tekhnologii*, 2012, No. S, pp. 19–35.

7. Bazyleva, O.A., Turenko, E.Yu., Arginbaeva, E.G., Vysokotemperaturnye intermetallidnye splavy dlya detaley GTD [High-temperature intermetallic alloys for GTE parts], *Aviatsionnye materialy i tekhnologii*, 2013, No. 3, pp. 26–31.

8. Bazyleva, O.A., Turenko, E.Yu., Rassokhina, L.I., Bitiutskaya, O.N., Shitikov, A.V., Lapeev, B.S., Litye bloki soplovogo apparata 2-y stupeni TVD iz intermetallidnogo splava VKNA-4-VI [Cast blocks of the nozzle apparatus of the 2nd stage of the TVD from the intermetallic alloy VKNA-4-VI], *Liteinoe proizvodstvo*, 2014, No 10, pp. 7–12.

9. Lykov, P.A., Bromer, K.A., Roshchin, V.E., Bryndin, S.A., Opredelenie tekhnologicheskikh parametrov polucheniya metallicheskikh ultradispersnykh poroshkov [Determination of technological parameters for obtaining metallic ultradispersed powders], *Vestnik of the South Ural State University. Metallurgy*, 2011, Issue 14, pp. 17–19.

10. Nerush, S.V., Evgenov, A.G., Ermolaev, A.S., Rogalev, A.M., Issledovanie melkodispersnogo metallicheskogo poroshka zharoprochnogo splava na nikelevoy osnove dlya lazernoy LMD naplavki [Investigation of fine-dispersed metal powder of a high-temperature nickel-base alloy for laser LMD surfacing], *Voprosy Materialovedeniya*, 2013, No 4 (76), pp. 98–107.

11. Evgenov, A.G., Nerush, S.V., Vasilenko, S.A., Issledovanie melkodispersnogo metallicheskogo poroshka zharoprochnogo splava na nikelevoy osnove dlya lazernoy LMD naplavki [Preparation and testing of fine-dispersed metal powder of a high-chromium alloy on a nickel basis for laser LMD-surfacing], *Proceedings of VIAM*, 2014, No 5, Art. 04. URL: http://www.viam-works.ru (reference date 15/10/2017). DOI: 10.18577/2307-6046-2014-0-5-4-4.

12. Kablov, E.N., Additivnye tekhnologii – dominanta natsionalnoy tekhnologicheskoy initsiativy [Additive technologies as a dominant of the national technological initiatives], *Intellekt i tekhnologii*, 2015, No 2 (11), pp. 52–55.

13. Nerush, S.V., Evgenov, A.G., Issledovanie melkodispersnogo metallicheskogo poroshka zharoprochnogo splava marki EP648-VI primenitelno k lazernoy LMD-naplavke, a takzhe otsenka kachestva naplavki poroshkovogo materiala na nikelevoy osnove na rabochie lopatki TVD [Investigation of a fine-dispersed metal powder of a high-temperature EP648-VI alloy for laser LMD-surfacing, as well as an evaluation of the quality of deposition of a powdered material on a nickel base on the blades of the TVD], *Proceedings of VIAM*, 2014, No 3, Art. 01. URL: http://www.viam-works.ru (reference date 16/10/2017). DOI: 10.18577/2307-6046-2014-0-3-1-1.

14. Nerush, S.V., Ermolaev, A.S., Rogalev, A.M., Vasilenko, S.A., Issledovanie tekhnologii vosstanovleniya tortsa pera rabochey lopatki pervoy stupeni turbiny vysokogo davleniya (TVD) iz splava ZhS32-VI metodom lazernoy gazoporoshkovoy naplavki s primeneniem metallicheskogo poroshka splava ZhS32-VI, izgotovlennogo metodom atomizatsii [Research of the technology of restoration of the working blade of the high-pressure turbine (HPT) from the alloy ZhS32-VI by the method of laser gas-powder

overlaying using the metal powder of the alloy ZhS32-VI, manufactured by the atomization method], *Proceedings of VIAM*, 2016, No 8 (44), p. 4. URL: http://www.viam-works.ru (reference date 16/10/2017). DOI: 10.18577/2307-6046-2016-0-8-4-4.

15. Evgenov A.G., Bazyleva O.A., Korolev V.A., Arginbaeva E.G., Perspektivy primeneniya splava na osnove intermetallida Ni3Al tipa VKNA-4UR v additivnykh tekhnologiyakh [Prospects for the use of an alloy based on the intermetallide Ni3Al of the VKNA-4UR type in additive technologies], *Aviatsionnye materialy i tekhnologii*, 2016, No. S 1 (43), pp. 31–35. DOI: 10.18577 / 2071-9140-2016-0-S1-31-35.

16. Evgenov, A.G, Rogalev, A.M., Nerush, S.V., Mazalov, I.S., Issledovanie svoystv splava EP648, poluchennogo metodom selektivnogo lazernogo splavleniya metallicheskikh poroshkov [Investigation of the properties of the EP648 alloy obtained by the selective laser alloying of metallic powders], *Proceedings of VIAM*, 2016, No 02, Art. 02. URL: http://www.viam-works.ru (reference date 15/10/2017). DOI: 10.18577 / 2307-6046-2015-0-2-2-2.

17. Evgenov, A.G., Sukhov, D.I., Nerush, S.V., Rogalev, A.M., Mekhanicheskie svoystva i struktura splava sistemy Ni-Cr-W-Mo-Al-Ti-Nb, poluchayemogo metodom selektivnogo lazernogo splavleniya [Mechanical properties and structure of the alloy of the Ni-Cr-W-Mo-Al-Ti-Nb system obtained by the selective laser fusion method] *Tekhnologiya mashinostroyeniya*, 2016, No 3, pp. 5–9.

18. Evgenov, A.G., Rogalev, A.M., Karachevtsev, F.N., Mazalov, I.S., Vliyanie goryachego izostaticheskogo pressovaniya i termicheskoy obrabotki na svoystva splava EP648, sintezirovannogo metodom selektivnogo lazernogo splavleniya [The effect of hot isostatic pressing and heat treatment on the properties of the EP648 alloy synthesized by the selective laser fusion method], *Tekhnologiya mashinostroeniya*, 2015, No 9, pp. 11–16.

20. Techel, A., et al., *Laser Additive Manufacturing of Turbine Components, Precisely and Repeatable*, Dresden: Fraunhofer Institute for Material and Beam Technology (IWS). URL: http://www.lia.org/blog/category/laser-insights-2/laser-additive-manufacturing/

21. Louvis, E., et al., Selective laser melting of aluminum components, *Journal of Materials Processing Technology*, 2011, V. 211, No 2, pp. 275–284.

UDC 621.793.7:539.538

STUDYING INFLUENCE OF TECHNOLOGICAL PARAMETERS OF COLD GAS DYNAMIC SPRAYING ON THE WEAR RESISTENCE OF ALUMINUM – CARBON NANOFIBERS COATINGS

A.N. SKVORTSOVA[1], O.V. TOLOCHKO[2], T.I. BOBKOVA[1], Cand. Sc. (Eng), E.A. VASILYEVA[1], M.V. STARITSYN[1]

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015, St Petersburg, Russian Federation. E-mail: mail@crism.ru

[1]Peter the Great St Petersburg Polytechnic University, 29, Polytechnicheskaya St, 195251 St Petersburg, Russian Federation

Received January 10, 2018

Abstract—Microhardness, coefficient of friction, modulus of elasticity, elastic recovery coefficients and plastic deformation resistance of functional coatings are determined. To study the wear resistance of coatings, tests were carried out for the intensity of wear with abrasive action. Experimental values of wear intensity of functional coatings are obtained, which allows predicting their service life. Mechanical and wear-resistant characteristics were thoroughly studied and coatings with highest properties were determined.

Keywords: functional coatings, cold gas dynamic spraying, physical and mechanical properties, carbon nanofibers, carbon nanotubes, aluminum, coefficient of friction

DOI: 10.22349/1994-6716-2018-93-1-126-136

REFERENCES

1. Iijima S., Helical microtubules of graphitic carbon, *Nature*, (1991), No 354, pp. 56–58.

2. Lee Y.H., The physical property and application of carbon nanotubes, *Sae Mulli*, 2005, No 51, pp. 84–144.

3. Skvortsova A.N., Lycheva K.A., Voznyakovskii A.A., Koltsova T.S., Larionova, T.V., Mekhanizmy uprochneniya i svoystva kompozitsionnykh materialov s uglerodnyimi nanovoloknami [Strengthening mechanisms and properties of composite materials with carbon nanofibres], *Materials Physics and Mechanics*, (2016), V. 25, No 1, pp. 30–36.

4. Skvortsova, A.N., Lycheva, K.A., Voznyakovskii, A.A., Koltsova, T.S., Kompozitsionnye materialy na osnove alyuminiya, uprochnennye uglerodnymi nanovoloknami [Composite materials based on aluminum, reinforced carbon nanofibers], *Nauchno-tekhnicheskie vedomosti Sankt-Peterburgskogo gosudarstvennogo politehnicheskogo universiteta*, 2015, No 3(226), pp.78–84.

5. Gerashchenkov, D.A., Farmakovsky, B.V., Vasilyev, A.F., Mashek, A.Ch., Issledovanie temperatury potoka v protsesse kholodnogo gazodinamicheskogo napyleniya funktsionalnykh pokrytiy [Investigation of the flow temperature in the process of cold gas-dynamic spraying of functional coatings], *Voprosy Materialovedeniya*, 2014, No 2(77), pp. 87–96.

6. Tonitzki, A., Skvortsova, A.N., Koltsova, T.S., Ganin, V., Danilova, M.A., Shamshurin, A.I., Aluminum – carbon nanofibers composite coating produced by cold spraying, *Nauchno-tehnicheskie vedomosti SPbPU. Estestvennye i inzhenernye nauki*, 2016, No 3 (249), pp. 81–88.

7. Bakshi, S.R., Lahiri, D., Agarwal, A., Carbon nanotube reinforced metal matrix composites, *International Materials Reviews*, (2010), V. 55(1), p. 41.

8. Rudskoy, A.I., Tolochko, O.V., Koltsova, T.S., Nasibulin, A.G., Synthesis of carbon nanofibers on the surface of particles of aluminum powder, *Metal Science and Heat Treatment*, 2014, V. 55, No 9–10, pp. 564–568.

9. Lycheva, K.A., Skvortsova, A.N., Koltsova, T.S., Issledovanie vliyaniya rezhimov mehanoaktivatsii na poluchenie vyisokoprochnogo materiala aliuminii – uglerodnye nanovolokna [Investigation of the influence of mechanoactivation regimes on the production of high-strength aluminum-carbon nanofibers], *Nedelya nauki SPbPU*, 30 November – 5 December 2015]

10. Breki, A.D., Koltsova, T.S., Skvortsova, A.N., Tolochko, O.V., Aleksandrov, S.E., Lisenkov, A.A., Provotorov, D.A., Sergeev, N.N., Maly, D.V., Sergeev, A.N., Ageev, E.V., Gvozdev, A.E., Antifriktsionnye svoystva kompozitsionnykh materialov na osnove aliuminiya, uprochnennykh uglerodnyimi nanovoloknami, pri trenii po stali 12X [Antifriction properties of composite materials on the basis of aluminum hardened by carbon nanofibers, with friction on steel 12Kh, *Izvestiya Yugo-Zapadnogo gosudarstvennogo universiteta. Seriya: Tekhnika i tekhnologii*, 2016, V. 4 (21), pp. 11–23.

11. Min-Feng Yu, Lourie, O., Dyer, M.J., Moloni, K., Kelly, T.F., Ruoff, R.S., Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load, *Science*, 2000, V. 287, Issue 5453, pp. 637–640.

12. Bakshi, S.R., Singh, V., Balani, K., McCartney, D.G., Seal, S., Agarwal, A., Carbon nanotube reinforced aluminum composite coating via cold spraying, *Surface & Coatings Technology*, (2008), V. 202, pp. 5162–5169.

13. Bobkova, T.I., Deev, A.A., Bystrov, R.Yu., Farmakovsky, B.V., Nanesenie iznosostoykikh pokrytiy s reguliruemoy tverdostyu s pomoschyu sverhzvukovogo holodnogo gazodinamicheskogo napyleniya [Application of wear-resistant coatings with adjustable hardness by means of supersonic cold gas-dynamic spraying], *Metalloobrabotka*, 2012, No 5–6, pp. 45–49.

14. Laha, T., Agarwal, A., Effect of sintering on thermally sprayed carbon nanotube reinforced aluminum nanocomposites, *Materials Science and Engineering: A*, 2008.V. 480, pp. 323–332.

15. Zhang, D., Shipway, P.H., McCartney, D.G., Cold gas dynamic spraying of aluminum: The role of substrate characteristics in deposit formation, *J. Therm. Spray Technol.*, 2005, V. 14, pp. 109–116.

16. Gogolinsky, K.V., Lvova, N.A., Useinov, A.S., Primenenie skaniruyuschikh zondovykh mikroskopov i nanotverdomerov dlya izucheniya mehanicheskih svoystv tvyordykh materialov na nanourovne [The use of scanning probe microscopes and nanohardnessers to study the mechanical properties of hard materials at the nanolevel], *Zavodskaya laboratoriya. Diagnostika materialov*, 2007, V. 73, No 6, pp. 28–36.

17. Farmakovsky, B.V., Geraschenkov, D.A., Bystrov, R.Yu., Vasilyev, A.F., Ulin, I.V., Bobkova, T.I., Iznosostoykie funktsionalno-gradientnye pokryitiya na osnove kvazikristallov, poluchennye metodom sverhzvukovogo holodnogo gazodinamicheskogo napyileniya [Wear-resistant functional gradient coatings on the basis of quasicrystals, obtained by the method of supersonic cold gas-dynamic spraying], *Voprosy Materialovedeniya*, 2017, V. 90, No 2, pp. 130–135.

UDC 678.074:620.17

CHANGES IN RUBBER PROPERTIES DURING STORAGE AND OPERATION STUDIED BY EXPRESS METHOD OF DYNAMIC MECHANICAL ANALYSIS

N.V. VAKULOV [1,2], A.V. MYSHLYAVTSEV [2], Dr Sc (Eng), V.I. MALYUTIN [1], N.S. MITRYAEVA [2]

[1] *FSUE "Federal Research and Production Center Progress", 4, 5th Kordnaya St, 644050 Omsk, Russian Federation*

[2] *Omsk State Technical University, 11, Mira Pr., 644050 Omsk, Russian Federation*

Received November 17, 2017

Abstract—The paper considers changes in the properties of rubber in large-sized products using the method of dynamic mechanical analysis (DMA) in comparison with the previous physical and mechanical investigation data. It is possible to predict changes in properties of rubber during storage or operation if using the combined estimation and prediction curve for the most characteristic indicator of aging.

Keywords: rubber, dynamic properties, dynamic mechanical analysis

DOI: 10.22349/1994-6716-2018-93-1-137-142

REFERENCES

1. Kuzminsky, A.S., Lezhnev, N.N., Zuev, Yu.S., *Okislenie kauchukov i rezin* [Oxidation of rubbers], Moscow: Goskhimizdat, 1957.

2. Zaikov, G.Ye., Starenie i stabilizatsiya polimerov [Aging and stabilization of polymers], *Plasticheskie massy*, 2008, No 2, pp. 54–56.

3. Brown, R.P., *Practical Guide to the Assessment of the Useful Life of Rubbers*, Shrewsbury: Rapra Technology Ltd, 2001.

4. Bartenev, G.M., *Struktura i relaksatsionnye svoystva elastomerov* [Structure and relaxation properties of elastomers], Moscow: Khimiya, 1979.

5. State Standard GOST 9.713-86: *Edinaya sistema zashchity ot korrozii i stareniya reziny. Metod prognozirovaniya izmeneniya svoystv pri termicheskom starenii* [Unified system of protection against corrosion and aging of rubber. Method for predicting changes in properties during thermal aging], Moscow: Izdatelstvo Standartov, 1987.

UDC 678.067.5:621.777:621.396.67

RADIOTECHNICAL HOT PRESSED GLASS FIBER PLASTICS FOR SHIP AERIAL FAIRINGS AND ANTENNAS PROTECTION IN RADIO CONNECTION AND RADIO LOCATION SYSTEMS

V. E. BAKHAREVA, Dr Sc (Eng), I. V. NIKITINA, Cand Sc (Chem), A. A. CHURIKOVA

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received September 4, 2017

The article is devoted to the urgent scientific problem of creation and introduction in shipbuilding of high-strength, water-resistant dielectric glass-reinforced hot pressed plastics on the basis of bi- and polyfunctional epoxy-amine binders and glass fabrics from alkali, quartz and silica glass.

Keywords: fiberglass, hot pressing, aerial fairings, antenna, radar stations, strength and dielectric properties, water absorption, porosity.

DOI: 10.22349/1994-6716-2018-93-1-143-158

REFERENCES

1. *Sovremennye mashinostroitelnye materialy. Nemetallicheskie materialy* [Modern machine-building materials. Non-metallic materials], Gorynin, I.V., Oryshchenko, A.S., Bakhareva, V.E., Nikolaev, G.I. (Eds.), St Petersburg: Professional, 2014.

2. Bakhareva, V.E., Oryshchenko. A.S., *Vysokoprochnye stekloplastiki dlya arkticheskogo mashinostroeniya* [High-strength fiberglass for Arctic engineering], St Petersburg: Professional, 2017.

3. Chawla, K. K., *Composite Materials: Science and Engineering*, Springer Science & Business Media, 2013.

4. Plastics in Europe, *Reinforced Plastics*, 1987, V. 31, No 7, pp. 175–180.

5. Mikhailin, Yu.A., *Termoustoichivye polimery i polimernye materialy* [Thermally stable polymers and polymer materials], St Petersburg: Professional, 2006.

6. Composites Materials Boeing Aerospace Co, *Mater. Eng*., 1988, V. 105, No 3, p. 63.

7. Reinforced Plastics in Ship Radio Engineering, *Reinforced Plastics*, 1987, V. 31, No 5, pp. 110–115.

8. *Composite Materials: Mechanics, Mechanical Properties and Fabrication*, Kawata K., Akasaka T., (Eds.), Elsevier Science Publishers B.V., 1982.

9. Oryshchenko, A.S., Anisimov, A.V., Bakhareva, V.E., Sargsian, A.S., Churikova, A.A., Sozdanie vysokoprochnykh vodostoykikh dielektrikov i razrabotka tekhnologii izgotovleniya izdeliy radiotekhnicheskogo naznacheniya i sudovoy elektroizolyatsii [Creation of high-strength waterproof dielectrics and the development of technology for the manufacture of products for radio engineering purposes and ship's electrical insulation], *Voprosy Materialovedeniya*, 2014, No 3(79), pp. 97–108.

10. Glass Reinforced Plastics Details of Antennas, *Reinforced Plastics*, 1987, V. 31, No 5, pp. 132–134.

11. Davydova, I.F., Kavun, N.S., Stekloplastiki – mnogofunktsionalnye kompozitsionnye materialy [Fiberglass, as multifunctional composite material], *Aviatsionnye materialy and tekhnologii*, E. Kablov, (Ed.), Moscow, 2012, pp. 253–260.

12. Gurtovnik, I.G., Sokolov, V.I., Trofimov, N.N., Shalgunov, S.I., *Radioprozrachnye izdeliya iz stekloplastikov* [Radio-transparent products from fiberglass], Moscow: Mir, 2003.

13. Gurtovnik, I.G., Sportsmen, V.N., *Stekloplastiki radiotekhnicheskogo naznacheniya* [Stekloplastiki of radio engineering designation], Moscow: Khimiya, 1987.

14. Bakhareva, V.E., Kontorovskaya, I.A., Petrova, L.V., *Izdeliya elektroizolyatsionnogo naznacheniya iz stekloplastikov i tekhnologiya ikh izgotovleniya* [Insulating products from fiberglass plastic and technology of their manufacturing], Leningrad: LDNTP, 1981.

15. Bakhareva, V.E., Kontorovskaya, I.A., Petrova, L.V., Utkina, V.F., *Ekspluatatsionnaya stoykost epoksidnykh kompozitsionnykh materialov* [Performance resistance of epoxy composite materials], Leningrad: Rumb, 1987.

16. Bakhareva, V.E., Kontorovskaya, I.A., Murovich, V.L., Stepanova, I.I., Vliyanie strukturno-tekhnologicheskikh i ekspluatatsionnykh faktorov na svoistva epoksidnykh stekloplastikov [Influence of structural-technological and operational factors on the properties of epoxy fiberglass plastics], *Vysokoprochnye armirovannye polimernye materialy konstruktsionnogo naznacheniya* [High-strength reinforced polymeric materials for structural purposes], Leningrad: LDNTP, 1978, pp. 73–79.

17. Manin, V.N., Gromov, A.I., *Fiziko-khimicheskaya stoykost polimernykh materialov v usloviyakh ekspluatatsii* [Physical and chemical resistance of polymer materials under operating conditions], Leningrad: Khimiya, 1980.

18. Malkin, A.Ya., Chalykh, A.E., *Diffuziya i viazkost polimerov. Metody izmereniya* [Diffusion and viscosity of polymers. Methods of measurement], Moscow: Khimiya, 1979.

19. Remizov, I.A., Chalykh, A.E., Popov, V.Ya., Opredelenie konstant diffuzii zhidkostey v polimere metodami sorbtsii i spektroskopii vnutrennego otrazheniya [Determination of the diffusion constants of liquids in a polymer by sorption methods and internal reflection spectroscopy], *Vysokomolekuliarnye soedineniya. Seriya A*, 1982, V. 24, pp. 1630–1635.

20. Reitlinger, S.A., *Pronitsaemost polimernykh materialov* [Permeability of polymeric materials], Moscow: Khimiya, 1974.

21. Perrin, A.A., Sedletsky, R.V., Analiz i eksperimentalnoe obosnovanie sinkhronno-volnoobraznogo kharaktera izmeneniya mekhanicheskoy prochnosti i dielektricheskikh poter pri vodopogloshchenii (vodosbrose) v konstruktsionnykh polimernykh kompozitakh (sfero-, steklo-, ugleplastikakh) [Analysis and experimental substantiation of the synchronous-wave-like character of the change in mechanical strength and dielectric losses during water absorption (spillway) in structural polymeric composites (sphero-, glass-, carbon plastics)], *Voprosy Materialovedeniya*, 2015, No 4 (84), pp. 80–90.

UDC 678.686:536.46

FACTORS INFLUENCING THE FIRE-RESISTANCE OF EPOXY COMPOSITIONS MODIFIED WITH EPOXY-CONTAINING PHOSPHAZENES

I.V. TEREKHOV[1], Cand. Sc. (Chem), E.M. CHISTYAKOV[2], Cand. Sc. (Chem), S.N. FILATOV[2], Dr Sc. (Chem), I.S. DEEV[1], Cand. Sc. (Eng), E.V. KURSHEV[1], S.L. LONSKII[1]

[1]*Federal State Unitary Enterprise “All-Russian Scientific Research Institute of Aviation Materials” (FSUE VIAM), 17, Radio St, 105005 Moscow, Russian Federation. E-mail: admin@viam.ru*

[2]*Dmitry Mendeleev University of Chemical Technology of Russia, 9, Miusskaya Sq. 125047 Moscow, Russian Federation,*

Received November 23, 2017

The fire-resistance (State Standard GOST 28157-89, analogue of UL-94 test) of epoxy compositions based on D.E.R.-330 resin, isomethyltetrahydrophthalic anhydride and new epoxy-containing aryloxycyclotriphosphazenes was studied. Thermogravimetric analysis and microstructural studies of the coke residue formed during combustion were carried out. It has been determined that resistance to combustion of the cured compositions increases significantly as grows phosphazenes content in them. This is due both to the increase in the amount of porous coke residue formed during combustion (which acts as a barrier to flame propagation and heat transfer from the flame to the sample), and to the increase in the size of the pores formed therein. The obtained data can be used to create tough and flame-resistant composites for microelectronics, aviation and other industries.

Keywords: microstructure, fire-resistance, polycondensation, phosphazenes, epoxy resins.

ACKNOWLEDGEMENTS

The research was carried out with the financial support of the Russian Foundation for Basic Research in the framework of the scientific project No 16-33-00254/17.

DOI: 10.22349/1994-6716-2018-93-1-159-168

REFERENCES

1. Song, T., Li, Z., Liu, J., Yang, S., Synthesis, characterization and properties of novel crystalline epoxy resin with good melt flow ability and flame retardancy based on an asymmetrical biphenyl unit, *Polymer Science: Ser. B.*, 2013, V. 55 (3–4), pp. 147–157.

2. Kablov, E.N., Antipov, V.V., Senatorova, O.G., Aluminium fiberglass SIAL-1441 laminates and cooperation with “Airbus” and “TU Delft”, *Tsvetnye Metally*, 2013, No 9, pp. 50–53.

3. Wu, N., Xiu, Z., Du, J., Preparation of microencapsulated aluminum hypophosphite and flame retardancy and mechanical properties of flame-retardant ABS composites, *Journal of Applied Polymer Science*, 2017, V. 134 (33), No 45008.

4. Liang, T., Jiang, Z., Wang, C., Liu, J., A facile one-step synthesis of flame-retardant coatings on cotton fabric via ultrasound irradiation, *Journal of Applied Polymer Science*, 2017, V. 134 (30), No 45114.

5. Yang, Y., Luo, H., Cao, X., Kong, W., Cai, X., Preparation and characterization of a water resistance flame retardant and its enhancement on charring–forming for polycarbonate, *Journal of Thermal Analysis and Calorimetry*, 2017, V. 129 (2), pp. 809–820.

6. Dehestani, M., Teimortashlu, E., Molaei, M., Ghomian, M., Firoozi, S., Aghili, S., Experimental data on compressive strength and durability of sulfur concrete modified by styrene and bitumen, Data in Brief, 2017, V. 13, pp. 137–144.

7. Jin, X., Sun, J., Zhang, J.S., Gu, X., Bourbigot, S., Li, H., Tang, W., Zhang, S., Preparation of a novel intumescent flame retardant based on supramolecular interactions and its application in polyamide 11, *ACS Applied Materials and Interfaces*, 2017, V. 9 (29), pp. 24964–24975.

8. Yashchenko, V.S., Vasilevskii, D.A., Bezruchenko, V.S., Dokuchaev, V.N., Olkhovik, V.K., New high-tensile thermally stable copolymers of poly(p-phenylene-1,3,4-oxadiazole), *Polymer Science. Ser. B*, 2014, V. 56 (3), pp. 307–313.

9. Volynsky, A.L., Bakeev, N.F., A new approach to the preparation of nanocomposites based on a polymer matrix, *Polymer Science: Ser. C*, 2011, V. 53 (1), pp. 35–47.

10. Nazarov, V.G., Stolyarov, V.P., Petrova, G.N., Gryaznov, V.I., Buznik, V.M., Special features of surface fluorination of thermoplastic polyurethane elastomers and its effect on the polymer properties, *Inorganic Materials: Applied Research*, 2016, V. 7 (5), pp. 773–778.

11. Kokhanovskaya, O.A., Razdiakonova, G.I., Likholobov, V.A., Physicochemical properties and structure of aerogel type composites on the basis of polyvinyl alcohol/carbon black, *Inorganic Materials: Applied Research*, 2017, V. 8 (5), pp. 739–744.

12. Horrocks, A.R., Price, D., *Fire retardant materials*, Abington: Woodhead Publishing Limited, 2001.

13. Lu, S.Y., Hamerton, I., Recent developments in the chemistry of halogen-free flame retardant polymers, *Progress in Polymer Science*, 2002, V. 27, pp. 1661–1712.

14. Liu, R., Wang, X., Synthesis, characterization, thermal properties and flame retardancy of a novel nonflammable phosphazene-based epoxy resin, *Polymer Degradation and Stability*, 2009, V. 94, pp. 617–624.

15. Chen-Yang, Y.W., Lee, H.F., Yuan, C.Y., A flame-retardant phosphate and cyclotriphosphazene-containing epoxy resin: Synthesis and properties, *Journal of Polymer Science. Part A*, 2000, V. 38, pp. 972–981.

16. Inoue, K., Kaneyuki, S., Tanigaki, T., Polymerization of 2-(4-metha-cryloyloxyphenoxy) pentachlorocyclotriphosphazene, *Journal of Polymer Science. Part A*, 1992, V. 30, pp. 145–148.

17. Medici, A., Fantin, G., Pedrini, P., Gleria, M., Minto, F., Functionalization of phosphazenes. 1. Synthesis of phosphazene materials containing hydroxyl groups, *Macromolecules*, 1992, V. 25, pp. 2569–2574.

18. Yuan, W.Z., Zhu, L., Huang, H.B., Zheng, S.X., Tang, X.Z., Synthesis, characterization and degradation of hexa-armed star-shaped poly(l-lactide)s and poly(d,l-lactide)s initiated with hydroxyl-terminated cyclotriphosphazene, *Polymer Degradation and Stability*, 2005, V. 87, pp. 503–509.

19. Ottman, G., Lederle, H.F., Hooks, H., Kober, E., Aminophenoxy- and isocyanatophenoxyphosphonitriles, *Inorganic Chemistry*, 1967, V. 6, pp. 394–395.

20. Bing, B., Li, B., Synthesis, thermal property and hydrolytic degradation of a novel star-shaped hexa[p-(carbonylglycinomethyl-ester)phenoxy]cyclotriphosphazene, *Science in China. Ser. B. Chem*., 2009, V. 52 (12), pp. 2186–2194.

21. Brown, D.E., Allen, C.W., Homo- and copolymerization of (Methacryloyl ethenedioxy) pentachlorocyclotriphosphazene, *Journal of Inorganic and Organometallic Polymers and Materials*, 1991, V. 1 (2), pp. 189–198.

22. Terekhov, I.V., Filatov, S.N, Chistyakov, E.M., Borisov, R.S., Kireev, V.V., Synthesis of oligomeric epoxycyclotriphosphazenes and their properties as reactive flame-retardants for epoxy resins, *Phosphorus, Sulfur Silicon Relat. Elem*., 2017, V. 192 (5), pp. 544–554.

23. Korobeinichev, O.P., Shvartsberg, V.M., Shmakov, A.G., The chemistry of combustion of organophosphorus compounds, *Russian Chemical Reviews*, 2007, V. 76 (11), pp. 1023–1049.

UDC 621.791.042:669.14.018.295

INFLUENCE OF BORON MICROALLOYING ON THE STRUCTURE AND PROPERTIES OF JOINTS WELDING ROLLED HIGH-STRENGTH STEEL WITH A STANDARD YIELD POINT OF 750 MPa BY FLUX-CORED WIRE

P.V. MELNIKOV, Cand. Sc. (Eng), V.V. GEZHA, Cand. Sc. (Eng),

G.D. MOTOVILINA, Cand. Sc. (Eng), V.A. MOGUILNIKOV

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

Received December 7, 2017

Abstract—The effect of boron on the structure and mechanical properties of a welded high-strength steel with a standard yield strength of 750 MPa has been studied. The flux-cored wire of grade 48PP-69 has been developed on the basis of results.

Keywords: flux-cored wire, microalloying of welded joint, semi-automatic welding with shielding gas

ACKNOWLEDGEMENTS

Experimental studies were carried out on the equipment of the Center for the Collective Use of scientific equipment "Composition, structure and properties of structural and functional materials" of the National Research Center "Kurchatov Institute" – CRISM Prometey with the financial support of the Min-

istry of Education and Science under the agreement No. 14.595.21.0004, the unique identifier RFMEFI59517X0004.

DOI: 10.22349/1994-6716-2018-93-1-169-174

REFERENCES

1. Grabin, V.F., *Metallovedenie svarki plavleniem* [Metallurgy of welding by melting], Kiev: Naukova dumka, 1982.

2. Pokhodnya, I.K., Orlov, L.N., Shevchenko, G.A., Shlepakov, V.N., Vliyanie legirovaniya na mekhanicheskie svoystva svarnykh shvov, vypolnennykh poroshkovymi provolokami [Effect of alloying on the mechanical properties of welded joints made with powdered wires], *Avtomaticheskaya svarka*, 1985, No 7 (388), pp.10–11.

3. Evans, G.M., Microstructure and properties of ferritic steel welds containing Al and Ti, *Welding Journal*, 1995, August, pp. 249–261.

4. Hayakawa, N., Sakaguchi, S., Kawabata, F., Okatsu, M., Ota, M., Nishiyama, S., Nagatani, K., Isisaki, K., Patent RU 2434070 C22C38/00, B23K35/30, B23K9/23: A high-strength welded steel pipe, the weld metal of which has high resistance to cold cracking, and the process of its fabrication, Publ. 20.11.2011, Bull. 32, p. 26.

5. Faynberg, L.I., Rybakov, A.A., Alimov, A.N., Rozert, R., Mikrolegirovanie shvov titanom i borom pri mnogodugovoy svarke gazonefteprovodnykh trub bolshogo diametra [Microalloying of joints with titanium and boron for multi-arc welding of large-diameter gas-oil pipes,], *Avtomaticheskaya svarka*, 2007, No 5, pp. 20–25.

6. Podgaetsky, V.V., O vliyanii khimicheskogo sostava shva na ego mikrostrukturu i mekhanicheskie svoystva [On the effect of the chemical composition of the weld on its microstructure and mechanical properties], *Avtomaticheskaya svarka*, 1991, No 2, pp. 1–9.

7. Oerlikon Schweisstechnik Gmbh, Consumables, (reference date 15/03/2018), URL: https://www.oerlikon-welding.com

8. Drahtwarenfabrik-Drahtzug Stein Gmbh & Co KG, Materialien & Verfahren, (reference date 15/03/2018), URL:http://www.drahtzug.com/de/unternehmen/materialien-und-verfahren/

9. *Stainless Steel Welding: ESAB Technical Handbook*, (reference date 15/03/2018), http://www.esab.com/gb/en/support/upload/Technical-Handbook-Stainless-Steel-Welding.pdf

10. Makarenko, V.D., Belyaev, V.A., Prokhorov, N.N., Shatilo, S.P., Chernov, V.Yu., Vliyanie modifitsiruyushchikh dobavok na mekhanicheskie i vyazkoplasticheskie svoystva svarnykh soedineniy neftegazoprovodov [Effect of modifying additives on the mechanical and viscoplastic properties of welded joints of oil and gas pipelines], *Svarochnoe proizvodstvo*, 2001, No 5, pp. 9–13.

11. Houdremont, E., *Handbuch der Sonderstahlkunde*, Springer-Verlag, 1956.

12. Burkhard, J., Lau, T., North, T.H., Esperance, G.L., Effect of aluminium on the Ti-O-B-N balance in submerged arc welding, *Welding Journal*, 1988, pp. 25–30.

UDC 621.791.92:669.35'295

INVESTIGATING FORMATION, STRUCTURE AND PROPERTIES OF COATINGS BASED ON Cu–Ti ALLOYS

A.I. KOVTUNOV, Dr Sc. (Eng), T.V. SEMISTENOVA, Cand. Sc. (Eng), A.M. OSTRYANKO

Togliatti State University, 14, Belorusskaya St, 445020 Samara Region, Togliatti, Russian Federation.E-mail: office@tltsu.ru

Received December 11, 2017

Abstract—The paper offers technology of argon-arc surfacing with titanium wire in order to form heat and wear resistant coating based on the titanium cuprides. The influence of surfacing modes on the chemical compound and structure of formed coatings is determined. The wear resistance and heat resistance at 600°C and 800°C were researched for copper–titanium coating with 8–63% titanium.

Keywords: titanium cuprides, microhardness, argon-arc surfacing with titanium wire, copper, titanium, heat resistance, wear resistance.

ACKNOWLEDGEMENTS

The work was carried out within the framework of the grant RFFI (РФФИ) № 17-48-630361 р_а

DOI: 10.22349/1994-6716-2018-93-1-175-181

REFERENCES

1. Kolpacheva, O.V., *Elektronnaya energeticheskaya struktura tetragonalnykh kupridov titana i splavov Cu–Ti–Ni* [Electronic energy structure of tetragonal cuprides of titanium and Cu–Ti–Ni alloys]: Author's abstract of the thesis for a scientific degree of the candidate of sciences (Phys-Math), Rostov-na-Donu, 2007.

2. Shmorgun, V.G., Gurevich, L.M., Slautin, O.V., Arisova, V.N., Evstropov, D.A., Formation of Ti–Cu-Based inermetallic coatings on the surface of the copper during contact melting, *Metallurgist*, 2016, V. 59, Is. 9–10, pp. 974–979. URL: https:// doi.org/10.1007/s11015-016-0203-0.

3. Yu, F., Wang, H., Yuan, G. et al. Effect of Cu content on wear resistance and mechanical behavior of Ti–Cu binary alloys, *Appl. Phys. A*, (2017), V. 123, p. 278. URL: https://doi.org/10.1007/s00339-017-0921-6.

4. Evstropov, D.A., *Formirovanie struktury i svoystv kompozitsionnykh pokrytiy sistemy Cu–Ti na poverkhnosti mednykh detaley* [Formation of the structure and properties of composite coatings of the Cu–Ti system on the surface of copper parts], Thesis for a scientific degree of the candidate of sciences (Eng), Volgograd, 2016.

5. Bateni, M.R., Szpunar J.A., Ashrafizadeh, F., Zandrahimi, M., The effect of novel Ti–Cu intermetallic compound coatings on tribological properties of copper, *The Annals of University of Galati*, 2003.

6. Morozova, E.A., Muratov, V.S., Lazernoe legirovanie poverkhnosti titana medyu [Laser doping of titanium surface with copper] // The successes of modern natural science. – 2009. – No. eleven.

7. Krasheninnikov, S.V., Kuzmin, S.V., Lysak, V.I., Issledovanie protsessov formirovaniya pokrytiy metodom diffuzionnoy intermetallizatsii [Investigation of the formation of coatings by diffusion intermetallization], *Svarka vzryvom i svoystva svarnykh soyedineniy* [Welding by explosion and properties of welded joints]: Interuniversity collection of scientific papers, Volgograd: VolgGTU, 2002, pp.102–110.

8. Radyuk A.G., Titlyanov, A.Ye., Ukraintsev, A.Ye., Formirovanie diffuzionnykh sloev na poverkhnosti medi i ee splavov [Formation of diffusion layers on the surface of copper and its alloys.], *Tsvetnye metally*, 2007, No 5, pp. 95–97.

9. Radek, N., Experimental studies of the Cu–Mo and Cu–Ti electrospark coatings modified by laser beam, *Advances in Manufacturing Science and Technology*, 2008, V. 32, No 2, pp. 53–68.

10. Kovtunov, A.I., Semistenov, D.A., Semistenova, T.V., Starodubtsev, A.D., Peculiarities of formation of wear-resistant layers during mechanized surfacing of aluminum on steel, *Technology of Mechanical Engineering*, 2016, No 3, pp. 47–50.

11. Kovtunov, A.I., Plakhotny, D.I., Gushchin, A.A., Bochkarev, A.G., Plakhotnaya, S.E., Vliyanie rezhimov naplavki na strukturu i svoystva pokrytiy sistemy titan–alyuminiy [Influence of surfacing regimes on the structure and properties of coatings of the titanium–aluminum system], *Svarka i Diagnostika*, 2016, No 2, pp. 35–37.

12. Elrefaey, A., Solid state diffusion bonding of titanium to steel using a copper base alloy as interlayer, Journal of materials processing technology, 2009, V. 209, No 5, pp. 2746–2752.

13. Krasheninnikov, S.V., Issledovanie osobennostey formirovaniya i svoystv intermetallidnykh pokrytiy sistem Ti–Cu i Ti–Ni na poverkhnosti stalnykh detaley [Investigation of the features of the formation and properties of intermetallic coatings of Ti–Cu and Ti–Ni systems on the surface of steel spare parts]: Author's abstract of the thesis for a scientific degree of the candidate of sciences (Mechanical Engineering), Volgograd, 2006.

UDC 620.193.2:621.785.5:621.88

SOME ASPECTS IN STUDYING CORROSION OF 25Kh1MF (25Cr1MoW) STEEL FASTENERS AFTER ALUMINIZING

M.I. OLENIN, Cand. Sc. (Eng), V.I. GORYNIN, Dr Sc., B.I. BEREZHKO, Cand. Sc. (Eng),
I.M. KHOVRATOVICH, A.V. PTASHNIK

NRC "Kurchatov Institute" – CRISM "Prometey", 49, Shpalernaya St, 191015 St Petersburg, Russian Federation. E-mail: mail@crism.ru

AO "Krasny Oktyabr", 110, Lenina Prospect, 400007 Volgograd, Russian Federation

Received July 31, 2017, in final form November 24, 2017

Abstract—The resistance to atmospheric corrosion of 25Kh1MF (25Cr1MoW) steel after aluminizing and thermal improvement has been studied. It is established that the reduced resistance of the aluminized layer to atmospheric corrosion is caused by surface defects such as cracks or pores or by absence of a layer containing the intermetallide Fe_3Al. In the aluminized layer containing aluminum-doped ferrite, aluminum nitrides have been found that prevent cold diffusion welding of fasteners' thread surfaces.

Keywords: steel fasteners, thread surfaces, corrosion damage, cold diffusion welding, aluminizing, thermal improvement

ACKNOWLEDGEMENTS

Experimental studies were carried out on the equipment of the Center for the Collective Use of scientific equipment "Composition, structure and properties of structural and functional materials" of the National Research Center "Kurchatov Institute" – CRISM Prometey with the financial support of the Ministry of Education and Science under the agreement No. 14.595.21.0004, the unique identifier RFMEFI59517X0004.

DOI: 10.22349/1994-6716-2018-93-1-182-189

REFERENCES

1. Blanter, M.E., *Teoriya termicheskoy obrabotki* [Theory of Heat Treatment], Moscow: Metallurgiya, 1984.

2. Arzamasov, B.N., *Khimiko-termicheskaya obrabotka metallov v aktivirovannykh gazovykh sredakh* [Chemical-Thermal Treatment of Metals in Activated Gases], Moscow: Mashinostroenie, 1979.

3. Zemskov G. V., Kogan R. L., *Mnogokomponentnoe diffuzionnoe nasyshchenie metallov i splavov* [Multicomponent diffusion saturation of metals and alloys], Moscow: Metallurgiya, 1978.

4. *Progressivnye metody termicheskoy i khimiko-termicheskoy obrabotki* [Progressive methods of thermal and chemical-thermal processing], Yu. M. Lakhtin, Ya. D. Kogan (Eds.), Moscow: Mashinostroenie, 1972

5. Houdremont, E., *Handbuch der Sonderstahlkunde*, Springer-Verlag, 1956.

6. Polevoy, S.N., Evdokimov, V.D., *Uprochnenie metallov* [Hardening of Metals]: A Handbook, Moscow: Mashinostroenie, 1986.

7. *Termicheskaya obrabotka v mashinostroenii* [Heat treatment in mechanical engineering]: Handbook, Yu. M. Lakhtin, A. G. Rakhshtadt (Eds.), Moscow: Mashinostroenie, 1980.

8. Goldstein, J. Newbury, D., (8 authors), Scanning electron microscopy and X-ray microanalysis, Kluwer, 2003.

9. *Mikroanaliz i rastrovaya elektronnaya mikroskopiya* [Microanalysis and scanning electron microscopy], F. Moris, L. Meni, R. Tixie, (Eds.), Moscow: Metallurguia, 1985.

10. Gorynin, V.I., *Vysokoprochnye materialy dlya rezbovykh soedineniy* [High strength materials for threaded fasteners], St Petersburg: Prometey, 2016.

11. Birger, I.A., Iosilevich, G.B., *Rezbovye soedineniya* [Threaded joints], Moscow: Mashinostroenie, 1973.

UDC 621.039.531:539.367

MATHEMATICAL MODEL OF RADIATION-INDUCED SHAPE CHANGE IN FUEL SUBASSEMBLIES OF THE BN-TYPE REACTOR CORE AND ITS IMPLEMENTATION IN ANSYS SOFTWARE PACKAGE

A.V. RYABTSOV, O.Yu. VILENSKY, Cand. Sc. (Eng)

Joint Stock Company "I.I. Afrikantov OKB Mechanical Engineering" (Rosatom State Corporation enterprise),
15, Burnakovsky proezd, 603074 Nizhny Novgorod, Russian Federation; E-mail: sigma@okbm.nnov.ru

Received June 5, 2017, in final form, November 13, 2017

Abstract—One of main operability criteria for fuel subassemblies (FSAs) in fast sodium reactor cores, i.e. the criterion of tolerable shape change in hexagonal wrapper tube is formulated. The equations which enable one to inquire into kinetics of the stress-strained state of a three-dimensional body are adapted to FSAs operating conditions. A mathematical model of radiation-induced shape change in ferritic-martensitic steel of grade EP-450 is proposed. With regard to the proposed model and data on the radiation-induced shape change in other current and prospective structural materials of BN reactor cores, blocks for recording of radiation-induced swelling and radiation-induced creep are developed for ANSYS software package, which made it possible to utilize its potentials within this area of focus. The performed test case with proposed models of the radiation-induced swelling and radiation-induced creep demonstrates that the developed blocks sufficiently describe the radiation-induced shape change in the examined structural materials exposed to radiation. A calculation of the radiation-induced shape change in the FSA hexagonal wrapper tube with various speeds of the radiation-induced swelling and the radiation-induced creep moduli is performed. The calculations results and the results of FSAs post-irradiation dimension inspection are compared. Recommendations for use of the proposed models aimed at performing calculations, as well as estimating the radiation-induced shape change and defining the stress-strained state of FSAs are made.

Keywords: radiation-induced shape change, fuel subassembly, core, BN-type reactor, radiation-induced swelling, radiation-induced creep, mathematical model, numerical computation, analytical solution, test case.

DOI: 10.22349/1994-6716-2018-93-1-190-199

REFERENCES

1. Kaydalov, V.B., Lapshin, D.A., Ryabtsov, A.V., Iskhakov, S.A., Raschetnoe modelirovanie radiatsionnogo formoizmeneniya TVS [Computational simulation of radiation-induced shape change in fuel assemblies of the BN-type reactors], *Problemy prochnosty i plastichnosty*, Nizhny Novgorod, 2013, No. 75(1), pp. 33–39.

2. Zabudko, L.M., Likhachev, Yu.I., Proshkin, A.A., *Rabotosposobnost TVS bystrykh reactorov* [Fast reactor FSA operability], Moscow: Energoatomizdat, 1988, p. 66.

3. Kapustin, S.A., Gorokhov, V.A., Vilensky, O.Yu., Kaydalov, V.B., Margolin, B.Z., Buchatsky, A.A., Modelirovanie napryazhenno-deformirovannogo sostoyaniya konstruktsiy iz nerzhaveyushchikh staley, ekspluatiruyushchikhsya v usloviyakh intensivnykh termoradiatsionnykh vozdeystviy [Studying the stressed-strained state of stainless steel structures working under intensive thermal-radiation loading], *Problemy prochnosti i plastichnosti*, 2007, No 69, pp.106–116.

4. Chuev, V.V., *Povedenie konstruktsionnykh materialov v spektre neytronov bystrogo reaktora bolshoy moshchnosti* [Behavior of Structural Materials in the Neutron Spectrum of a Large Fast Reactor], Thesis for the Doctor Degree of Sciences, Zarechny, 2007.

5. Dvoryashin, A.M., Porollo, S.I., Konobeev, Yu.V., Garner, F.A., Vliyanie vysokodoznogo neytronnogo obluchenuya na strukturu ferritno-martensitnoy stali EP-450 [Effect of the high dose neutron irradiation on the structure of ferrite-martensite EP-450 steel], *Proceedings of the 7th Russian conference on reactor material science*, Dimitrovgrad, 2003, pp. 45–60.

6. Borodin, O.V., Bryk, V.V., Voevodin, V.N., et al., Radiatsionnoe raspukhanie ferritno-martensitnykh staley EP-450 i NT-9 pri obluchenii metallicheskimi ionami do sverkhvysokikh doz [Radiation Swelling of the EP-450 and NT-9 Ferritic-Martensitic Steels under Metallic Ion Irradiation to Super-high Doses], *Voprosy Atomnoy Nauki i Tekhniki*, 2011. No. 2, Series: Physics of Radiation-Induced Damage and Radiation Materials Science (97), pp. 10–15.

7. Vilenskiy O.Yu., Ryabtsov A.V.. Matematicheskiye modeli radiatsionnogo raspukhanija i radiatsionnoi polsuchesti chekhlovoi stali ЭП-450 sborok aktivnoy zony reactorov bistrikh natrievikh [Mathematical models for radiation swelling and radiation creep in the EP-450 wrapper-tube steel for fuel subassemblies of a sodium-cooled fast reactor core], Voprosy atomnoy nauki i tekhniki (Problems of Atomic Science and Technology), 2017. No. 3, Series: Nuclear and reactor constants, pp. 199–207.