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Surface Hardening of Nodular Cast Iron by GTAW Remelting

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Abstract

The study reported in this paper was aimed at establishing the effect of values of parameters characterizing the process of superficial remelting of a nodular iron casting on the quantity of introduced heat, geometry of remeltings as well as parameter λ and hardness of cementite eutectic. The remelting process was carried out using GTAW method, at electric arc length of 3 mm in argon atmosphere, welding current intensities I = 50, 130, 210, and 300 A, and electric arc scanning speeds v_s = 200, 400, and 800 mm/min. The measurements included estimation of the quantity of heat introduced to the casting in the electric arc-induced remelting process with the use of flow calorimeter. Widths and depths of remetlings were assessed with the use of metallographic method. As a result of fast solidification, cementite eutectic was obtained in remelted material in which, in the course of cooling down to ambient temperature, austenite was subject to partial transformation into martensite. To characterize the cementite eutectic, value of the structural parameter λ was assessed. Values of the parameter were similar for areas of occurrence of both fibrous and laminated eutectic. Remeltings were examined at half of their depths. Micro-hardness measurements were taken in the same areas. The established quantitative relationships may prove to be useful in practice for the purpose of predicting values of parameter λ and hardness of remeltings in studies aimed at improving resistance of cast-iron castings to abrasive wear.

Keywords: Solidification Process, Mechanical Properties, Nodular cast iron, GTAW process, Surface layer

1. Introduction

With the development of technology, expectations concerning components of machines and devices operated under increasingly heavy loads in abrasive wear conditions become more and more demanding. Improvement of service properties of machine parts by using expensive alloying elements contributing to crystallization of hard and abrasion-resistant microstructure components is an unattractive option in view of the related increase of manufacturing costs. As a result, an increased interest in such welding techniques of forming overlay welds, coatings, and remeltings was observed which would allow to obtain service properties better than those of the substrate material. Creation of conditions for fast solidification of unalloyed grey cast iron is a factor allowing to assume that crystallization proceeds in a metastable system. The cementite eutectic which is then formed constitutes a mixture of austenite and cementite [1, 2]. Depending on rate of cooling down to ambient temperature, austenite is subject to transformation into pearlite, bainite, their mixture, or, partially, into martensite. Authors of [3] have found that superficial layer of nodular cast-iron castings, after remelting with a laser beam and cooling down to ambient temperature, contained 65–70% austenite, 16–20% cementite, and martensite constituting the rest.

To complete transformation of supercooled austenite into martensite, it is necessary to apply a sub-zero treatment.

A microstructure parameter characterizing cementite, lamellar, and fibrous eutectic is the interphase distance λ. The meaning of this geometrical parameter is explained in Figure 1.

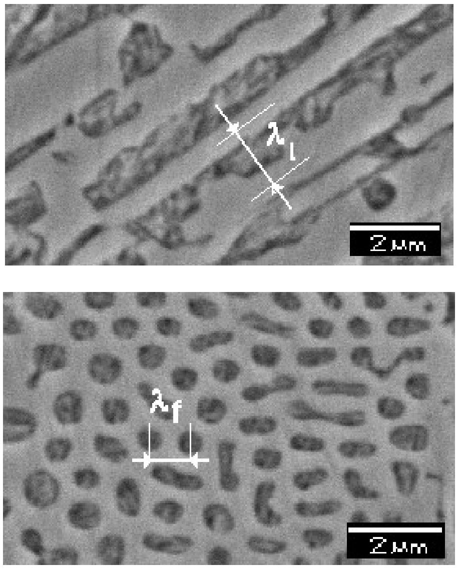

Fig. 1. Determination of structural parameter λ in lamellar and fibrous cementite eutectic

The abrasive wear resistance of cast irons showing the cementite eutectic structure depends on value of the structural parameter λ and on type and share of microstructure components that would form as a result of transformation of supercooled austenite in the course of the process of cooling down to ambient temperature and conditions of possible sub-zero treatment.

Studies concerning growth of cementite eutectic allowed to determine the degree of supercooling value necessary to obtain, at given growth rate, the required value of the parameter λ [4, 5]. According to authors of [6], the highest growth rate at which the cementite eutectic forms is 170 μm/s.

To estimate the rate of growth of solid phase u in remeltings made with the use of concentrated heat stream, certain authors [2, 5] used a formula given by Shamanin [7] in the form

$$u = v_s \cos\Theta \tag{1}$$

where v_s is the electric arc scanning speed and Θ is the angle between the vector of speed of scanning with electric arc and the vector of solid phase growth rate.

Using the above relationship, authors of [8] estimated the rate of growth of cementite eutectic in remeltings made with the use of GTAW method on nodular cast-iron castings. They have found that at the speed of scanning with electric arc in helium atmosphere equaling 200 mm/min, increasing the electric arc current intensity value from 50 A to 300 A resulted in a decrease of the solid phase growth rate from 132 μm/s to 31 μm/s.

The possibility to increase hardness of cast-iron castings and the importance of employing welding techniques for this purpose were reported by authors of [8]. In studies aimed at improvement of abrasive resistance of a 20-mm thick plate castings of nodular cast iron with pearlitic-ferritic matrix and hardness 15 HRC, application of hardening allowed to increase the hardness up to 40 HRC. The use of a 20-mm thick steel chill in the casting process made possible to create, in the superficial area of the casting, such conditions of crystallization which resulted in formation of cementite eutectic showing the structural parameter value λ = 3.2 μm. In the course of cooling down to ambient temperature, the austenite was subject to transformation into pearlite. Microstructure of these areas revealed also presence of vanishingly small content of graphite eutectic. Hardness of the material at depths of up to 2 mm from the casting surface was 44 HRC, compared to 39 HRC at depth of 4 mm. As a result of remelting of this portion of the casting surface which was not directly reproduced by the chill with the use of GTAW method in argon atmosphere, said remelting being carried out in the form of overlying passes (runs), solidification in the superficial region of the material led to formation of cementite eutectic with hardness of 65 HRC. Values of the structural parameter λ measured at half-depth of these remeltings was 1.2 μm. In the remelted areas, austenite was subject to partial transformation into martensite (Fig. 2).

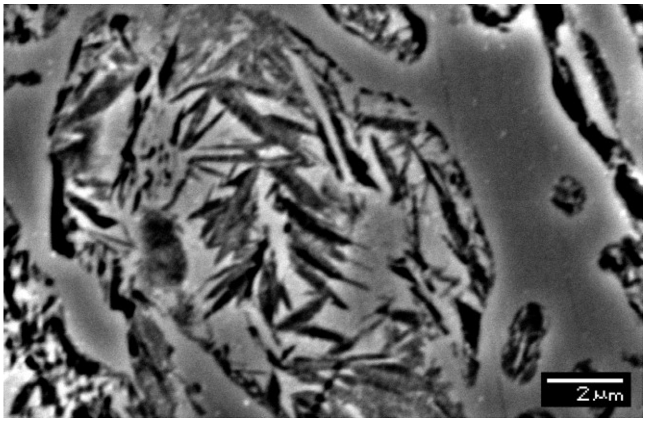

Fig. 2. Microstructure of a remelting in which austenite was subject to partial transformation into martensite in the course of cooling down to ambient temperature

Bearing in mind the possibility of providing conditions for fast solidification in superficial layer of grey cast-iron castings, it seems to be appropriate to establish quantitative relationships describing the effect of values of operating parameters defining the remelting process (the electric arc current intensity and the electric arc scanning speed) on depth and width of the remelting pass (run), as well as values of structural parameter λ and hardness of the obtained cementite eutectic. When developing such relationships, it must be remembered that in any system in which a number of variables take different values, it is a matter of interest to investigate their effect on values of other variables. Algebraic and/or analytic relationships describing the plurality of the involved physical processes are to complicated to express them in the form of simple mathematical formulae. However, even in case of absence of any obvious interdependence between the variables, it is still possible to strive to interrelate them in any of known diagrammatic forms or with the use of algebraic expressions. Although such formulae can be devoid of any physical meaning, they offer the possibility to predict values of certain variables based on knowledge of values of other ones.

In view of the above, the objective adopted for the present study was to develop diagrammatic relationships allowing to predict geometrical parameters of remeltings, values of the structural parameter characterizing the cementite eutectic formed in the remeltings, and hardness of the eutectic, depending on values of the electric arc current intensity and the speed of scanning with electric arc.

2. The experiment

The material used for the study were plate-shaped castings with dimensions 300 mm × 200 mm × 20 mm of unalloyed nodular cast iron (3.56%C, 2.03% Si, 0.21% Mn, 0.010% S, 0.04% P, 0.77% Cu, 0,69% Ni, 0.01% Mo, 0.05% Mg) made in industrial conditions. Such cast iron is typically used for machine components that locally need to show a particularly high abrasion resistance. From the castings, test plates with dimensions 210 mm × 50 mm × 10 mm were cut out. Remeltings on cast-iron plates were made with concentrated heat stream (GTAW method). To determine the quantity of heat introduced into test plates, they were mounted on a flow calorimeter [9]. The used current intensity values were I = 50, 130, 210, and 300 A, whereas the heat source was moved with speeds v_s = 200, 400, and 800 mm/min. The process was carried out with the use of tungsten electrode with diameter of 2.4 mm producing electric arc with length of 3 mm in the atmosphere of argon. The remeltings were 150-mm long.

From the test plates, specimens were cut out in the plane perpendicular to longitudinal axis of remeltings and then metallographic sections were prepared in order to disclose the microstructure. The sections were also used to measure width w and depth d of remeltings. Values of structural parameter λ of cementite eutectic, in view of high fineness of the latter, were assessed using VEGA Tescan scanning electron microscope. The measurements were taken in areas situated at half of actual remelting depths. The obtained results allowed to conclude that values of the structural parameter in case of fibrous and lamellar eutectic might be considered equivalent. Measurements of the parameter λ were taken along 20 measuring lines crossing at least 5 fibers or lamellas. Hardness measurements were carried out in remelting areas laying at half depths of remeltings with the use of Indentec ZHVμ Micro Vickers hardness tester (Zwick Roell). The load applied to indenter was 100 g. For each pass, measurements were taken from 5 different metallographic sections.

3. Research results and analysis

Results of examination of the effect of the electric arc current intensity and the speed of scanning with electric arc on the quantity of heat intercepted by the test casting, width and depth of remeltings, and parameter λ and hardness characterizing the formed cementite eutectic, are given in Table 1.

A diagrammatic representation of the effect of values of the electric arc current intensity and the speed of scanning with electric arc on the quantity of heat introduced to superficially remelted casting is presented in Figure 3.

Table 1.
Results of measurements and calculations of thermal, geometrical, and structural parameters of remeltings

No.	Remelting process parameters		Intercepted heat quantity	Geometrical parameters of remelting		Structural parameter	Hardness
	I (A)	v_s (mm/min)	Q_{cal} (kJ)	w (mm)	d (mm)	λ (μm)	HV0.1
1	50	200	21.0	2.4 ± 0.1	0.5 ± 0.03	0.59 ± 0.03	835 ± 6
2	130		60.4	5.0 ± 0.1	1.3 ± 0.03	0.79 ± 0.03	780 ± 6
3	210		115.2	7.1 ± 0.2	2.2 ± 0.05	1.00 ± 0.03	753 ± 5
4	300		192.9	10.1 ± 0.2	2.9 ± 0.05	1.23 ± 0.03	733 ± 5
5	50	400	7.4	1.6 ± 0.1	0.3 ± 0.02	0.45 ± 0.03	875 ± 6
6	130		21.5	3.5 ± 0.1	1.0 ± 0.03	0.60 ± 0.03	833 ± 6
7	210		42.0	5.8 ± 0.2	1.7 ± 0.03	0.76 ± 0.03	810 ± 6
8	300		69.3	8.1 ± 0.2	2.4 ± 0.05	0.89 ± 0.03	780 ± 5
13	50	800	1.0	1.0 ± 0.1	0.1 ± 0.01	0.24 ± 0.03	892 ± 6
14	130		3.5	2.1 ± 0.1	0.6 ± 0.01	0.32 ± 0.03	879 ± 6
15	210		8.0	3.8 ± 0.1	1.2 ± 0.03	0.41 ± 0.03	870 ± 6
16	300		14.2	5.1 ± 0.2	1.8 ± 0.03	0.50 ± 0.03	861 ± 6

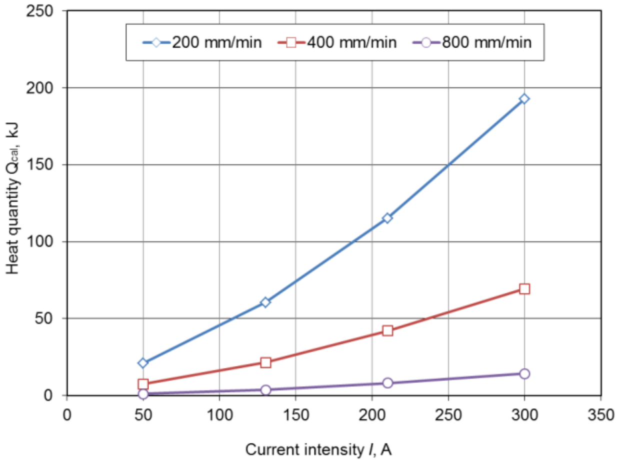

Fig. 3. The effect of the electric arc current intensity and the speed of scanning with electric arc on the quantity of heat introduced to the test casting

The obtained results show that together with increasing electric arc current intensity and decreasing speed of scanning with electric arc, the amount of heat introduced to castings increases. However, it must be borne in mind that the heat energy introduced to material of a casting is used first, to heat the material up to the melting point, then to melt, and finally to overheat the material. As the process continues, temperature of the material adjacent to the remelted area increases. The wider is the heated-up area, the longer is the period of local exposure to heat which depends on the speed of scanning the surface with electric arc.

A parameter characterizing the share of heat used effectively to form a remelting in the total quantity of heat intercepted by a casting is the melting efficiency [10]. Its value increases with increasing electric arc current intensity and increasing speed of scanning with electric arc.

The process of crystallization of cementite eutectic requires that liquid metal is cooled down to the solidification point. Occurrence of necessary degree of supercooling required to ensure that the eutectic crystallizes in a metastable system depends on the quantity of heat accumulated in the remelting area and the temperature of the material surrounding the remeltings. It should be also borne in mind that value of the heat conductivity of the material surrounding the liquid alloy in the remelting depends on temperature.

The value of the heat flux flowing out from the remelting region depends further on size of the contact surface between the region and the substrate. Such multitude of variables having an effect on eutectic growth and thus on value of structural parameter λ makes any detailed description of the process even more complicated.

In view of the above, an attempt was made to establish simple relationships which could be used for the purpose of industrial practice.

The effect of the electric arc current intensity and the electric arc scanning speed on width and depth of remeltings is presented in Figures 4 and 5.

The obtained results indicate that remelting depths and widths increase with increasing value of the electric arc current and with decreasing scanning speed. Within the analyzed range of parameters, the relationships can be described as linear ones.

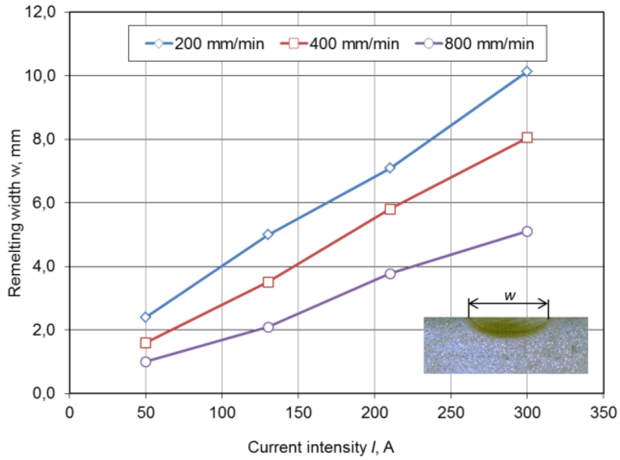

Fig. 4. The effect of the electric arc current intensity and the electric arc scanning speed on width of remeltings made on a plate cast from nodular cast iron

The effect of value of the electric arc current intensity and the speed of scanning with electric arc on value of the structural parameter λ characterizing the cementite eutectic is presented in Fig. 6.

The obtained results indicate further that values of the parameter λ demonstrated by the formed cementite eutectic increase with increasing electric arc current intensity and decreasing speed of scanning with electric arc.

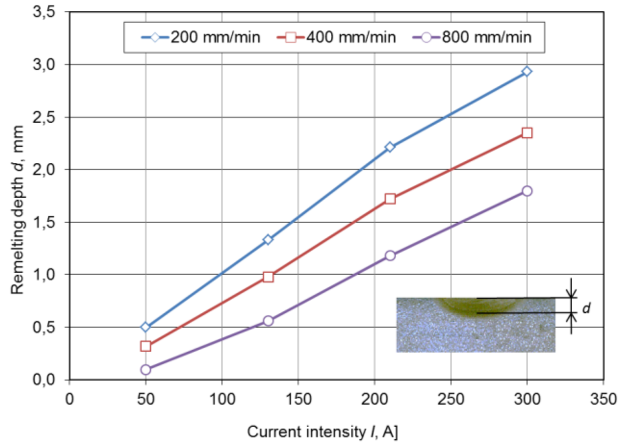

Fig. 5. The effect of the electric arc current intensity and the electric arc scanning speed on depth of remeltings made on a plate cast from nodular cast iron

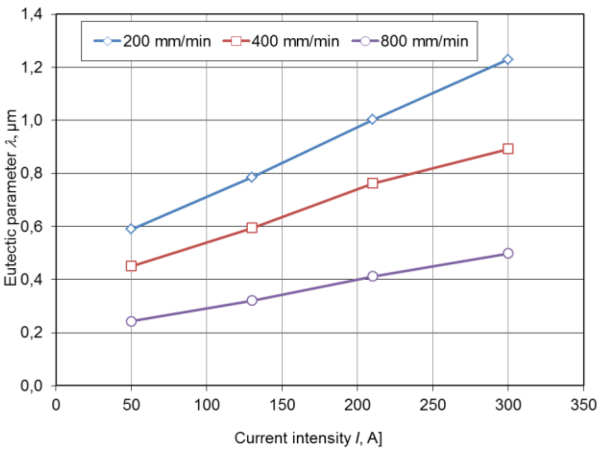

Fig. 6. The effect of the electric arc current intensity and the speed of scanning with electric arc on values of the parameter λ characterizing the cementite eutectic formed in remeltings made on nodular cast iron plate castings

Figure 7 represents a diagrammatic relationship which allows to predict hardness of remeltings made on a nodular cast-iron casting depending on the adopted values of parameters defining the surface remelting process.

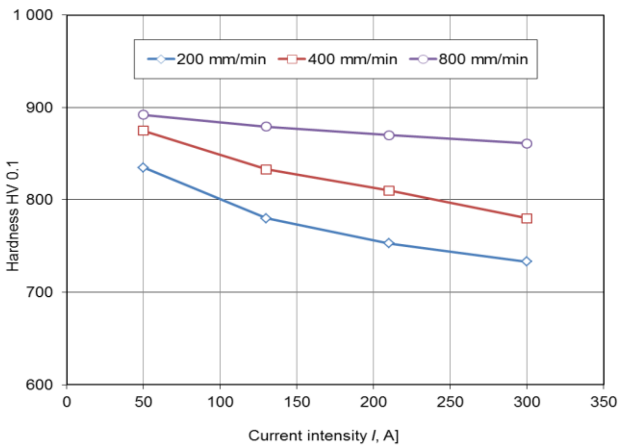

Fig. 7. The effect of the electric arc current intensity and the speed of scanning with electric arc on hardness of remeltings made on nodular cast-iron plate casting

The obtained results indicate that hardens of the remelted material decreases with increasing value of the electric arc current and decreasing speed of scanning with electric arc. It is a well-known fact that hardness of remeltings increases with decreasing value of parameter λ. On the other hand, value of λ decreases with increasing degree of alloy supercooling. The obtained results allow therefore to conclude that the degree of supercooling was higher in remeltings with small widths and depths. These remeltings were characterized with relatively smaller volumes of liquid metal which resulted in higher cooling rates. This, in turn, created favorable conditions for more effective transformation of supercooled austenite into martensite which had a beneficial effect in the form of higher hardness of the remelted material.

4. Conclusions

The established relationships between values of structural parameter λ characterizing cementite eutectic and its hardness on one hand and values of parameters defining the technological process of surface remeltings with the use of GTAW method in atmosphere of argon on the other can be used for the purpose of forming nodular cast-iron machine components resistant to abrasive wear.

Surface improvement of nodular cast-iron castings with the use of the surface remelting technique creates conditions for fast solidification of superficial regions which contributes to crystallization of cementite eutectic. As a result of fast cooling down to ambient temperature, austenite present in the eutectic is transformed partly into martensite. Those castings which show presence of cementite eutectic in their superficial layer and in which residual austenite was subject to a partial transformation into martensite, will be characterized with high resistance to abrasive wear. Hardness of the layer can be made even higher by forcing the residual austenite to be transfored completely into martensite by means of sub-zero treatment. This, however, requires further research, e.g. dilatometric measurements, to determine values of TM_f (end-of-martensitic-transformation temperature).

We assume that in further studies on the subject, remeltings will be performed in the form of overlapping passes (runs).

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