MATERIALS SCIENCE / МАТЕРИАЛОВЕДЕНИЕ

UDC 669:539.381.296
DOI 10.17073/0368-0797-2023-5-580-586

Original article
Оригинальная статья

Effect of heat treatment on deformation inhomogeneity of carbon steel / stainless steel bimetal

S. P. Buyakova[1], **K. N. Kayurov**[2], **S. A. Barannikova**[1]

[1] **Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences** (2/4 Akademicheskii Ave., Tomsk 634055, Russian Federation)
[2] **Scientific Production Enterprise of Geophysical Equipment "LUCH"** (34 2nd Yurginskaya Str., Novosibirsk 630051, Russian Federation)

sbuyakova@ispms.ru

Abstract. The work is devoted to the study of the effect of annealing on mechanical properties and inhomogeneity of plastic deformation of a bimetallic plate made of stainless / carbon steel with the dimensions of the working part 50×7×2 mm. To develop laser technology for producing bimetals of various compositions, the contact zone of two dissimilar steels is of greatest interest. Since the performance characteristics of the entire product as a whole depend on the structure and properties of this zone, interaction of the components of the bimetal in the process of its manufacture leads to appearance of heterogeneity of various types near the interface and in the volumes adjacent to it. The research material was obtained by laser cladding of wire AISI 304 stainless steel on a plate of low-carbon steel St3. Bimetallic samples were subjected to vacuum heating at a temperature of 700 °C at various times from 2 to 8 h. The use of data on the distributions of local strains by the speckle photography method made it possible to consider the process of plastic flow in the initial section of tension diagram and to establish the effect of annealing temperature on plastic strain localization during mechanical tests. For a quantitative assessment of deformation inhomogeneity in the main and cladding layers, we used spatiotemporal distributions of local elongations and the corresponding values of the variation coefficient. It was established that the level of deformation inhomogeneity of microvolumes at the interface during tension is higher than that of the bimetal main layers. With increase in the annealing time, increase in the variation coefficient in the joint zone is noted, which is more significant on the stainless steel side, and this increases the probability of microcracks initiation. The increased level of deformation inhomogeneity of microvolumes of the cladding layer carburized zone is contingent on the increased localization of deformation in nearby microvolumes due to structural heterogeneity.

Keywords: plastic deformation, localization, bimetal, low carbon steel, stainless steel

Acknowledgements: The work was performed within the framework of the complex project "Organization of high-tech production of rotary controlled systems for opening complex formations and drilling wells with a large deviation from the vertical in difficult geological conditions, in the Arctic" (grant agreement No. 075-11-2022-019 dated April 06, 2022), the financial support of the Ministry of Science and Education of the Russian Federation (decree of the Government of the Russian Federation dated 09.04.2010 No. 218).

For citation: Buyakova S.P., Kayurov K.N., Barannikova S.A. Effect of heat treatment on deformation inhomogeneity of carbon steel/stainless steel bimetal. *Izvestiya. Ferrous Metallurgy*. 2023;66(5):580–586. https://doi.org/10.17073/0368-0797-2023-5-580-586

О влиянии нагрева на неоднородность деформации биметалла углеродистая сталь – нержавеющая сталь

С. П. Буякова[1], **К. Н. Каюров**[2], **С. А. Баранникова**[1]

[1] **Институт физики прочности и материаловедения Сибирского отделения РАН** (Россия, 634055, Томск, пр. Академический, 2/4)
[2] **Научно-производственное предприятие геофизической аппаратуры «ЛУЧ»** (Россия, 630051, Новосибирск, ул. 2-я Юргинская, 34)

sbuyakova@ispms.ru

Аннотация. Работа посвящена изучению влияния отжига на механические свойства и неоднородность пластической деформации биметаллической пластины из нержавеющей / углеродистой сталей с размерами рабочей части 50×7×2 мм. Для отработки лазерной технологии получения биметаллов различных композиций наибольший интерес представляет изучение зоны контакта двух разнородных сталей. Поскольку от структуры и свойств данной зоны зависят эксплуатационные характеристики всего изделия в целом, взаимодействие составляющих биметалла в процессе его изготовления приводит к возникновению неоднородности различных видов вблизи границы раздела и в объемах, прилегающих к ней. Материал исследований получали методом лазерной наплавки проволоки нержавеющей стали AISI 304 на пластину из низкоуглеродистой стали Ст3. Биметаллические образцы с наплавкой подвергали вакуумному нагреву при температуре 700 °C в течение различного времени (от 2 до 8 ч). Использование данных о распределениях локальных деформаций методом спекл-фотографии позволило рассмотреть процесс пластического течения на начальном участке диаграммы растяжения и установить влияние температуры отжига на локализацию пластической деформации в процессе механических испытаний. Для количественной оценки неоднородности деформации в основном и плакирующем слоях использовали пространственно-временные распределения локальных удлинений и соответствующие величины коэффициента вариации. Установлено, что уровень неоднородности деформации микрообъемов на интерфейсе в процессе растяжения выше, чем основных слоев биметалла. С увеличением времени отжига отмечается повышение значений коэффициента вариации в зоне соединения, более значительное со стороны нержавеющей стали, что увеличивает вероятность зарождения микротрещин. Повышенный уровень неоднородности деформации микрообъемов науглероженной зоны плакирующего слоя обусловлен усилением локализации деформации в близлежащих микрообъемах из-за структурной неоднородности.

Ключевые слова: пластическая деформация, локализация, биметаллы, низкоуглеродистая сталь, нержавеющая сталь

Благодарности: Работа выполнена в рамках комплексного проекта «Организация высокотехнологичного производства роторных управляемых систем для вскрытия сложных пластов и бурения скважин с большим отходом от вертикали в сложных геологических условиях, Арктике» (соглашение о предоставлении субсидии от 6 апреля 2022 № 075-11-2022-019), реализуемого Институтом физики прочности и материаловедения Сибирского отделения РАН при финансовой поддержке Минобрнауки России в рамках постановления Правительства РФ от 09.04.2010 № 218.

Для цитирования: Буякова С.П., Каюров К.Н., Баранникова С.А. Влияние термической обработки на неоднородность деформации биметалла углеродистая сталь – нержавеющая сталь. *Известия вузов. Черная металлургия*. 2023;66(5):580–586.
https://doi.org/10.17073/0368-0797-2023-5-580-586

Introduction

To effectively handle materials within power-generating or oil refining equipment subjected to simultaneous mechanical loading and high temperatures, it is imperative to develop novel methods for evaluating their performance [1]. These methods should comprehensively consider the influence stemming from various structural and mechanical inhomogeneities [2 – 4]. Despite their high strength, bimetallic materials are particularly susceptible to delamination at their interfaces. Defects like delamination may arise during the manufacturing and operational phases of bimetallic materials, thereby somewhat restricting their industrial applications [5 – 8]. The unevenness of deformation in bimetallic composites during rolling is contingent upon several factors, including the disparity in deformation resistances between components, initial layer thicknesses, stacking sequence, parameters within the deformation zone, and the magnitude of contact friction forces and tangential stresses at the interface [9 – 12]. This deformation irregularity within bimetallic composites detrimentally affects the rolling process and the resultant bimetal properties. It leads to the accumulation of significant residual stresses, which, in turn, can induce bimetal delamination, bending, warping, and the fracturing of harder layers [13 – 16].

An exceptionally promising domain for advancing laser cladding technology using high-performance lasers lies in leveraging cladding materials presented in solid and powder metal strips [17; 18]. The primary motivation driving the shift from conventional coating methods (thermal spraying and arc surfacing) toward laser-based techniques is the superior quality of the coatings produced. This superiority stems from the reduced mixing coefficient between the clad material and the substrate, along with heightened adhesion characteristics [19].

Given that the processes occurring in the vicinity of the interface during laser cladding can significantly influence material properties [20], the objective of this study was to examine the influence of temperature-time factors on the inhomogenity of plastic deformation in bimetallic plates.

Materials and methods

The investigation focused on studying the deformation inhomogeneity of a bimetal comprising low-carbon steel St3 and AISI 304 stainless steel, achieved through laser cladding. The St3 low-carbon steel plate measured approximately 6 mm in thickness, while the AISI 304 stainless steel formed a clad layer of about 1 mm thickness. The laser cladding process, using filler wire, was conducted on plates composed of low-carbon steel St3 at the experimental facility of the Institute of Strength Physics and Materials Science of the Siberian Branch of the RAS. The application of the laser cladding technique involved introducing filler wire into the laser impact zone using a standard arc torch and a semi-automatic welding machine PDGO-601. In this particular laser cladding setup, AISI 304 stainless steel filler wire with a diameter of 1.0 mm served as the material for the clad layer. Employing the fiber laser LS-15, boasting a capacity of 15 kW, facilitated a productivity range of 130 – 170 g/min, resulting in deposited beads measuring 0.8 – 1.5 mm in width. To ensure the creation of a uniform monolithic coating, cladding parameters were meticulously selected based on established technological modes. These included specific settings for scanning width (approximately 30 mm), laser output power (4 kW), and speed (65 mm/min). The scanning process was executed using the “triangular” mode at a frequency of 25 Hz. Upon metallographic examination of crosssections and XRD (*X*-ray diffraction) analysis, it was observed that none of the samples exhibited pores, cracks, or unmelted powder particles.

When subjected to heating, bimetals composed of distinct chemical compositions display variations in the rate and direction of diffusion for carbon and alloying elements, contingent upon the temperature of heating [3]. Following heat treatment (conducted via vacuum heating up to 700 °C and holding for durations of 2, 4, 6 and 8 h), the distribution of chemical elements within the steel layers of the bimetallic plate was analyzed. This examination was performed using the LEO EVO 50 scanning electron microscope (Carl Zeiss, Germany), equipped with an Oxford Instruments attachment for *X*-ray dispersive micro-analysis. These analyses were conducted at the NANOTECH Center for Collective Use, part of the ISPMS SB RAS. Microhardness measurements were carried out using the PMT-3 microhardness tester, following the methodology outlined in GOST 9450 – 76.

During mechanical uniaxial tensile tests performed on flat samples measuring 50×7×2 mm, the deformation fields were recorded using the Walter+Bai LFM-125 testing machine. The deformation rate was set at $6.67 \cdot 10^{-5}$ s^{-1} and tests were conducted at room temperature. These tests simultaneously employed an adapted speckle photography technique, as detailed in [21 – 23], to capture the deformation fields. In analyzing the plastic distortion tensor, the local elongation along the direction of the sample's tensile axis εxx is often considered the most natural component for visualization and analysis. Shear and rotational components exhibit more intricate distributions, rendering them less convenient for analysis. The distributions obtained through these techniques reflect local deformation increments rather than integral values from the commencement of the loading process. Fig. 1, *a* illustrates a typical distribution of local deformations $\varepsilon_{xx}(x, y)$ within the sample subsequent to laser cladding, where the total tensile deformation measures 0.01. This data presentation elucidates that post-yield point, plastic deformation becomes localized within specific zones of the sample, while other material volumes exhibit minimal deformation at the given increment. To quantitatively assess the degree of deformation inhomogenity across various layers of the bimetal (substrate and cladding), the coefficient of variation of local deformations ε_{xx} was employed. This coefficient is calculated as the ratio of the standard deviation to the arithmetic mean *n* of measurements:

$$\nu = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\langle\varepsilon_{xx}\rangle - \varepsilon_{xx_i}\right)^2}}{\langle\varepsilon_{xx}\rangle},$$

where $\langle\varepsilon_{xx}\rangle = \frac{\sum_{1}^{n}\varepsilon_{xx_i}}{n}$.

When $\nu > 0.4$ it is considered that the distribution of local elongations ε_{xx} within the sample demonstrates a substantial level of inhomogenity $\langle\varepsilon_{xx}\rangle$ rendering the value not representative [24].

Results and discussion

The hardness observed within the junction zone of the bimetal was notably higher compared to the hardness measured in both the substrate and the surfacing areas outside this zone (Fig. 1, *b*). Following heat treatment, as the heating duration increased, the average

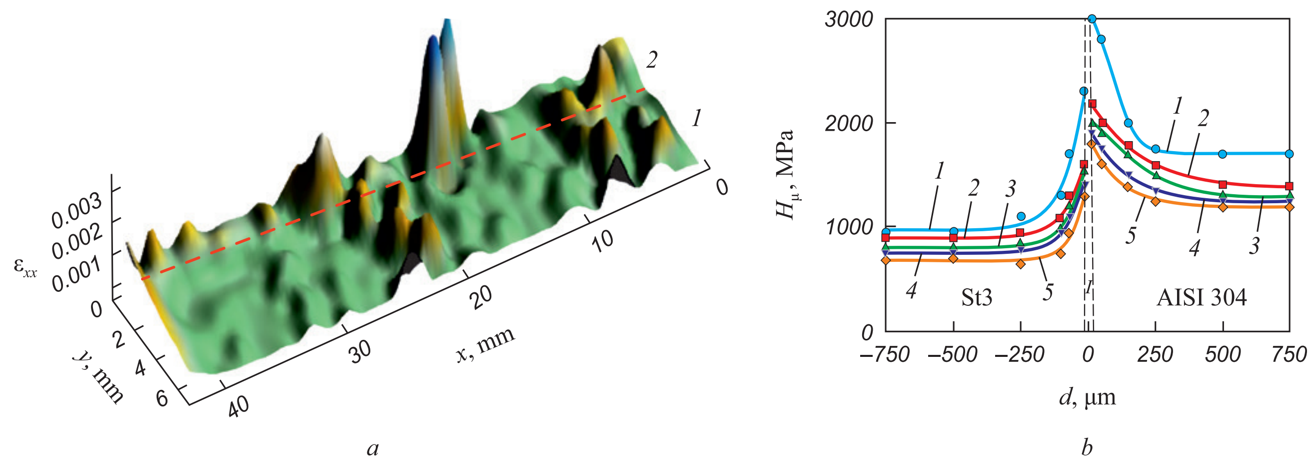

Fig. 1. Distribution of local deformations ε_{xx} in the substrate (*1*) and surfacing (*2*) at the initial stage of plastic flow (*a*) and the change in microhardness along the width of the sample (*b*) after laser surfacing (*1*) and after heat treatment at 2 (*2*), 4 (*3*), 6 (*4*) and 8 h (*5*) (dotted line (*I*) marks the junction zone)

Рис. 1. Распределение локальных деформаций ε_{xx} в подложке (*1*) и наплавке (*2*) на начальной стадии пластического течения (*а*) и изменение микротвердости по ширине образца (*b*) после лазерной наплавки (*1*) и после термической обработки в течение 2 (*2*), 4 (*3*), 6 (*4*) и 8 ч (*5*) (пунктирной линией (*I*) отмечена зона соединения) hardness levels observed in the substrate and surfacing decreased significantly. However, the hardening gradient between the two types of steels near the junction zone remained consistent.

Fig. 2 illustrates the influence of heating duration on the distribution of fundamental elements (iron, chromium, nickel, manganese) across the thickness of the sample.

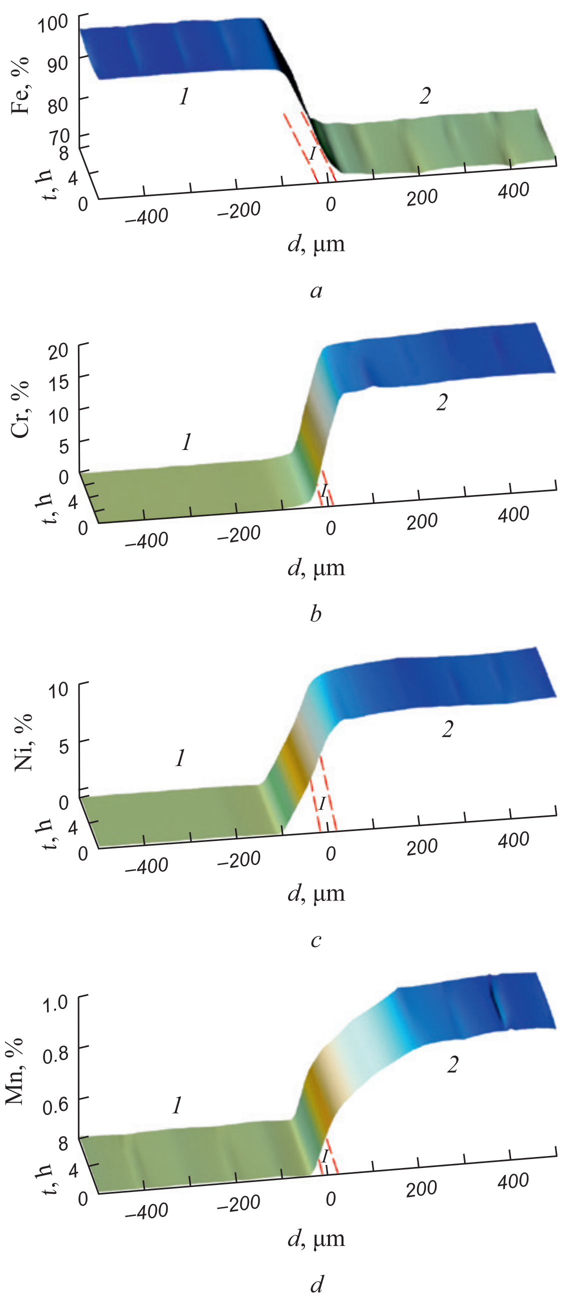

Fig. 2. Effect of annealing time on distribution of iron (*a*), chromium (*b*), nickel (*c*) and manganese (*d*) over the thickness of the sample:
1 – low-carbon steel; *2* – stainless steel;
I – transition layer in the junction zone

Рис. 2. Влияние времени отжига на распределение железа (*a*), хрома (*b*), никеля (*c*) и марганца (*d*) по толщине образца:
1 – низкоуглеродистая сталь; *2* – нержавеющая сталь;
I – переходный слой в зоне соединения

The depicted data indicates that the impact of heating remains insignificant for each of the steel types when compared to their initial states without heat treatment.

The bimetal consists of low-carbon and stainless steel, with a distinct transition layer (*I*) between them. Within this transitional zone, the concentrations of iron, chromium, nickel, and manganese exhibit a linear variation. The diffusion depth of chromium and nickel into the base layer of low-carbon steel extends up to 20 μm. During the heating process, alloying elements diffuse from the austenitic (stainless) steel into the carbon (pearlitic) steel, while carbon diffuses in the opposite direction.

In Fig. 3, *a*, the impact of heating duration on the distribution of carbon throughout the sample thickness is depicted.

Within the span from carbon steel to stainless steel, the distribution of carbon content manifests in distinct layers: following the transition layer (*I*), there exist decarburized (*II*) and supercarburized (*III*) layers. The thickness

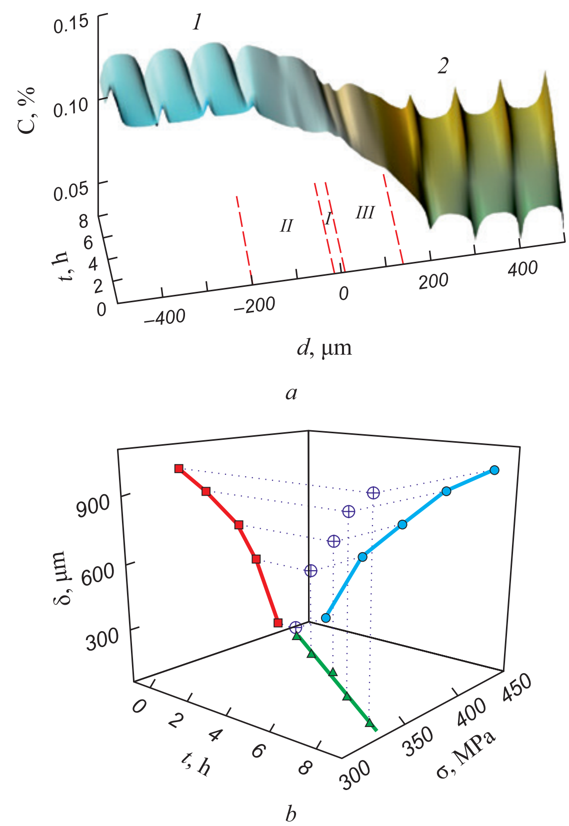

Fig. 3. Carbon distribution over the thickness of the surfaced sample (*a*), depth of decarburization δ of the base layer and tensile strength σ of the bimetal depending on annealing duration *t* (*b*):
1 – low-carbon steel; *2* – stainless steel;
I – transition layer in the junction zone

Рис. 3. Распределение углерода по толщине образца с наплавкой (*a*), а также глубина обезуглероживания δ основного слоя и предел прочности σ биметалла в зависимости от длительности отжига *t* (*b*):
1 – низкоуглеродистая сталь; *2* – нержавеющая сталь;
I – переходный слой в зоне соединения

of these layers varies in response to the duration of heating. With prolonged annealing periods, the expanding decarburized ferrite zone on the carbon steel side exhibits reduced strength characteristics. Consequently, this contributes to a decrease in the tensile strength of the bimetal (Fig. 3, *b*). The process of chromium diffusion from the austenitic phase and carbon diffusion in the opposite direction results in the formation of a thin carbide layer on the carbon steel side.

The structural and chemical inhomogeneities near the substrate and cladded layer interface play an important role in shaping the nature of plastic deformation around the transition zone. Ensuring compatibility of deformations at the bimetal interface necessitates an equivalent deformation of metal microvolumes adjoining the interface. Consequently, the levels of deformation inhomogeneity within these microvolumes at the interface layers, as assessed by the coefficient of variation of local deformations ν, are expected to be uniform. By meeting these conditions, the stress conditions within these regions become more intricate.

Fig. 4 illustrates the impact of heat treatment on the changes in the coefficient of variation (ν), which serves as an indicator of the degree of deformation inhomogeneity near the transition zone of the bimetal during the initial stages of deformation. In the bimetal state subsequent to laser cladding, notable differences in the levels of deformation inhomogenity are observed among the microvolumes in the boundary zones of the stainless and carbon steel sides, nearly twofold (Fig. 4, curve *1*). The reduced level of deformation heterogeneity is characteristic of the microvolumes in the decarburized zone,

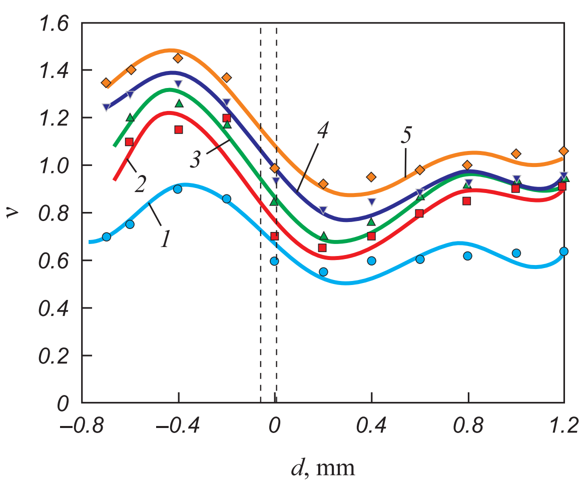

Fig. 4. Change in the level of inhomogeneity of deformation ν by thickness of the sample layers at the initial stage of plastic flow in the state after laser surfacing (*1*) and after annealing at 2 (*2*), 4 (*3*), 6 (*4*) and 8 h (*5*)

Рис. 4. Изменение уровня неоднородности деформации ν по толщине слоев образца на начальной стадии пластического течения в состоянии после лазерной наплавки (*1*) и после отжига в течение 2 (*2*), 4 (*3*), 6 (*4*) и 8 ч (*5*)

directly adjacent to the interface, as well as in the state post-cladding (Fig. 4, curve *1*). The existence of a carbide interlayer leads to the emergence of microcracks and a more non-uniform distribution of local deformations within the carburized layer of austenitic steel, with a total deformation of $\varepsilon = 0.01$. Research outlined in [23] demonstrates that at the bimetal's yield point, the Lüders band originating in the main St3 steel layer can act as a "wedge" in accordance with the Barenblatt wedging model [25], potentially initiating cracks in the cladding layer. Due to heightened local stresses at the interface, the Lüders band contributes to the formation of martensitic α′-phase and the emergence of isolated zones of localized deformation in the clad layer during the initial phase of plastic flow.

After heat treatment, with increasing annealing duration (Fig. 4, curves *2 – 5*), the coefficients of variation of deformation inhomogeneity in the substrate and the cladded metal notably escalate. Even after prolonged annealing, the two steels near the junction zone still exhibit distinct levels of deformation inhomogeneity. Statistical analysis utilizing the double *t*-criterion method [24] indicates a "significant" difference in the coefficients of variation of deformation heterogeneity between the substrate and the deposited metal.

This study underscores the influence of structural inhomogeneity near the layer interface on the distribution of local deformations when subjecting the bimetal obtained by laser cladding to uniaxial tension. The nature of deformation inhomogeneity in the transition zone and the primary layers varies, potentially impacting the properties of bimetal products. To maintain or prevent a decrease in the mechanical properties of bimetals composed of carbon steel and stainless steel, manufacturing should adhere to technological modes that ensure minimal levels of deformation inhomogeneity within microvolumes at the transition zone.

Conclusions

The bimetal obtained through laser cladding exhibits a considerable increase in hardness within the junction zone. Subsequent heating up to 700 °C, with holding durations ranging from 2 to 8 h, does not diminish the hardening gradient. This lack of reduction is attributed to the formation of a carbide interlayer due to the diffusion of components.

The heat treatment process results in the growth of a decarburized layer on the carbon steel side and a subsequent reduction in the tensile strength of the bimetal.

Elevated values of the coefficient of variation of local deformations within the carburized layer of the cladded metal are linked to heightened concentration of deformations, stemming from the presence of chromium carbides and microcracks. Prolonged annealing durations further escalate the coefficients of variation of deformation inhomogeneity within both the substrate and the cladded metal.

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Information about the Authors

Svetlana P. Buyakova, *Dr. Sci. (Eng.), Chief Researcher, Head of the Laboratory of Physical Mesomechanics and Non-Destructive Testing,* Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences
ORCID: 0000-0002-6315-2541
E-mail: sbuyakova@ispms.ru

Konstantin N. Kayurov, *General Director,* Scientific Production Enterprise of Geophysical Equipment "LUCH"
ORCID: 0000-0001-9545-5400
E-mail: kayurov@looch.ru

Svetlana A. Barannikova, *Dr. Sci. (Phys.–Math.), Leading Researcher of the Laboratory of Strength Physics,* Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences
ORCID: 0000-0001-5010-9969
E-mail: bsa@ispms.ru

Сведения об авторах

Светлана Петровна Буякова, *д.т.н., главный научный сотрудник, заведующий лабораторией физической мезомеханики и неразрушающих методов контроля,* Институт физики прочности и материаловедения Сибирского отделения РАН
ORCID: 0000-0002-6315-2541
E-mail: sbuyakova@ispms.ru

Константин Николаевич Каюров, *генеральный директор,* Научно-производственное предприятие геофизической аппаратуры «ЛУЧ»
ORCID: 0000-0001-9545-5400
E-mail: kayurov@looch.ru

Светлана Александровна Баранникова, *д.ф.-м.н., ведущий научный сотрудник лаборатории физики прочности,* Институт физики прочности и материаловедения Сибирского отделения РАН
ORCID: 0000-0001-5010-9969
E-mail: bsa@ispms.ru

Contribution of the Authors

S. P. Buyakova – formulation of the concept, literary review, analysis of the results.
K. N. Kayurov – selection of laser cladding modes, discussion of the results.
S. A. Barannikova – conducting studies of mechanical characteristics and localization of deformation, discussion of the results, writing the text.

Вклад авторов

С. П. Буякова – формулирование концепции работы, обзор литературы, анализ результатов.
К. Н. Каюров – подбор режимов лазерной наплавки, обсуждение результатов.
С. А. Баранникова – проведение исследований механических характеристик и локализации деформации, обсуждение результатов, написание текста статьи.

Received 09.03.2023
Revised 20.04.2023
Accepted 10.05.2023

Поступила в редакцию 09.03.2023
После доработки 20.04.2023
Принята к публикации 10.05.2023