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INFLUENCE OF GEOMETRY OF FUSION LINE ON DECARBONIZATION IN DISSIMILAR WELD JOINTS AFTER HEAT TREATMENT

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ABSTRACT *Welded joints of dissimilar steels are widely used in various components of the steam-water circuit at thermal and nuclear power plants. In such welded joints after tempering and during high-temperature operations, carbon migrates through the fusion surface from less alloyed steel to more alloyed steel due to the difference in the chemical potential of carbon in these steels. Decarburization in the weld-adjacent area of the heat affected zone of less alloyed steel, which occurs due to carbon migration, can lead to the formation of defects and subsequent failures in service. It was noticed that the thickness of the decarburized layer varies depending on the geometry of the fusion line: after heat treatment in places of convexity of the more alloyed weld in the base metal the thickness of the decarburized layer in the heat affected zone is less than in places of concavity of the weld. To numerically estimate the influence of the shape of the fusion line on the intensity of decarburization in the weld-adjacent zone, it is proposed to use a geometric factor. The aim of the work was to find such a function for use as the geometric factor, which would allow to estimate locally the variable concavity of a complex curve (in our case - the fusion line) from a point outside the curve and express it through a scalar parameter. An integral function* $\Phi_L(t)$ *is proposed, which "scans" the fusion line L from the point t in the heat affected zone; the obtained numerical value of this function for each point t can be interpreted as the order of decarburization of this point during tempering or high-temperature operation at a given geometry of the fusion line L, and can be used to construct a scalar field of the decarburization order in the heat affected zone of less alloyed steel by implementation of* $\Phi_L(t)$ *using computer vision software.*
Keywords*: decarburized layer; welded joints; dissimilar steels; carbon diffusion; fusion line; heat affected zone; computational geometry*

ВПЛИВ ГЕОМЕТРІЇ ЛІНІЇ СПЛАВЛЕННЯ НА ЗНЕВУГЛЕЦЮВАННЯ В ЗВАРНИХ З'ЄДНАННЯХ РІЗНОРІДНИХ СТАЛЕЙ ПРИ ВІДПУСКУ

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АНОТАЦІЯ *Зварні з'єднання різнорідних сталей широко використовуються в різних вузлах контуру пароводяної суміші на теплових та атомних електростанціях. Внаслідок різниці в хімічному потенціалі вуглецю після відпуску та при високотемпературній експлуатації в них відбувається міграція вуглецю через поверхню сплавлення з боку менш легованої сталі в більш леговану сталь. Зневуглецювання в пришовній ділянці зони термічного впливу менш легованої сталі, що виникає внаслідок міграції вуглецю, може призводити до утворення дефектів та послідуючих руйнувань при експлуатації. Помічено, що товщина зневуглецьованого прошарку варіюється в залежності від геометрії лінії сплавлення: після термічної обробки в місцях випуклості більш легованого шва в основний метал товщина прошарку в зоні термічного впливу менша, ніж в місцях увігнутості шва. Для числової оцінки впливу форми лінії сплавлення на інтенсивність зневуглецювання в пришовній зоні було запропоновано використовувати геометричний фактор. Метою роботи було знаходження такої функції для використання в якості геометричного фактору, яка давала б змогу локально оцінити перемінну увігнутість складної кривої (в нашому випадку – лінії сплавлення) з точки поза кривою та виражалася через скалярний параметр. Запропоновано інтегральну функцію* $\Phi_L(t)$*, що «сканує» лінію сплавлення L з точки t в зоні термічного впливу; отримане числове значення цієї функції для кожної точки t може бути інтерпретоване як порядок зневуглецювання цієї точки при відпуску чи високотемпературній експлуатації при даній геометрії лінії сплавлення L, та може бути використане для побудови скалярного поля порядку зневуглецювання в зоні термічного впливу менш легованої сталі при імплементації цієї функції* $\Phi_L(t)$ *за допомогою програм комп'ютерного бачення.*
Ключові слова*: зневуглецьований прошарок; зварні з'єднання; різнорідні сталі; дифузія вуглецю; лінія сплавлення; зона термічного впливу; обчислювальна геометрія*

Introduction

In order to reduce the cost of construction of modern power plants, different sections of the steam-water circuit are made of steels of different alloying systems: sections with lower steam parameters are made of ferritic steels with 1…2.25% Cr, with higher steam parameters – of more heat-resistant and corrosion-resistant austenitic steels and ferritic-martensitic steels with 9… 12% Cr [1,2]. Therefore, it is necessary to obtain welded joints between ferritic and austenitic steels, as well as between ferritic steels with different chromium

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content. It is known that the joints of dissimilar steels can be a source of potential problems during service. For example, due to the difference in thermal expansion coefficients between austenitic and ferritic steels, thermal stresses may be developed in such joints during high-temperature service, as well as oxide notches near the fusion line on the ferritic side of the weld due to selective stress corrosion [3]. However, a common problem, that arises not only in the joints between ferritic and austenitic steels, but also in the joints of ferritic steels with different chromium content, is primarily related to the redistribution of carbon [4,5].

Carbon is an interstitial alloying element and helps to strengthen steels through solid-solution and dispersion mechanisms. In the presence of a gradient of chemical potential in the lattice, the diffusion of carbon arises in the direction of lowering the chemical potential [6]. Due to the fact that other alloying elements, in particular chromium, reduce the chemical potential of carbon, so at elevated temperatures in the joints of dissimilar steels there is an active migration of this element from less alloyed steel to more alloyed one. As a result, a decarburized layer is formed in the weld-adjacent area of the heat affected zone (HAZ) of less alloyed steel, which has a reduced strength and can be detected by measuring the hardness [7,8].

The development of a decarburized layer in the joints of dissimilar steels, which operate at elevated temperatures, is associated with the formation of type IIIa cracks (according to the classification [9,10]). In particular, a statistical study during an inspection of power plants in the UK found that a significant amount of damage to welded joints of dissimilar steels was of type IIIa [10].

The purpose of the article

While performing metallography of welded joints of dissimilar steels an author of the article had noticed a pattern that, depending on the sign and the magnitude of the curvature of the fusion line (FL), the development of the decarburized layer in less alloyed steel intensifies or weakens. No reference to this effect was found in the literature, so the author attempted to characterize it using geometric methods.

Basic research materials

The literature uses the concept of the effective thickness of the diffusion layer, which is determined as the shortest distance from the saturation surface (in the case of welded joints of dissimilar steels – from the fusion line) to the place of measurement, characterized by the nominal value of a base parameter [11]. The base parameter is either the concentration of the diffusing element, or a mechanical property (hardness), or a structural feature, such as poor etchability of the decarburized area.

Metallographic studies on welded joints between martensitic and austenitic steels in the state after tempering have shown that in places of bending of the fusion line (FL) can be observed variation of the effective thickness of the decarburized layer in HAZ by the structural feature of etchability. In particular, in the places of convexity of the FL in the direction of the base metal there is less decarburization, and in the places of convexity of the FL in the weld – more decarburization. Fig. 1, 2 show micrographs of the structure of the welded joint of steel P91 (wt.%: C–0.1, Si–0.34, Mn–0.47, Cr–8.52, Mo–0.93, Ni–0.28, V–0.2, Nb–0.072), welded with Fox CN 23/12 Mo-A electrodes (wt.%: C–0.01, Si–0.63, Mn–0.73, Cr–23.0, Mo–2.6, Ni–13.1) in the state after tempering 760 ° C, 2 h.

This effect is observed both on convexities of small radius of curvature (Fig. 1) and on convexities of large radius of curvature (Fig. 2). A common macroscopic characteristic is that the front of decarburization tries to reach the flattering of its boundary (Fig. 3).

A possible explanation for this effect is that the carbon atom, which is disposed in the HAZ directly near the convexity in the weld (Fig. 4, top), has many possible shortest paths to the fusion line, and, according to the probabilistic theory of random walks [12], can choose any of them. At the same time, the carbon atom near the convexity in the direction to HAZ has only one shortest path, which with increasing intensification of diffusion can lead to restriction of the flow through this path by its maximum carrying capacity (Fig. 4).

In connection with the above, there may arise the problem of modeling the development of the decarburization front in HAZ of less alloyed steel depending on the local curvature of the fusion line in the welded joint of dissimilar steels. It is desirable to obtain a function that would give a numerical value for each point of the heat affected zone, depending on 1) the distance of this point from the fusion line and 2) the local curvature of the fusion line in the vicinity of this point.

For example, for each HAZ point we should obtain such numerical values Φ that the values at a point on the Φ_1 line are approximately equal to each other point on that line and greater than the values at the points on the Φ_2 line, which in turn are greater than the values at the Φ_3 points, etc (Fig. 5).

The obtained numerical value can be interpreted as the order of onset of decarburization of each HAZ point: the greater the value at a particular point, the faster it will begin to decarburize in a continuous diffusion process at elevated temperature in a homogeneous isotropic material with a certain curvature of the fusion surface. Therefore, the following requirements are laid down before the function: 1) a point, closer to the fusion line (in the direction, perpendicular to the FL), must have higher values of the function than a point farther from the FL; 2) near the concave areas of the FL values are relatively higher than near the convex areas.

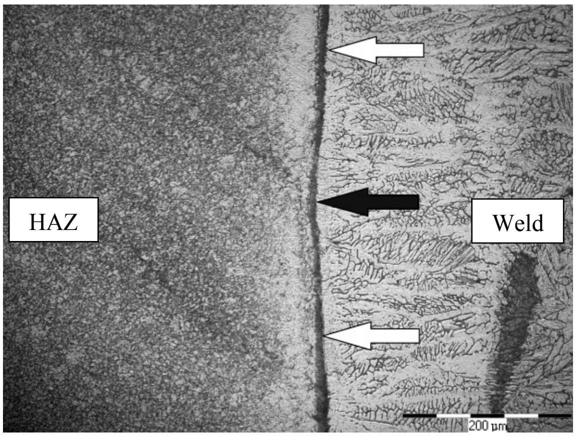

Fig. 1 – Convexity of small radius of curvature (white arrows indicates increased decarburization in HAZ, dark arrow – reduced decarburization in HAZ), magnification x200

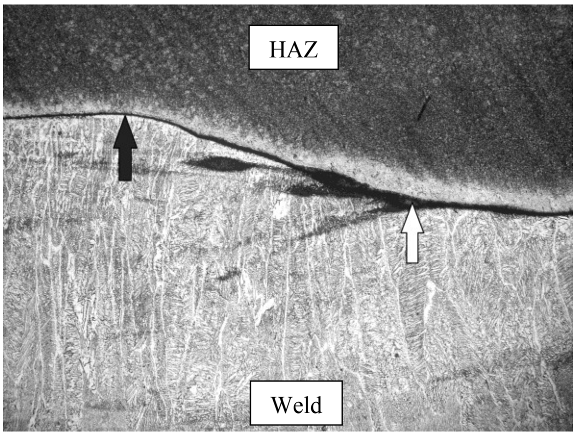

Fig. 2 – Convexity and concavity of a large radius of curvature (white arrows indicates increased decarburization in HAZ, dark arrow – reduced decarburization in HAZ), magnification x50

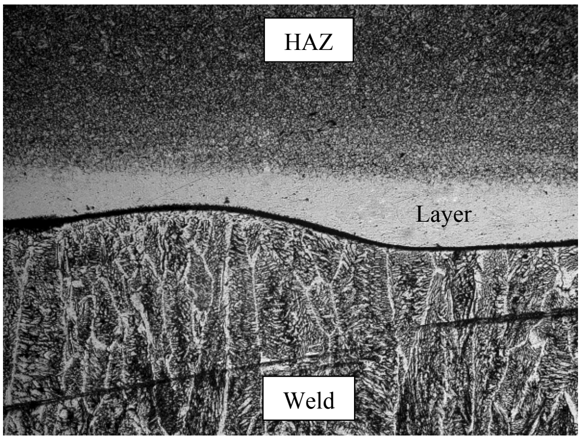

Fig. 3 – Overlaying with austenitic electrodes Fox CN 23/12 Mo-A on a plate of P91 steel after tempering 750 °C, 18 h, magnification x100

Geometric factor. For the geometric analysis of the influence of the shape of the fusion surface on decarburization, the author has proposed a geometric factor $\Phi_L(t)$, which is based on the function $\varphi_R(x)$. If we take the point t in the HAZ at a distance C from the nearest point of the fusion line and draw a circle of radius R > C around it, then a certain part of the fusion line will be inside the circle (Fig. 6). The ratio of the radius of the circle R to the length of the fusion line inside the circle L we can take as a parameter $x = L/R$. We introduce the condition: if the circle does not intersect the curve of the fusion line (i.e. R<C), then $\varphi_R(x) = 0$. The function $\varphi_R(x)$ is continuous and monotonically increasing as the parameter x increases. The total contribution of all functions $\varphi_R(x)$ with increasing $R \to \infty$, to estimate the curvature of the fusion line and the distance of the point t from the FL, can be determined using the integral

$$\Phi_L(t) = A \cdot \int_0^\infty \psi(R) \cdot \varphi_R(x) dR \qquad (1)$$

where A is a coefficient that can be used to normalize the function $\Phi_L(t)$; $\psi(R)$ is a function that should ensure the convergence of the integral with a possible increase of the function $\varphi_R(x)$ to infinity at $R \to \infty$.

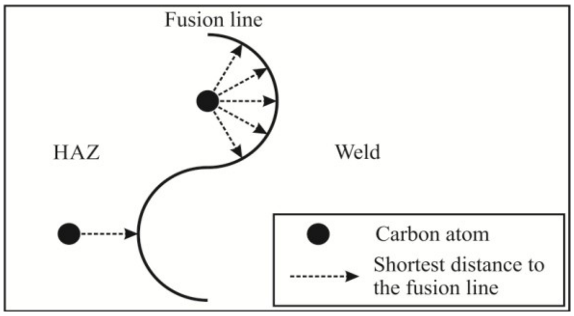

Fig. 4 – Scheme of the possible mechanism of influence of the fusion line geometry on the diffusion of carbon

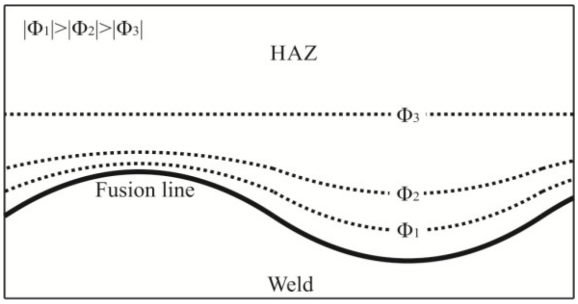

Fig. 5 – Requirements for the obtained values of some function Φ at HAZ points for estimating the distance and local curvature of the fusion line

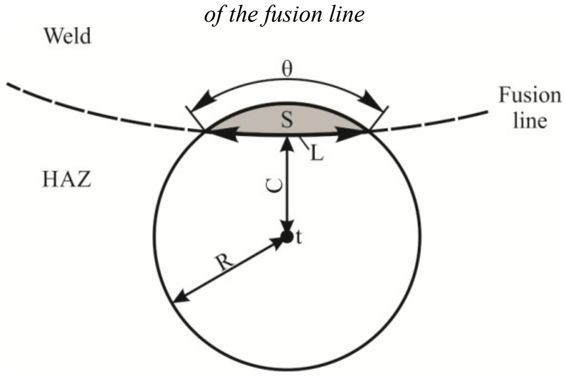

Fig. 6 – Geometric interpretation of parameters L, R and θ

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The function $\psi(R)$ should be chosen in such a way that the total integral $\Phi_L(t)$ takes into account largely the local curvature of the fusion line directly near the point t, and as the radius of the circle R increases, the contribution of $\varphi_R(x)$ decreases in proportion to the function of radius R. The reason for decreasing of a role of $\varphi_R(x)$ with increasing R may be that at large scales there is no difference in the length L between the convex and concave shapes of the fusion line (Fig. 7), however, as shown above, there is a fundamental physical difference in decarburization between the point near the convex FL or a point near the concave FL. For fairly simple forms of the fusion line, x has a value of the order 2, so $\varphi_R(x)$ is a bounded function. The elementary functions, whose integrals converge in the range from 0 to ∞, are the family of functions $1/\mathrm{a}^x$ (a>1), so the integral of such a function, multiplied by a certain number *M*, which is the upper smallest boundary of the function $\varphi_R(x)$, also converges.

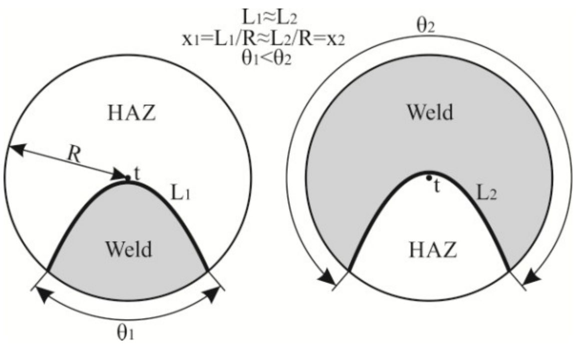

Fig. 7 – Extreme cases with unlimited increase in radius

For example, the geometric factor of a certain point t, depending on the fusion surface L, can be calculated using the formula:

$$\Phi_L(t) = \int_0^\infty e^{-R} \cdot \varphi_R\left(\frac{\mathrm{L}}{-}\right) dR$$

where $\varphi_R(x) = B \cdot x = B \cdot (L/R)$ (B – some constant, for example, 1).

As the distance from the fusion line increases, the influence of the geometric factor decreases, so at a relatively large distance from the fusion line the decarburization front ceases to repeat the wavy shape of the fusion line and becomes uniformly rectilinear, so the values of the function $\Phi_L(t)$, as well as the decarburization front, begin to spread in a straight line (Fig. 3, 5).

For complex forms of the fusion line, the parameter $x = L/R$ can be a discontinuous function and theoretically increase indefinitely in the case of fractal self-repetition of the fusion line (although even in the case of unlimited growth of the parameter x integral for $\Phi_L(t)$ in (1) converges if, for example, the function $\psi(\ ) = \mathrm{e}^{-R}$, and the function $\varphi_R(x)$ is of exponential type: $\varphi_R(x) \leq \mathrm{K} \cdot \mathrm{e}^{\mathrm{a} \cdot R}$, where a<1 [13, p. 113]). In this case, instead of the parameter $x = L/R$, the author recommends to use 1) the parameter θ – the angle of the arc, cut off by the fusion line inside the circle of radius R (0<θ<2π), or its normalized variant θ/2π (0<θ/2π<1); 2) the area of the cut section of the weld S (or S/R) (Fig. 6). Such parameters are also devoid of the disadvantage shown in Fig. 7: the convex shape of the fusion line has an angle less than π, and the concave – more than π.

The function $\varphi_R(x)$ uses the property of a circle that, at the same length L of the truncated curve, the shortest distance C_V to the convex curve of constant curvature will be less than the distance C_C to the concave curve (Fig. 8): $C_C = C_V + \Delta$. Accordingly, for the same value of $\varphi_1(x) \cdot \mathrm{e}^{-1}$ (for a circle of radius R=1) the point t_C for a concave FL will be located farther from the fusion line than the point t_V for a convex FL, at a distance Δ. If we place the point t_C at the distance C_V from the concave fusion line, then the circle of radius 1 from it will have a larger value of the parameter x (due to the fact that *L2* > *L1*), and, accordingly, a larger value of $\varphi_1(x) \cdot \mathrm{e}^{-1}$ than in the original case, which corresponds to the increased decarburization for the concave FL in comparison with the convex FL at the same distance C_V.

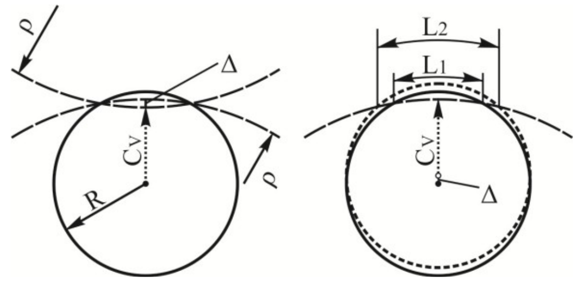

Fig. 8 – The difference between concave and convex fusion lines for parameter $\varphi_R(x)$

When analyzing the structural components using a light microscope, the Cavalieri principle is usually used, from which it follows that the required ratios in the plane of the section are the same as in the volume of the sample [14, p.25]. However, due to the fact that in reality the microslice (microphotograph) is a two-dimensional section of the three-dimensional fusion surface, it is possible for two identical fusion lines in the photomicrograph to have a different shape of the decarburized layer. For example, in the case of a convex shape of the fusion line on the section, the two extreme cases of the fusion surface will be an elliptical paraboloid and a hyperbolic paraboloid (Fig. 9). The surface, cut off by a sphere of radius R emanating from the point t, will have a different area P or a different solid angle ζ in these two cases. For the three-dimensional case, formula (1) is also valid, and as parameters we can use the ratio of the cut off area to the square of the radius of the sphere $y = P/R^2$, the solid angle ζ or the cut off volume V.

The practical value of the function $\Phi_L(t)$ lies in the possibility of its implementation in the software of computer vision systems for the analysis of microphotographs with a discrete step ΔR and construction of three-dimensional graphs of $\Phi_L((x,y))$

(where x, y are point t coordinates on a macrograph or a panorama of micrographs) for complex configurations of joints of dissimilar steels, found in units of power equipment operating at elevated temperatures. In areas with maximum values of $\Phi_L((x,y))$ decarburization and softening will develop more rapidly than in other areas, which may indicate the formation of local stress concentrators in these places during the high-temperature service.

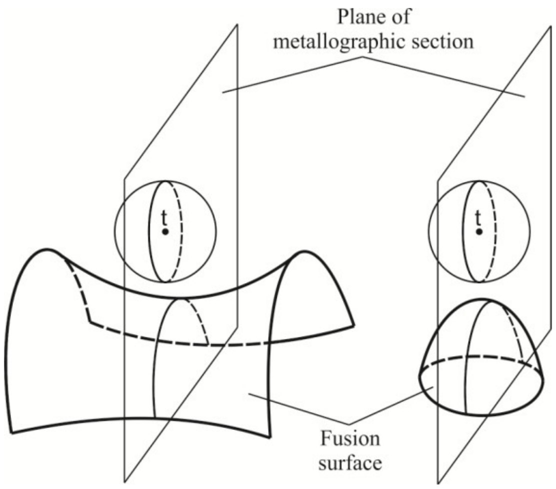

Fig. 9 – Hyperbolic and elliptical paraboloids having the same parabolic cross section, but different values of Φ(t)

Conclusions

It is shown that the shape of the diffusion layer depends on the geometry of the fusion line: in places of convexity of the fusion line in the direction of the base metal there is less decarburization, and in places of convexity of the fusion line in the weld there is more decarburization.

The geometric factor $\Phi_L(t)$ is proposed, which allows to estimate the order of decarburization in points t of the heat affected zone.

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АННОТАЦИЯ *Сварные соединения разнородных сталей широко используются в разных узлах контура пароводяной смеси на тепловых и атомных электростанциях. В результате разницы в химическом потенциале углерода после отпуска и при высокотемпературной эксплуатации в них происходит миграция углерода через поверхность сплавления со стороны менее легированной стали в более легированную сталь. Обезуглероживание в пришовном участке зоны термического влияния менее легированной стали, возникающей вследствие миграции углерода, может приводить к образованию дефектов и последующих разрушений при эксплуатации. Замечено, что толщина обезуглероженной прослойки варьируется в зависимости от геометрии линии сплавления: после термической обработки в местах выпуклости более легированного шва в основной металл толщина прослойки в зоне термического влияния меньше, чем в местах вогнутости шва. Для числовой оценки влияния формы линии сплавления на интенсивность обезуглероживания в пришовной зоне было предложено использовать геометрический фактор. Целью работы было нахождение такой функции для использования в качестве геометрического фактора, которая позволяла бы локально оценить переменную вогнутость сложной кривой (в нашем случае – линии сплавления) из точки вне кривой и выражалась через скалярный параметр. Предложена интегральная функция* $\Phi_L(t)$*, «сканирующая» линию сплавления L из точки t в зоне термического воздействия; полученное числовое значение этой функции для каждой точки t может быть интерпретировано как порядок обезуглероживания этой точки при отпуске или высокотемпературной эксплуатации при данной геометрии линии сплавления L, и может быть использовано для построения скалярного поля порядка обезуглероживания в зоне термического влияния менее легированной стали при имплементации этой функции* $\Phi_L(t)$ *с помощью программ компьютерного зрения.*

Ключевые слова: *обезуглероженная прослойка; сварные соединения; разнородные стали; диффузия углерода; линия сплавления; зона термического влияния; вычислительная геометрия*

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