sciendo CzOTO 2019, volume 1, issue 1, pp. 738-744

FATIGUE PROPERTIES OF NODULAR CAST IRONS ALLOYED BY Si, Mo AND Cu

doi: 10.2478/czoto-2019-0094
Date of submission of the article to the Editor: 30/11/2018
Date of acceptance of the article by the Editor: 28/01/2019

Alan Vaško[1] – *orcid id: 0000-0002-3937-2691*
Marek Krynke[2] – *orcid id: 0000-0003-4417-1955*
[1]University of Žilina, **Slovakia**, *alan.vasko@fstroj.uniza.sk*
[2]Czestochowa University of Technology, **Poland**

Abstract: In recent years, the research of nodular cast iron has been focused on increasing fatigue resistence. In the paper, two types of alloyed nodular cast irons have been investigated – SiMo-nodular cast iron alloyed by 4% of silicon and 1% of molybdenum and SiCu-nodular cast iron alloyed by 4% of silicon and 1.5% of copper. SiMo-nodular cast iron is suitable for high-temperature applications, for example the exhaust manifolds of the combustion engines. SiCu-nodular cast iron is used in various components of tribotechnical units. These components are often loaded by fatigue. The mechanical and fatigue behaviour of both nodular cast iron types has been studied by means of tensile test, impact bending test, hardness test and fatigue tests. Fatigue tests were realised at low frequency cyclic push-pull loading up to 10 million cycles. The relationship between the amplitude of stress and number of cycles to failure was investigated and the fatigue strength was determined. Mechanical and fatigue properties of both nodular cast iron types are correlated with the microstructure of specimens.

Keywords: nodular cast iron, SiMo, SiCu, fatigue

1. INTRODUCTION

Nodular cast iron, also known as ductile cast iron or spheroidal cast iron, is a type of graphitic cast iron which contains graphite in the form of nodules. The spheroidal shape of graphite does not cause such a high concentration of stress as a lamellar graphite. Therefore, nodular cast iron has higher tensile strength and plasticity as well as higher fatigue strength than lamellar cast iron (Bokůvka et al., 2014). Nodular cast iron is a group of cast structural materials with a wide application in engineering practice, especially in the automotive industry (Konečná et al., 2011).

Nodular cast irons alloyed by Si and Mo are often used for high temperature applications, for example castings of the exhaust pipes of the combustion engine or turbo charger housings. These castings are able to perform many thousands of cycles that can range from below freezing temperatures to those higher than 750°C. SiMo-nodular cast iron usually has a ferritic matrix, but may also contain pearlite and carbides. Increasing content of silicon promotes the stability of the microstructure and properties at low and high temperature by forming a highly ferritic matrix structure and by raising the austenite transformation temperature. Increasing concentration of silicon increases yield strength, but lowers toughness and elongation. Therefore, the material can be very brittle at room temperature. Molybdenum partially segregates during solidification and forms a carbidic phase on grain boundaries. This carbidic network improves dimensional stability, increases tensile strength, creep resistance and corrosion resistance but reduces plastic properties (Roučka et al., 2018; Matteis et al., 2014; Åberg et al., 2012; Stawarz, 2017).

Nodular cast irons alloyed by Si and Cu are used in various components of tribotechnical units. SiCu-nodular cast iron is characterized by a high content of pearlite in a matrix and the presence of inclusions of a structurally free copper-bearing phase. Copper is a graphitizing element and it increases the degree of pearlitization of the structure. By hardening ferrite and pearlite, copper increases strength and hardness of nodular cast iron. It also raises corrosion resistance, improves wear resistance and decreases friction coefficient of nodular cast irons (Siľman et al., 2003; Gumienny et al., 2017; Razumakov et al., 2016; Lacaze et al., 2016).

The aim of this study was to compare the microstructure, mechanical and fatigue properties of two types of the nodular cast irons described above, that is SiMo-nodular cast iron and SiCu-nodular cast iron.

2. METHODOLOGY OF RESEARCH

For experiments, two types of nodular cast irons were used:

- SiMo-nodular cast iron with content of silicon 4 % and content of molybdenum 1 %, which corresponds to EN-GJS-XSiMo4-1;
- SiCu-nodular cast iron with content of silicon 4 % and content of copper 1.5 %, which corresponds to EN-GJS-XSiCu4-1.5.

Melting was realised in an electric induction furnace at the Department of Foundry Engineering at Brno University of Technology.

Charge composition of the melts is given in Table 1. The basic charge of the melts was made up of 60% of steel and 40% of pig iron with additives for the regulation of chemical composition, i.e. carburizer, ferrosilicon FeSi75, ferromolybdenum FeMo65 or copper. The content of these additives was chosen to achieve required chemical composition of the melts and eutectic degree approximately $S_C \approx 1.0$. For modification the FeSiMg7 modifier was used and for inoculation the FeSi75 inoculant was used.

Table 1
Charge composition of the melts

Melt	**Charging raw materials (kg)**								
	steel	pig iron	carbu rizer	FeSi75	FeMo65	Cu	modifier FeSiMg7	inoculant FeSi75	cover sheet
GJS-SiMo	27	20	1.2	2.1	1.1		0.5	0.4	3
GJS-SiCu	27	20	1.1	2.1		0.7	0.5	0.4	3

Both types of nodular cast irons were cast into sand molds in the shape of Y blocks. The resultant chemical composition of the melts is given in Table 2. Test specimens for structural analysis, mechanical tests and fatigue tests were machined from the Y blocks.

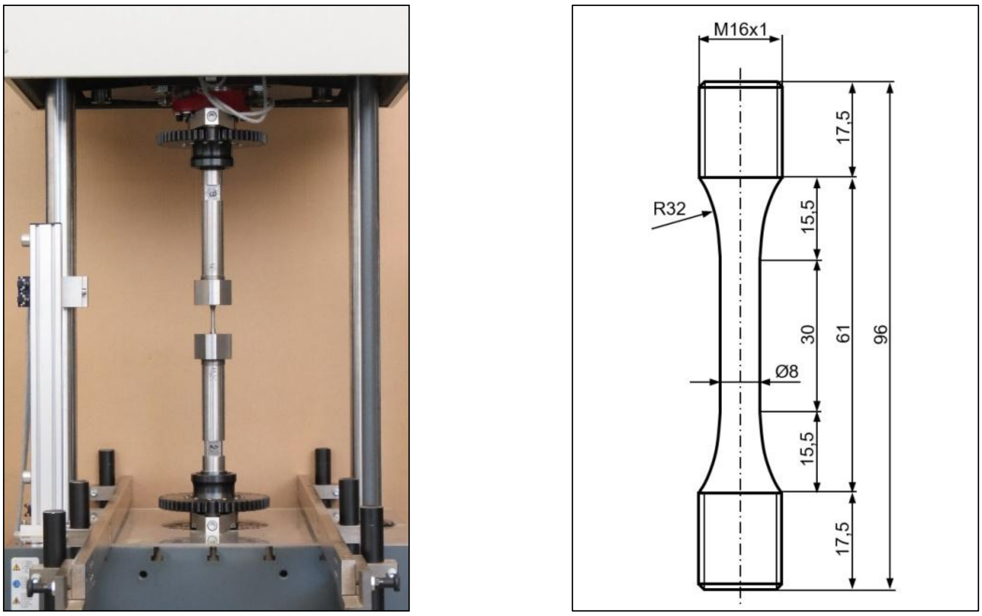
Table 2
Chemical composition of the melts

Melt	**Content of chemical elements (weight %)**									
	C	**Si**	**Mn**	**P**	**S**	**Mo**	**Cu**	**Ni**	**Mg**	**S_C**
GJS-SiMo	3.021	4.094	0.376	0.026	0.032	0.938	0.115	0.059	0.039	1.002
GJS-SiCu	3.281	4.156	0.363	0.028	0.037	0.009	1.394	0.055	0.049	1.096

Metallographic analysis of the specimens was made by the light metallographic microscope Neophot 32. The specimens for metallographic analysis were prepared by usual metallographic procedure. Microstructure of the specimens was evaluated according to STN EN ISO 945 (STN 42 0461) and by automatical image analysis (using NIS Elements software) (Skočovský and Vaško, 2007; Belan et al., 2016). The subject of image analysis was the evaluation of shape factor, equivalent diameter of graphite, count of graphitic nodules per unit of area and content of ferrite.

Tensile test was made according to STN EN ISO 6892-1 by means of the testing equipment Instron 5985 with a loading range F = 0 to 50 kN. For tensile test, cylindrical test specimens with diameter d_0 = 10 mm and measured length l_0 = 50 mm were used. Impact bending test was made according to STN EN ISO 148-1 by means of the Charpy hammer PSW 300 with a nominal energy of 300 J. For impact bending test, test specimens of square cross-section with a width a_0 = 10 mm and length l_0 = 55 mm were used. Brinell hardness test was made according to STN EN ISO 6506-1 by means of the testing equipment CV-3000 LDB with a hardmetal ball of diameter D = 10 mm forced into specimens under the load F = 29 430 N (3000 kp) (Kopas et al., 2014). The values of mechanical properties were determined as an average of 3 measurements.

Fatigue tests were carried out according to STN 42 0362 at low frequency sinusoidal cyclic push-pull loading (stress ratio R = –1) at ambient temperature (T = 20 ± 5 °C). They were realised in the high cycle fatigue region (from 10^5 to 10^7 cycles) at frequency $f \approx 75$ Hz using the fatigue experimental machine Zwick/Roell Amsler 150HFP 5100 (Fig. 1 a). For fatigue tests, specimens of circular cross-section with a diameter d_0 = 8 mm were used. Shape and parameters of the specimens for fatigue tests are shown in Fig. 1b. For fatigue tests, 15 specimens from both melts were used to determine the fatigue characteristics (relationship between the amplitude of stress σ_a and number of cycles to failure N_f as well as fatigue strength) (Uhríčik et al., 2018).

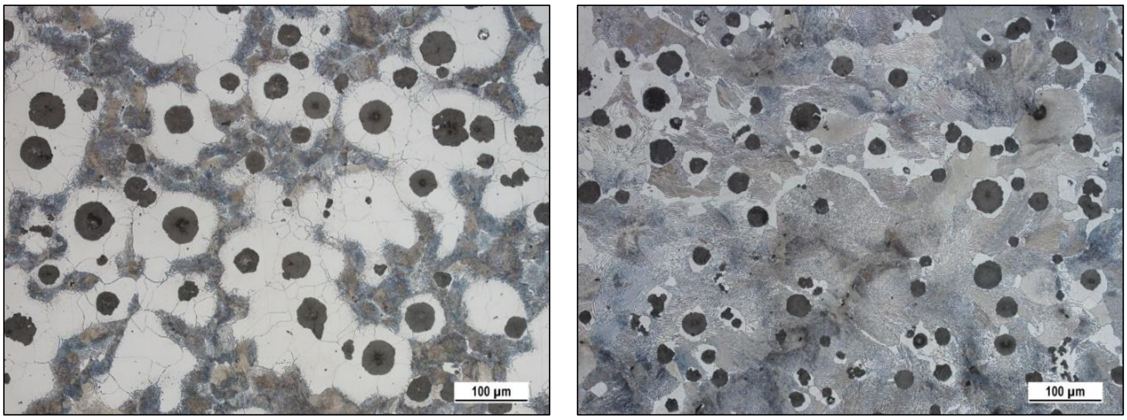


a) fatigue experimental machine b) shape and parameters of the specimen

Fig. 1. Experimental machine and test specimen used for fatigue tests

3. RESULTS AND DISCUSSION

From a microstructural point of view, the specimen of GJS-SiMo is ferrite-pearlitic nodular cast iron (Fig. 2a) and the specimen of GJS-SiCu is pearlite-ferritic nodular cast iron (Fig. 2b). Evaluation of the microstructure of the specimens by STN EN ISO 945 (STN 42 0461) and by image analysis (shape factor, equivalent diameter of graphite, count of graphitic nodules per unit of area and content of ferrite) are presented in Table 3.



a) GJS-SiMo, ferrite-pearlitic nodular cast iron b) GJS-SiCu, pearlite-ferritic nodular cast iron

Fig. 2. Microstructure of the specimens

Content of ferrite in the specimen of GJS-SiCu is lower than in the specimen of GJS-SiMo because of pearlitizing effect of copper. Graphite occurs predominantly in a perfectly-nodular shape in both specimens. Size of graphite in the specimen of GJS-SiCu is smaller than in the specimen of GJS-SiMo but an average count of graphitic nodules per unit of area in the specimen of GJS-SiCu is higher than in the specimen of GJS-SiMo. Different microstructure is caused by different charge composition.

Table 3
Microstructure of the specimens

Melt	Microstructure (according to STN EN ISO 945)	Shape factor	Equivalent diameter of graphite (μm)	Count of graphitic nodules (mm^{-2})	Content of ferrite (%)
GJS-SiMo	90%VI6 + 10%V6 – Fe80	0.88	31.2	122.8	59.4
GJS-SiCu	90%VI6/7 + 10%V6 – Fe15	0.84	24.3	172.4	19.7

Results of mechanical tests (tensile test, impact bending test and Brinell hardness test) are given in Table 4. The specimen of GJS-SiCu has higher yield strength $R_{p0,2}$, tensile strength R_m and Brinell hardness HBW, but lower elongation A and absorbed energy K0 than the specimen of GJS-SiMo. It has connection with the microstructure of the specimens, especially with the character of matrix (content of ferrite and pearlite) and also with size of graphite and count of graphitic nodules.

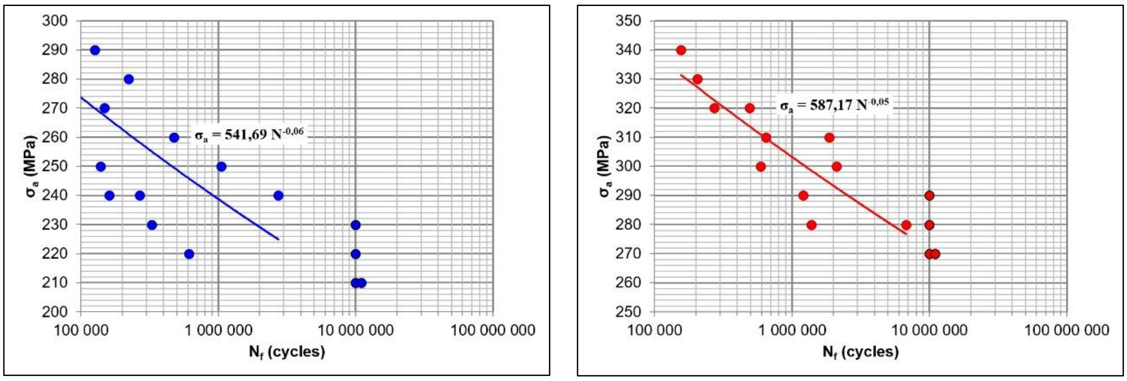
Table 4
Mechanical properties of the specimens

Melt	$R_{p0,2}$ (MPa)	R_m (MPa)	A (%)	K0 (J)	HBW 10/3000/10
GJS-SiMo	515.3	573.9	1.4	11.3	213.7
GJS-SiCu	631.1	652.7	0.7	8.0	247.3

For fatigue tests, 15 specimens from both melts were used to obtain Wöhler fatigue curves $\sigma_a = f(N)$ and determine fatigue strength σ_c for $N = 10^7$ cycles. Results of fatigue tests (relationship between stress amplitude σ_a and number of cycles to failure N_f) obtained at low frequency cyclic loading ($f \approx 75$ Hz) are shown in Table 5. Obtained data were approximated by the power function with using of least square method (Fig. 3) (Pobočíková and Sedliačková, 2012). The number of cycles to failure increases with a decreasing stress amplitude.

Table 5
Results of fatigue tests

SiMo		SiCu	
σ_a (MPa)	N (cycles)	σ_a (MPa)	N (cycles)
290	126 423	340	156 090
280	221 498	330	204 735
270	147 798	320	272 443
260	476 629	320	489 613
250	138 928	310	647 829
250	1 049 015	310	1 865 221
240	160 633	300	591 650
240	267 007	300	2 115 797
240	2 731 405	290	1 205 020
230	328 162	290	> 10 000 074
230	> 10 000 012	280	1 387 744
220	610 426	280	6 786 110
220	> 10 000 002	280	> 10 000 064
210	> 10 000 010	270	> 10 000 026
210	> 10 000 073	270	> 10 000 041



a) GJS-SiMo, σ_c = 210 MPa b) GJS-SiCu, σ_c = 270 MPa

Fig. 3. Wöhler curves $\sigma_a = f(N)$

The values of fatigue strength σ_c determined for N = 10^7 cycles in comparison with tensile strength R_m are given in Table 6. The specimen of GJS-SiCu has higher tensile strength R_m as well as fatigue strength σ_c than the specimen of GJS-SiMo. Results of experiments have shown that the fatigue strength of nodular cast irons increases with an increasing tensile strength what corresponds with previous study (Vaško, 2017).

Table 6

Comparison of tensile strength and fatigue strength

Melt	R_m (MPa)	σ_c (MPa)
GJS-SiMo	573.9	210
GJS-SiCu	652.7	270

In comparison with unalloyed types of nodular cast irons (Vaško, 2017), the specimen of GJS-SiCu has higher tensile strength and fatigue strength than the specimens of non-alloyed nodular cast irons (the difference is more than 10%). The specimen of GJS-SiMo has higher tensile strength but a slightly lower fatigue strength than the specimens of non-alloyed nodular cast irons.

4. CONCLUSION

The results of the experiments show that the charge composition influences the microstructure, mechanical as well as fatigue properties of nodular cast iron. The experimental results can be summarized to the following points:

- Copper has a pearlitizing and graphitizing effect, therefore the specimen of GJS-SiCu has lower content of ferrite, smaller size of graphite and higher count of graphitic nodules per unit of area than the specimen of GJS-SiMo.
- These structural changes have brought about a change of mechanical properties, which depend especially on the character of matrix (content of ferrite) as well as on size of graphite and count of graphitic nodules. Therefore, the specimen of GJS-SiCu has higher yield strength, tensile strength and hardness, but lower elongation and absorbed energy than the specimen of GJS-SiMo.
- Fatigue strength of nodular cast irons has connection with tensile strength. The specimen of GJS-SiCu has higher tensile strength, therefore it also has higher fatigue strength than the specimen of GJS-SiMo.

ACKNOWLEDGEMENT

The research has been supported by the Scientific Grant Agency of Ministry of Education, Science, Research and Sport of Slovak Republic, grant project VEGA No. 1/0533/15 and by the Culture and Educational Grant Agency of Ministry of Education, Science, Research and Sport of Slovak Republic, grant project KEGA No. 049ŽU-4/2017.

REFERENCES

Åberg, L. M., Hartung, C., 2012. *Solidification of SiMo Nodular Cast Iron for High Temperature Applications*, Transactions of the Indian Institute of Metals, 6, 633-636.

Belan, J., Kuchariková, L., Tillová, E., 2016. *The Microstructure Analysis of DV-2 Turbine Blade Damage Made from Ni-base Superalloy*, 33rd Danubia Adria Symposium on Advances in Experimental Mechanics, Portoroz, 124-125.

Bokůvka, O., Nicoletto, G., Guagliano, M., Kunz, L., Palček, P., Nový, F., Chalupová, M., 2014. *Fatigue of Materials at Low and High Frequency Loading*, EDIS, Žilina.

Gumienny, G., Kacprzyk, B., Gawroński, J., 2017. *Effect of Copper on the Crystallization Process, Microstructure and Selected Properties of CGI*, Archives of Foundry Engineering, 1, 51-56.

Konečná, R., Nicoletto, G., Bubenko, L., Fintová, S., 2013. *A Comparative Study of the Fatigue Behavior of Two Heat-Treated Nodular Cast Irons*, Engineering Fracture Mechanics, 108, 251-262.

Kopas, P., Vaško, M., Handrik, M., 2014. *Computational Modeling of the Microplasticization State in the Nodular Cast Iron*, Applied Mechanics and Materials, 474, 285-290.

Lacaze, J., Sertucha, J., 2016. *Effect of Cu, Mn and Sn on Pearlite Growth Kinetics in As-Cast Ductile Irons*, International Journal of Cast Metals Research, 29, 73-77.

Matteis, P., Scavino, G., Castello, A., Firrao, D., 2014. *High Temperature Fatigue Properties of a Si-Mo Ductile Cast Iron*, Procedia Materials Science, 3, 2154-2159.

Pobočíková, I., Sedliačková, Z., 2012. *The Least Square and the Weighted Least Square Methods for Estimating the Weibull Distribution Parameters – A Comparative Study*, Communications, 14, 88-93.

Razumakov, A.A., Stepanova, N.V., Bataev, I.A., Lenivtseva, O. G., Riapolova I.I., Emurlaev, K.I., 2016. *The Structure and Properties of Cast Iron Alloyed with Copper*, Materials Science and Engineering, 124, 012136.

Roučka, J., Abramová, E., Kaňa, V., 2018. *Properties of type SiMo ductile irons at high temperatures*, Archives of Metallurgy and Materials, 2, 601-607.

Siľman, G.I., Kamynin, V.V., Tarasov, A.A., 2003. *Effect of Copper on Structure Formation in Cast Iron*, Metal Science and Heat Treatment, 45, 7-8.

Skočovský, P., Vaško, A., 2007. *Quantitative Evaluation of Structure of Cast Irons*, EDIS, Žilina. (in Slovak).

Stawarz, M., 2017. *SiMo Ductile Iron Crystallization Process*, Archives of Foundry Engineering, 1, 147-152.

Uhríčik, M., Palček, P., Chalupová, M., Frkáň, M., 2018. *The Influence of the Structure on the Fatigue Properties of Aluminium Alloys for the Casting*, MATEC Web of Conferences, 157, 07013.

Vaško, A., 2017. *Fatigue Properties of Nodular Cast Iron at Low Frequency Cyclic Loading*, Archives of Metallurgy and Materials, 4, 2205-2210.