

# Fracture Pattern Analysis of Bainite High-Strength Cast-Iron Commercial Products Depending on Structural Condition

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Mechanical properties, microstructure and fracture pattern of bainite nodular cast-iron after austempering are studied in the range of temperatures 260-420 °C. Nonharmonic character of function of mechanical properties change in various temperature intervals of isothermal soaking is determined. Dependence of nonharmonic behavior of function of mechanical properties on structural condition is shown. Interrelation between fracture pattern of bainite nodular cast-iron and its metallic matrix type is illustrated fractographically.

Keywords: NODULAR CAST-IRON, AUSTEMPERING, METALLIC MATRIX, LOWER BAINITE, UPPER BAINITE, STRUCTURE, ELECTRON MICROSCOPY, FRACTURE, FRACTOGRAPHY, MECHANICAL PROPERTIES, HARDNESS, DUCTILITY

## Introduction

It is known that microstructure of austenite decomposition products depends on intermediate transformation temperature [1]. According to authors [1, 2], "combined" structures of isothermal decomposition are formed in certain temperature intervals of transformation. According to model suggested by M. Takahashi and H. Bgadeshia [3], in the process of bainite reaction, which goes with formation of lower bainite, stage of upper bainite formation is observed that is related to austenite saturation by carbon.

Suggested model is based on fundamental rules by A. B. Grenigera and A. R. Troyano [4] about "phenomenon of incomplete reaction". According to this "phenomenon", austenite is divided into high-carbon and low-carbon sections during bainite transformation. According to "relaxation theory of polymorphic transformation" by G. V. Kurdyumov and A. L. Roytburd [5], each section has its own relaxation mechanism. As a result, austenite transformation in each section is defined by C-diagram.

In addition, according to A. A. Zhukov [6], bainite transformation in cast-iron is accompanied

by fast "austenite predecomposition" on two  $\gamma$  - phases - depleted and enriched by carbon. It is because there is a section with negative curvature, where "spinodal" interval van der Waals takes places, on Gibbs' concentration dependence curves [7].

According to [8], temperature interval of austempering 300-360 °C is characterized by "combined" [1, 2] structural conditions. Thereupon, considering the fundamental statements [1, 2, 7] it is possible to assume that the simultaneous presence of two initial  $\gamma$  - phases defines morphological features of bainite aggregates, which coexistence in the field of "transition" structures and nonharmonic behavior of functions of mechanical properties [8] cause their specific behavior and, as consequence, fracture pattern of products.

The task of present research is detailed electron-microscopic analysis of morphological types of bainite matrix formed at various parameters of austempering in bainite nodular cast-irons for the purpose of fracture pattern identification and carrying out of measures related to optimization of thermal hardening regimes of products to raise their service reliability.

## Methodology

The material of investigation is nodular cast-iron with ferrite-pearlite microstructure of matrix as received for the subsequent heat treatment by isothermal hardening method (austempering). Chemical composition of nodular cast-iron produced by JSC "Rovenskiy Foundry" is presented in **Table 1** as compared to recommended requirements of DSTU 3925-99. Analysis of data from **Table 1** shows that the test object corresponds to BЧ400-15 cast-iron by concentration of components under DSTU 3925-99. Isothermal hardening (austempering) regimes were chosen taking into account technological possibilities of industrial equipment of Ukrainian producer - "A.Staki-Rejl" [9]. Methodical maintenance of nodular cast-iron austempering in experimental conditions is considered in work [8].

Structural analysis and preparation of materials were carried out according to GOST 3443-87 "Iron Casts with Various Graphite Shape. Structure Determination Methods". Samples were polished in chromium-acetic electrolyte by electroplating technique for observation of microstructure with the use of raster electron-microscopic analysis.

Objects of fractographic investigation were heat-treated bainite nodular cast-irons (after austempering at 260-420 °C) after tensile test. Metallographic specimens and fracture surfaces were finally cleaned by ultrasonic method. Raster electron-microscopic and fractographic investigations were carried out on microscope REM-106-I. Accelerating potential and magnifications are specified on micrographs presented in the work.

Mechanical properties and hardness of bainite nodular cast-iron after austempering at different temperatures of isothermal soaking were defined by GOST 1497-84 "Metals. Tensile Test Methods" and by GOST 9012-59 "Metals and Alloys. Brinell Hardness Test Method".

## Results and Discussion

**Figure 1a, b** illustrate results of mechanical tests. As follows from **Figure 1a**, hardness of bainite nodular cast-iron decreases almost linearly from 486 HB at 260 °C to 350 HB at 320 °C with rise in temperature of salt melt from 260 to 320 °C. Intensity of hardness drop (350→329 HB) reduces in the temperature interval 320-360 °C which is obviously indicative of the formation of transition structures from "lower" to "upper" bainite in this range [8]. At 360-420 °C the trend to active linear drop of bainite nodular cast-iron hardness (329→241 HB) is observed again.

Ductility of bainite nodular cast-iron changes in another way - "δ<sub>5</sub>" intensively grows reaching the value 7.5 % at isothermal soaking temperature growth from 260 to 360 °C. After that, this characteristic almost does not change and remains at the level of 7.5-8.0 % at 380 - 420 °C (**Figure 1b**).

Conducted investigations enable to conclude that bainite nodular cast-iron has the maximum hardness at 260 °C and the greatest values of ductility are reached at 380-420 °C in the investigated interval of isothermal soaking temperatures. That is these characteristics are provided with the formation of characteristic structural conditions of "lower" or "upper" bainite in the first and second cases [8].

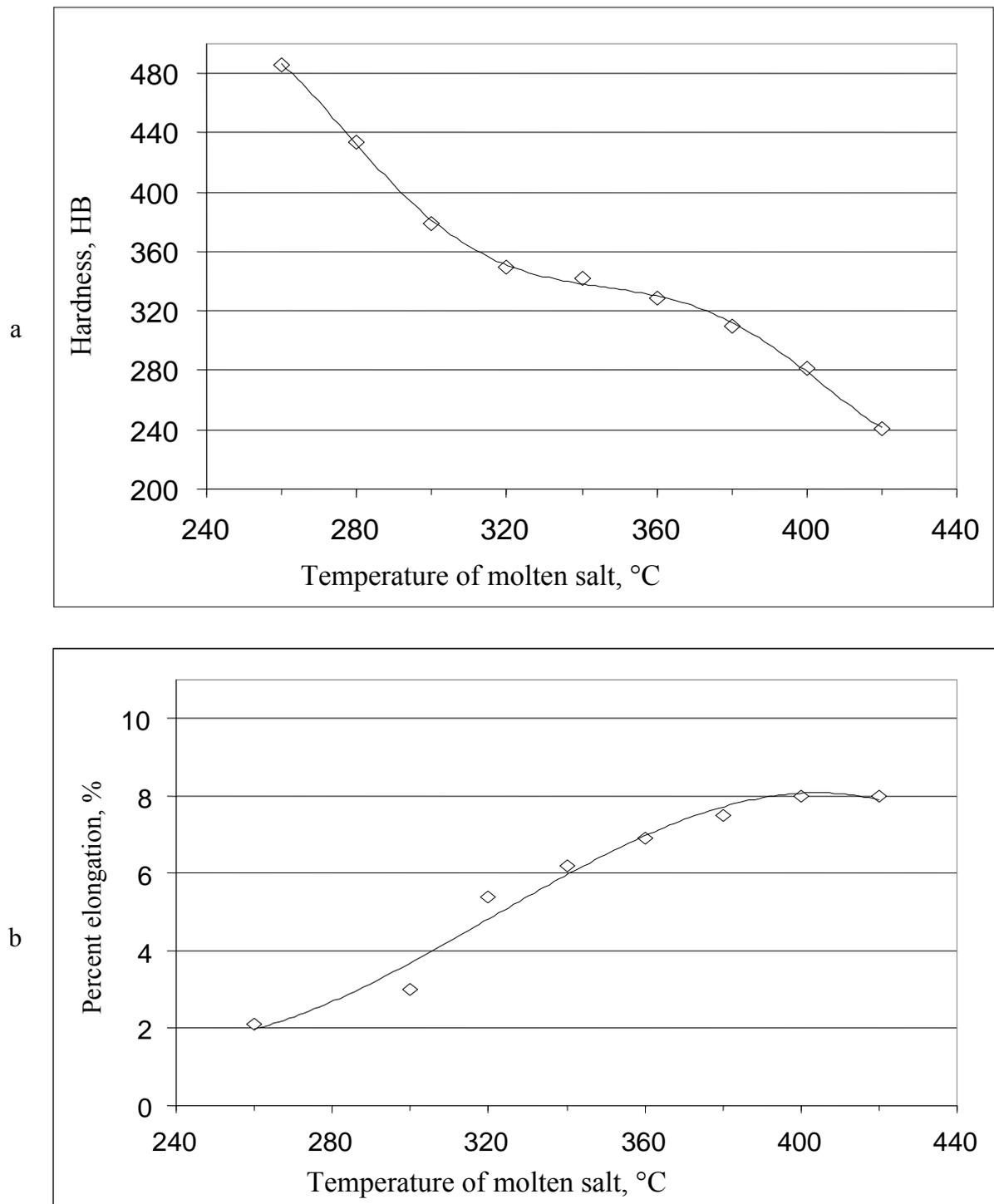
**Table 1.** Basic components of nodular cast-iron produced by JSC "Rovenskiy Foundry" as compared to recommended requirements of DSTU 3925-99

Cast-iron grade by DSTU 3925/ Test object	Mass fraction of elements *, %					
	Carbon	Silicon	Manganese	Sulfur	Phosphorus not more than	Chromium
BЧ 400 – 15 by DSTU 3925	3.3–3.8	1.9–2.6	0.2–0.6	0.02	0.1	0.05
Nodular cast- iron produced by JSC "Rovenskiy Foundry"	3.63	2.33	0.49	0.015	0.058	<0.05

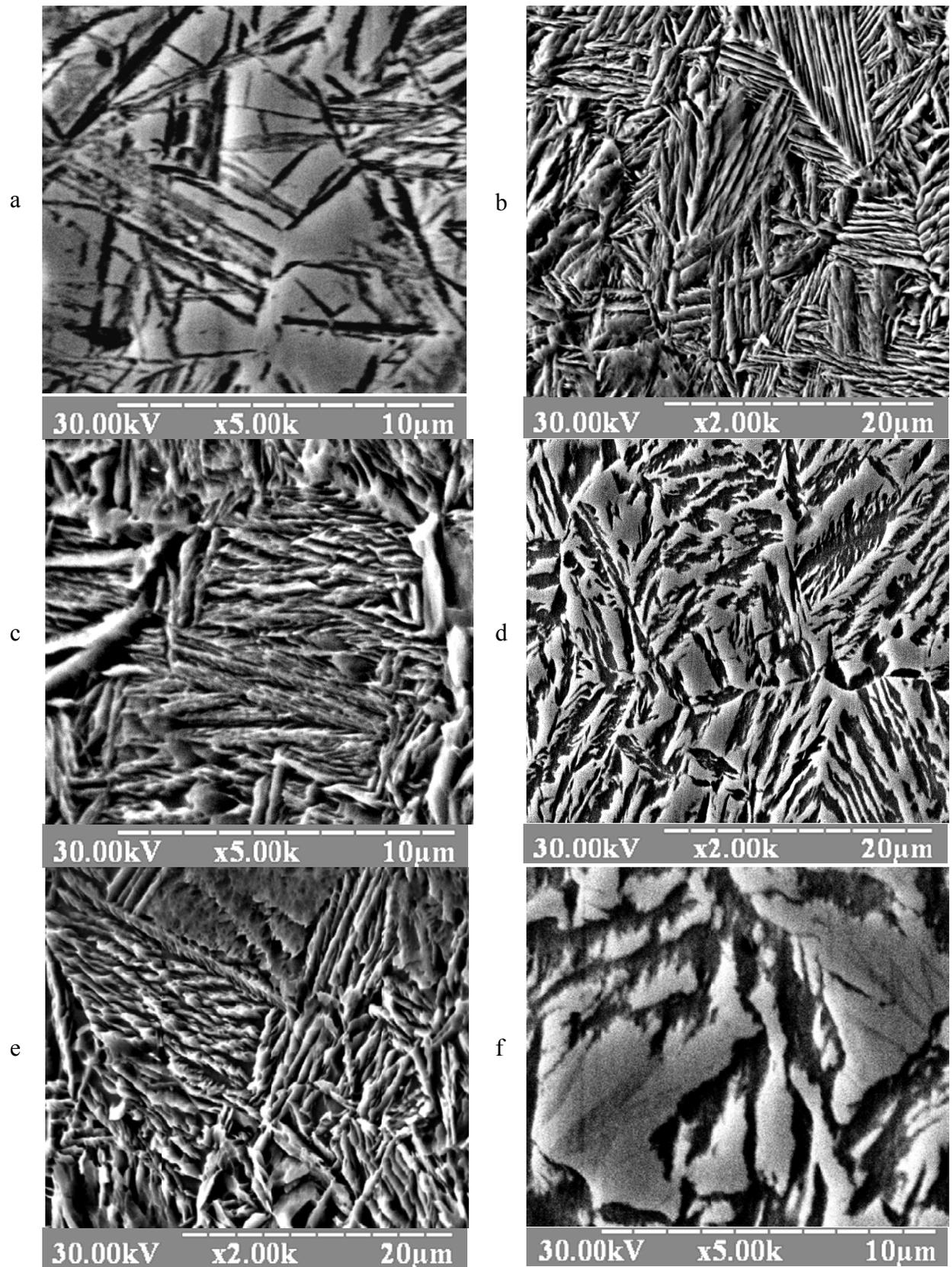
\* according to DSTU 3925-99: "Alloying with nickel, cuprum and other elements is allowed"

Change of harmonious character of behavior of functions of mechanical properties in the specified temperature intervals (260-320; 320-360; 360-420 °C) was a reason for additional investigation of bainite nodular cast-iron matrix formation during austempering at the specified

temperatures of isothermal soaking. **Figure 2a** testifies that “martensite-like” structure, typical for “lower” bainite, is formed in the temperature interval to 320 °C. This “martensite-like” structure defines high hardness of product (**Figure 2a**) and very low level of ductile characteristics (**Figure 1b**).



**Figure 1.** Dependence of hardness values (a) and percent elongation (b) of investigated bainite nodular cast-iron on austempering temperatures



**Figure 2.** Raster electron microscope images (*a, d, f* – mechanical preparation of samples; *b, c, e* – electropolishing) of bainite nodular cast-iron structures after austempering at temperatures, °C: *a* - 280; *b, c* - 320; *d, e* - 380; *f* - 420

Temperature range 320-360 °C is characterized by “spinodal decomposition” of austenite [6] with formation of two solid solutions of  $\gamma$  - phase containing various amount of dissolved carbon. This phenomenon leads to specific kinetics of structure formation of bainitic  $\alpha$  - phase. As a result, "combined" structures are observed (**Figure 2b**).

**Figure 2c** illustrates the fact of needle crystals formation on the boundary lines of initial austenitic grain and mass arrangement of "plumose" structures in grain body of parent phase disintegrating in the second turn [5]. Quantitative ratio of components with "needle" and "plumose" morphology changes with the rise in temperature from 320 to 360 °C. Ductility of alloy increases (**Figure 1b**), and hardness decreases slightly (**Figure 1a**). In our opinion, this is explained by qualitatively equal structural condition of cast-iron matrix in the analyzed temperature range.

**Figure 2d, e** shows that temperatures of "upper" bainite formation (360-420 °C), providing high diffusibility of atoms of elements dissolved in  $\gamma$  - phase, cause shift-diffusion recrystallization  $\gamma \rightarrow \alpha$  with the formation of "plumose" bainite structures which are featured by the highest indexes of ductility (**Figure 1b**) and the lowest hardness (**Figure 1a**). Besides, decomposition of residual austenite is observed with formation of martensite crystals at temperatures close to 420 °C (**Figure 2f**). The reason of ductility growth inhibition beginning from 380 °C (**Figure 1b**) at continuous drop of hardness (**Figure 1a**) should be explained using fractographic investigation method.

Hence, the presence of various structural conditions ("lower" bainite with needle morphology of  $\alpha$  - phase, "combined" structure, "upper" bainite with "plumose" morphology) in three temperature intervals also explains nonharmonic character of behavior of functions of thermal dependence of mechanical characteristics. It is obvious that such behavior of properties should affect the features of bainite nodular cast-iron fracture mechanisms after their austempering at certain temperatures with the formation of corresponding structures.

Results of fractographic investigation of fractured samples of bainite nodular cast-iron after austempering are presented in **Figure 3**.

Micrographs in **Figure 3a** illustrate the presence of intercrystalline brittle fracture of sample at the formation of lower bainite structure in it in the field of temperatures to 300 °C which correlates well with data in **Figure 1b**. Faceted surfaces of transcrystalline fracture that

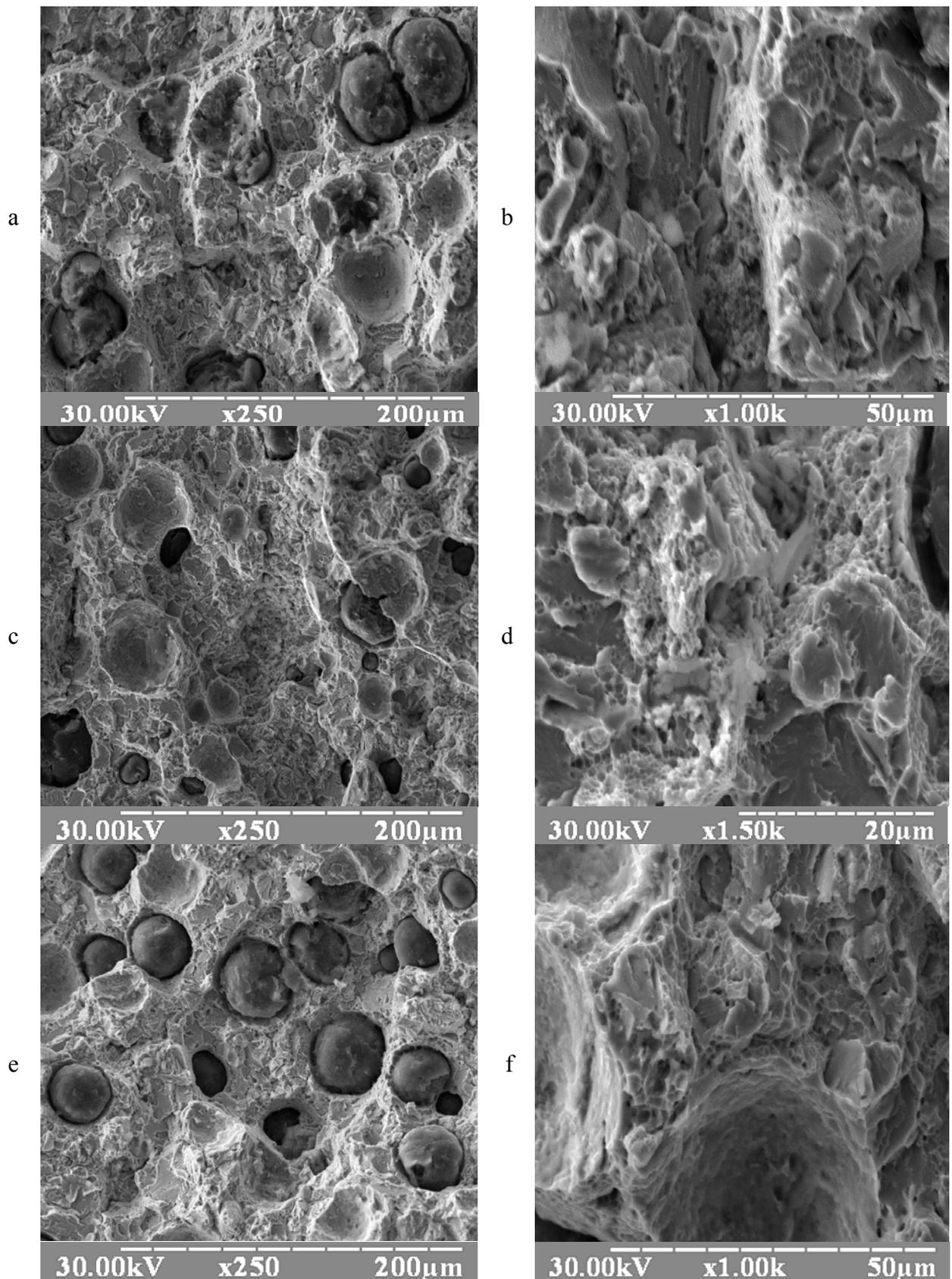
characterize brittle fracture and river lines as result of second order chip are clearly visible in **Figure 3b**. Thus, the formation of “martensite-like” lower bainite in bainite nodular cast-iron (**Figure 2a**) causes extremely low level of ductile characteristics (**Figure 1b**) at maintenance of high hardness values (**Figure 1a**).

Transition in the temperature range 320-360 °C is featured by intermediate fracture mechanism (**Figure 3c, d**). In this case, intercrystalline fracture (**Figure 3c**) and sections of brittle transgranular quasispalling (**Figure 3d**) are indicative of intermediate fracture mechanism. Therefore, at temperature rise in the researched interval of "combined" structures formation (**Figure 2b, c**) hardness almost does not vary during change of ratio between structural constituents of various morphological types, and the percentage elongation (**Figure 1b**) continuously grows with increase of plumose bainite amount (**Figure 2c**).

Fracture is ductile in the temperature range of "upper" bainite formation (380-420 °C). **Figure 3f** illustrates permanent developing process of viscous intercrystalline fracture. Moreover, there are areas of intergranular chip in places of discontinuity matrix - spherical graphite (**Figure 3e**). In our opinion, this explains the constant parameter of percent elongation (**Figure 1b**) at continuous drop of hardness (**Figure 1a**). In this case, the presence of graphite that is spherical but foreign by its properties to metal matrix in the structure of bainite nodular cast-iron is the limiting factor of development of ductile characteristics of material irrespective of condition of "upper" bainite (**Figure 2d-f**).

The regularities of bainite nodular cast-iron structure formation by Specifications of Ukraine 27.1-23365425-604:2006 in a wide temperature range of austempering and related features of fracture mechanisms allowed "A.Staki-Rejl" to choose heat treatment regimes for products with specific service conditions:

- bainite nodular cast-iron with "lower" bainite - elements with high hardness and wear-resistance without special requirements to plastic and viscous characteristics of material;
- bainite nodular cast-iron with "upper" bainite - constructional elements with high indexes of strength, ductility and viscosity without special requirements to hardness and contact-fatigue wear-resistance;
- bainite nodular cast-iron with “transition” matrix ("combined" structure) - details able to harden during maintenance under effect of deformation phase transformation at dynamic load.



**Figure 3.** Fracture patterns of bainite nodular cast-iron samples. Austempering temperatures, °C: *a, b* - 280; *c* - 320; *d* - 360; *e, f* - 380

## Conclusions

1. Nonharmonic character of behavior of functions of corresponding parameters in the temperature intervals 260-320; 320-360; 360-420 °C is determined as a result of investigations of bainite nodular cast-iron mechanical properties by Specifications of Ukraine 27.1-23365425-604:2006. Maximum hardness of bainite nodular cast-iron and the greatest values of ductility are observed at 260 °C and 380-420 °C respectively.

2. It is shown that the presence of various structural conditions of matrix ("lower" bainite with needle morphology of  $\alpha$  - phase, "combined" structure, "upper" bainite with "plumose" morphology) in three researched temperature intervals explains the nonharmonic character of behavior of functions of thermal dependence of mechanical characteristics.

3. The fact of dependence of bainite nodular cast-iron fracture type on austempering temperature is illustrated - brittle intergranular fracture at the formation of "lower" bainite; viscous intercrystalline fracture of bainite nodular cast-iron with "upper" bainite and combined fracture mechanism in the presence of matrix with "transition" structure.

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## Анализ характера разрушения промышленных изделий из бейнитных высокопрочных чугунов в зависимости от структурного состояния их матрицы

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Хулин А.Н., Сухомлин В.И.

Изучены механические свойства, микроструктура матрицы и характер разрушения БЧШГ после аустемперинга в интервале температур 260-420 °C. Установлен негармонический характер функции изменения механических свойств в различных температурных интервалах изотермической выдержки. Показана зависимость негармонического поведения функции механических свойств от структурного состояния матрицы. Фрактографически проиллюстрирована связь характера разрушения БЧШГ с типом их металлической матрицы.