Theory and Processes of Formation and Sintering of Powder Materials
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Structure and properties of hot-forged powder steel–bronze bimetal with SiC additives

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Abstract. One of the main problems in the production of bimetals is associated with the difference in the physico-mechanical and structural properties of the materials being joined. Both solid-phase and liquid-phase methods are used to obtain bimetals. The main technological task is to create conditions for the formation of a transition zone between the working layer and adhesively bound substrate. We analyzed the known methods for producing compact and powder bimetals (insert molding, diffusion welding in the solid phase, infiltration, hot isostatic pressing, etc.). The bonding strength of bimetal layers is evaluated according to the results of mechanical shear or pull tests; however, such an assessment does not enable to determine if the product can be operated in the mode of frequent thermal cycles. The above method, which involves joint hot repressing of previously separately cold-pressed and sintered blanks of the working layer and substrates, is promising in terms of improving the mechanical and tribotechnical properties, reducing the risk of structural degradation of particles of hardening additives, as well as enhancing the quality of the connection of steel–bronze bimetal layers. In this case, the working layer is heated through heat transfer from the side of the substrate warmed up to a higher temperature. We studied the impact of technological conditions for obtaining hot-forged powder steel–bronze bimetal on the structure, features of thermal fatigue failure and tribological properties and presented the research results. For structural analysis, thermal fatigue and tribotechnical tests, the bimetal samples with vertical and horizontal arrangement of layers were obtained. The atomized iron powder PZhRV 3.200.28 was used as a base for fabricating the substrate from PK40 steel. Graphite powder GK-3 (GOST 4404-78) was used as a carbonaceous additive. The working layer was fabricated from BrO10 bronze powder obtained by atomizing. To improve the tribotechnical characteristics of the working layer, bronze powder was mixed with superfine grinding micropowder F1000 of black silicon carbide 53S. The quality of bonding of bimetal layers was assessed based on the thermal shock test results. Tribotechnical tests were carried out in the dry friction mode according to the "shaft–block" scheme. We proposed the technique for producing hot-forged powder bimetal "PK40 steel–BrO10 bronze", which includes the following independent procedures: cold pressing of the substrate and working layer blanks, their sintering in a reducing environment, pre-deformation heating of the substrate and working layer at temperatures that ensure their satisfactory formability, assembly of heated substrate and working layer blanks in the mold and subsequent joint hot repressing. The resulting bimetal is characterized by increased values of thermal fatigue and wear resistance in comparison with the control samples manufactured using the traditional technology of hot repressing of the cold-pressed bimetallic blank.

Keywords: hot forging, porous blanks, powder bimetal, discontinuities, microcracks, thermal fatigue failure, structural powder steel, tin bronze, working layer, substrate, wear, friction coefficient, silicon carbide

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Структура и свойства горячештампованного порошкового биметалла типа «сталь–бронза» с добавками SiC

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Аннотация. Одна из главных проблем при получении биметаллов (БМ) связана с различием физико-механических и структурных характеристик соединяемых материалов. При получении БМ нашли применение как твердофазные, так и жидкофазные методы. Основная задача технологии заключается в необходимости создания условий формирования переходной зоны между рабочим слоем и подложкой, имеющей с ними адгезионные связи. Приведен анализ известных способов получения компактных и порошковых биметаллов (заливка, диффузионная сварка в твердой фазе, инфильтрация, горячее изостатическое прессование и др.). Оценка прочности связи слоев БМ зачастую проводится по результатам механических испытаний на срез или отрыв, однако такая оценка не обеспечивает возможность анализа осуществимости эксплуатации изделия в режиме частых теплосмен. Перспективным в плане повышения показателей механических и триботехнических свойств, снижения риска структурной деградации частиц упрочняющих добавок, а также улучшения характеристик качества соединения слоев биметаллов «сталь–бронза» является использование ранее предложенного способа, заключающегося в совместной горячей допрессовке предварительно раздельно холоднопрессованных и спеченных заготовок рабочего слоя и подложки. При этом разогрев рабочего слоя осуществляется за счет передачи тепла со стороны подложки, нагретой до более высокой температуры. Представлены результаты исследования влияния технологических условий получения горячештампованного порошкового биметалла «сталь–бронза» на структуру, особенности термоусталостного разрушения и трибологические свойства. Для проведения структурного анализа, термоусталостных и триботехнических испытаний получали образцы БМ с вертикальным и горизонтальным расположениями слоев. При получении подложки из стали ПК40 в качестве основы применяли распыленный железный порошок ПЖРВ 3.200.28. Углеродсодержащей добавкой служил порошок графита ГК-3 (ГОСТ 4404-78). Рабочий слой изготавливали из порошка бронзы БрО10, полученного методом распыления. Для повышения триботехнических характеристик рабочего слоя порошок бронзы смешивали с измельченным шлифовальным микропорошком F1000 карбида кремния черного 53С. Оценку качества соединения слоев БМ проводили по результатам испытаний на термоудар. Триботехнические испытания проводили в режиме сухого трения по схеме «вал–колодка». Предложена технология получения горячештампованного порошкового биметалла «сталь ПК40 – бронза БрО10», включающая самостоятельное выполнение операций холодного прессования заготовок подложки и рабочего слоя, их спекания в восстановительной среде, преддеформационного нагрева подложки и рабочего слоя при температурах, обеспечивающих удовлетворительную деформируемость подложки и рабочего слоя, сборки нагретых заготовок подложки и рабочего слоя в пресс-форме и последующей совместной горячей допрессовки. Полученный биметалл характеризуется повышенными значениями термо- и износостойкости в сравнении с образцами-свидетелями, изготовленными по традиционной технологии горячей допрессовки холоднопрессованной биметаллической заготовки.

Ключевые слова: горячая штамповка, пористые заготовки, порошковый биметалл, несплошности, микротрещины, термоусталостное разрушение, конструкционная порошковая сталь, оловянистая бронза, рабочий слой, основа, износ, коэффициент трения, карбид кремния

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Introduction

The use of bimetals in industrial production enables to significantly reduce the specific quality of metal per structure and enhance their operating parameters and reliability [1]. The main problem with bimetals is that the materials to be joined have different physical, mechanical and structural properties (coefficients of thermal conductivity and linear expansion, crystal lattice parameters, structure of electronic shells, formability, melting temperatures, etc.). Both solid-phase and liquid-phase methods are used to obtain bimetals. The main technological task is to create conditions for the formation of a transition zone between the working layer and adhesively bound substrate.

The impact of the temperature of the bimetal production process on the transition zone thickness and the bonding strength of layers is not straightforward. When bimetals are obtained by insert molding, diffusion in the steel–copper boundary zone occurs at temperatures above 850 °C [2]. Plastic deformation of bimetal by 45–50 % helps to reduce the temperature of the diffusion onset to 700 °C. The size of the transition zone and the bonding strength of bimetal layers during diffusion welding in the solid phase is noticeably affected by the phase transformation in the steel substrate: Fe diffusion from AISI 1010 steel to copper at the transformation temperature of 845 °C is lower than at $t = 770$ °C due to the consumption of the internal energy for the phase transformation [3].

When solid phase diffusion welding is carried out to join tin bronzes and steels, no dendritic or zone liquations, or shrinkage interdendritic porosity, characteristic of bronzes of this class and associated with a wide temperature and concentration range of their solidification, are formed in the working layer [1]. Lowering of welding temperature prevents growth of liquation precipitates of tin in the joint zone, which reduces the probability of defect formation [4]. Thus produced joints are stable at short-time heating to 800–850 °C, which allows later to perform heat treatment of the steel substrate that forms part of bimetal to increase its strength properties.

The solid phase diffusion welding ($t = 680$ °C; $\tau = 1$ h) of lead bronze–steel bimetal ensures the formation of a diffusion layer with low microhardness at the interface, which helps to avoid possible brittle rupture in this zone [5]. On the contrary, when bronze–stainless steel bimetal is prepared by the method of vacuum casting ($t = 1160$ °C; $\tau = 1$ h), the interface transition layer formed has higher microhardness and elastic modulus than the matrix alloys. The fracture of this bimetal prefers to occur along the interface transition layer, and the fracture mode is cleavage fracture [6]. The transition zone embrittlement is also caused by the diffusion of bronze atoms along the steel grain boundaries. The microstructure of grain boundaries is formed as the network of eutectic structure “leaks” between the grains.

A similar effect is observed when the sinter–brazing technique is implemented [7]. Prolonged contact of molten solder results in a network along the grain boundaries of the base material, which leads to cracking when the material cools down and shrinks. The presence of bronze in the structure of the grain boundaries of the bimetal transition zone represents a potential danger in terms of initiation of destruction during testing and operation. In particular, during the friction process, the grain boundary (or interparticle) network of the copper-containing phase can be deformed, which will reduce wear resistance by analogy with infiltrated powder steel [8]. The use of the material in the mode of frequent thermal cycles can lead to emergence of cracks, the localization of which can be associated with the iron–copper interphase boundaries within the transition zone, not only with the layers interface.

It should be noted in this regard that the quality assessment of bonding of bimetal layers should be comprehensive. It will provide for an objective and extensive analysis of the impact that the structural effects emerging during the bimetal production in the transition zone have on the products performance reliability. When the bonding strength of bimetal layers is evaluated according to the results of mechanical shear or pull tests, the grain boundary diffusion (or grain boundary wetting if the liquid phase is present) turns out to be a positive factor [9]. However, in light of the above, such a conclusion does not seem entirely legitimate, since under other test conditions, the network of plastic material along the grain boundaries in the transition zone can initiate deformation (pressing through) processes and cause defect formation.

Powder bimetals produced by the infiltration method are characterized by the presence of pores, which serve as reservoirs of liquid lubricant and help reduce the friction coefficient in the tribocoupling. Nevertheless, bimetals on a high-density steel substrate have higher tribological properties as this substrate is stronger [10]. Therefore, effective methods for producing high-density powder bimetals should be developed.

Tin bronzes are among the most common and promising materials used to obtain the bimetal working layer. In 2006, the European Union updated the RoHS regulation in order to ban lead and lead containing substances in the equipment [11]. Therefore, though lead-containing bronzes have an obvious advantage – they can reduce the bimetal friction coefficient by forming a film of structurally free lead in the tribocoupling –

when choosing the working layer material, it should be kept in mind that these bronzes will probably have to be replaced with lead-free ones.

The tribological properties of bronzes can be improved by introducing ultrafine additives of solid particles, which provide inhibition of plastic deformation in the soft copper phase [12–14]. Positive results were obtained when SiC particles were introduced into powder and compact bronzes [15; 16]. During friction, SiC particles are cut off and joined by adhesive bonds with the surface of the counterbody, which results in the formation of a thin film. The hard and durable SiC film formed between the tribocoupling surfaces minimizes the risk of plastic deformation and provides enhanced wear resistance.

When producing a copper–SiC composite by hot isostatic pressing (HIP), SiC particles disintegrate at temperatures above 850 °C, silicon diffuses into the copper matrix, and the resulting carbon, which is practically insoluble in copper, causes the formation of discontinuities and cracks in the zone of interfacial interaction. To prevent structural degradation, SiC particles are coated with molybdenum or titanium nitride [17; 18]. However, the coating is characterized by uneven thickness and ruptures, which results in individual pores on the interfacial areas during subsequent HIP.

The spark plasma sintering technique yields positive results in terms of preventing the structural degradation of SiC particles. However, it requires specialized equipment and causes technological difficulties when the formability characteristics and melting temperatures of the bimetal working layer and substrate materials are drastically different. The contact interfacial interaction is much less probable in case of hot forging (HF) of a composite blank in which SiC particles are coated with titanium nitride [18]. In the cited work, forging took 15 s. In Russian terminology adopted in powder metallurgy, such processes are called pressing, while forging is the name for additional compaction of a porous blank on high-speed mechanical presses or hammers (deformation continues for 50–100 and 2–8 ms, respectively) [19–21].

Hot forging of porous blanks (HFPB) of steel–BrO5Ts5S5 bronze bimetal with non-isothermal heating ensures the fabrication of a material with antifriction properties, not inferior to cast analogues [22]. However, when a bimetallic blank is subject to non-isothermal heating, bronze can melt impregnating steel substrate pores localized in close proximity to the layers interface. The dimensions of the melting and impregnation zones are often uncontrollable, resulting in instability of the bimetal properties. Other destabilizing factors are liquation processes and the grain boundary network of the copper-containing phase forming in the transition zone.

The method, which involves joint hot repressing of previously separately cold-pressed and sintered blanks of the working layer and substrates, is promising in terms of improving the mechanical and tribotechnical properties, as well as the quality of bonding of steel–bronze bimetal layers [23]. In this case, the working layer is heated through heat transfer from the side of the substrate warmed up to a higher temperature. The optimal duration of equalizing the assembly “substrate blank – working layer blank” until its hot repressing is determined by the formula obtained by solving heat balance set of equations. This enables to assign an optimal temperature regime for hot repressing characterized by the minimum required contact interaction of the bronze melt with the solid surface of the steel substrate. It has been established that when the bimetals of the “steel–bronze” type are produced by hot forging of separately heated substrate and working layer blanks, the optimal thermal conditions for the formation of the layer fusion zone are achieved when the substrate and working layer are heated to temperatures of 1150 and 520 °C, respectively. In this case, when a bimetal blank is assembled in a mold, thermal equilibrium is ensured at the interface at t = 970÷990 °C, which is accompanied by the formation of a small amount of liquid phase [24].

The purpose of this paper, which continues the earlier performed research, was to study the impact of technological conditions for producing hot-forged powder steel–bronze bimetal on the structure and features of thermal fatigue failure and tribological properties.

Methods

For structural analysis, thermal fatigue and tribotechnical tests, the bimetal samples with vertical and horizontal layers were obtained (Fig. 1). The atomi-

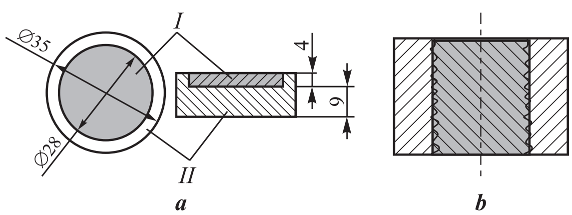


Fig. 1. Scheme of a bimetallic sample with horizontal (***a***) and vertical (***b***) layers

I – working layer, BrO10 bronze; *II* – substrate, PK40 steel

Рис. 1. Схема биметаллического образца с горизонтальным (***a***) и вертикальным (***b***) расположениями слоев

I – рабочий слой, бронза БрО10; *II* – подложка, сталь ПК40 zed iron powder PZhRV 3.200.28 was used as a base for manufacturing substrate from PK40 steel (PJSC Severstal, Cherepovets). Graphite powder GK-3 (GOST 4404-78) was used as a carbonaceous additive. The working layer was made from BrO10 bronze powder obtained by spraying at Most-Tsvetmet LLC (Bataysk) (see the Table). To improve the tribotechnical characteristics of the working layer, bronze powder was mixed with superfine grinding micropowder F1000 of black silicon carbide 53S made by JSC Volzhsky Abrasive Works (Volzhsky). The particles of the initial micropowder were 1–10 μm in size and 0.5–1.0 μm after grinding.

The planetary ball mill SAND-1 (pilot plant, Yerevan) was used for grinding. The ratio of the mass of the grinding media to that of the crushed powder was 12:1. The grinding media were made of hard alloy. Grinding was performed in acetone, which was poured into the vessel with SiC powder. The content of SiC powder in the charge varied. To ensure a uniform distribution of SiC particles throughout the volume of bronze powder, the charge of the working layer material was also prepared in the planetary ball mill SAND-1, which minimized the likelihood of components segregation [25].

Flow diagrams for obtaining samples are presented in Fig. 2. Static cold pressing (SCP) of the substrate and working layer blanks was performed separately. The blanks porosity after SCP was 22–25 %. The cold-pressed substrate blank was sintered in a dissociated ammonia environment (1150 °C, 1 h). The porous blank of a bronze working layer was sintered at t = 800 °C for 1 h (flow diagram *2*). Some working layer blanks were not sintered so that a comparative analysis could be conducted (flow diagram *3*). Pre-deformation heating of the blanks was conducted for 10 min. The optimal temperatures of 1150 and 520 °C were chosen for separate heating of the substrate and working layer blanks (flow diagrams *2*, *3*) [24].

Hot repressing of the porous working layer and substrate blanks was conducted jointly. The working layer blank was installed into the heated substrate blank. After equalizing the temperature in the volume of assembly of the bimetallic sample blank, HF was performed using a pendulum impact tester, the falling parts mass being 100 kg. The equalizing duration was determined using the equation given in [23].

Process flow diagram *1* presented a standard technology for producing hot-forged bimetals. In this case, the sintered bimetallic blank was heated at t = 950 °C and subjected to hot repressing.

The bimetal samples after HF were cooled in air. They were cut and the resulting parts were used for structural analysis, thermal fatigue and tribological tests. The quality of the connection of bimetal layers was assessed based on the thermal shock test results. In this case, the sample was heated in an inductor to a temperature of 870 °C and then cooled in water. After that, it was cleaned of scale and inspected for cracks and delaminations in the transition zone. The number of heating–cooling cycles until defects developed was recorded.

Thermal resistance enables to evaluate the resistance of a material to thermal shocks and plastic deformation [26]. Thermal fatigue failure develops under the impact of repeated plastic deformations when thermal stress exceeds the yield point. Thermal resistance is an informative criterion for assessing the degree of adhesive interaction at the interphase boundaries of heterogeneous and bimetallic materials.

Characteristics of the powders used

Характеристики используемых порошков

Material	Content, wt. %	Physical and technological properties			
		Granulometric composition	Apparent density ρ_h, g/cm^3	Flow rate, g/s	Compactibility at pressure 600 MPa, g/cm^3
PZhRV 3.200.28	Fe – base C – 0.03 O – 0.30 Si – 0.04 Mn – 0.12 P – 0.02 S – 0.01	+200 – 0 +160 – 3.7 +45 – 78.8 –45 + 17.5	2.72	32	7.27
BrO10	Cu – 90.130 Sn – 9.750 P – 0.198 O – 0.640	+150 – 5.50 +106 – 54.22 +75 – 21.04 +45 – 14.70 –45 – 4.54	3.30	30	7.68

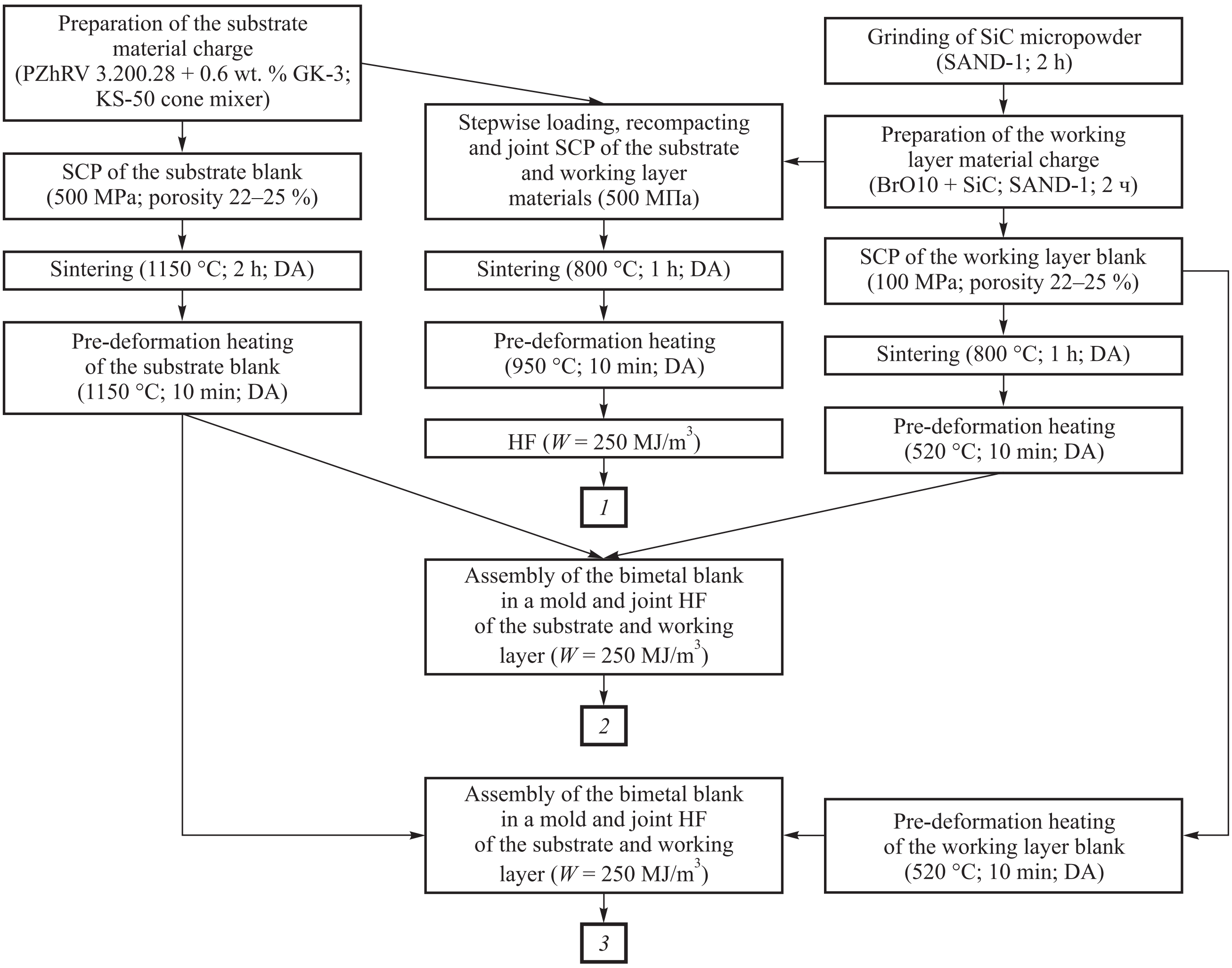


Fig. 2. Flow diagrams for producing hot-forged powder bimetal “PK40 steel–BrO10 bronze”
DA – dissociated ammonia, *W* – reduced compaction work

Рис. 2. Технологические схемы получения горячештампованного порошкового БМ «сталь ПК40 – бронза БрО10»
DA – диссоциированный аммиак, *W* – приведенная работа уплотнения

Tribotechnical tests were carried out on the friction machine MI in the dry friction mode according to the “shaft–block” scheme. The counterbodies were made of U8A steel, heat-treated to 50–55 HRC_e. The counterbodies had the following dimensions: outer and inner diameters – 50 and 12 mm, respectively, height – 15 mm, and working surface roughness – $R_a = 0.63$ µm. Before testing, the run-in of the sample was performed at a pressure of 2.5 MPa for 10 min, which ensured complete contact of the friction surfaces. The counterbody rotation frequency was 210 min^{-1}, the sliding speed was 0.55 m/s.

For metallographic studies, we used an AltamiMET-1M optical microscope (Altami LLC, Russia) and a Quanta 200 i 3D scanning microscope-microanalyzer (FEI Company, USA). Unetched and etched sections were studied. Etching was performed in 3 % nital, since it provides sufficient contrast when the structure of the bimetal transition zone and the substrate material, PK40 steel, is analyzed.

Microhardness was measured using a HVS-1000 digital microhardness tester (L.H. Testing Instruments Co., Ltd, China) according to GOST 9450-76 (0.2 N; 10 s).

Results and discussion

The maximum values of heat resistance were demonstrated by samples with a horizontal arrangement of layers, fabricated by hot repressing of sintered working layer and substrate blanks, assembled in a mold before deformation (flow diagram *2* in Fig. 2; Fig. 3, curve *1*). The fracture sites are multiple and are mainly associated with the “steel–bronze” interphase boundaries in the transition zone on the substrate side (Fig. 4, *a*). This zone is characterized by pores and discontinuities filled with molten bronze upon contact

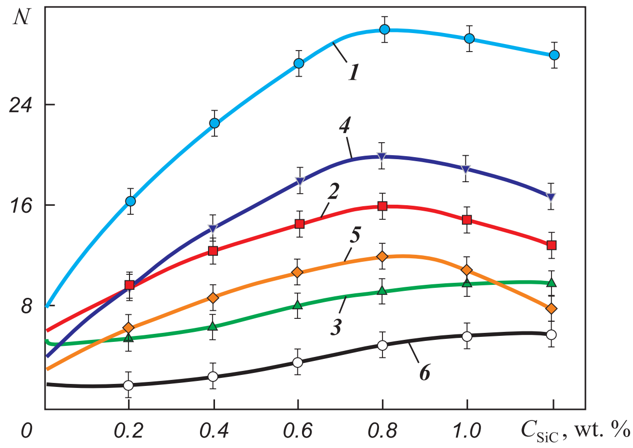


Fig. 3. Impact of the SiC content in the working layer material charge on the bimetal thermal resistance

1–3 – horizontal arrangement of layers, ***4–6*** – vertical arrangement of layers ***2***, ***5*** – process flow diagram *1*; ***1***, ***4*** – flow diagram *2*; ***3***, ***6*** – flow diagram *3*
N – number of cycles

Рис. 3. Влияние содержания SiC в шихте материала рабочего слоя на термостойкость БМ

1–3 – горизонтальное расположение слоев, ***4–6*** – вертикальное ***2***, ***5*** – технологическая схема *1*; ***1***, ***4*** – схема *2*; ***3***, ***6*** – схема *3*
N – число циклов

of a substrate blank heated to 1150 °C with a relatively cold (520 °C) working layer blank. The impregnation depth is 0.2–0.5 mm.

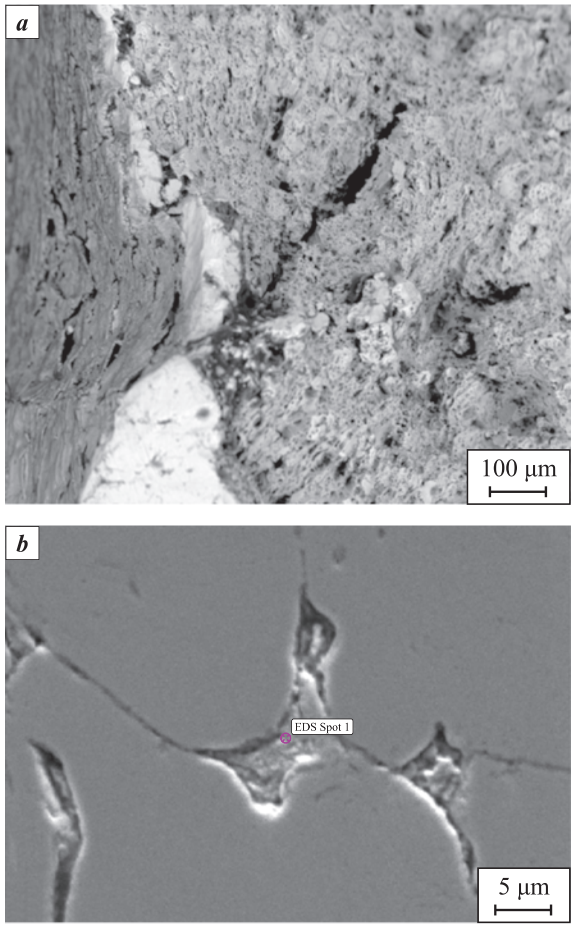
During thermal cycling, microcracks also form in the working layer material at the “matrix-SiC” interface (Fig. 4, *b*). Cracking of agglomerates of SiC particles is observed in the samples containing more than 0.8 wt.% silicon carbide.

The structure of the working layer includes the α phase and the eutectoid α + δ. The substrate structure consists of ferrite perlite. Pearlite is sorbitic, 340–360 HV (Fig. 5). Wetting of the steel substrate grain boundaries with molten bronze is not observed. A ferrite strip (140–160 HV) is adjacent to the interface on the substrate side, with the pearlite zone located below. The formation of a banded structure (ferrite strip – pearlite strip) in the transition zone on the substrate side is attributed to the displacement of carbon forming part of austenite, from the interface during the copper diffusion into steel [2].

The $N(C_{SiC})$ dependence is non-monotonic: an increase in C_{SiC} to 0.8 wt. % results in enhanced thermal stability as dispersed SiC particles strengthen interparticle boundaries of the working layer material. A further growth of C_{SiC} causes a drop in thermal stability as agglomerates of silicon carbide particles are formed.

The thermal stability of the control samples (flow diagram *1*) is noticeably lower (Fig. 3, curve *2*) compared to the bimetal fabricated according to flow diagram *2* (Fig. 3, curve *1*). This is attributed to unfavorable temperature conditions for sintering and hot deformation of the steel substrate and the bimetal transition zone: sintering at t = 800 °C and hot repressing at t = 950 °C do not ensure the formation of cohesive bonds between iron powder particles and lead to residual pores in the substrate and at the bimetal layers interface. In this case, the impact of SiC particles on thermal stability is also non-monotonic.

The lowest heat resistance was demonstrated by the samples fabricated according to process flow diagram *3*, the implementation of which did not include



C	Fe	Si	Total
35.2	7.5	57.3	100.0

Fig. 4. Formation of cracks during thermal-cycle fatigue failure of bimetal and elemental analysis of a selected area of the working layer material

Flow diagram *2*, C_{SiC} = 0.8 wt. %
a – transition zone; ***b*** – working layer, “matrix–SiC” interface

Рис. 4. Формирование трещин при термоциклическом усталостном разрушении БМ и элементный анализ выделенной области материала рабочего слоя

Схема *2*, C_{SiC} = 0,8 мас. %
a – переходная зона;
b – рабочий слой, граница раздела «матрица–SiC»

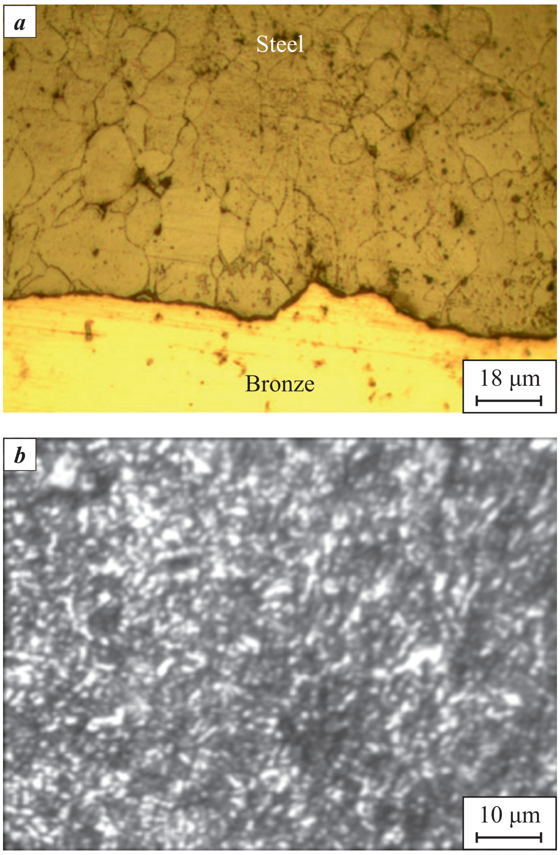


Fig. 5. Microstructure of hot-forged powder bimetal

Flow diagram *2*, C_{SiC} = 0.8 wt. %
a – transition zone; ***b*** – substrate, PK40 steel
Horizontal layer arrangement

Рис. 5. Микроструктура горячештампованного порошкового БМ

Схема *2*, C_{SiC} = 0,8 мас. %
a – переходная зона; ***b*** – подложка, сталь ПК40
Расположение слоев горизонтальное

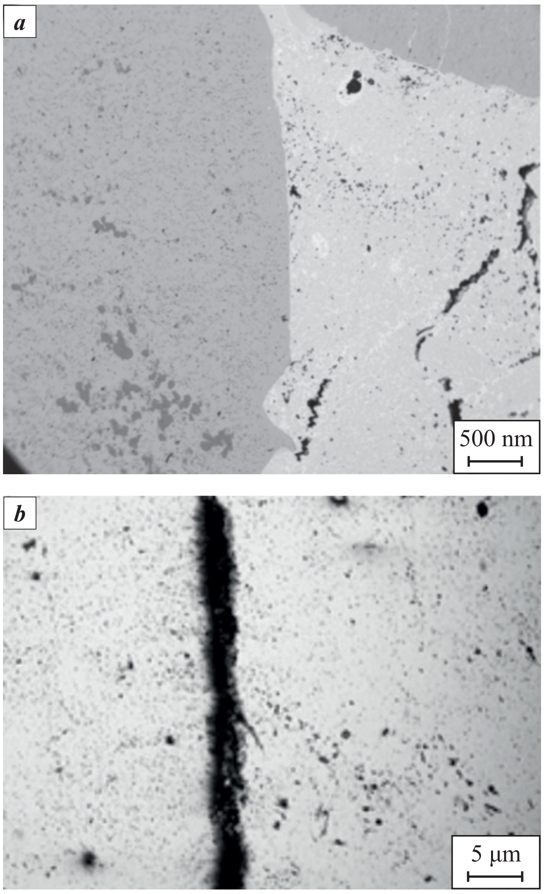


Fig. 6. Microstructure of powder bimetal (flow diagram *3*) after thermal fatigue tests (***a***) and in the as-sintered state (***b***)

Horizontal layer arrangement, C_{SiC} = 0.8 wt. %

Рис. 6. Микроструктура порошкового БМ (схема *3*) после испытаний на термоусталость (***a***) и в состоянии после спекания (***b***)

Расположение слоев горизонтальное, C_{SiC} = 0,8 мас. %

sintering of cold-pressed working layer blanks (Fig. 3, curve *3*). During the tests, cracks formed both at the layers interface and in the working layer material (Fig. 6, *a*).

The samples of this group proved more prone to crack formation due to high probability of hydrogen embrittlement of copper alloys [27]. The oxygen content in the initial BrO10 powder is 0.64 wt. % (see the Table). When the sample is heated during sintering and before hot deformation in a dissociated ammonia environment, copper-containing oxides, localized at interparticle and grain boundaries, are reduced, with the water vapor being formed, which leads to the appearance of bubbles, cracks and delaminations.

During 1 h sintering, the conditions were provided for removing steam from the body of the working layer blank. Delaminations and cracks formed at the sintering stage were eliminated during subsequent hot deformation (Fig. 6, *b*). In contrast, during joint hot repressing of the substrate and the unsintered working layer blank, these defects formed almost synchronously with the deformation, making their elimination unlikely. The impact of this factor was predominant, outweighing the strengthening effect of SiC additives.

The above-described features of the impact of C_{SiC} on the thermal stability of the samples with horizontal layers are also valid for the samples with vertical layers (Fig. 3, curves *4*–*6*). The difference is that their absolute value of heat resistance is lower, which is attributed to greater magnitude of thermal stresses that develop in the sample material during testing.

Maximum wear resistance was demonstrated by bimetal samples obtained according to flow diagram *2*, containing 0.8 wt. % SiC (Fig. 7, curve *1*). In this case, the dependence $f(P)$ is non-monotonic: as P increases in the range of 3–5 MPa, the friction coefficient f drops. Apparently, this is attributed to the formation of a solid SiC film on the tribocoupling surfaces (Fig. 7, *a*; curve *4*) [16].

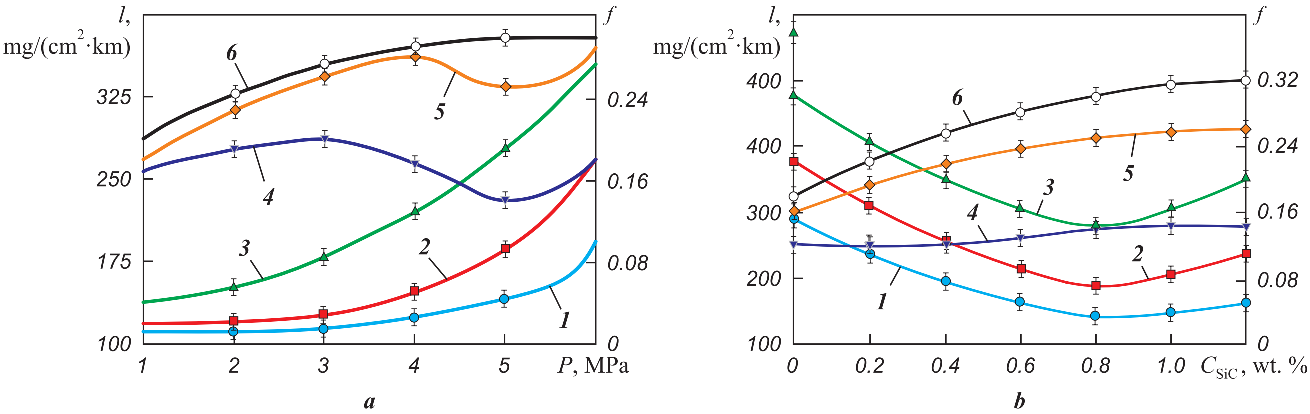


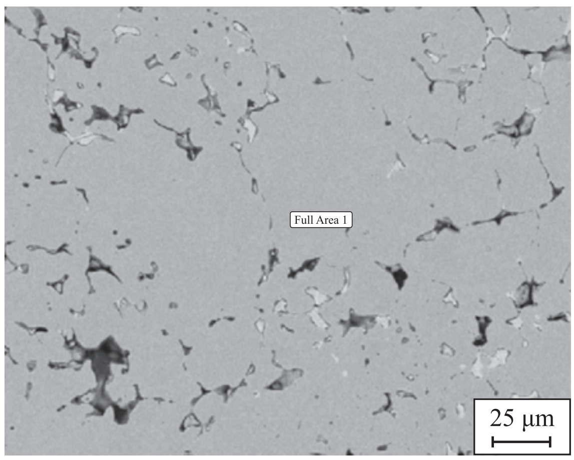
Fig. 7. Dependences of the wear (***1–3***) and friction coefficient (***4–6***) of the bimetal working layer on the specific load (***a***) and SiC content (***b***) during tests under dry friction conditions
2, ***5*** – process flow diagram *1*; ***1***, ***4*** – flow diagram *2*; ***3***, ***6*** – flow diagram *3*
a – C_{SiC} = 0.8 wt. %; ***b*** – P = 5 MPa
Horizontal layer arrangement

Рис. 7. Зависимости износа (***1–3***) и коэффициента трения (***4–6***) материала рабочего слоя БМ от удельной нагрузки (***a***) и содержания SiC (***b***) при испытаниях в условиях сухого трения
2, ***5*** – технологическая схема *1*; ***1***, ***4*** – схема *2*; ***3***, ***6*** – схема *3*
a – C_{SiC} = 0,8 мас. %; ***b*** – P = 5 МПа
Расположение слоев горизонтальное

The wear resistance of the samples fabricated according to flow diagrams *1* and *3* is noticeably lower. An increased load during testing of samples fabricated according to flow diagram *1* in the range of 4–5 MPa leads, as in the previous case, to a slight drop of the friction coefficient, but its absolute values remain quite high (Fig. 7, *a*; curve *5*). The samples fabricated according to flow diagram *3* are characterized by discontinuities and microcracks localized near the "SiC–bronze" boundaries, the formation mechanism of which is described above (Fig. 8). SiC particles, weakly bonded with the matrix material, flake during friction, which pushes up the wear values and the friction coefficient (Fig. 7, *a*; curve *3*, *6*). After testing, deep scratches formed as a result of the abrasive impact of SiC particles are visualized on the samples working surface.

An enhanced abrasive effect caused by an increased content of SiC particles in the working layer material results in the growth of the *f* values of the samples fabricated according to flow diagram *3* (Fig. 7, *b*; curve *6*). At the same time, the absolute wear values are high, despite their decrease in the range $C_{SiC} = 0 \div 0.8$ wt. % (Fig. 7, *b*; curve *3*). The latter is apparently attributed to dispersion strengthening of interparticle boundaries and inhibition of plastic deformation in the bronze layer during friction [12].

Compared to the studied group of samples, the wear resistance of the control samples (flow diagram *1*) is higher, and the *f* values are lower (Fig. 7, *b*; curve *2* and *5* respectively). The $f(C_{SiC})$ dependence is monotonic: growing C_{SiC} leads to an increase in *f* values. In contrast to the samples fabricated according to flow diagram *3*, high values of wear and friction coefficient are attributed not to defects in the working layer, but to undercompaction of the substrate and transi-



C	Fe	Si	Total
29.1	9.3	61.6	100.0

Fig. 8. Microstructure of hot-forged powder bimetal and elemental analysis of the material selected area
Flow diagram *3*; working layer; C_{SiC} = 0.8 wt. %; horizontal layer arrangement

Рис. 8. Микроструктура горячештампованного порошкового БМ и элементный анализ выделенной области материала
Схема *3*; рабочий слой; C_{SiC} = 0,8 мас. %; расположение слоев горизонтальное

tion zone, caused by the relatively low temperature of pre-deformation heating (950 °C). The porosity of the substrate of these samples amounted to 5–7 %. The residual pores in the substrate result in the working layer being "pressed through" during loading in the course of tests. The effect of this factor was predominant, though introduction of SiC particles caused the effect of dispersion strengthening of the bronze layer (Fig. 7, *b*; curve *2*).

The implementation of flow diagram *2* ensured optimal conditions for the structure formation. In this case, the samples had the lowest values of wear and friction coefficient (Fig. 7, *b*; curves *1* and *4*). The dependence of f values on C_{SiC} in the studied concentration range is rather weak. The samples containing 0.8 wt. % SiC demonstrated the greatest wear resistance. The residual porosity of the substrate and working layer materials is 0.5–1.0 wt. %.

Conclusions

1. We proposed the technique for producing hot-forged powder bimetal "PK40 steel–BrO10 bronze", which includes the following independent procedures: cold pressing of the substrate and working layer blanks, their sintering in a reducing environment, pre-deformation heating of the substrate and working layer at temperatures that ensure their satisfactory formability, assembly of heated substrate and working layer blanks in the mold and subsequent joint hot repressing. The resulting bimetal is characterized by increased values of thermal fatigue and wear resistance in comparison with the control samples manufactured using the traditional technology of hot repressing of the cold-pressed bimetallic blank.

2. The introduction of SiC powder into the working layer material contributes to the bimetal thermal and wear resistance enhancement due to dispersion strengthening of the interparticle boundaries. The optimal content of SiC additive is 0.8 wt. %.

3. Preliminary sintering of the porous working layer blank enables to reduce the oxides that form part of the bronze powder and later to remove the reaction products from the body of the blank, which hinders defect formation during hot deformation.

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I. V. Ivanova – conducting tribological tests.
L. I. Svistun – formulating the main concept, editing the text and conclusions.
R. A. Vodolazhenko – studying the structure and composition of test samples.

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