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Influence of copper on effects of precipitation hardening of ductile cast iron

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Abstract

Ductile cast iron with different copper content was precipitation hardened. Cast iron with 0.48 % Cu content was ferritized. That operation was ended with rapid quenching, and then aged. Cast iron with 1.27 or 2.10 % Cu content was spheroid annealing. After rapid quenching cast iron was aged. Not alloy cast iron with small copper content (0.04 %) had a chemical composition similar to cast iron with 0.48 % Cu content. Such copper was for tests in order to obtain an answer for the question whether only copper is responsible for precipitate hardening effects. Metalographic microscope tests (LM, SEM) of mechanical properties (R_m, R_p, A_5, Z, K and H) and x-ray diffraction tests were performed. It has been stated, that hardening of ferretic cast iron let to obtain tensile strength above 500 MPa and elongation approx. 23 %. Precipitation hardening of ductile cast iron efficiently compensates reducing of hardening caused by partial graphitization and spheroidization of pearlitic cementite.

Keywords: Copper ductile cast iron; Precipitation hardening

1. Introduction

Copper shows that solubility in iron increases together with temperature, reaching the maximal value of 2.2 % of mass in eutectoidal transformation temperature of 850 °C [1]. Border saturation crossing causes ε phase extraction. It is solid solution of iron in copper with 98.9 % Cu content at eutectoidal temperature. Copper's solubility in cementite can be omitted [2].

The character of the Fe-Cu phase equilibrium graph shows the possibility of precipitation hardening. In the early stadium of hyperquenched Fe-Cu alloys aging, the particles of ε iron solid solution in copper, matrix coherent are extracted. After 10 nm size crossing non-diffusion reconstruction of particles lattice into RSC lattice appears and that is connected with partial coherency break. The further growth of ε phase particles is anisotropic. They are in the shape of small bars ended with spherical bowls. The proportion of length to diameter is approx. 4 and is independent of particles sizes. Between crystal lattice of ε phase and ferritic matrix there is an K-S orientation. The average sizes of ε phase particles obtained in given aging conditions are independent of copper content in alloy [3].

The strengthening effect of ε phase extraction is used in heat treatment of low-carbon welding steel of HSLA type [4-7].

According to authors [4], the maximal strength properties of low-carbon steel with 1.52 or 1.73 % Cu content are obtained after aging at a temperature of 500 °C. Minimal elongation and impact strength there was always after aging at a temperature of 450 °C.

The mechanical properties of HSLA steel with 1.58 % Cu content were optimized in the paper [5]. Maximal hardness was after aging at a temperature of 450 °C.

Low carbon steel (0.02 %C) with 1.0; 1.5 or 2 % Cu content was hyperquenched from a temperature of 950 °C and aged in the range of 400 to 750 °C for two hours. After aging at a temperature of 450 °C steel had the biggest hardness and the smallest at a temperature of 650 °C. According to authors hardness of steel depends on copper content and with its growth the hardness increases. Steel aging in the range of 550÷575 °C caused impact strength decrease up to 50 % relatively to supply state [6].

In the paper [7] it was stated that ε phase is the main phase that extracts during aging of low carbon steel with 1.41 % Cu content (HN3MCu1,5 steel) and that gives precipitation consolidation effect. The maximal growth of steel plastic strain ΔR_p was after being quench-hardened at a temperature of 900 °C and aging at temperature of 640 °C for three hours.

The author [8] presents the dependence of hardness of low carbon steel (0.08 % C) with 1 % Cu content on aging time. The maximal hardness growth of approx.80 % in relation to solution heat treatment state was after 10 hours of aging at a temperature of 450 °C. The further elongation of aging time resulted in continuous decrease of hardness.

The significance of precipitation hardening on steel with copper content resulted in further researches on analogous cast iron heat treatment.

The aim of the researches in the paper [9] was to define the aging conditions of ferritized ductile cast iron with 0.48 % Cu content. The optimal temperature of aging was 450 °C. The maximal growth of hardness in relation to solution heat treatment state was 15 %.

According to authors [10] of the paper on precipitation hardening of gray and ductile cast iron authors state that as a result of natural aging it is possible to obtain the growth of tensile strength in the range of 3.8÷13.5 %. Artificial cast iron aging at a temperature of 70 or 148 °C fasten the process. Larger strength was obtained after aging at a temperature of 148 °C. Estimated activation energy in the first stadium of aging was 84 kJ/mol. The strength changes in the function of aging time was described with the Avramie equation. The authors [10] were particularly interested in the process of cast iron aging. The growth of nitrogen content increases strength, hardness and microhardness of ferrite.

The article [11] contains researches on the possibilities of some improvement in the mechanical properties of ferritic malleable cast iron. Hyperquenching at a temperature in the range of 715÷740 °C and naturally aging of malleable cast iron resulted in the growth of strength in the range of 20÷40 %. At the same time plasticity decreased. Aging after being hyperquenched at a lower temperature (671÷693 °C) was not efficient and the crossing of 732 °C temperature caused the danger of α→γ transformation and of martensite receiving during water cooling.

The aim of this article is to define the effect of copper content on mechanical properties of ductile cast iron precipitation hardened. The further aim is to define the most effective conditions of solution heat treatment from the technical and economical point of view.

The tests were performed on cast iron grades with such copper content that is needed for full matrix ferritizing and also for ensuring the possibly high participation of eutectoidal cementite during solution heat treatment.

2. Material, program and methodology of investigations

The tests were performed on three copper cast iron grades, marked as B, C, D and on not-alloy cast iron marked as A. Table 1 presents the chemical composition of iron cast. Table 2 presents the characteristics of the structure and basic mechanical properties.

A and B cast iron was melted in induction furnace of lattice frequency with a capacity of 1,5 ton and also poured in the shape of YII ingots.

C and D cast iron was melted in electric arc furnace and poured in the shape of plates of trapezium section 200x50x27 and length 550 mm, with riser head of trapezium section of 120 mm height and upper base length of 105 mm. Plates with the thickness of 8 mm were cut from the testing casts of A,B,C and D iron cast. Cylinders with 20 mm in diameter were made from YII ingots of B cast iron and next after being precipitation hardened five – times strength specimens with 10 mm in measuring diameter were turned. Plates with the thickness of 14 mm were also cut and then hyperquenched and from these the impact strength specimens without notch of the 10x10x55 mm dimensions were made.

Hyperquenching was performed in electric chamber furnace and aging in salt furnace.

Figures 1÷4 present the heat treatment program of a temperature-time system of each cast iron grades.

Table 1.
Chemical composition of cast iron

Cast iron	Element content, mass %.									Coefficients	
	C	Si	Mn	P	S	Cr	**Cu**	Ti	Mg	Sc*	K_G’’
A	3.82	3.41	0.19	0.057	0.020	0.04	**0.04**	0.019	0.05	1.20	12.7
B	3.76	3.07	0.35	0.07	0.040	0.04	**0.48**	0.024	0.06	1.13	10.1
C	3.42	2.32	0.32	0.09	0.006	<0.10	**1.27**	-	0.06	0.97	4.4
D	3.35	2.45	0.54	0.09	0.007	<0.10	**2.10**	-	0.11	0.96	2.4

* coefficients of S_c eutectic saturation and coefficients of K_g“ izographitization during eutectoid transformation were calculated for the formula [12]

Table 2.
Structure and mechanical properties of cast iron

Cast iron	Metal matrix, vol. %			Graphite		Mechanical properties		
	Ferrite	Pearlite	Cementite	vol. %	N_G, mm^{-2}	H, HB	R_m, MPa	A_5, %
A	86.7	13.2	0.1	12.0	94	180	513	18.6
B	19.0	81.0	0.0	10.4	108	257	670	3.0
C	3.3	96.7	0.0	10.0	114	260	736	2.0
D	0.0	99.7	0.3	8.8	121	269	765	2.4

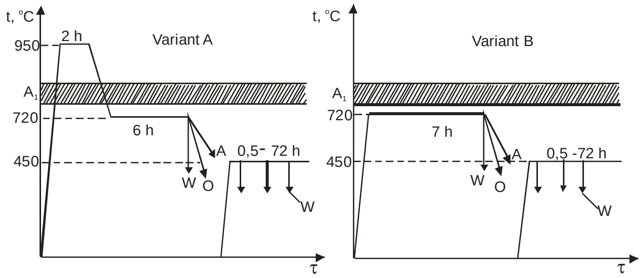

Fig. 1. Scheme of precipitation hardening of B cast iron with accordance to the variant A or B

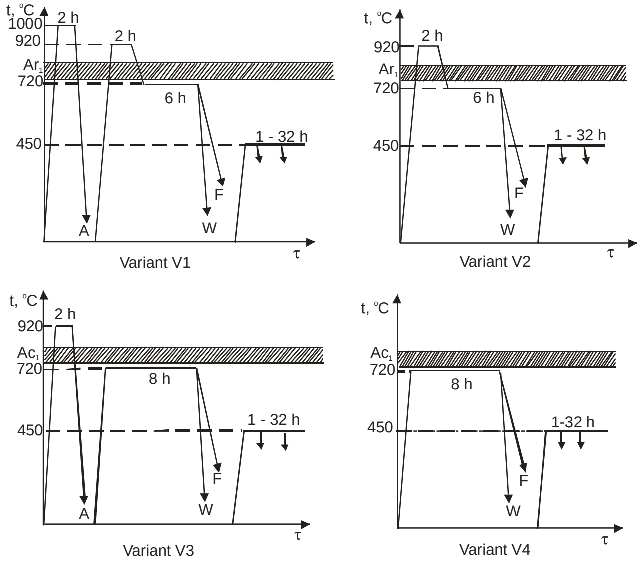

Fig. 2. Scheme of heat treatment of strength and impact strength test specimens of B cast iron

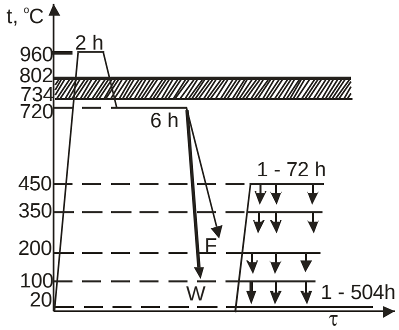

Fig. 3. Scheme of heat treatment of B cast iron

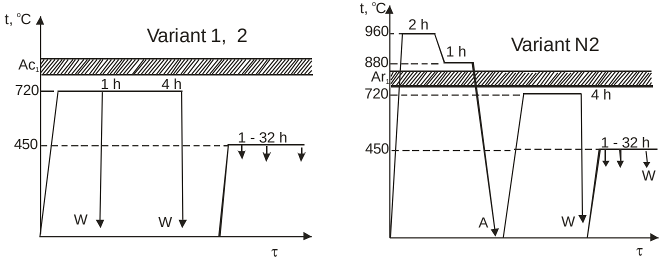

Fig. 4. Scheme of heat treatment of C and D cast iron with accordance to the variant 1 (1 hour), variant 2 (4 hours) and D cast iron with accordance to the variant N2

In figures 1÷4 the type of cooling center in solution heat treatment operation was marked: W-water, O-oil, A-air, F- furnace.

Five hardness measurements of Brinell's method were performed on each specimen (ball with 2,5 mm diameter, loading 1840 N). Qualitative and quantitative microscope tests on scanning and glowing microscope and x-ray diffraction tests were performed on selected specimens. Standard tension test of B cast iron was performed on a testing machine of the loading range up to 400 kN. R_m, R_p, A_5, and Z were determined as the average of three specimens. Impact strength examination was performed on the of Charpy's pendulum system of energy 300 J. The impact strength value was determined as the arithmetic average of four tests.

3. The results of investigations and their analysis

Hyperutectic B cast iron with the high value of K_G coefficient (table 1) was ferritized. Cast iron ferritie structure shows the greatest plasticity in the process of heat treatment, the strength, however, was relatively small. With the copper content it makes it possible to increase both the strength and the hardness of cast iron. Quick cooling that ends ferritizing causes ferrite solution heat treatment of copper. The next aging should improve strength properties. The possibility of plasticity decrease, however, should be taken into account.

The kinetics of graphitization of eutectoidal cementite of B cast iron at a subcritical temperature of 720 °C was examined in the first place. Fig. no. 5 shows that the copper content in B cast iron made no difficulties with graphitization of eutectoidal cementite which kinetics generally suits to not-alloy cast iron [13].

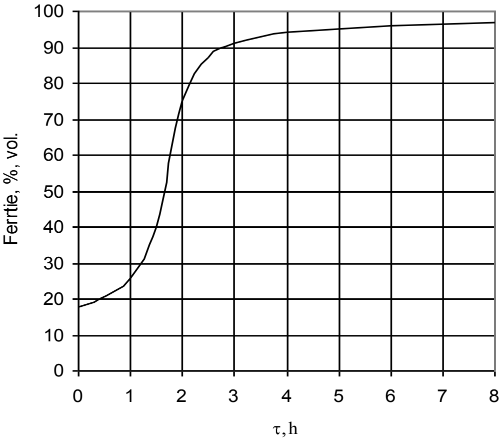

Fig. 5. Participation of ferrite in dependence on annealing time in 720 °C temperature

With the aim to obtain maximal hardness growth, on the basis of personal researches and literature [4-6,8,9] it was decided to choose the aging temperature of 450 °C. The aging temperature was common to all variants of precipitation hardening (fig. 1÷4).

Ferritic matrix in cast iron can be obtained as a result of single-stage and two-stage ferritizing together with matrix crystallization. The effects of two-stage ferritizing are more beneficial [13] but the working itself is more expensive.

B cast iron was precipitation hardened in the process of two-stage or single-stage ferritizing (fig. 1). Ferritizing was ended with water, oil or air cooling. Cooling speed of iron cast plates of the 200x45x8 mm dimensions was measured with thermocouple NiCr-Ni placed inside of them. Average cooling speed was calculated on the basis of cooling curves in the temperature range of 720÷100 °C and the results were as follows: 44,3 K/s in water, 10,9 K/s in oil and 0,56 K/s in air. After hyperquenching plates were cut into cubes of 20x20x8 mm dimensions and aged up to 72 hrs. Dependence of hardness H on aging time τ was approximated with $H=a\cdot\tau^b$ function.

Table 3 presents the parameters of the approximation function.

Table 3.
Parameters of the approximation function

Va-riant	Cooling medium	Parameters of the equation		Correlation coefficient,	ΔH, %
		a	b	r	
A	water	173,6862	0,0229	0,9381	20,4
	oil	175,9042	0,0204	0,9218	21,0
	air	174,5637	0,0234	0,9658	20,8
B	water	175,2529	0,0141	0,9543	13,0
	oil	171,4291	0,0192	0,9232	13,5
	air	173,3565	0,0179	0,9767	12,6

According to table 3 there was an exact relation of cast iron hardness with its aging time. The maximal hardness growth ΔH in percentage of B cast iron two-stage ferritized after aging was higher than in single-stage ferritized.

The hardness graph H in the function of aging time τ (fig. 6) was prepared on the basis of approximation equations (table 3).

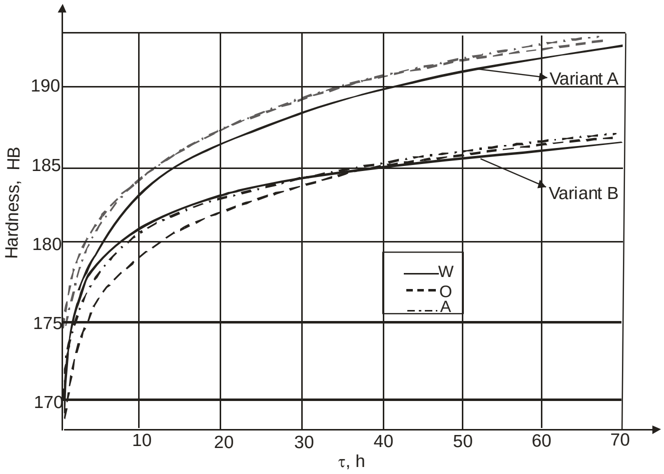

Fig. 6. Hardness of cast iron in relation to aging time in 450 °C temperature. Cooling before aging: W – in water, O – in oil, A – in air

According to figure no.6 the larger hardness of two-stage ferritized cast iron can be noticed. The way of ferritizing had an influence on kinetics and value of hardness obtained in the process of aging. The influence of cooling speed (cooling center) was not clear and unimportant. The hardness differences can be due to crystallization and better homogenizing of two – stage ferritized cast iron. Of great importance were also both size and form of ferrite's grains. The average chord of ferrite's grains was defined by secant – random method. In two – stage ferritized cast iron it was 0.011 mm and in single-stage ferritized – 0.019 mm.

In order to evaluate the influence of preliminary normalization and solution heat treatment methods on mechanical properties of B cast iron precipitation hardened the heat treatment were performed according to variants presented in figure no.2.

Table 4 presents the results of statistical analysis of B iron cast mechanical properties dependent on aging time.

Correlation coefficients of equations describing R_m, R_p changes and especially H in the function of aging time τ, have values that testify about their large independency. The connection of their plastic features (A_5, Z) with aging time is usually weak.

Values of changes of mechanical properties of cast iron precipitation hardened in relation to the ferritized one are presented in the table 5.

From tables 4 and 5 it results, that most efficient connection of strength and plastic properties, after precipitation hardening, appeared in cast iron with ferritic matrix after two-stage ferritizing. In the best case tensile strength reached R_m=516÷525 MPa by elongation A_5=22÷23.5 %. Initial normalizing of cast iron did not effect positively on aging effects.

Table 4.
Results of statistical analysis of B iron cast mechanical properties in the function of aging time

Variant treatment, wg fig.2	Property	Regression equation τ = aging time, hours	Correlation coefficient, r
V1	R_m, MPa	$R_m = 472{,}94 \cdot \tau^{0{,}0168064}$	0,856
	R_p, MPa	$R_p = 354{,}04 \cdot \tau^{0{,}0148002}$	0,937
	A_5, %	$A_5 = 21{,}85 - 0{,}021143 \cdot \tau$	-0,289
	Z, %	$Z = 20{,}10 - 0{,}030097 \cdot \tau$	-0,964
	H, HB	$H = 173{,}45 \cdot \tau^{0{,}0163814}$	0,964
V2	R_m, MPa	$R_m = 477{,}92 \cdot \tau^{0{,}0264909}$	0,981
	R_p, MPa	$R_p = 356{,}04 \cdot \tau^{0{,}0265519}$	0,934
	A_5, %	$A_5 = 23{,}20 - 0{,}0286255 \cdot \tau$	-0,510
	Z, %	$Z = 23{,}53 - 0{,}0115559 \cdot \tau$	-0,114
	H, HB	$H = 177{,}75 \cdot \tau^{0{,}0200587}$	0,990
V3	R_m, MPa	$R_m = 505{,}80 \cdot \tau^{0{,}0200587}$	0,945
	R_p, MPa	$R_p = 400{,}76 \cdot \tau^{0{,}0104118}$	0,969
	A_5, %	$A_5 = 19{,}86 + 0{,}0258932 \cdot \tau$	0,376
	Z, %	$Z = 17{,}67 + 0{,}0270282 \cdot \tau$	0,456
	H, HB	$H = 183{,}26 \cdot \tau^{0{,}019458814}$	0,980
V4	R_m, MPa	$R_m = 496{,}86 \cdot \tau^{0{,}0194588}$	0,956
	R_p, MPa	$R_p = 378{,}52 \cdot \tau^{0{,}0297869}$	0,933
	A_5, %	$A_5 = 18{,}85 + 0{,}03182012 \cdot \tau$	0,568
	Z, %	$Z = 19{,}70 + 0{,}0508197 \cdot \tau$	0,467
	H, HB	$H = 179{,}73 \cdot \tau^{0{,}0211166}$	0,967

Table 5.
Extreme values of changes of mechanical properties of B cast iron precipitation hardened in relation to the ferritized one

Variant	ΔR_m, %	ΔR_p, %	ΔH, %	$M = \Delta R_m/\Delta H$
V1	9.9	11.2	13.5	0.73
V2	14.1	13.8	13.8	1.02
V3	6.0	4.3	9.0	0.67
V4	6.9	9.1	7.8	0.88

Impact strength test results of cast iron B as the function of aging time for individual variants of precipitation hardening are presented in fig. 7, whereas breaking angle φ (internal angle measured after connection of a broken impact strength specimen) – in fig. 8.

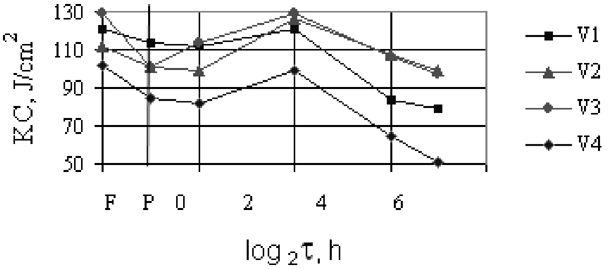

Fig. 7. Impact strength of B cast iron in relation to aging time τ for the variant V1÷V4, F – after ferritizing, P – after solution heat treatment

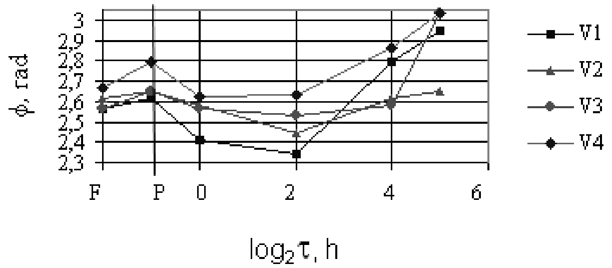

Fig. 8. Breaking angle φ of the B cast iron specimen in relation to aging time τ for the variant V1÷V4, F – after ferritizing, P – after solution heat treatment

From figures 7 and 8 it results, that single-stage ferritized cast iron (V4) showed the smallest impact strength and the largest breaking angle φ. Impact strength is especially sensitive on the grain size, segregation and fragile structure contents. The amount of remaining parts of eutectoildal cementite was 3.5 %. It was inconveniently distributed in periphery areas of eutectoidal grains.

Appearance in all variants of the local impact strength maximum and minimum of the φ angle (fig. 7,8) can be explained in the following way: the course of impact strength changes and the B cast iron angle φ during aging in the 450 °C temperature in the period of time up to 4 h resulted from precipitation of phases from solution heat treated ferrite. In the beginning there was precipitation of metalstable phases, and only after that extending of aging time caused precipitation of the stable phase. Small parts with large density, equally distributed in ferrite grains and at least partly coherent acted with dislocations influencing on hardening. Extending of aging time led to stabilization of the precipitating phase that might had beard on ferrite borders and on interphases borders matrix – precipitations. Usually their borders are incoherent what influenced on the B cast iron impact strength.

Values of impact strength and breaking angle φ changes of the precipitation hardened cast iron in relation to the ferritized one were presented in the tab. 6.

Table 6.
Extreme values of ΔK and Δφ of B cast iron

Variant	ΔKC, %	Δφ, %
V1	-34,7	15,0
V2	-11,6	1,3
V3	-24,2	18,4
V4	-51,0	13,7

Data included in the table 6 point that for B cast iron the most beneficial was precipitation hardening with solution heat treatment after two-stage ferritization.

In the presence of large number of contents and additions in cast iron characterized with changing dissolvability in α iron one can assume that not only copper is responsible for precipitation hardening effects. In papers [10,11] the effect of cast iron hardening,

In normalized not-alloy A spheroid cast iron, next annealed in 600÷650 °C temperature it was noticed that the initial annealing period caused the increase of strength properties without visible changes of a microstructure. It was assumed, that it was probably a result of aging [14]. To answer whether only copper is responsible for precipitation hardening results there was made a decision to test not-alloy A ductile cast iron with a chemical composition similar to B cast iron (table 1). A cast iron was heat treated with accordance to the scheme in fig. 3. Hardness test results were defined as regression equations and placed in the table 7.

Table 7.
Hardness of A cast iron as a function of aging time τ

Aging temperature, ^{o}C	Regression equation H = aτ +b, hours	Correlation coefficient, r	Determination coefficient, r^2
~20 ^{o}C (natural)	H = 174,1-0,0057τ	-0,361	0,130
100	H = 167,8-0,0063τ	-0,044	0,002
200	H = 166,9-0,0345τ	-0,531	0,282
350	H = 167,9-0,1008τ	-0,807	0,651
450	H = 164,1-0,0232τ	-0,467	0,218

A cast iron hardness in the function of aging showed in each case the decreasing tendency. Connection of hardness with aging time was small except 350 °C temperature (tab. 7).

Microscopic observation of the naturally aged cast iron and the one aged 450 °C temperature (fig. 9a,b) did not show precipitations. In cast iron aged in 100 °C temperature after 1 hour there were visible small precipitations (fig. 9c) that after extended time to 72 hours had a shape of needles (fig.9d). Creation of needle precipitations was an effect of aging in 200 °C temperature during 1 hour (fig. 9e). Extending of aging time up to 72 hours led to the increase of oriented towards each other needle precipitations (fig. 9f). Crystallographic orientation and morphologic of precipitations point, that this is iron nitride. The presence of those precipitations did not affect the hardness of aged cast iron (table 7).

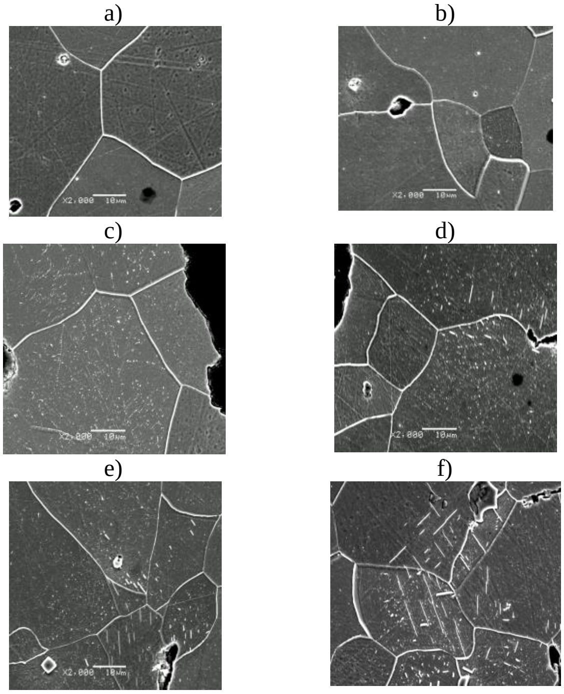

Fig. 9. Microstructure of A cast iron aged in temperature and time: a) room – 21 days b) 450 °C – 64 hours, c) 100 °C – 1 hour, d) 100°C – 72 hours, e) 200 °C – 1 hour, f) 200 °C – 72 hours. SEM, mag. 2000x, etch. HNO_3 2 %

The larger addition of copper in cast iron causes strong pearlitization of matrix. Cast iron with 2.08 % of the Cu content (cylinder with 30 mm diameter) had totally pearlitic matrix [15]. Pearlitic copper ductile cast iron shows large tensile strength (above 600 MPa), plastic strain, but plastic properties are small. In order to improve plastic properties of copper cast iron, it can be spheroidally annealed in sub-critical temperature. Partial graphitization and spheroidization of eutectoidal cementite causes significant decrease of strength properties and hardness. To compensate it the operation of spheroid annealing was ended with rapid quenching, and next cast iron was aged. It was assumed, that aging in the 450 °C temperature does not change anything in content and shape of eutectoidal cementite. C cast iron (1.27 % of Cu) was precipitation hardened according to variants 1 and 2, whereas D cast iron (2.10 % of Cu) according to variants 1, 2 or N2 (fig.4).

C cast iron matrix was pearlitic – ferritic with a small content of ferrite amounting 3.3 %. D cast iron matrix was pearlitic with an insignificant content of cementite (0.3 %). D cast iron normalization (variant N2) caused crumbling of pearlite. Normalization resulted with the strong increase of hardness in comparison to the raw state (approx. 80 HB).

Solution heat treatment with accordance to the variant 1 C and D cast irons in 4 h time (fig. 4) did not change the percentage structural content of matrix. But there were observed hardness changes that state for the appearance of the initial spheroidization stage of eutectoidal cementite. It had a form of small decrease of hardness in relation to the raw state (2 HB for C cast iron and 6 HB for D cast iron).

Solution heat treatment of C and D cast iron with accordance to the variant 2 for 4 hours resulted with development of graphitization and spheroidization of eutectoidal cementite. In C cast iron presence of ferrite in matrix was 32 % mainly by precipitations of graphite. In D cast iron 4 hours soaking during solution heat treatment led to usually ball cementite equally distributed in ferrite matrix. Decrease of hardness accompanied to described changes of structures and for C cast iron amounted 48 HB, and for D cast iron – 10 HB in relation to the raw state.

As a result of D cast iron solution heat treatment, initially normalized, (N2 variant) there was a ball cementite structure on the background of fine-grained ferrite. In that case hardness amounted 226 HB so it was smaller of 33 HB than cast iron solution heat treated according to the variant 2. It states for intensification of spheroidization process. The reason has to be search in crumbling of ferrite grains as a result of over-crystallization of matrix of normalized cast iron.

On the base of hardness test results there was prepared a chart of C and D cast iron hardness as a function of aging time (fig. 10).

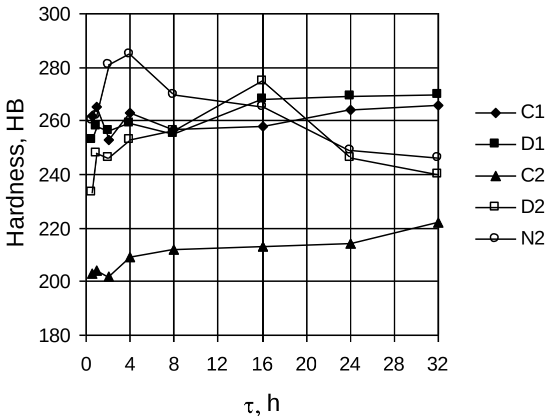

Fig. 10. C and D cast iron hardness as a function of aging time for variant 1, 2 or N2

From fig. 10 results, that solution heat treatment in 1 hour time was ineffective as well for cast iron with the smaller content of copper (1.27 %) as well as for the bigger one – (2.10 %). Solution heat treatment of D cast iron, preceded with normalizing (N2 variant), let to obtain a very beneficial structure of equally distributed cementite balls on the background of fine-grained ferrite, which after 4 hours aging time strongly hardened (hardness increase up to 26 %). That hardening with surplus compensated decrease of hardness caused by spheroidization.

In the table 8 there were presented test results of the ferrite lattice parameter.

X-ray examinations (table 8) showed, that the lattice parameter of the α phase – increases along with the content of copper and extended solution heat treatment time. Aging caused contraction of ferrite lattice.

Table 8.
Ferrite lattice parameter a_α

Cast iron	Working state	a_α, nm
C	Raw	0,28640
D	Raw	0,28643
C	Solution heat treatment with accordance to the variant 1	0,28640
C	Solution heat treatment with accordance to the variant 2	0,28662
D	Solution heat treatment with accordance to the variant 1	0,28645
D	Solution heat treatment with accordance to the variant 2	0,28664
D	Solution heat treatment with accordance to the variant N2	0,28665
D	Solution heat treatment with accordance to the variant 2 and aging in time of 16 hours	0,28638
D	Solution heat treatment with accordance to the variant N2 and aging in time of 4 hours	0,28642

4. Conclusions

1. Connection of cast iron ferritization with the small content of copper (0.48 %), ended with rapid quenching and then aging in 450 °C temperature, let to obtain beneficial association of strength properties (R_m above 500 MPa) and plastic ones (A_5 above 20 %).
2. It should be acknowledged, that only copper was an element significantly shaping mechanical properties of cast iron precipitation hardened.
3. Very beneficial matrix structure and properties was obtained by cast iron with the large content of copper (2.10 %) with the usage of heat treatment, which consisted of initial normalizing, spheroidization in sub-critical temperature in 4 hours time and rapid quenching and aging.
4. There should be undertaken an attempt to define the term “supersaturation of alloy” similarly to the term “hardenability” and define for an individual alloy the speed of shower cooling in the operation of solution heat treatment (thickness of a cast) that guaranties efficiency of aging.

References

[1] T.B. Massalski, Binary Alloy Phase Diagrams. ASM International, 1990.

[2] A. Kosowski, Cz. Podrzucki, Żeliwo stopowe. Skrypt uczelniany nr 825, AGH Kraków, 1981.

[3] J.W. Martin, R.D. Doherty, B. Cantor, Stability of microstructure in metallic systems, Second edition, Cambridge University Press, 1997.

[4] S.K. Dhua et al., Effect of tempering temperatures on the mechanical properties and microstructures of HSLA – 100 type copper-bearing steels. Materials Science and Engineering A vol. 318. Is. 1-2, 2001, 197-210.

[5] P.K. Ray et al., Optimization of mechanical properties of an HSLA steel trought control of heat treatment variables. Materials Science and Engineering A. vol. 346. Is 1-2, 2003, 122-131.

[6] S.M. Pytel, B. Rynkar, Low carbon copper-bearing structural steels. I Krajowa Konferencja Naukowa (Materiałoznawstwo-Jakość - Odlewnictwo), Kraków, 1997, 177-184 (in Polish).

[7] J. Lis, P. Wieczorek, Precipitation strengthening and mechanical properties of ultra low carbon bainitic steel with Cu addition. Inżynieria materiałowa. Nr 2 (121), 2001, 96-102 (in Polish).

[8] T. Malkiewicz, Metaloznawstwo stopów żelaza. T. I. PWN, Warszawa – Kraków, 1968.

[9] T. Szykowny, Analysis of dispersive hardening of the low Cu–content spheroidal cast iron. Zeszyty Naukowe ATR w Bydgoszczy. Nr 193, Mechanika 38, 1995, 131-137 (in Polish).

[10] L. Richards, W. Nicola, Final; technical report: Age strengthening of gray cast iron, phase III. University of Missouri. Report No. DOE/ID13851, 2003, June 26.

[11] P. B. Burgess, Age hardening ferritic malleable cast iron. Casting T. 56. No 3, 1969.

[12] N.G. Giršovič, Spravočnik po čugunnomu litju. Izd. Mašinostroene, Leningrad, 1978.

[13] J. Piaskowski, A. Jankowski, Żeliwo sferoidalne. WNT, Warszawa, 1974.

[14] H. Oleszycki, Effect of heating, soaing and cooling on forming pearliyic structure and mechanical properties of unalloyed cast iron. ATR Bydgoszcz, 1982 (in Polish).

[15] E.N. Pan et.al., Einfluβ von Kupfer, Zinn und mangan auf die eutektoide Umwandlung von graphitischen Guβeisen. Giesserei-Praxis. No15/16, 1988, 193-207.