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REPARATION OF A MASSIVE MACHINE PART MADE OF GREY CAST IRON

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Abstract: The analysis of the reparation procedure of the damaged turbine diaphragm from the ironworks plant, which was subjected to wear during the long-term exploitation process, is presented in this paper. The two-thirds of the bearing volume of the turbine diaphragm, made of grey cast iron EN-GJL-150, were damaged, and its functional properties were lost. The reparation was executed by the multi-layer hard-facing process. The procedure included verification of the material's chemical composition, mechanical properties and metallographic structure, necessary for definition of the appropriate methodology for the part's rehabilitation. The hard-facing was executed with preheating, as well as the post-welding heat treatment, with specifically selected filler materials and all the adequate welding process parameters. The executed hard-facing procedure turned out to be the cost efficient since, as a rule, the costs of reparation did not exceed 20 % of the price of that would be paid for acquiring the new part.

Keywords: Grey cast iron, turbine diaphragm, reparation, hard-facing

1. INTRODUCTION

The goal of repair welding/hard-facing is to reduce the maintenance costs through reducing the costs required for the procurement of new parts and by reducing the downtime costs due to, very often, long lasting procurement of a new part. According to data from the literature and the author's experience, it is known that the costs of reparative surfacing, as a rule, do not exceed 20 % of the price of a newly acquired part, (Arsić et al., 2016). Hard-facing and repair welding are crucial techniques for restoring the functionality of machine parts made from challenging materials such as grey cast iron. These methods not only reduce maintenance costs but extend the service life of components, as well. For instance, Marković et al. (2022) demonstrated how the selection of appropriate filler materials significantly improves the performance of hard-faced gear surfaces under experimental and operational conditions, emphasizing the role of tailored metallurgical properties in ensuring durability. Similarly, Belan et al. (2023) explored the impact of structural parameters, including graphite shape and matrix composition, on ultrasonic wave propagation and attenuation in graphitic cast irons, highlighting the relationship between material structure and mechanical behavior. These studies underscore the importance of precise material characterization and technique optimization in achieving successful repairs.

Repair surfacing began to be applied in nuclear power plants, and then in mechanical engineering, mining, construction and process industry, all the way to the food industry and agriculture.

Grey cast iron is a cast material, mainly consisting of iron with carbon present in the form of lamellar graphite. Though it belongs to a group of poorly weldable materials (Pouranvari, 2010), in industrial practice one can often encounter the damaged parts made of this material that require repair, which must be done by welding. Most often, these are the working machine parts of a complex geometry and large mass, the re-manufacturing of which would be too demanding and/or expensive. Problems in welding of castings are reflected in the possibility of cracks appearing in the welded joints due to the low deformation capacity of the material and due to the large temperature gradient (Ivković et al., 2023.a; Ivković et al., 2023.b). This is especially pronounced in the case of parts of large dimensions and significant operational damage. To prevent this, welding/repairs must be carried out extremely carefully. Welding/hard-facing of parts made of grey cast iron represents a very complex and difficult practical problem in ensuring their functional correctness after the repair. Today, modern ways of welding castings such as laser or plasma are used in the industry, but traditional welding is still in use (Hamilton, et al. 2022, Sadeghi, et al. 2017), which was applied in this work.

The procedure for repair by welding and hard-facing of the damaged turbine diaphragm is considered in this paper. Due to wear and tear in the process of a long-term exploitation of the turbine diaphragm in the Smederevo ironworks (Serbia), two-thirds of the bearing volume was damaged and functional properties were lost. According to the user's documentation, the turbine diaphragm was made of EN-GJL-150 (SL 150 – mark by Serbian standards) grey cast iron.

The proposed procedure for the damaged diaphragm repair included examination of the chemical composition, mechanical properties and metallographic structure of the basic material of the turbine diaphragm, its weldability and eventual necessity of the heat treatments, and based on the analysis of the possibility and justification of the repair, the appropriate technology of welding/hard-facing.

2. THE TURBINE DIAPHRAGM MATERIAL PROPERTIES VERIFICATION

The turbine diaphragm, rehabilitation of which is described in this paper, had a diameter of Ø 1570 mm, Figure 1. According to manufacturer’s documentation, it was made of was made of grey cast iron EN-GJL-150.

Since it was decided to repair the turbine diaphragm by welding/hard-facing, a part of the turbine material was provided for the materials properties’ verification. The chemical composition of the material is given in Table 1 and its mechanical properties in Table 2, (ISO 185:2020 standard). Both tables give the standard prescribed values, as well as values obtained by the corresponding tests.

Table 1

Chemical composition of grey cast iron EN-GJL-150, wt.%

Element	C	Si	Mn		S	P
Standard value	2.5-4.0	1.0-3.0	0.25-1.1		0.025-0.25	0.05-1.0
Experimental value	3.62	0.72	0.50		0.15	0.55

Table 2

Mechanical properties of grey cast iron EN-GJL-150

Property	Yield strength YS [MPa]	Tensile strength TS [MPa]	Elongation A5 [%]	Impact energy E_I [J]	Hardness
Standard value	100	150	0.6	8 - 13	-
Experimental value	98	141	0.6	8,1	148

Based on the results of the performed testing, it can be seen that only the Si content is lower than that provided by the standard by approximately 30%, which affected the reduction of tensile strength and yield strength.

The metallographic tests were performed to check the structure of the obtained material. The structure of the examined sample corresponds to the structure of grey cast iron, according to the corresponding standard. The graphite lamellae are distributed in the ferrite-perlite base in some places in the form of large rosettes in Figure 2(a), and in a larger percentage they are distributed according to Figure 2(b). The participation of graphite in the structure is not the same everywhere, as shown in Figures.

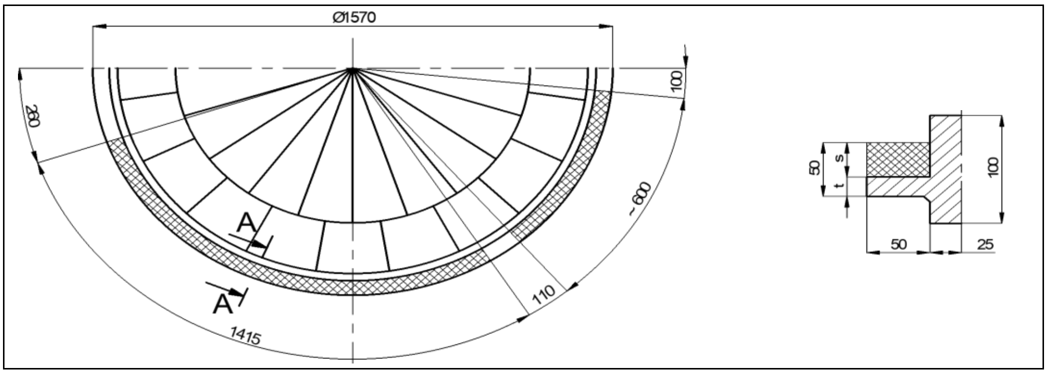
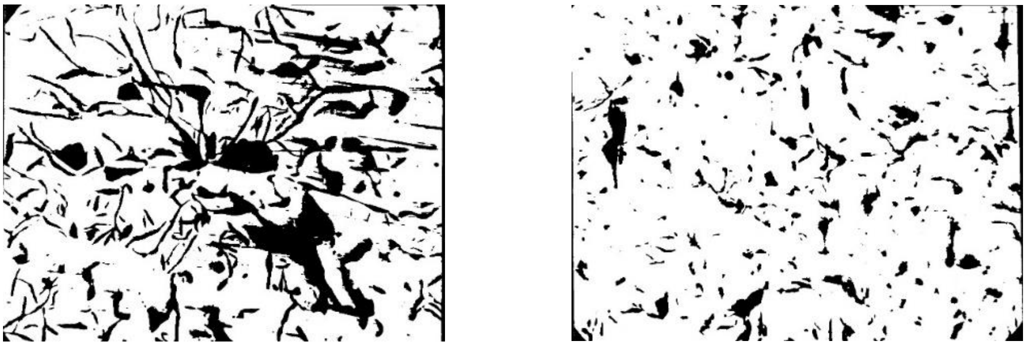


Fig. 1. Appearance of the damaged part of the turbine diaphragm; detail on the right is the section A-A; t is the minimal thickness (18/22/35 mm – relief), s is the hard-faced layer thickness (32/28/15 mm), hatched is the surface that is to be hard-faced.



(a) (b)

Fig. 2. Results of metallographic test; (a) Large lamellas of graphite, (magnification 100×); (b) Finer lamellas of graphite, (magnification 100×). Etched in 3 % nital solution.

Based on the chemical composition, tensile strength, hardness and metallographic images, the tested sample can be classified in the grey cast iron of 150 material class.

The classification and categorization of grey cast iron is usually determined based on the amount of carbon equivalent C_e and the effect of solidification rate. The empirical expression for C_e contains the amount of total carbon T_e (C - bound in the metal base - bound and free carbon - graphite) and that amount of silicon and phosphorus, which are equivalent in effect to carbon:

$$C_e = C + \frac{1}{3} \cdot (Si + P) = 3.62 + \frac{1}{3} \cdot (0.72 + 0.8) = 4.1267 \ \approx 4.13\%. \tag{1}$$

Cast iron with a carbon equivalent of $C_e < 4.3$ belongs to the hypotectoid casts, which usually have a flaky graphite structure.

The influence of the solidification rate of the material on its structure, and thus on its mechanical properties, is the cause of large differences in properties in different sections and wall thicknesses of the same cast made of ordinary grey cast iron. In a thicker wall (above 12 mm) the structure is mainly only ferrite and coarse graphite. The disadvantages of ordinary grey cast iron can be mitigated with special additives (modification agents), which was not the case here. Therefore, the grey cast iron class 150 has the weakest mechanical properties.

The application of welding/hard-facing during the repair of damaged cast parts made of grey cast iron has a thermal effect on the properties of the base material, so it is necessary to know the thermal and physical properties of grey cast iron from which the parts in question are made, Table 3, (Wei et al., 2024).

Table 3
Thermal physical properties of grey cast iron EN-GJL-150

Density at 20 °C [g/cm^3]	Linear expansion coefficient from 100 to 700 °C	Thermal conductivity coefficient
7.8	$11.0 \cdot 10^{-6}$	0.66

Under the property of weldability, one distinguishes the physical weldability and technological weldability. The physical weldability is characterized by the possibility of physical-chemical processes to create a welded joint. The technological weldability is characterized by all the properties of the base metal that determine its reactions to the changes that occur during the welding. Thus, the physical weldability of grey cast iron is good, and the technological weldability is poor. Obtaining the required properties of the welded joint is possible only under the condition that certain technological measures were applied to improve its weldability.

Achieving that the welded joints/hard-faced layers have the mechanical properties closest to the base material ones depends on the chemical composition of the base material, the chemical composition of the additional material/filler metal and the cooling rate of the weld metal.

In general, the weldability of the cast part is better if the fracture surface is light grey, and worse when the fracture is black, which was the case with the turbine diaphragm.

3. THE HARD-FACING TECHNOLOGY

Taking into account the results of the base material tests, ensuring the related properties of the base material and the weld metal of the turbine diaphragm was mainly related to the regulation of the cooling rate. Depending on the cooling rate, the grey cast iron solidifies in a stable or unstable system. The fact that the cooling rate during the solidification of grey cast iron weld metal is several tens of times higher than the cooling rate during the graphitization of castings, determines the solidification and cooling of the welded joint according to the metastable system.

The two methods can be used for welding/hard-facing of the grey cast iron: hot welding and cold welding. When it is required that the chemical composition of the base material and the weld metal must be similar, the hot welding is applied using the high-temperature preheating. The welding process with high-temperature preheating can eliminate the problem of the hardening structure in the heat-affected zone, because the welding thermal cycle is regulated to a certain extent, especially by reducing the cooling rate. However, the extent to which the application of technological measures in this way would provide a hard-faced layer with the required properties, without cracks, depends on the chemical and structural composition of the specific cast part, which was difficult to predict in relation to the years of exploitation and the extent of damage to the turbine diaphragm.

To regulate the cooling rate and the solidification rate to the level required for graphitization is possible by applying the high-temperature preheating, while adjusting the chemical composition of the additional material/filler metal.

The high-temperature preheating provides sufficient time to eliminate soluble gases from the molten weld metal, and is also a stress-relieving annealing process. The hard-faced layer structure and properties become close to the base material. The preheating temperature is limited by the eutectoid transformation temperature of the grey cast iron (723 °C).

By analyzing the damage to the turbine diaphragm, it was concluded that the bearing volume was damaged to the extent of 1/3 to 2/3, Figure 1. Keeping this fact in mind, it was necessary to determine the real possibilities and justification of the repair, on the one hand, or after the repair, predict the operation with reduced load, if possible. The quality requirements for repair are also directly related to the grey cast iron quality class and exploitation requirements.

Considering the level of damage to the turbine diaphragm, a high-temperature preheating of the casting as a whole was performed with a preheating temperature in the interval of 550 ± 50 °C and a maximum heating rate up to the preheating temperature in the range of 100 to 150 °C/h, while the temperature of the casting during the hard-facing (working temperature) could not be higher than 650 °C and lower than 450 °C. The chamber furnaces were used to achieve the preheating temperature, maintain the working temperature during the hard-facing and maintain the required cooling rate.

The heat treatment after the hard-facing was performed directly from the hard-facing temperature, by annealing to eliminate the residual stresses. The diagram of the heating - hard-facing - cooling thermal cycle is shown in Figure 3. Activities during the implementation of the turbine diaphragm hard-facing technology are given in Table 4.

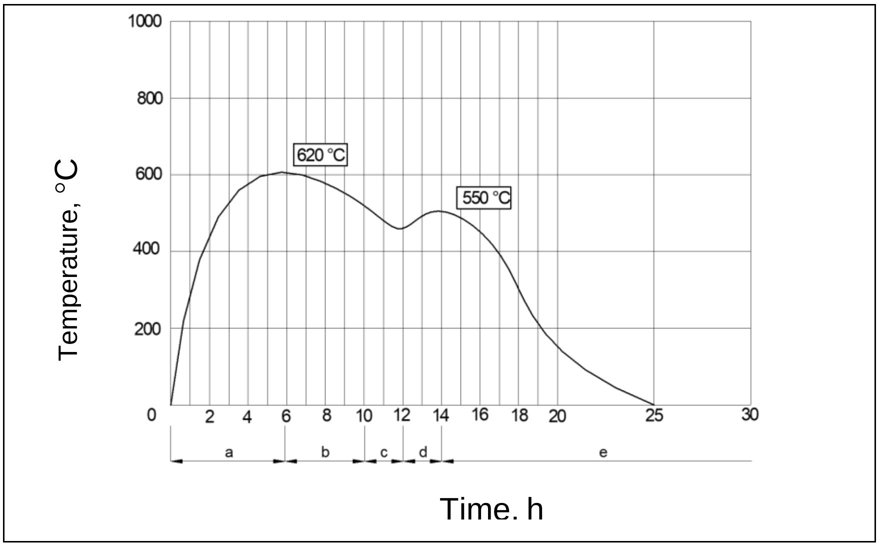


Fig. 3. The thermal cycle of the diaphragm hard-facing: a – heating, b – hard-facing, c – hard-facing end, d – annealing, e – cooling.

Table 4
General specification of the hard-facing technology of the turbine diaphragm

Activity	Way of execution	
Preparation	Hard-faced layer shape	According to the mold for the required shape
	Mandatory cleaning of surfaces for hard-facing	
	Mechanical	Machining by milling, grinding and cutting
Thermal cycle of the whole part	Preheating	Average value $T_V = 550 \pm 50$ °C Maximum heating rate 100 – 150 °C/h, in the case of the whole part heating
	Interlayer temperature	Temperature during the hard-facing $T_{hf} = T_V$ ±5 0°C
	Cooling down to 300°C	Cooling rate 40 °C/h for the parts sensitive to stresses
Heat treatment after the hard-facing		Without cooling after the hard-facing
Welding procedure	MIG/MAG	Hard-facing
Filler metal		Electrodes for grey cast iron hard-facing

3.1. Preparation for hard-facing

Removal of products deposited during exploitation and storage of the casting was carried out by light grinding. For the purpose of hard-facing the worn surfaces, all the bruises and deformed layers due to wear were removed. The preparation of surfaces for hard-facing included shaping of those surfaces accompanied by the shape and dimensions control.

3.2. Execution of hard-facing

Considering that the hard-facing requires application of the same general rules as welding, the following was done when repairing the turbine diaphragm:

- The electrodes were placed on the + pole with a slightly increased current (140 A - for the first welding pass with an electrode of Ø 3.25 mm diameter and 160 A - for the other welding passes with an electrode of Ø 4 mm diameter), because the wider and smoother welds would be obtained;
- First, the edges of the prepared surfaces (periphery) of the cleaned surface were welded due to the less heat input to the parts of a smaller thickness on the diaphragm, so that the base material would eventually deforms towards the inside. During the further welding, the slag would gather towards the cone and after solidification it could be easily removed;
- For hard-facing, a CSi type electrode was used (electrode SL 250 with weld metal hardness 270 HB and tensile strength 270 MPa), which produces the wider interlayer, and the hard-faced layer would have good machinability;
- Electrode swaying was applied for the size of the electrode diameter;
- For the welding of larger surfaces on the turbine diaphragm, to reduce the thermal stresses and deformations, the procedure of the combined welded layer was used.

A sketch of one of the turbine diaphragm segments is shown in Figure 4, while the order of welds/layers deposition and the direction of application, for ensuring as small heat concentration as possible, are shown in Figure 5.

To obtain evenness of the welded surface and a favorable thermal effect, each subsequent welded layer overlapped the previous one by one third of its width. Welding was performed by trained welders, experienced in welding/hard-facing of grey cast iron. During the rehabilitation process of the turbine diaphragm, supervision by the welding technologist was provided.

4. DISCUSSION AND CONCLUSIONS

Quality requirements and acceptance criteria in this case were limited for the following reasons;

- The turbine diaphragm damage amount was 1/3 to 2/3 of its bearing volume;
- The dimensions, structural solution, level of damage and condition of the basic material (old casting) of the turbine diaphragm did not allow the full application of thermal treatment;

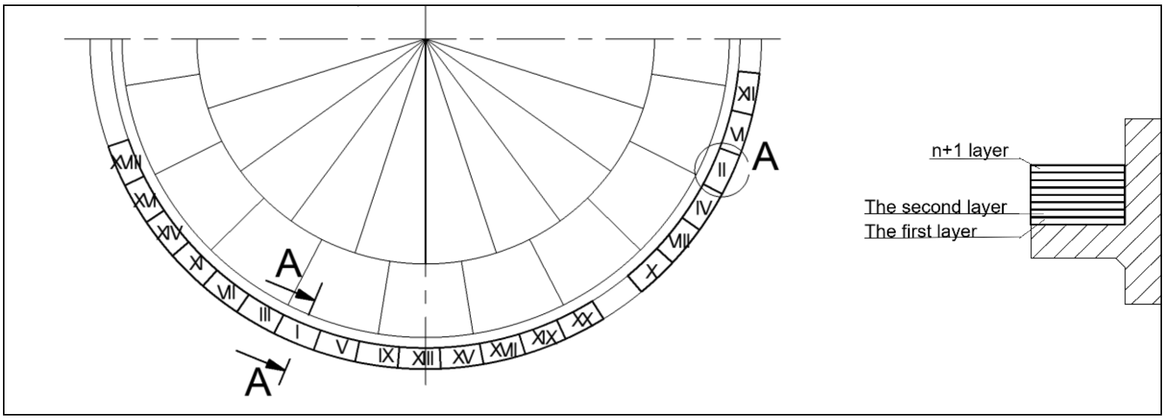


Fig. 4. The sketch of a turbine diaphragm segment with detail A on the right.

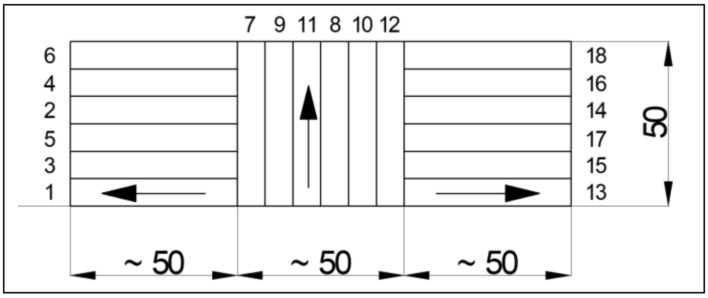


Fig. 5. The order and directions of layers deposition

- Requirements for the quality of the welded layers (overhang, sinking, overlaps), as well as the finishing and dimensional checking were difficult due to the constructional solution of the diaphragm itself;
- There were no special requirements for the hardness of welded surfaces. The hardness of the hard-faced surface, which depends exclusively on the applied electrode, was tested with a portable hardness tester;
- Visual control was performed prior to the hard-facing, during the hard-facing and after the hard-facing. Before the hard-facing control of all the preparatory operations was executed, as well. During the welding, control of the welding technology basic parameters was continuously conducted – the appearance of welds, overhangs of welds, notches, pitting, surface cracks and surface porosity. A complete visual inspection was carried out after the hard-facing;
- Ultrasonic tests were used to check the homogeneity of the inner part of the hard-faced layers. From the aspect of standardization in the field of welding/hard-facing of the grey cast iron only national standards exist, as well as instructions and recommendations. In this case, only the ISO C.H3.016/1985 standard for marking electrodes was used, which essentially does not represent a standard related to welding/hard-facing.

To ensure quality during the welding/hard-facing of the grey cast iron, it is often necessary to perform the qualification (certification) of the provided technology, for the purpose of eliminating the possible failures that may occur in the process of welding/hard-facing. For the repair of damage to the turbine diaphragm, the qualification of the applied hard-facing technology was not performed. However, the repaired turbine diaphragm was successfully used in operation, which, to a certain extent, certifies that the applied hard-facing technology was justified.

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