

USING THE HEREDITY EFFECT FOR CONTROL OF THE STRUCTURE OF THE DEPOSITED METAL DURING ELECTRIC ARC SURFACING WITH FLUX-CORED WIRES (Review)

A.A. Babinets

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

Modern views on the relationship between structure and properties in steels and alloys are considered. It is shown that a promising method of influencing the structure and properties of the deposited metal is the use of the heredity effect — the transfer of properties from the initial charge materials to the finished products. A detailed classification of the types of heredity is given according to its manifestations in steels and alloys, which can be divided into three main interrelated groups — metallurgical, structural and technological. It is shown that from the point of view of the influence of initial materials on the structure and properties of finished parts, heredity can be considered both positive and negative. The main factors affecting the degree of manifestation of the effect of structural heredity in steels and alloys are defined and described. Such factors include: chemical composition and degree of doping with chemical elements; degree of defectiveness of the initial structure; size, shape and structure of the initial charge materials; use of modifying additives or external physical influences. The main problems and prospects of using the heredity effect in electric arc surfacing are described. The main directions that will allow controlling the structure and properties of the deposited metal by influencing the degree of manifestation of the heredity effect in it have been determined. The most promising are methods of control by changing the initial parameters of surfacing materials, as well as by means of regulation of heat input due to technological or physical influences. The use of the heredity effect in various surfacing methods can provide a significant impact due to producing the optimal structure of the deposited metal and the absence of harmful impurities in it.

KEYWORDS: electric arc surfacing, deposited metal, flux-cored wire, heredity, structure, operational properties

INTRODUCTION

The main task to be solved at wear-resistant electric arc surfacing is development of such materials and technologies, which will provide the specified chemical composition, structure, high quality and other necessary properties of the deposited metal. Taking into account the operating conditions of specific parts, this is most often achieved through complex alloying of the deposited metal by such elements as Cr, Mo, W, V, Ti, which are added in the form of ferroalloys or other components to the composition of the charge of electrode or filler surfacing materials [1, 2]. Today, however, the technical and economic possibilities for improvement of the deposited metal properties due to such an approach have been practically exhausted.

The structure and properties of the deposited metal can be also controlled by different physical, chemical and technological actions, for instance by its modification and alloying [3]. However, the influence of modifying and microalloying elements is rather complicated, particularly at application of complex additives. They can simultaneously promote improvement of certain properties of the deposited metal, and form undesirable inclusions, which can become the nuclei of cracks or other defects.

It is known that the metal structure and properties can be controlled due to the effect of structural heredity, i.e. the transfer and preservation of the structure (for instance, fine-grained) from the initial charge materials to the finished part structure, leading to an increase of their operational properties [4].

Such an approach is used, for instance, in metallurgical production. On the other hand, the effect of structural heredity is almost not used in surfacing (welding) production. When studying the regularities of formation and change of the deposited metal structure, the attention is usually focused on the influence of alloying element content and surfacing thermal cycle on them. The influence of the initial structure of electrode or filler materials on the deposited metal structure is almost unstudied. At the same time, such a connection certainly exists in the “initial surfacing material – weld pool – deposited metal” system [4, 5].

The main problems of application of structural heredity effect at different surfacing methods, first of all the arc, are apparently associated with the special features of these methods and distinguish them from metallurgical processes [4]:

- deposited metal crystallization occurs on a solid substrate, which is partially remelted, and, hence, its

initial chemical composition and structure influence the deposited metal structure and properties;

- unlike a metallurgical furnace the temperature-time parameters of the weld pool are not stationary; they may also differ at application of different surfacing methods, and are rather difficult to control.

At the same time, application of some technological measures to control the structural heredity effect at arc and plasma surfacing methods are known [4–6], which resulted in improvement of the deposited metal structure and properties.

THE OBJECTIVE OF THE WORK

is analysis of the features of the heredity effect (i.e. preservation of primary object features in the secondary objects) in steels and alloys; factors, influencing it, as well as determination of the prospects for and ways of using this effect at arc surfacing of parts to optimize their structure and operational properties.

BASIC CONCEPTS ABOUT THE CONNECTION BETWEEN THE STRUCTURE AND PROPERTIES AND HEREDITY EFFECT IN STEELS AND ALLOYS

It is widely known that the properties of steels and alloys are determined by their structure and features of structure change under the impact of external physical, chemical or technological factors, to which also such high-temperature processing methods as surfacing (welding) certainly belong [1–6]. In the general case it is assumed that a finer structure of steel or alloy ensures better properties (physical, mechanical, technological, service, etc.) of the finished parts.

The “heredity” term for metals and alloys is usually used to describe the phenomenon at which the shape of any elements of the metal structure is preserved after direct (at cooling) and reverse (at heating) polymorphous transformation. The heredity of the crystallographic orientation is ensured by ordering of rearrangement of one lattice into another one, and restoration of the grain shape is provided by preservation of chemical heterogeneity (segregation of impurities and inclusions along the old grain boundaries) [7].

In metallurgy the positive or negative influence of the initial charge materials on the melt structure, and through it also on the structure and physico-mechanical properties of solid metal, was called “metallurgical heredity”. Its manifestations are associated with preservation in the melt of nonmetallic phases, gases, impurities and elements of the crystalline structure of initial metal, due to technological background of production, preparation, melting, deoxidation and crystallization of the charge metal [7–13].

Proceeding from different views on the processes associated with the heredity phenomenon, it can be classified in different ways. In keeping with [13], heredity is the totality of many processes, among which the following physical phenomena can be singled out in particular:

- deformational heredity, which is characterized by incomplete recovery of the properties of deformed and recrystallized metal. Deformational heredity depends on the nature of the metal and is manifested irrespective of the presence of polymorphous transformation;

- phase heredity, which is determined by crystallographic correspondence of the dislocation structures of the phases at polymorphous transformation and is the base for thermomechanical treatment of the alloys from metals, which undergo a polymorphous transformation (for instance, iron). This phenomenon is also responsible for defect accumulation at thermal cycling;

- boundary heredity, which is associated with incomplete healing of defects in regions, corresponding to old grain boundaries after migration of the latter. This kind of heredity is very resistant (sometimes it is not relieved at heating to premelting temperatures), and it strongly depends on the influence of impurities, included into the solid solution and precipitating in the form of phases.

In [14–17] the authors give another classification of heredity, based on manifestations of the characteristic features at manufacture of parts from steels and alloys. In keeping with this classification, heredity can be divided into three main interrelated groups: metallurgical, structural and technological:

1. Metallurgical heredity is the ability of the cast metal to preserve the structural features and properties of the initial charge materials and liquid metal. It is due primarily to the chemical composition, charge quality, state of the melt and its treatment conditions (temperature, mixing, flux treatment, deoxidation, modification, etc.). At each production stage, certain structural elements appear in the melt, which have hereditary characteristics of cast metal properties at this stage.

2. Structural heredity is observed in those cases, when at close chemical composition, content of impurities and nonmetallic inclusions of initial materials and approximately the same conditions of melt cooling the solidified metal has different micro- and macrostructure. This is attributable to preservation in the metal after the phase or structural transformation, of certain features of its initial structure at different levels (macroscopic, micro- and submicroscopic). One of the kinds of structural heredity after the phase or

structural transformation is presence of chemical heterogeneity in the steel, which is manifested in preservation of segregation areas, forming at melt crystallization.

At first, the structural heredity was understood only as regeneration of coarse grains in the preheated steel. Modern concepts about structural heredity are not limited by pure restoration of the grain size at heat treatment. Structural heredity is manifested both in the form of restoration of grain dimensions and in the form of preservation of their orientation, or modification of the grain boundary, according to the initial structure [15, 16]. It may be accompanied by decomposition of the characteristic structural elements and preservation of the initial coarse-grained structure that is particularly important for the processes of high-temperature treatment, as it may lead to lowering of the mechanical properties of the deposited metal.

3. Technological heredity associated with preservation of special features of the structure of the initial components during the next operations of part manufacture. It is due to the influence of diverse technological factors. Forming of certain characteristics of technological heredity occurs at all the stages of melting, crystallization, deformation, deformation-heat, heat treatment, etc. In the opinion of the author of [17], in the majority of the cases these are exactly the technological factors which are responsible for forming of the structural features and manifestations of the metallurgical and structural heredity in steels and alloys.

The influence of material preparation and technological parameters of surfacing on the quality of the manufactured parts apparently can be an example of technological heredity at surfacing: monitoring the content of gases, nonmetallic inclusions, impurities in the deposited materials; controlling the heat input and crystallization conditions; use of additional external treatment of the molten metal pool, etc. [4].

In view of the influence of initial materials on the structure and properties of finished products, heredity can be regarded both as positive and negative. Transfer of the initial material fine-grained structure to the deposited metal structure or its certain modification that leads to an improvement of the part operational properties can be as example of the positive influence. For instance, in [18] an example of positive heredity is formation in the overheated coarse-grained steel of primary boundaries of austenite grains of a complex (serrated) shape, which were inherited from the initial fine-grained metal structure. Producing such a complex grain shape due to the structural heredity effect, increases the steel crack resistance, as well as its strength characteristics. Another example of positive

heredity is improvement of the degree of steel sheet protection from local impact loads of a considerable intensity as a result of hereditary thermomechanical strengthening which consists in inheriting the dislocation substructure, formed during previous high-temperature deformation, by austenite newly formed in case of heating, and also by martensite at further quenching [19].

Negative heredity can be manifested, contrarily, in preservation or restoration of the coarse-grained initial structure of source materials, preservation of the content of impurities, etc., that may impair the properties of the produced deposited metal and requires taking of additional technological measures [9]. Conditionally the simplest method to remove the negative structural heredity which is manifested as preservation of the coarse-grained structure, is conducting heat treatment [20]. For instance, in [21, 22] it is shown that in medium manganese steels, the heredity effect can be manifested, depending on heat treatment mode, resulting in formation of coarse ferrite grains in metal layers with a low manganese content, leading to lowering of steel ductility, because of crack propagation along the interface of the coarse- and fine-grained regions. After heat treatment of such steel at a sufficiently high temperature cementite can dissolve, forming ultra-fine uniformly distributed austenite grains, thus increasing the steel ductility.

However, in some cases the manifestations of negative heredity cannot be completely removed by heat treatment. In [23] the case of structural heredity in cast steel of 30Kh2N4MF type was studied. It was determined that after preliminary high-temperature tempering fine grains form in steel at heating, which at reheating to 1050–1150 °C is replaced by coarse grains, coinciding by their size, shape and crystallographic orientation with the initial cast austenite grains. This restoration is attributable to nucleating orienting impact of residual austenite, which did not decompose at high-temperature tempering and was preserved at reheating to critical range temperatures.

In metallurgy the negative heredity is most often eliminated due to application of different methods, such as preparation and selection of the charge component ratio; optimal selection of melting and pouring technologies; metal refining due to melt vacuumizing; electroslog remelting, electromagnetic stirring, treatment by ultrasound or electric current, electrohydropulse treatment, alloying, modification, etc. [7, 14, 24].

Application of the majority of the abovementioned methods involves certain difficulties, primarily, economic. Expensive equipment, high energy costs, problems of fitting into the available technological processes complicate application of these methods

of melt treatment in metallurgical production. Application of the majority of the above-listed methods of removing the negative heredity in arc surfacing methods is significantly complicated.

Thus, heredity is not just a peculiarity of transformation in real crystalline alloys, which is manifested in the form of inheriting of the initial structure shape and dimensions by the final structure, which can be revealed by metallographic methods [13]. Heredity in steels and alloys is a totality of many phenomena, leading to preservation in them of the special features of the structure, phase-structural state and properties of the initial material after various technological impacts, which result in the respective structural and phase transformations [14–17]. Such a definition is based on the concept of realization of the possibilities of forming certain hereditary characteristics (structural features) in steels and alloys at all the stages of the technological process of part manufacturing, also by the methods of arc surfacing.

MAIN FACTORS INFLUENCING THE EFFECT OF STRUCTURAL HEREDITY IN STEELS AND ALLOYS

Chemical composition and degree of alloying by chemical elements are the important factors, determining the degree of manifestation of structural heredity, depending on which the steels can be divided into several groups (see Table 1), where “+” symbol denotes the manifestation of structural heredity, and “–” mean its absence [9].

For manifestation of structural heredity, carbon content in the steel should not be lower than 0.2 %. Here, the higher is the steel alloyed by such carbide-forming elements as Cr, Mo, W, V, Ti, the wider the temperature range, in which the structural heredity forms. Alloying influences the critical heating rate, at which grain size restoration can take place. For instance, structural heredity is readily manifested in structural alloyed and high-alloyed steels (high-speed, maraging, corrosion-resistant, etc.) and here it little depends on the heating rate. For low-carbon low-alloyed steels with regular ferrite-pearlite structure the possibility of formation of structural heredity is practically excluded [9]. Lowering of carbon content from 0.08 to 0.008 % prevents restoration of the initial austenite grains even at very rapid heating [16].

Influence of the heating rate on the process of grain formation at heating and cooling of steel with the ordered structure is given in Figure 1 [9]. At rapid heating (100–200 °C/min) of the quenched and untempered steel a special crystallographically ordered mechanism of austenite formation is realized, resulting in restoration of the initial structure grains. As the

Table 1. Influence of steel type and heating rate on structural heredity [9]

Steel type	Heating rate		
	High	Moderate	Slow
Low-carbon low-alloyed	–	–	–
Alloyed	+	–	+
High-alloyed	+	+	+

heating rate is reduced, the processes of tempering and normal diffusion-controlled mechanism of austenite formation, accompanied by grain refinement, develop. At intermediate heating rates (100–150 °C/min), when complete martensite decomposition has enough time to take place before the start of $\alpha \rightarrow \gamma$ -transition, the structural heredity of steel is not manifested. Here $\alpha \rightarrow \gamma$ -transition coincides with recrystallization, and fine grains form at once, i.e. the normal unordered recrystallization mechanism is implemented. At rather slow heating (1–2 °C/min) of many steel austenite also forms by the crystallographically ordered mechanism, resulting in restoration of the initial structure grains at such heating, i.e. the structural heredity is strongly expressed.

Initial structure defects and other structural features of steels and alloys certainly influence the occurrence of the heredity effect, but these dependencies are insufficiently studied. It is known that relative to initial structure defects heredity depends on the nature of initial defectiveness, particularly, of dislocation structure, as well as on the composition and conditions of steel or alloy heat treatment [13, 16]. The heredity effect grows and is preserved to higher temperature values at heating, if the grain boundaries

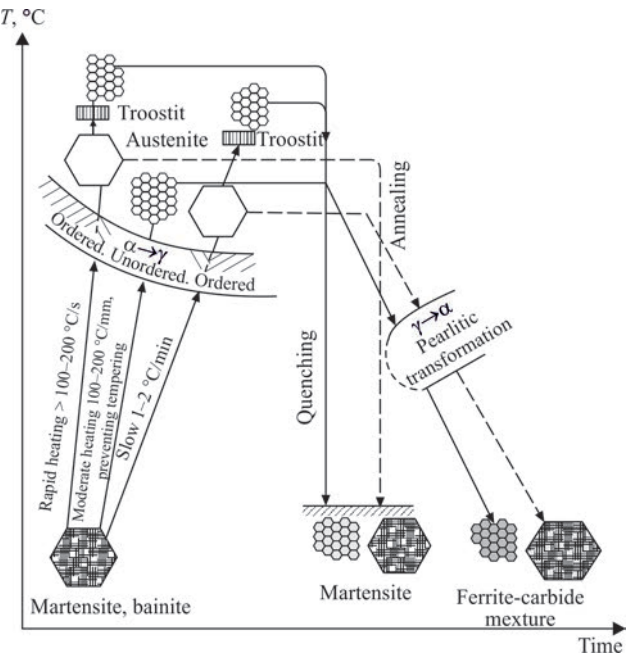


Figure 1. Scheme of recrystallization of steel with initial ordered structure at heating and cooling [9]

are preliminarily enriched in additives. This effect is greater, the more the additives differs from the matrix by its properties and the stronger is their interaction. This is confirmed by the data of [25], where the influence of charge material structure on the properties of cast iron melts was studied, and where it was determined that microadditives not only enhance the energy inequality of different interatomic interactions, but also lead to appearance of noticeable structural features in the solid state.

In metallurgical production the considerable influence of admixtures in the charge on the structure and properties of the finished products is the subject of many papers. Application of a low-grade charge leads to melt contamination by impurities, usually uncontrolled, which noticeably influence the nature of metal solidification. Some of these impurities are resistant and influence structure formation not only during blast furnace smelting, but also during subsequent remelting operations, with manifestation of the heredity effect [9]. By the data of [26] the peculiarities of intercrystalline boundary structure in steels and alloys also are very important for manifestation of the heredity effect.

Application of modifiers can also influence the degree of manifestation of structural heredity in steels and alloys, for instance, enhancing the grain refinement effect. As was noted above, one of the methods of manufacturing products from steels and alloys with a more homogeneous fine-grained structure is application of their modification technologies. The essence of the process consists in introducing special additives (modifiers) into the liquid metal, which initiate the process of heterogeneous formation of a large number of crystallization nuclei (modifiers of the 1st kind), or surface-active additives, which slow down the increase of solid-phase grain size during melt crystallization (modifiers of the 2nd kind).

In keeping with the data of technical literature, not only chemical elements or compounds, but also materials, which were prepared accordingly, i.e. their initial properties were modified, can be such modifiers. For instance, it is possible to use as modifying additives the materials of the same chemical composition, but with a highly-dispersed structure and improved mechanical properties, which were produced due to high-rate crystallization [14, 27, 28]. So, investigations of the influence of such modifiers revealed an essential increase of the dispersity and homogeneity of the cast structure, mechanical properties and brittle fracture resistance of carbon steels with different carbon content as a result of hereditary modification [27].

Similar results were obtained in [28], where the possibility of purposeful increase of the dispersity of

the cast structure of steel at introducing additives of analogous composition dispersion-structured by rapid crystallization into the melt was demonstrated in the case of 45L and R6M5L steels. Such additives preserve in the melt the incorporated in them hereditary features (short-range order), lead to formation of a significant number of crystallization nuclei and ensure formation of a homogeneous fine-grained structure over the entire cross-section of the castings (Figure 2). For R6M5L steel the grain size is decreased by 4–5 numbers, compared to initial values. Hereditary modification performed in such a way, is sufficiently controllable and versatile with rather long-term technological viability.

Thus, incorporating the necessary hereditary elements in the initial charge components and specially structured modifiers opens up the possibility of actively influencing the structure and properties of steels and alloys.

The size (granulometric composition) and shape of the initial surfacing materials also influence the metal final structure. In terms of refinement of its microstructure, a promising approach seems to be introducing into the liquid metal the additives of fine-, micro- or nanosized charge materials, which obviously, can enhance the effect of heredity, similar to the effect of chemical elements-modifiers [29]. For instance, in keeping with the data of [11], one of the most probable factors influencing the manifestation of structural heredity, is the initial size of graphite inclusions, on which the degree of their dissolution in the melt depends.

At present, only some publications are available, which are devoted to the problem of heredity in surfacing production. The majority of the works, where attention is paid to the processes at the stage of formation of the initial powder materials and influence of their particle shape and size on the final mechanical properties of the produced steels and alloys, pertain to metallurgical production. Somewhat generally it can be considered that the smaller are the charge initial dimensions, the finer will be the metal structure and the higher its operational properties [30].

For the surfacing (welding) production valid is the statement that the size of charge material powder particles in electrode or filler wires should meet certain requirements as to granulation. It affects such characteristics as friability, flowability, etc. of the charge, which determine the dozing quality and homogeneity at wire filling and, hence, influence the surfacing process stability and deposited metal quality. From practical experience it is known that in terms of improvement of the homogeneity of flux-cored wire charge, presence of a dust-like fraction with <50 μm particle

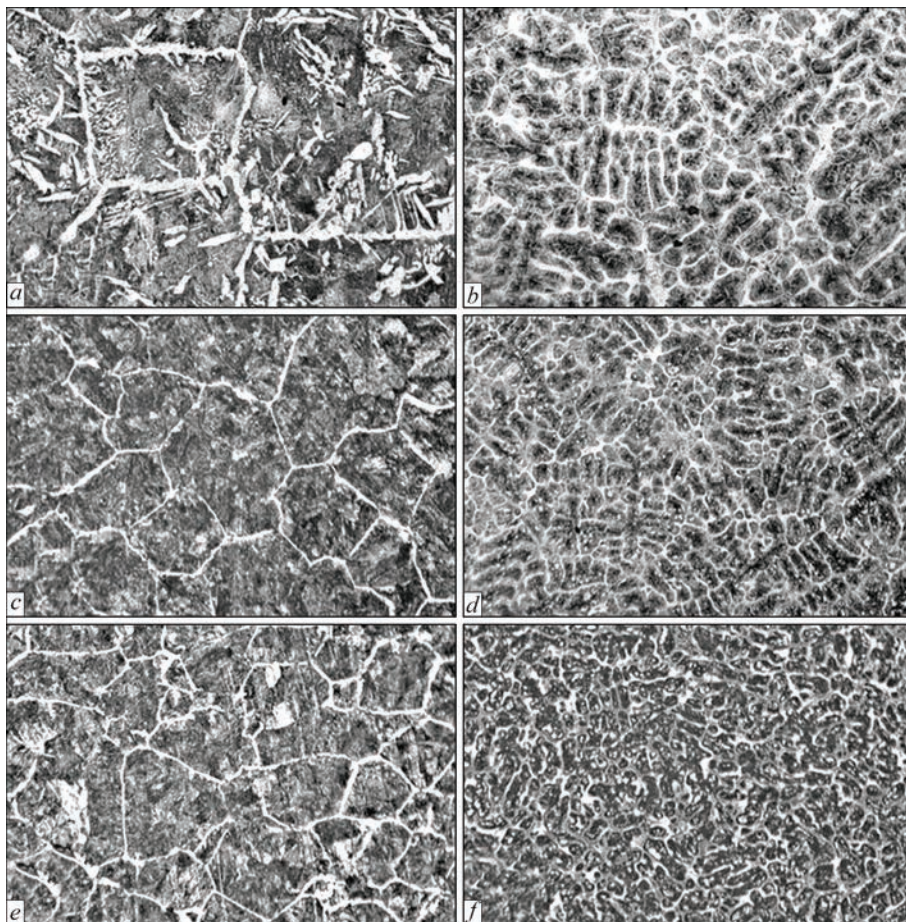


Figure 2. Transformation of the structure of 45L (*a, c, e*) and R6M5L steels (*b, d, f*), depending on dispersity of the modifying additive structure in the quantity of 20 % [28]: *a, b* — without additives; *c, d* — $V_{\text{cool}} = 350 \text{ }^{\circ}\text{C/s}$; *e* — $V_{\text{cool}} = 650 \text{ }^{\circ}\text{C/s}$ ($\times 100$)

size and of coarse particles of more than $300 \text{ }\mu\text{m}$ size is undesirable in powder materials used for flux-cored wire manufacture.

At the same time, there are practically no data on the influence of the size of initial charge material particles on the size of the produced final structure of the deposited metal. It may be related, primarily, to the high temperature in the melting zone. It is common knowledge that for arc surfacing methods the temperature in the arc column, through which the molten metal drop passes, can reach $6000\text{--}8000 \text{ }^{\circ}\text{C}$. Here, the temperature of the drop proper reaches $2150\text{--}2350 \text{ }^{\circ}\text{C}$ [1, 2]. It is obvious that under such conditions the majority of hereditary characteristics inherent to the initial charge materials, is lost and it is difficult to establish a connection between the properties of primary and secondary objects.

Proceeding from that, the influence of structural heredity can be manifested to the greatest degree in such surfacing technologies, where the surfacing materials are fed into the melting zone, bypassing the highest temperature zone, and where there is no rigid connection between arc current and surfacing material melting rate. So, in [5] the influence of the powder initial structure and granulometric composition on

the structure of the deposited metal of 10R6M5 type produced by plasma surfacing, was studied. The filler powder consisted of a mixture of fine ($40\text{--}125 \text{ }\mu\text{m}$) and coarse ($200\text{--}400 \text{ }\mu\text{m}$) fractions, taken in different proportions. It is found that addition of 15 % of coarse fraction powder to fine-grained powder does not lead to any particular changes in the deposited metal structure (Figure 3, *a*). Increase of the content of powders of coarse fractions ($200\text{--}250$ or $315\text{--}400 \text{ }\mu\text{m}$) up to 30 % led to refinement of the deposited metal structure (Figure 3, *b*).

At further increase of the abovementioned fraction content to 45 %, the deposited metal preserves a mostly disoriented structural pattern, but coarser dendrites appear, which grow to the crystallization centers, which are the coarse powder particles (Figure 3, *c*). If such particles do not have enough time to melt completely, then they also act as crystallization centers (Figure 3, *d*) [5].

The given results show that when feeding the surfacing material in the form of a filler (at plasma-powder surfacing) the coarse powder particles ($\geq 200 \text{ }\mu\text{m}$) can become additional crystallization centers. In this case, their influence is similar to the action of granulated powders, which are added to the flux-cored wire

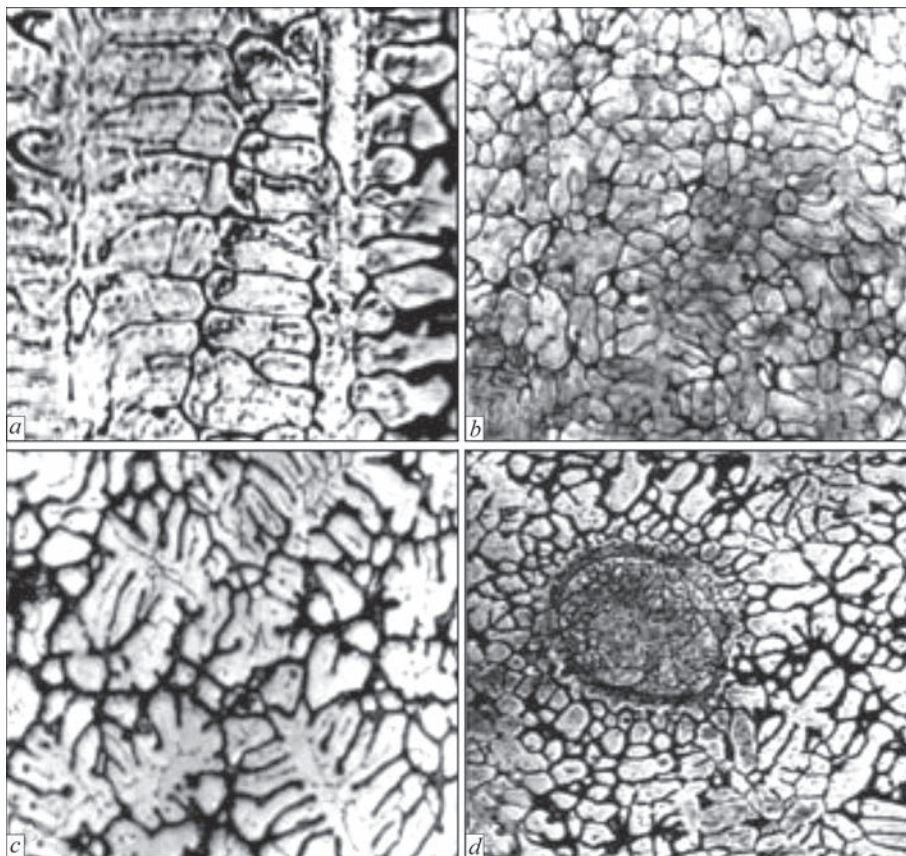


Figure 3. Microstructure of 10R6M5 deposited metal, produced at addition of coarse powder fractions into fine filler powder [5]: *a* — coarse fraction content 15 %; *b* — 30 %; *c* — 45 %; *d* — unmolten inclusion ($\times 400$)

core and are used in the form of electrode or filler materials in arc surfacing.

In [31] it is shown that application of granulated powder allows achieving more uniform filling of the flux-cored powder in arc surfacing, compared to standard wire with a charge from ferroalloys. Both the wires ensured production of deposited metal of the class of wear-resistant tool steel 35V9Kh3GSF. It was noted that the process of surfacing with flux-cored wire with granulated powder is stable, deposited metal formation is good, pores or other defects are absent. The resistance of rolling rolls surfaced by experimental wire with granulated powder was equal to the resistance of rolls surfaced by standard flux-cored wire based on ferroalloys. Here, the smaller the size of granulated powder grains, the higher is the wire fill factor that, obviously, should have influenced the welding-technological properties of the flux-cored wire and the deposited metal quality.

Another example of application of the abovementioned approaches and certain leveling of the influence of the welding arc high-temperature region at surfacing can be use of ultra-dispersed compositions of refractory metals in the flux-cored wire charge [6, 29, 30]. Application of such particles can have a positive influence on the deposited metal quality and can improve its operational properties.

So, in [6] the influence of ultra-dispersed carbide compositions added to the charge of flux-cored electrode wires on the properties of the deposited metal of the type of tool steels 35V9Kh3GSF and 30Kh4V2M2FS used at surfacing tools for hot pressure treatment of metals, was studied. The structure of metal deposited with standard flux-cored wires, consist of lath martensite (laths are elongated in one direction) and a small amount of residual austenite (Figure 4, *b*, *e*).

The structure of the metal deposited with experimental flux-cored wires with additives of ultra-dispersed carbide compositions, is more dispersed, and it has a somewhat different composition: alongside the laths it includes lamellar martensite (Figure 4, *d*, *g*). Residual austenite content is somewhat higher than in the metal deposited with standard wire. Alloying element distribution in the metal deposited with flux-cored wires using ultra-dispersed carbide compositions is more uniform, than at application of flux-cored wires with standard charge [6]. The mentioned features of application of ultra-dispersed carbide compositions in the flux-cored wire charge had a positive influence on the service properties of the deposited metal, improving its wear- and heat resistance.

It is obvious that by changing the technological parameters of the surfacing process it is possible to

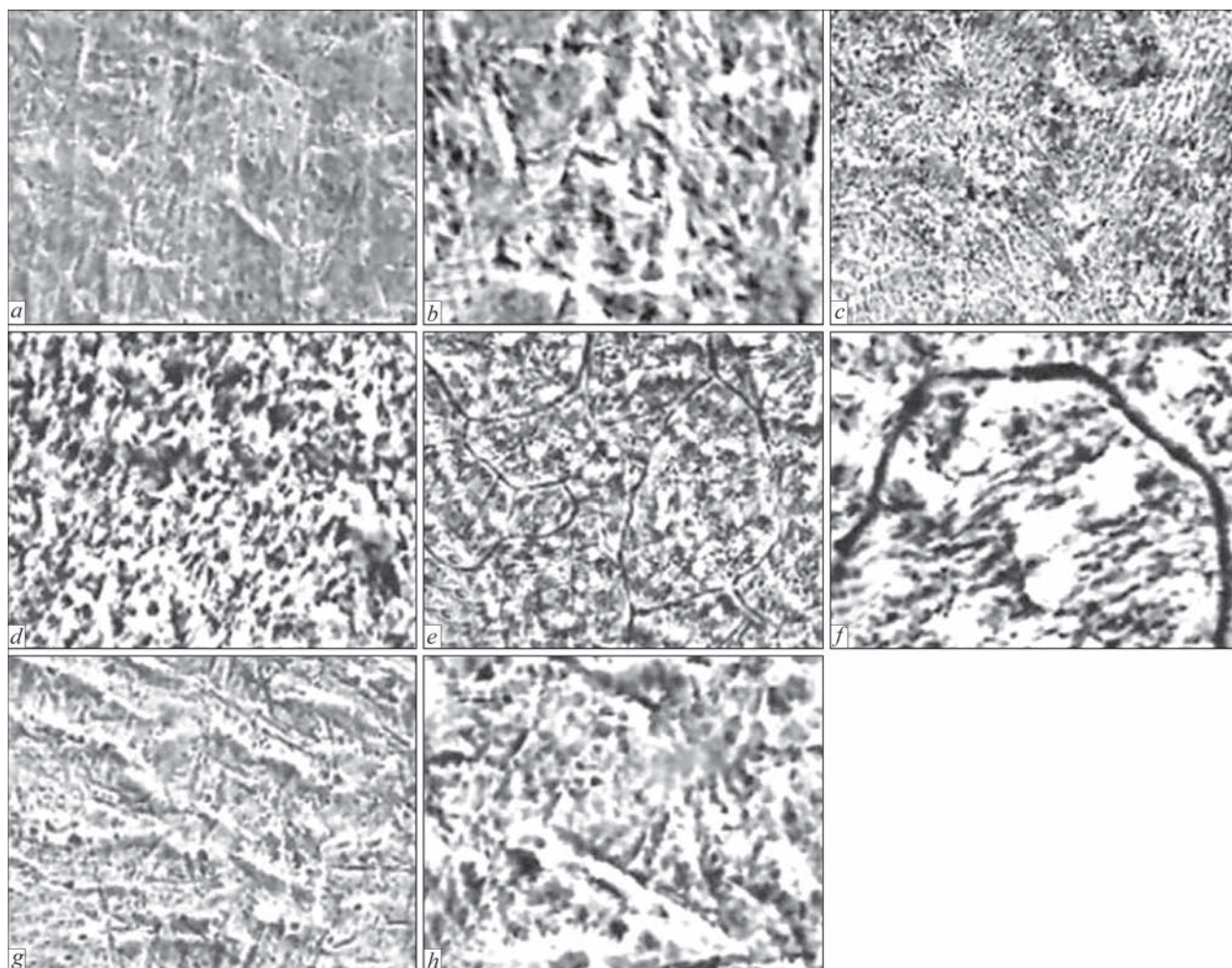


Figure 4. Microstructure of metal surfaced by flux-cored wires [6]: *a, b* and *e, f* — PP-Np-35V9Kh3GSF and PP-Np-30Kh4V2M2FS standard wires, respectively; *c, d* and *g, h* — experimental wires of similar type with additives of ultra-dispersed carbide compositions; *a, c, e, g* — $\times 900$; *b, d, f, h* — $\times 2000$

influence in a certain way the degree of manifestation of the structural heredity effect, as it is known that the solidification morphology, and, hence, the deposited metal microstructure, depend on the deposition rate, current and arc voltage, i.e. on the surfacing energy input. Moreover, by adjusting the amount of heat supplied to and removed from the part, it is possible to control the shape of the fusion line, penetration depth, and, therefore, the composition, structure and properties of the deposited metal to a certain extent [1, 2]. Thus, within certain limits, the degree of structural heredity can be controlled using methods, aimed at changing the metal melt crystallization conditions by varying the surfacing modes.

It is necessary to control the heating and cooling temperature and rate [32] and, depending on metal type, to avoid cyclic heating to high temperatures. For instance for high-speed steels heating up to 1260–1280 °C and subsequent quenching provides a rather fine-grained structure, but after reheating to the same temperature the steel structure is characterized

by very large grain size, leading to brittle naphthalene-like fracture of the tool in service [10].

For instance, for high-speed steel of R6M5 grade the critical melt temperature is 1500 °C (Figure 5). Crystallite grain size under the conditions of melt overheating in the temperature range of 1460–1500 °C changes after remelting, i.e. the dispersity and homogeneity of the initial structure are inherited at remelting in the subcritical temperature range. Now increase melt temperature above the specified temperature range leads to the process of radical restructuring of steel melts, transition to a more equilibrium state and loosing to a certain extent the characteristics of the initial charge billet [10].

Negative example of the heredity effect can result from repeated cyclic heating in multipass welding (surfacing) of heat-resistant [33, 34], high-strength [35] and stainless steels [36]. Structural heredity is manifested in the austenite memory effect, arising under the influence of high heating rates and peak welding or surfacing temperatures. As a result the initial coarse-grained structure is restored, because austenite cannot recrystallize.

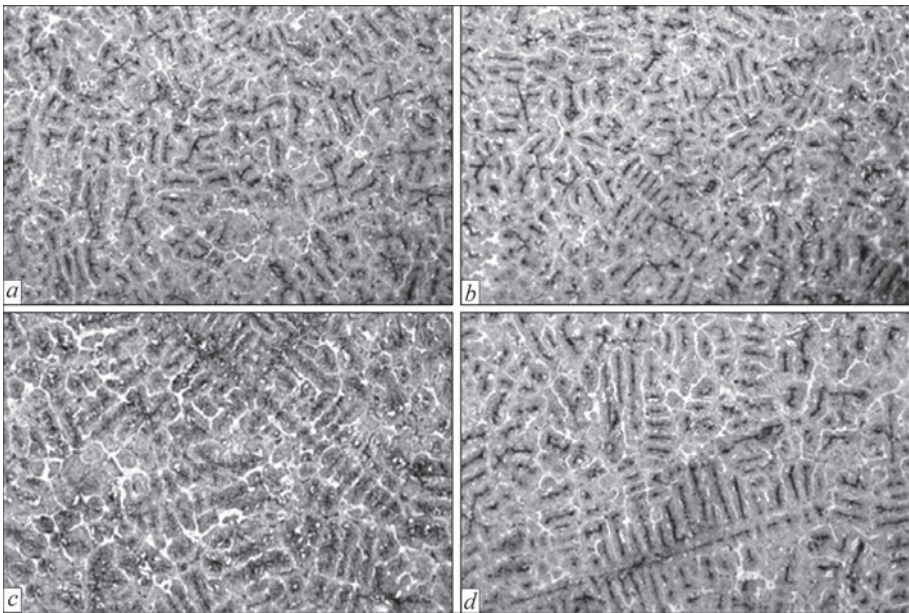


Figure 5. Structure of R6M5 steel, depending on remelting temperature [10]: *a* — 1460; *b* — 1500; *c* — 1540; *d* — 1620 °C (×100)

tallize, leading to higher brittleness and lower toughness in the zone of reheated metal regions. To avoid this effect, it is recommended to control the welding (surfacing) energy input at the level of 8 kJ/cm [35].

The influence of one-, two- and three-time remelting on transformation of the cast structure of the initial charge metal was studied in the case of R6M5L

steel [10, 12]. It was found that at subsequent remelting the grain size of the steel cast structure increases naturally with each remelting, the most significantly after three remelting operations. The size of R6M5L steel increases by 4–5 numbers on average after three-time remelting, compared to the grain of initial structural states of the billets (Figure 6). On the other hand,

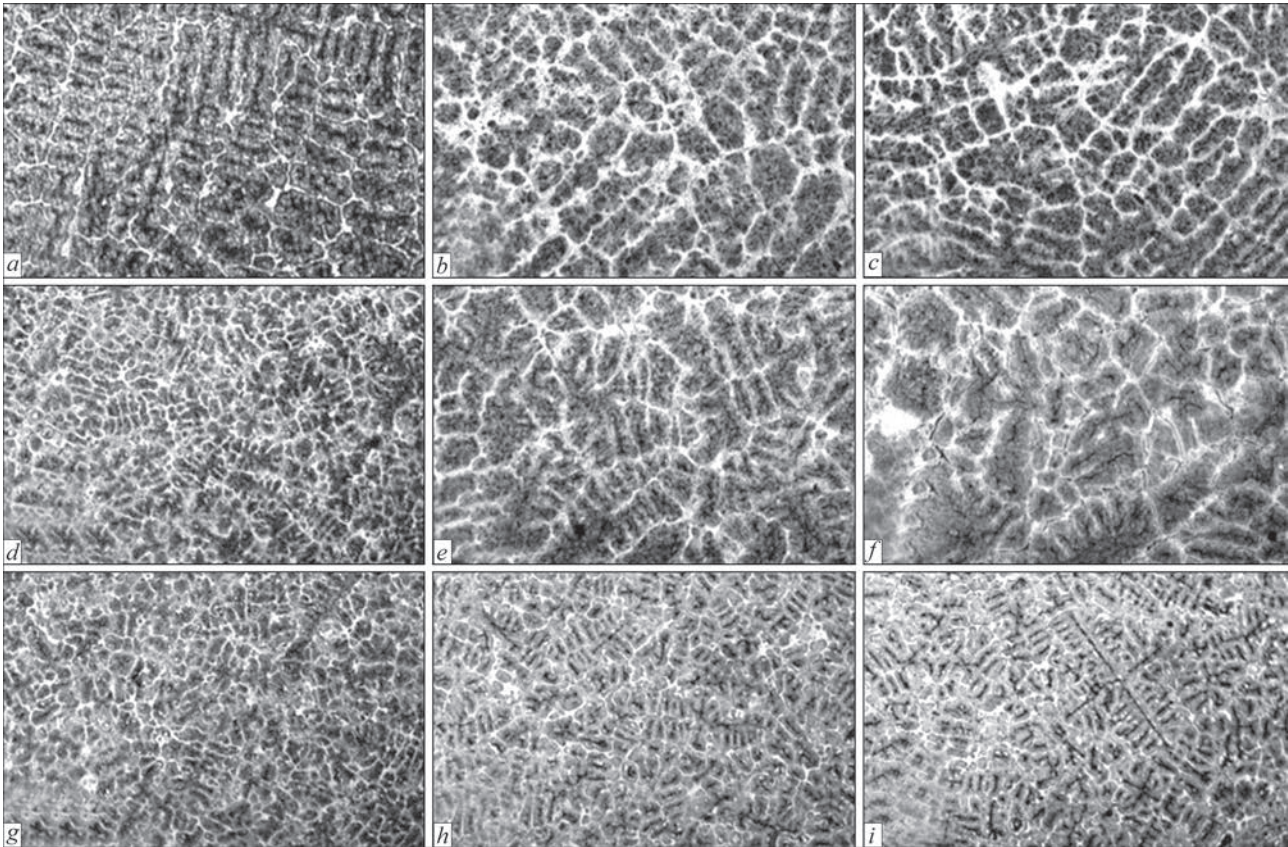


Figure 6. Transformation of R6M5L steel structure, depending on the number of remelting operations and crystallization conditions of the initial billet [12]: *a, d, g* — single remelting; *b, e, h* — double remelting; *c, f, i* — triple remelting; *a-c* — $V=2$; *d-f* — 350; *g-i* — 700 °C/s (×100)

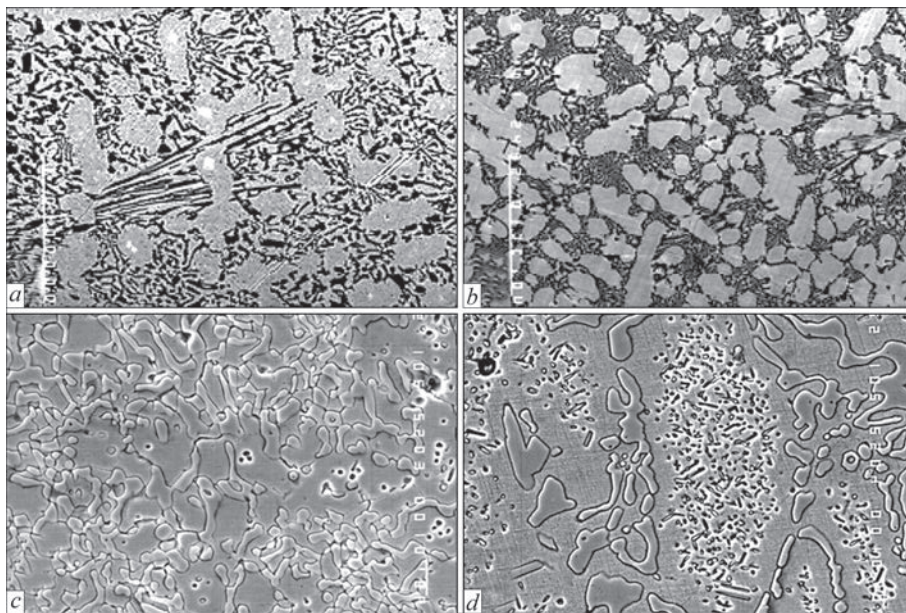


Figure 7. Microstructure of 250Kh25NT alloy [24]: *a, b* — cast state; *c, d* — after heat treatment; *a, c* — control metal; *d* — experimental metal; *a, b* — $\times 400$; *c, d* — $\times 1000$

at an essential increase of cooling rate ($700\text{ }^{\circ}\text{C}/\text{min}$) the incorporated level of non-equilibrium of the steel initial structures increases in proportion at crystallization of charge billets, and at subsequent remelting the high degree of non-equilibrium of rapidly cooled initial steels is preserved, compared to normal cooling steels that is indicative of the high stability of hereditary characteristics of initial billet structures formed at primary crystallization [12].

Application of different methods of external physical impact is another factor, which can influence the structural heredity effect. So, when studying the influence of electrohydropulse treatment (EHPT) of the metal melt on structural heredity of high-chromium wear-resistant cast irons it was determined that EHPT of the melt changes the structure formation conditions due to preservation of the hereditary structural characteristics at the change of aggregate state. Charge remelting by the traditional technology and with EHPT application showed that refinement of the structural components (eutectic carbides and matrix grains) occurred in the studied metal in the cast state. Further heat treatment revealed the presence of the characteristic structural features of the charge material (Figure 7) [24].

Such structural changes are attributable to EHPT influence on finer structural levels [24] that was confirmed by the results of X-ray phase analysis. Thus, the features of the melt structure formed by EHPT in it are fixed by structural elements and are preserved up to phase transition temperatures in the liquid and solid state, and are inherited at subsequent technological impacts (heat treatment).

The methods of weld pool treatment by high-frequency sound or mechanical vibrations will probably have certain potential as to enhancement of the heredity effect manifestation [37, 38]. For instance, in [37] it is shown that part treatment by ultrasonic vibrations during its arc welding results in formation of a more fine-grained structure, both in the weld and in the HAZ. Application of high-frequency (100 Hz) mechanical vibrations also leads to refinement of the deposited metal structural components and improvement of its structural homogeneity that has a positive effect on its service properties [38].

WAYS TO USE THE STRUCTURAL HEREDITY EFFECT IN ARC SURFACING

At present only separate publications are known in scientific-technical literature, which are devoted to the problem of the connection between the crystal-line structure of the initial solid materials with similar structures of the deposited metal, and the “heredity” term is practically not used in surfacing [4–6].

It follows from the conducted analysis, however, that investigation and development of the methods to control the structural heredity effect in arc surfacing can be a reserve for improvement of the operating properties of the surfaced parts. The main directions of investigations to improve the deposited metal structure and properties can be the ways to influence the following:

1. Initial parameters of surfacing materials: their chemical composition, impurity content, granulometric composition, structure and/or shape. In this case, using specially prepared electrode and/or filler materials for surfacing, it is possible to transfer the positive

properties from them to the deposited metal through the weld pool melt: fine-grained structure, uniform distribution of the strengthening phases (carbides, carbonitrides, carboborides), certain dendrite orientation, etc.

2. Weld pool crystallization rate by changing the value of heat input (energy input) through regulation of the electric and technological surfacing modes (current, voltage, surfacing material feed rate, use of pulsed, hybrid technologies, etc.).

As shown by previous studies, these methods of influence are rather promising. So far, however, only the influence of several individual factors has been studied, and the impact of other factors, also at their complex application, remains almost unstudied, for instance, influence of the granulometric composition and type of the surfacing metal materials at their application in the charge of flux-cored electrode and/or filler wires.

Based on this, it is necessary to take a balanced approach to selection of the base alloying system of experimental materials, considering the above determined features of manifestation of the heredity effect in steels and alloys. Carbon content in the deposited metal should be not lower than 0.2 %. Here, with increase of the degree of alloying with such elements as Cr, Mo, W, V, Ti, the structural heredity effect should be manifested under regular temperature conditions of metal crystallization during arc surfacing. Thus, promising materials in terms of effectiveness of manifestation of the structural heredity phenomenon in them, are alloyed and high-alloyed steels: tool, high-speed, maraging, corrosion-resistant, etc.

CONCLUSIONS

1. One of the promising, but practically unstudied methods to control the structure, and, therefore, also the properties of the deposited metal, is using the structural heredity effect, which is applied in metallurgy and foundry with the purpose of transfer and preservation of the fine-grained structure of the initial materials in the finished part structure, leading to an improvement of its operational properties.

2. Unlike metallurgy, application of structural heredity effect in surfacing production is complicated by the features inherent to all the fusion processes of surfacing (welding), namely influence of the initial chemical content and structure of the base metal, which is remelted and penetrates into the weld pool and deposited metal; as well as complex and fast-flowing temperature-time parameters of weld pool existence.

3. It has been preliminarily established that in arc surfacing methods the deposited metal structure and

properties can be controlled, using the heredity effect, in several ways, which can be applied separately or in a combination: by varying the initial parameters of surfacing materials (chemical and granulometric composition, structure, shape, etc.) and influencing metal pool solidification through regulation of the electric and technological surfacing modes and/or application of physical methods of its external treatment.

REFERENCES

1. Ryabtsev, I., Fomichov, S., Kuznetsov, V. et al. (2023) *Surfacing and additive technologies in welded fabrication*. Springer Nature Switzerland AG. DOI: <https://doi.org/10.1007/978-3-031-34390-2>
2. Ryabtsev, I.A., Kuskov, Yu.M., Pereplyotchkov, E.F., Babinets, A.A. (2021) *Surfacing. Control of base metal penetration and formation of deposited layers*. Kyiv, Interservice [in Russian].
3. Babinets, A.A., Ryabtsev, I.O. (2021) Influence of modification and microalloying on deposited metal structure and properties (Review). *The Paton Welding J.*, **10**, 3–10. DOI: <https://doi.org/10.37434/tpwj2021.10.01>
4. Ryabtsev, I.A. (2006) Structural heredity in the initial materials – metal melt – solid metal system (Review). *The Paton Welding J.*, **11**, 8–12.
5. Ryabtsev, I.A., Pereplyotchkov, E.F., Mits, I.V., Bartenev, I.A. (2007) Effect of initial structure and particle size composition of powder on structure of metal 10R6M5 deposited by the plasma-powder cladding method. *The Paton Welding J.*, **10**, 18–22.
6. Ryabtsev, I.A., Kondratiev, I.A., Gadzyra, N.F. et al. (2009) Effect of ultra-dispersed carbides contained in flux-cored wires on properties of heat-resistant deposited metal. *The Paton Welding J.*, **6**, 10–13.
7. Luchkyn, V.S., Tuboltsev, L.H., Padun, N.Y. et al. (2008) Structural characteristics of heredity of liquid cast irons and steels. *Fundamentalni ta Prykladni Problemy Chornoy Metalurgii*, **18**, 122–137 [in Russian].
8. Janerka, K., Jezierski, J., Bartocha, D., Szajnar, J. (2012) Heredity of the structure and properties of grey cast iron melted on a basis of steel scrap. *Advanced Materials Research*, **622–623**, 685–689. DOI: <https://doi.org/10.4028/www.scientific.net/amr.622-623.685>
9. Kutsova, V.Z., Kovzel, M.A., Nosko, O.A. (2007) *Phase transformations in special alloyed steels*. Dnipro, NMetAU [in Ukrainian].
10. Kondratyuk, S.Ie., Prymak, I.N., Shcheglov, V.M., Pliakhtur, O.O. (2009) Inheritance of the structure and manifestations of liquation during remelting of R6M5 steel. *Metaloznavstvo ta Obrobka Metaliv*, **3**, 3–10 [in Ukrainian].
11. Gubenko, A.Ja. (1991) Influence of the initial structural state of the melt on the properties of alloys. *Litejnoe Proizvodstvo*, **4**, 19–20 [in Russian].
12. Kondratyuk, S.Ie., Stoianova, O.M., Pliakhtur, O.O. (2012) The structural heredity of steels is related to the disbalance and and structural heredity of the charge materials. *Metaloznavstvo ta Obrobka Metaliv*, **1**, 3–9 [in Ukrainian].
13. Bokshetjn, S.Z., Bernshtejn, M.L. (1971) *Structure and properties of metal alloys*. Moscow, Metallurgiya [in Russian].
14. Kondratyuk, S., Veis, V., Parkhomchuk, Z. (2019) Structure formation and properties of overheated steel depending on thermokinetic parameters of crystallization. *J. of Achievements in Materials and Manufacturing Eng.*, **97(2)**, 49–56. DOI: <https://doi.org/10.5604/01.3001.0013.8537>

15. D'yachenko, S.S. (2000) Heredity in phase transformations: Mechanism of the phenomenon and effect on the properties. *Metal Sci. and Heat Treatment*, 42(4), 122–127. DOI: <https://doi.org/10.1007/BF02471324>
16. Meshkov, Yu.Ya., Pereloma, E.V. (2012) The effect of heating rate on reverse transformations in steels and Fe–Ni-based alloys. *Phase Transformations in Steels*, 1, 581–618. DOI: <https://doi.org/10.1533/9780857096104.4.581>
17. Timofeev, G.V. (2012) Structural heredity in rolled large sections from continuously cast billets. *Fundamentalni ta Prykladni Problemy Chornoy Metalurgii*, 25, 192–198 [in Russian].
18. Romaniv, O.N., Tkach, A.N., Vol'demarov, A.V. (1980) Method of complex improvement of the mechanical properties of low-tempered structural steels. *Materials Sci.*, 15, 373–378. DOI: <https://doi.org/10.1007/BF00720461>
19. Garasym, J. A., Bondarevskaya, N. A., Teliovich, R. V. et al. (2021) Influence of high-speed heat-setting on armor resistance of high-strength sheet metal of protective purpose. *Metallfiz. Noveishie Tekhnol.*, 43(9), 1235–1246. DOI: <https://doi.org/10.15407/mfint.43.09.1235> [in Ukrainian]
20. Delin, H., Zhang, F., Dingqiang, L., Yan, C. (1994) Re-investigation of austenite grain boundary inheritance in alloy steel. *Heat Treatment of Metals*, 1, 27–32, 50.
21. Ding, F., Guo, Q., Hu, B., Luo, H. (2022) Influence of softening annealing on microstructural heredity and mechanical properties of medium-Mn steel. *Microstructures*, 2, 2022009. DOI: <https://doi.org/10.20517/microstructures.2022.01>
22. Yang, D.P., Du, P.J., Wu, D., Yi, H.L. (2021) The microstructure evolution and tensile properties of medium-Mn steel heat-treated by a two-step annealing process. *J. Mater. Sci. and Technol.*, 75, 205–215. DOI: <https://doi.org/10.1016/j.jmst.2020.10.032>
23. Dang, S.-E., He, Y., Liu, Y., Su, Z.-N. (2014) Structural heredity of 30Cr2Ni4MoV steel. *Transact. of Materials and Heat Treatment*, S2, 61–65.
24. Volkov, G.V. (2011) Structural heredity in alloys after electrohydropulse treatment in the liquid state. *Naukovi Notatky*, 31, 56–62 [in Russian].
25. Tret'yakova, E.E., Rovbo, M.V., Hakimov, O.P., Churkin, V.S. (1991) Influence of the initial structure of cast irons on the surface tension of their melts. *Litejnoe Proizvodstvo*, 4, 11–12 [in Russian].
26. Movchan, B.A. (1970) *Crystallite boundaries in cast metals and alloys*. Kyiv, Tekhnika [in Russian].
27. Kondratyuk, S., Veis, V., Parkhomchuk, Z. (2020) The effect of thermal treatment of the melt before crystallization on the structure and properties of castings. *Archives of Materials Sci. and Eng.*, 104(1), 23–29. DOI: <https://doi.org/10.5604/01.3001.0014.3866>
28. Kondratyuk, S.E., Stojanova, E.N., Shcheglov, V.M. et al. (2013) Hereditary modification of steels with dispersed structured charge components. *Procesy Lyt'tya*, 2, 19–23 [in Russian].
29. Heath, G. (2006) Nanotechnology and Welding – Actual and possible future applications. In: *Proc. of the Castolin-Eutectic Seminar, 25 Oct 2006. Brussels, Belgium*, 25–35.
30. Klimpel, A., Kik, T. (2008) Erosion and abrasion wear resistance of GMA wire surfaced nanostructural deposits. *Archives of Mater. Sci. and Eng.*, 2, 121–124.
31. Kondratiev, I.A. (2015) Flux cored wire filled with granular alloy. In: *Surfacing. Technologies, Materials, Equipment*. Kyiv, PWI, 53–54 [in Russian].
32. Hu, Y., Chen, W., Han, H., Bai, R. (2016) Effect of cooling rate after finish rolling on heredity in microstructure and mechanical properties of 60Si2MnA spring steel. *Metallurgical Research & Technology*, 113(5), 508. DOI: <https://doi.org/10.1051/metall/2016024>
33. Peng, K., Yang, C., Lin, S., Fan, C. (2017) Effect of arc distance on HAZ thermal cycles and microstructural evolution 10CrNi3MoV steel. *Int. J. Adv. Manuf. Technol.*, 90, 3387–3395. DOI: <https://doi.org/10.1007/s00170-016-9639-4>
34. Arora, K.S., Pandu, S.R., Shajan, N. et al. (2018) Microstructure and impact toughness of reheated coarse grain heat affected zones of API X65 and API X80 linepipe steels. *Int. J. of Pressure Vessels and Piping*, 163, 36–44. DOI: <https://doi.org/10.1016/j.ijpvp.2018.04.004>
35. Lu, H., Xing, S., Chen, Z. et al. (2014) Microstructure and properties of GMAW multipass welding of Q-T high strength steel Q690D. *Heat Treatment of Metals*, 39(10), 120–124. DOI: <https://doi.org/10.13251/j.issn.0254-6051.2014.10.031>
36. Lu, X., Cen, Y., Wang, H., Wu, M. (2013) Structure and mechanical properties on DH40 ship building steel joints by multi-layer and multi-pass welding technology. *Transact. China Weld. Inst.*, 34(2), 79–83.
37. Kirian, V.I., Kajdalov, A.A., Novikova, D.P. et al. (2007) Improvement of welded joint structure under the impact of wide-band ultrasonic vibrations during welding. *The Paton Welding J.*, 2, 38–40.
38. Pokhmurskaya, G.V., Student, M.M., Vojtovich, A.A. et al. (2016) Influence of high-frequency mechanical vibrations of the item on structure and wear resistance of Kh10R4G2S deposited metal. *The Paton Welding J.*, 10, 20–25. DOI: <https://doi.org/10.15407/tpwj2016.10.04>

ORCID

A.A. Babinets: 0000-0003-4432-8879

CORRESPONDING AUTHOR

A.A. Babinets

E.O. Paton Electric Welding Institute of the NASU

11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.

E-mail: a_babinets@ukr.net

SUGGESTED CITATION

A.A. Babinets (2024) Using the heredity effect for control of the structure of the deposited metal during electric arc surfacing with flux-cored wires (Review). *The Paton Welding J.*, 10, 30–41.

DOI: <https://doi.org/10.37434/tpwj2024.10.05>

JOURNAL HOME PAGE

<https://patonpublishinghouse.com/eng/journals/tpwj>

Received: 27.05.2024

Received in revised form: 30.07.2024

Accepted: 28.10.2024