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Use of the dactyling effect to obtain a compositional structure in white iron during forming

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Abstract. Cast iron is traditionally used as a casting alloy for the manufacture of products operating in various industries. White cast irons are used for parts with high wear resistance due to the presence in their composite structure a large number of eutectic carbides, which are located around the dendrites of the solid solution and provide a high level of hardness and strength. The location of eutectic colonies in the form of a mesh causes a low level of ability to withstand impact loading, facilitates the chipping of individual "grains" in abrasive wear and limits the use of these alloys. The use of forming process allows us to grind the eutectic mesh in the structure of white cast iron, which significantly improves the complex of mechanical and operational properties. But the low level of plasticity of white cast iron in the cast state does not allow widespread using white cast iron plastic deformation. The possibility of hot deformation of cast iron workpieces with different speeds and schemes was investigated. The deformation rate of alloys was varied due to the use of different equipment for mass and small-series production using different types of metal forming.

1. Introduction

In modern mechanical engineering and metallurgy, cast iron continues to be used as one of the main foundry materials, retaining its primacy in the future, despite the growing interest in new structural and tool materials, including composite. Increasingly, cast irons of various grades are used for parts that require high structural strength and other special properties [1-3].

White cast irons have high hardness and wear resistance due to the presence a large number of carbide phases in the structure. However, low plasticity and toughness significantly limit the possibilities of their application from a technological point of view. The mechanical properties of eutectic-type alloys, which include cast iron and carbide steels, in the cast state are determined not only by the number but also by the morphology and distribution of the eutectic in the structure.

Then the directional influence on the structure of cast materials, including cast iron, is of great importance, which leads to its transformation and replacement by the reverse relative position of the components, and provides inversion of the microstructure [1, 2].

Nowadays, there are various methods of such focused influence on the formation of the structure of eutectic type alloys as follows: 1) the creation of favorable thermokinetic conditions of structure formation during solidification; 2) the use of alloying and modification; 3) heat treatment; 4) plastic deformation; 5) a combination of different methods [4, 5, 7].

One of the most transforming, both the shape of products from eutectic type alloys, and their microstructure, is hot metal forming in which there is a grinding of eutectic mesh.

The key factor is the reduced plasticity of eutectic carbides, especially iron carbide, which is the matrix phase in the eutectic of white low-alloy cast irons. The formation of cracks in the locations of ledeburite colonies, precedes the dissection of the carbide mesh and leads to the workpiece destruction



during plastic deformation. This problem was solved by creating a new class of alloys – dactylated cast iron [5]. The "dactylating" effect is the plasticization of cementite directly in the process of hot deformation due to its structuring during the development of phase transformations, which is observed in white cast iron alloyed with carbide-forming elements, especially vanadium [7-10].

Due to this effect in the deformation process ledeburite colonies change their original structure and they stretched, bent and crushed.

The aim of this work is to develop effective methods and deformation modes that facilitate the formation of a composite structure in cast iron workpieces, which is characterized by the presence of fibers from the solid carbide phase, surrounded by a more viscous matrix. Moreover, the structure of this matrix can be changed due to additional heat treatment.

The study was performed on alloys containing about 1.5-3.2 % by weight of vanadium and 2.35-3.02 % of C as shown on Table 1.

Table 1. Chemical composition of experimental alloys.

Number of an alloy	Chemical composition by weight, %					
	C	Cr	V	Si	S	P
1	2.35	0.89	1.50	0.45	0.04	0.05
2	2.78	0.81	1.89	0.43	0.03	0.05
3	3.03	0.96	2.76	0.34	0.04	0.04
4	2.36	0.45	–	0.36	0.04	0.03
5	3.00	0.81	–	0.41	0.035	0.04

Hot deformation was performed by various methods. Initially, by compression at temperatures of 900 °C, 950 °C, 1050 °C, the samples were deformed on a jaw plastometer at two deformation rates 1-3 and 30 s⁻¹. The loading was performed once and twice. Deformation in one pass was 25-51 %, and in two passes reached 80 % without destruction. Later hot forging and pressing were performed in conditions close to industrial. A pneumatic power hammer with a nominal dropping weight of 50 kg and a hydraulic forging press with a nominal force of 1.6 MN were used. The deformation rate on the power hammer reached 6000 mm/s, and it reached 40 mm/s on the press. In addition, in industrial conditions to obtain pipe workpieces with an outer diameter of 82 mm, inner diameter of 30 mm, length of 180 mm we carried out deformation of Ø 90 cast iron samples using a press with a force of 16 MN at a speed of 70-350 mm/s, as well as Ø50 samples on 20-70 piercing mill in rolls with notches.

To determine the effect of the workpiece size ratio (height/diameter) on the formation of a composite (fibrous) structure during hot forging of cast rods with a diameter of 38 mm made of cast iron with 2.4 % of C; 3.2 % of V; 1.78 % of Cr. There were cut workpieces of different heights (38 mm and 76 mm of *h*). After preliminary annealing, the samples were upset on a pneumatic hammer with a nominal dropping weight of 50 kg ($\Sigma\varepsilon = 55\%$), as well as with a lower deformation rate of 15-20 times on a hydraulic tensile testing machine with a nominal force of 35 MN ($\Sigma\varepsilon = 50\%$).

2. Theoretical and experimental study of a compositional structure in white iron.

In experimental samples of cast iron alloyed with vanadium, a carbide transformation is observed in eutectic cementite as shown on Fig. 1 *a*, which occurs without diffusion exchange with austenite and has the form of $[(\text{Fe}, \text{V}) 3\text{C}]_{\text{KI}} \rightarrow 0.06 (\text{V}, \text{Fe}) \text{C} + 0.02 \text{ austenite} + 0.92 [(\text{Fe}, \text{V}) 3\text{C}]_{\text{KII}}$ (in cementite K_I the concentration of vanadium corresponds to the level before the transformation, and in cementite K_II the concentration of vanadium corresponds to the level after the transformation, so $\text{K}_\text{I} > \text{K}_\text{II}$) [8].

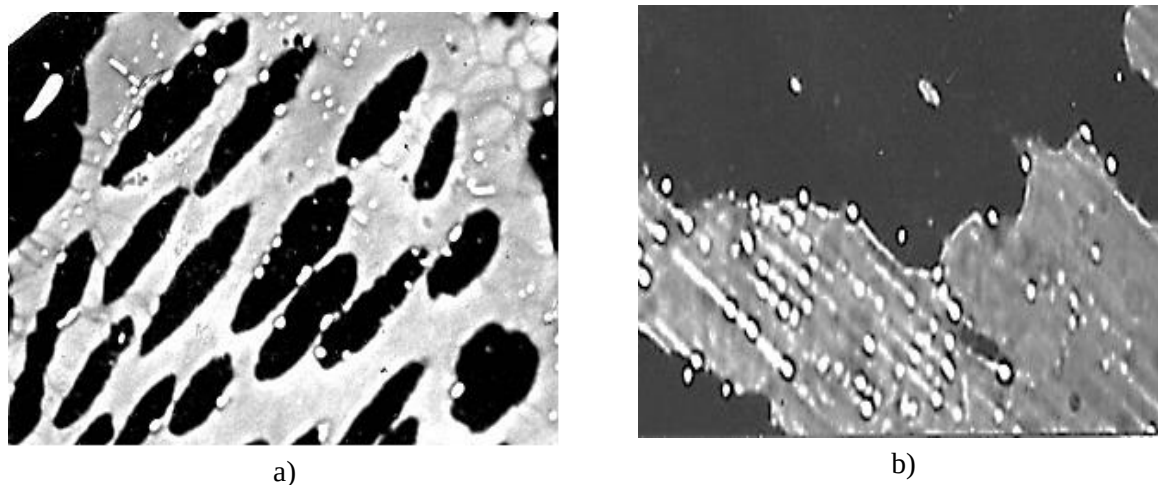


Figure 1. Isolation of vanadium carbides in alloyed cementite:
 a) multistage high-temperature annealing (1500°),
 b) the process of hot deformation in the sliding strips (2500°) [8, 9].

The minimum concentration of vanadium in iron carbide, which causes its oversaturation and decomposition into vanadium carbides, austenite and less alloyed cementite, largely depends on factors that change the level of its stability. At isothermal holding in cementite containing less than 2-2.5 % of V, carbide transformation is not observed. Pre-processing, which stimulating an increase in the defect of iron carbide, increases the intensity of its decomposition.

A specific feature of this phase transformation is the fact that it occurs directly in the process of hot deformation. During loading in austenite near crystals of still supersaturated cementite, clusters of dislocations are created and stresses arise that exceed the level of critical values of σ shift in iron carbide. In the surface layer of cementite dislocations are formed which form sliding lines, on which the particles of the stable phase of VC carbide are released (Figure 1, b).

The presence of VC crystals directly in the cement crystal enhances the action of external forces in relation to it, as it were, contributing to the "penetration" of stresses that cause the generation of dislocations in the cementite.

This transformation is similar to intermittent autocatalytic reactions associated with the formation of dislocations on the background of the reaction. The difference is that the stresses caused by the release of VC crystals are insufficient for the formation of dislocations in the cementite when external stresses are absented. Deformation is a kind of stimulator of phase transformations, due to which the plasticity of cast iron increases by 2-3 times.

This fact was emphasized by the test results on the plastometer, namely the nature of the true yield curves as shown on Figure 2, a. In non-alloy cast irons, regardless of the eutectic level, the yield stress increases with increasing deformation degree as can be seen on Figure 2, b.

Alloying causes an increase in deformation resistance. A characteristic feature of the appending of vanadium is not only more intensive hardening even at low deformation degrees, but also a gradual cyclic unhardening as shown on Figure 2, a.

With increasing speed, the resistance to deformation of cast iron increases. However, the type of yield curve is remained regardless of the test temperature. Attention should be paid to the "pulsating" decrease in yield stress in vanadium-alloyed cast iron during compression (Figure 2, a).

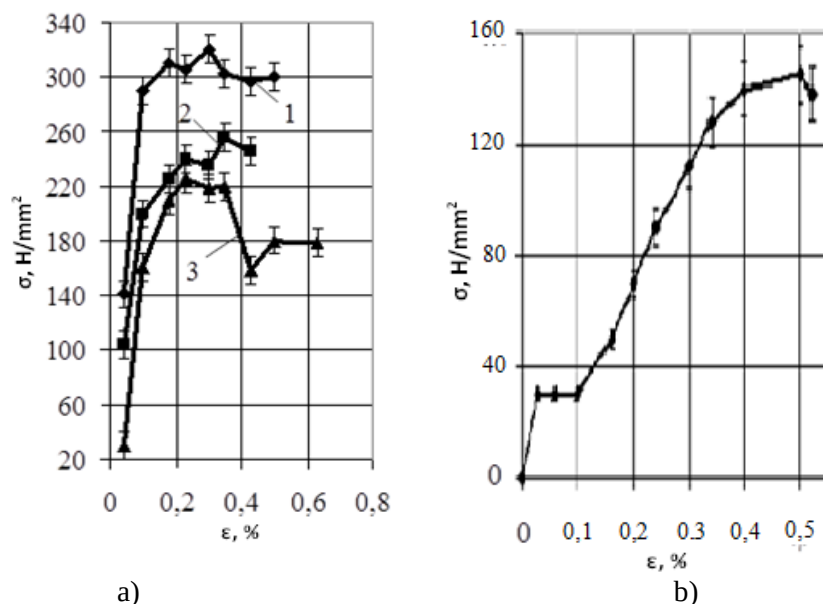


Figure 2. True yield curves of alloys 1 a and 4 b shown on Table 1, which were annealed before testing on the plastometer at a speed of 30 s^{-1} and at temperatures of 900°C (1), 980°C (2) and 1050 C (3).

Increased plasticity and susceptibility to plastic flow is provided by the development of carbide transformation in vanadium-saturated cementite. This leads to the formation of fibers from flattened eutectic colonies after forging as shown on Figure 3.

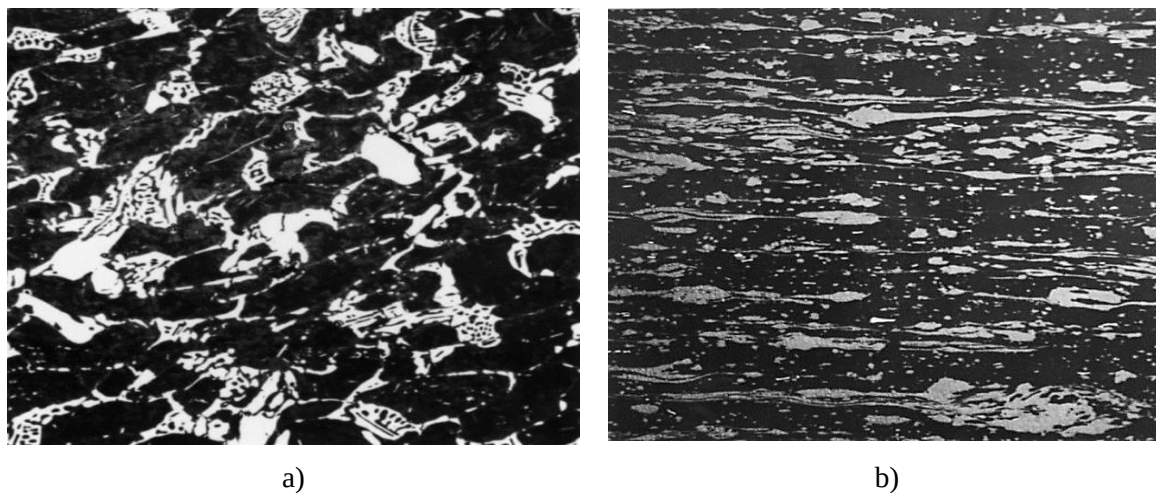


Figure 3. Microstructure of dactylated cast iron before (a) and after (b) hot forging, $350\times$.

Crushing of the eutectic mesh helps to reduce the resistance to deformation under repeated loading. Although the nature of the curve is preserved, the yield strength decreases by more than 2 times as shown on Figure 4.

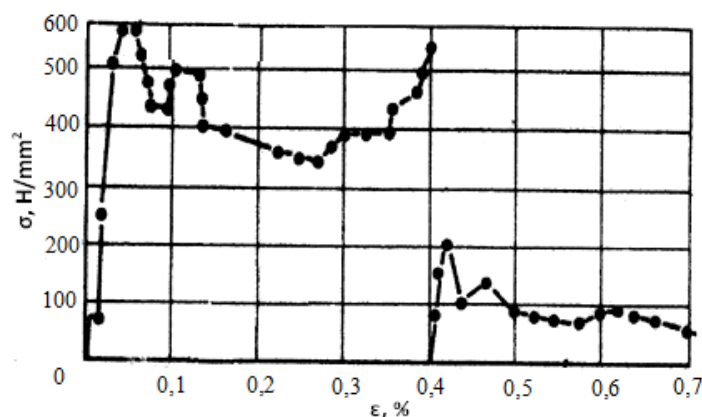


Figure 4. Flow curves at repeated loading of №3 alloy (Table 1) at a deformation rate of 30 s^{-1} and at a temperature of 900°C .

The structure of cast iron after deformation resembles stripes in steels, and we can estimate the distribution of the deformation degree on the sample height by the width b between the flattened eutectic colonies.

The deformation degree significantly affects the carbide striation of cast iron workpieces. Modelling in the licensed software product QForm [6, 10] allows us to predict the distribution of plastic deformations in cast iron samples depending on the parameters of hot upsetting and the size ratios of the initial workpieces (Figure 5).

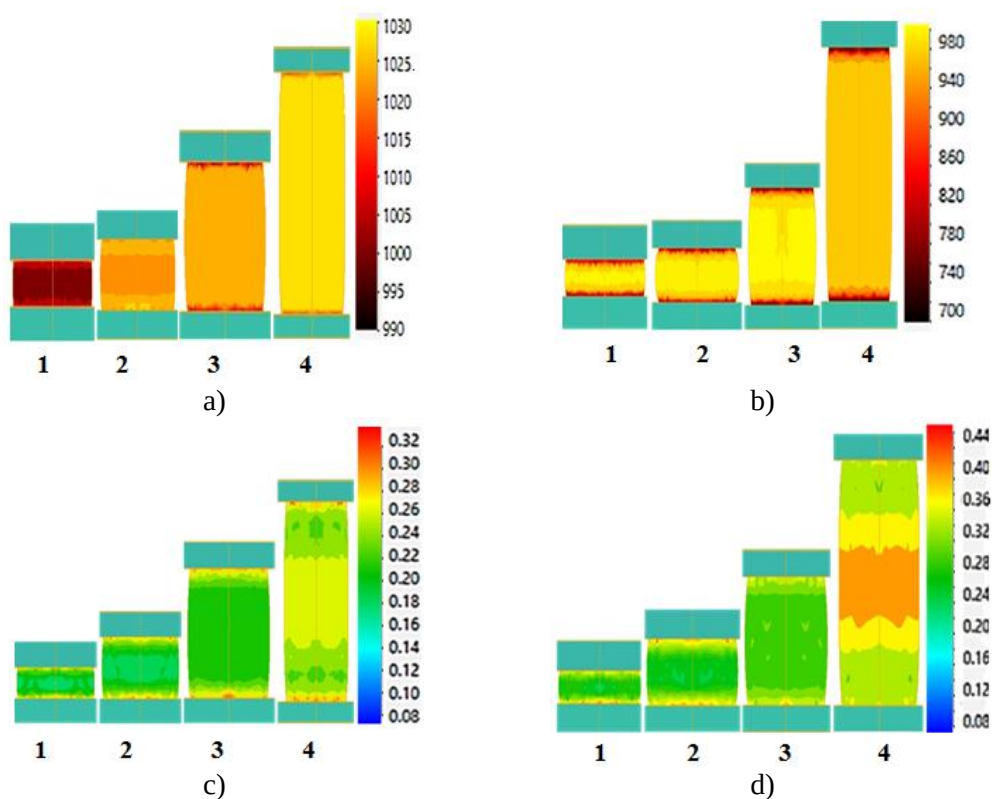


Figure 5. Temperature distribution (a, b) and plastic deformations (c, d) during upsetting on the power hammer (a, c) and on the press (b, d) at $\varepsilon = 20\%$:
 $1 - h_1/d_1 = 0.25$; $2 - h_2/d_2 = 0.5$; $3 - h_3/d_3 = 1.0$; $4 - h_4/d_4 = 2.0$.

As a model alloy used one containing 1.9 % of C. This alloy is heterophase and has a carbide mesh of secondary cementite in the structure, which is held at selected temperatures, it means as close as possible to the structural state of experimental cast iron. The ratio of height to diameter of the sample (h/d) was equal to 0.25, 0.5, 1.0, 2.0, and the deformation degree ε was simulated by 10 %, 20 % and 30 %.

The mathematical modelling results of the temperature distribution showed that increasing the deformation rate (compared to the press and the power hammer) at all stages of deformation is the deformation heating of the workpiece, which indicates a higher intensity of deformation on the power hammer. During the upsetting on the press, the workpiece is cooled in contact zones with the tool surface.

The results of quantitative microstructural analysis by the transverse method showed that a more homogeneous structure is formed during forging on a power hammer, and with increasing height of the sample austenite branches flatten to a greater extent and are parallel to the sample surface, it means perpendicular to the compressive stress. During forging at lower speeds on a tensile testing machine, the structure of the cast iron changes unevenly, especially in the workpiece with $h/d = 2$. In the central part of this sample, the eutectic mesh is completely crushed as can be seen on Figure 6.

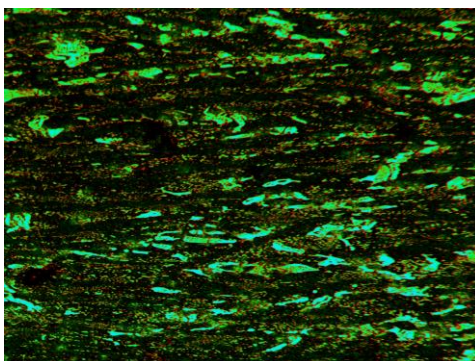


Figure 6. The microstructure of the sample central part with $h/d = 2$ after compression on the press, 100 $\times$.

The study of the behavior of white ductylated cast irons during compression allowed us to plan and successfully conduct hot pressing in industrial conditions to obtain a pipe workpiece.

Cast iron with a diameter of 90 and 55 mm was used as the initial roll bars. The level of mechanical properties of the samples cut from the workpiece of $\varnothing$ 55 mm has the following characteristics: ultimate tensile strength is 590 MPa, yield strength is 475-480 MPa, δ is 7.5-8 %, KCU is 3.0 MJ/m².

This allows us to recommend pressing and piercing to obtain a pipe workpiece from this alloy.

Pressing was performed at temperatures of 850 °C, 900 °C, 950 °C, 1000 °C and 1050 °C at a speed of 70 and 350 mm/s. External inspection of the pressed pipes did not reveal surface defects and traces of destruction as can be seen on Figure 7.



Figure 7. Macrostructure of extruded pipes and general view of templates.

The calculation of the average pressing pressures at different deformation modes revealed the following trends. The maximum values of the pressing pressure at the output of the workpiece in the deformation zone are 1.5-2 times higher than the average levels of the pressing pressure at the constant stage (Table 2). Increasing the pressing speed leads to an increase in the average pressing pressure, both at the initial moment of deformation and at a constant stage.

Table 2. Influence of temperature and deformation rate on the average level of pressing pressure.

Deformation temperature, °C	Average level of pressing pressure, MPa*		
	Pressing speed, mm/s		
	350	350	70
	furnace heating	induction heating	induction heating
1050	<u>1480-1530</u> 1000-1030	<u>910-1030</u> 595-640	<u>790-850</u> 505-575
1000	—	<u>1150-1185</u> 740-770	<u>880-960</u> 700-740
950	<u>1365</u> 890	<u>1140-1185</u> 710-810	<u>910-970</u> 710-740
900	—	<u>1345-1480</u> 890-970	<u>1110-1185</u> 810-865
—	—	<u>1630-1780</u> 1090-1110	<u>1285-1335</u> 913-970

* A numerator is the maximum values and a denominator is the pressure at a constant stage.

Furnace heating, in comparison with induction, leads to a significant increase in the average pressing pressure of white cast iron, especially at high temperatures. This is due to the fact that longer holding, especially above 950 °C leads to the rapid development of spheroidization and coalescence of deformed cementite.

As a result, the colonies of ledeburite become cementite monolithic (Figure 8, a).

Comparative analysis of the microstructure of pipes pressed at low speed by induction heating showed that with decreasing deformation temperature from 1050 °C to 850 °C the viscous flow of cementite and formation of carbide stripes is replaced by crushing of eutectic colonies (Figure 8, b, c). Moreover, at a temperature of 1050 °C, dynamic recrystallization of cementite is noticeable (Figure 8, c).

The nature of the release of vanadium carbides in cementite also changes, namely with increasing deformation temperature, the number of nucleation centers of VC particles decreases, and the size of carbide crystals increases. In the whole temperature range at low deformation rate the austenitic matrix retains its plasticity. Cementite crystals are divided and the solid solution fills the gaps between them. No cracks are detected. Increasing the deformation rate changes the picture of structural transformations. At high deformation temperatures of 950-1050 °C the influence of deformation heating is appeared. In all this temperature range there is a viscous flow of cementite and the formation of carbide fibers directed along the axis of deformation as shown on Figure 8, d, e, f.

At a deformation rate of 350 mm/s, even at a temperature of 1050 °C, dynamic recrystallization does not develop.

Reducing the deformation temperature to 850 °C can lead to brittle fracture of eutectic colonies. Low deformation temperatures in combination with high pressing rate cause a fast strengthening of the austenitic matrix and reduce its plasticity. The solid solution no longer has time to fill the gaps in the cementite, and microcracks are formed.

The nature of structural transformations during pressing is in good agreement with changes in the average pressing pressures of white cast iron depending on the deformation parameters. The change in the viscous flow of ledeburite colonies by the brittle fracture of hardened cementite and solid solution causes an increase in the work of deformation so the average pressing pressure increases. This

phenomenon is observed both at decrease in deformation temperature, at increase in deformation rate and increase in period of high-temperature holding at heating of workpieces under deformation. In addition, the strengthening of the phase components largely depends on the diffusion phenomena.

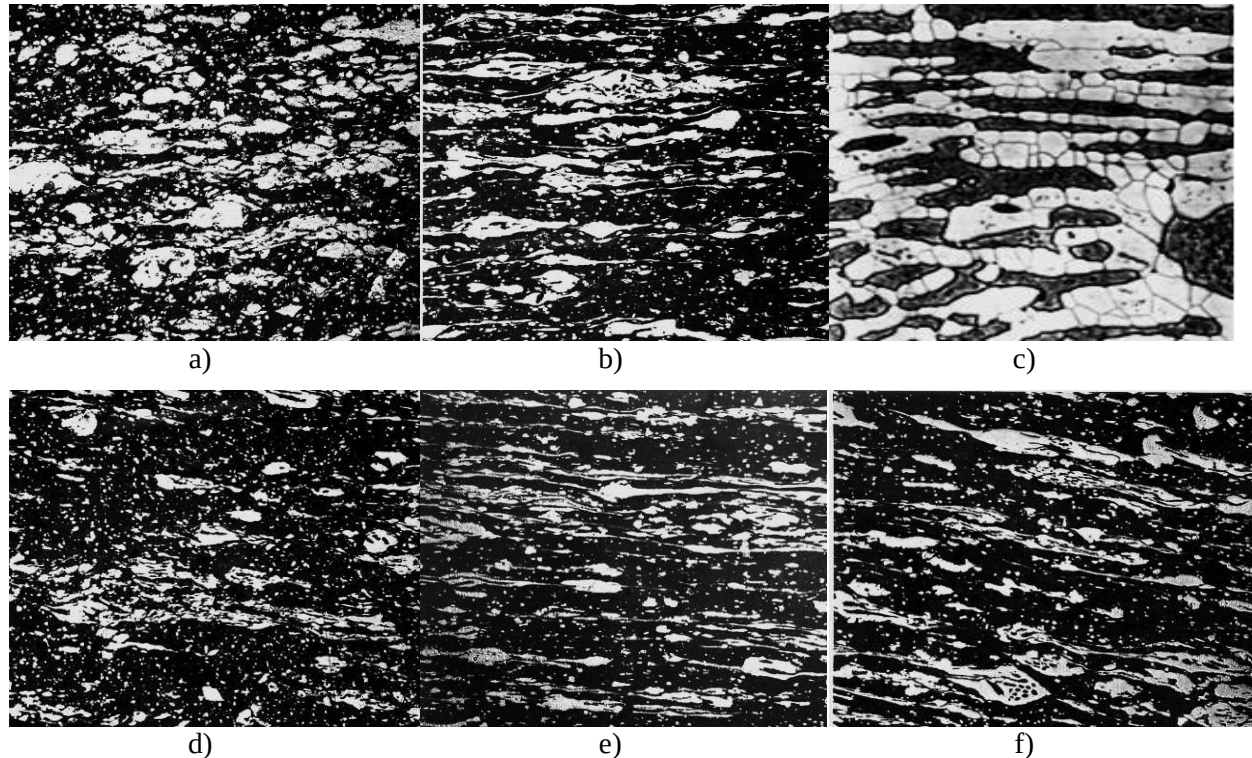


Figure 8. Microstructure of longitudinal samples of pipes at furnace and induction heating under different conditions of pressing: *a, b, d, e, f* – $\times 100$; *c* – $\times 850$.

The decrease in the diffusion mobility of atoms with a decrease in the deformation temperature, the formation of stratification zones or the lag of diffusion processes at high deformation rates inevitably cause the strengthening of structural components and a decrease in their plastic properties. The average pressing pressure increases.

Studies have shown that the optimal conditions for pressing white cast iron workpieces are low speed (70 mm/s), maximum deformation temperature (1050 °C) and the use of high-speed (induction) heating.

Similar results were obtained when piercing solid deformed cast iron workpieces of $\varnothing 50$ mm and a length of 200 and 250 mm, which was carried out on "20-70" piercing mills in rolls with a line at a temperature of 900-1100 °C. Optimal in terms of microstructural criteria of the obtained sleeves and ensuring sufficient plasticity were piercing temperatures of 900-950 °C. The rings cut at the beginning, middle and the end of the sleeves have a dense homogeneous macrostructure without any visible defects. The formation of the structure occurs in accordance with the previously described patterns in the developed deformations of dactylated cast irons, so there is a plastic flow of cementite, the release of VC, as well as the crushing of carbide inclusions. It should be emphasized once again that an increase in the processing temperature above 950 °C, especially with such a loading scheme, causes an increase in the particle size of eutectic carbides as shown on Figure 9.

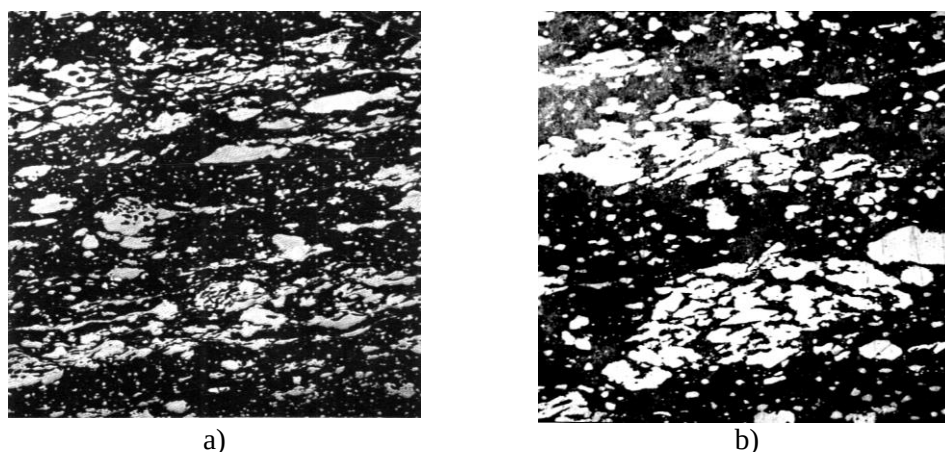


Figure 9. The microstructure of the sleeves obtained by the piercing at different temperatures of 950 °C (a) and 1050 °C (b), $\times 500$.

The formation of the matrix structure around the fibers of eutectic carbides in experimental alloys significantly depends on the modes after deformation annealing and further hardening, with which you can vary the properties of cast iron in a wide range.

3. Conclusions

- The paper shows the possibility of successful deformation of dactylated white cast irons by hot compression, which contributes to the formation of a composite structure in the form of carbide fibers.
- Dimensional h/d ratios and deformation rate affect the deformed structure in the workpiece volume. The most homogeneous structure is formed at a higher rate of deformation achieved by free forging on a power hammer, namely austenite branches and strips of flattened eutectic colonies are parallel to the surface of the sample, and perpendicular to the compressive stress.
- Pressing of pipes from the deformed white cast iron in the range of temperatures of 950-1050 °C with a speed of 70-350 mm/s allows us to receive high-quality pipe workpiece. The heating period of the initial workpiece under deformation should be minimal. After pressing, the pipe has a characteristic fibrous location of eutectic carbides.
- Piercing of cast iron workpiece in the temperature range of 900-950 °C provides high-quality sleeves. Eutectic carbides are extracted in the direction of deformation and divided.
- Economically alloyed ledeburite cast irons by plastic deformation and further heat treatment can be widely used as composite materials, such as mill rolls, guide rolls, etc.

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