Studies of Boriding Using Possibility to Increase the Corrosion Resistance of Cast Steel 20GL

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Abstract: This paper presents the findings of corrosion studies of cast steel 20GL (structural alloyed steel: G—1% of Mn, L—alloyed) with boriding, selected as a promising passive method of protecting hydraulic machine elements from hydro-solid particle erosion and corrosive effects. Earlier studies have shown the boriding efficiency to increase the solid particle erosion resistance of cast steel 20GL by two–eight times depending on the solid particles’ impact angle of 30° and 90°. The boriding was carried out in a melt based on sodium tetraborate, sodium fluoride and sodium chloride salts in a shaft furnace with external heating. Results indicated that the boriding process did not affect the initial roughness of cast steel 20GL but increased the surface microhardness by more than six times, up to 1680–2080 HV0.01. The total layer thickness after two boriding processes was from 80 to 150 µm. The results of corrosion resistance studies by electrochemical methods obtained in this work showed the positive effect of boriding of steel 20GL. Boriding turns steel 20GL from a low-resistant class (score 6) to a resistant class (score 4–5) on a 10-point scale of corrosion resistance of metals. The boriding at a depth of 150 ± 5 µm reduces the corrosion rate in the environment of 3% NaCl solution by 2.8 times and in the environment of 0.7% Na2SO4 solution by 4.1 times, compared with the initial material without modification. It is revealed that an increase in boriding depth leads to an increase in corrosion resistance. The results indicate that the boriding of hydraulic machine parts made of 20GL steel will increase their corrosion resistance, thus prolonging the operating and overhaul period.

Keywords: blade hydraulics; cast steel; corrosion wear; solid particle erosion; diffusion coatings; boriding; corrosion potential; electrochemistry; gravimetry

1. Introduction

The wear of the functional surfaces of blade hydraulics (pumps and hydraulic turbines) can be caused by a large number of damaging factors, which can include: cavitation-abrasion [1], cavitation [2], hydro-abrasion [3], corrosion [4], contact [5], as well as wear (destruction) from impact with foreign objects [6]. It is impossible to separate one factor from another when describing the wear of real hydraulics, and identification of the contribution of each factor to the overall wear process requires a large amount of laboratory research. Solid particle erosion and corrosion can make a major contribution in certain operating conditions or in certain areas on the surface of wearing parts. Therefore, when developing passive protection methods for such parts, comparative solid particle erosion and corrosion testing is a possible approach to select the final best method based on a combination of protective properties.

The front side, entrance and exit edges of blades and connections between blades and discs are subject to the most abrasive and corrosive wear [7–10]. Corrosive wear occurs due to chemical and electrochemical processes arising from the interaction of hydraulic machine parts with oxygen and other chemically active substances contained in the atmosphere and in the working environment [11–13]. Corrosive wear appears in the form of rust and pitting on the surfaces of hydraulic components.
The development of hydro-abrasive wear depends on the concentration, density, shape and size of solid particles, as well as on the mechanical properties of the component material and the rotation speed of the hydraulic machine rotor [14–16].

When the abrasive particles are carried by an active liquid medium, the solid particle erosion process is compounded by corrosive phenomena. Exposure to chemically active fluids forms an oxide film on the surface of metal parts, which is quickly destroyed by abrasive particles carried by the flow. Corrosion products are removed from the metal surface and new oxide films and corrosion points are formed, resulting in a significant increase in the severity of the damage.

The hydro-abrasive and corrosive wear of the flow parts of hydraulics leads to the significant deterioration of technical and economic parameters of their operation.

Wear resistance improvement methods are mainly focused on the protection of those surfaces of hydraulics that are more exposed to a particular type of impact. The challenges of reducing corrosion and hydro-solid particle erosion damage by selecting the most wear-resistant method of hardening the protected surface can be tackled using comparative tests of promising passive protection methods such as thermal spraying [17–21], ion-plasma coatings [22], cold gas dynamic spraying [23–25] and laser cladding [26]. Recently, when developing passive protection methods, special attention has been paid not only to the surface but also to the modification of the near-surface layer of the material, in particular the use of diffusion coatings [27].

The effect of boriding on the wear characteristics of protected equipment has not been adequately studied to date. According to the authors, the influence of a method such as boriding on the corrosion resistance of structural steels requires further study. The essence of the boriding process is that in, the boron-containing salt medium surrounding the part, atomic boron is deposited on the surface of the product, diffuses deep down and forms a surface layer consisting of borides. The boriding process can be carried out in liquid, solid and gaseous media [28]. Boriding has proven to be a relatively simple way to improve the wear resistance of structural steels through the formation of a modified layer of a specific structure, phase composition and increased hardness [29,30]. The corrosion resistance of borided steels depends on the boriding method, saturation time and temperature and the composition of the alloying elements in the steel [31]. Often, corrosion failure of parts occurs due to a shallow depth of coating and its imperfection. The modern literature provides limited information on solid particle erosion resistance of borided structural cast steels [32] and their behavior under corrosive attack [33,34]. Therefore, cast steel 20GL, used for the production of critical elements of hydraulic machine flow parts pump impellers, elements of hydraulic turbine flow parts), was chosen as the object of study.

Previously, a team of authors conducted research on the solid particle erosion resistance of borided 20GL steel samples [35]. The chemical composition of steel 20GL is given in Table 1.

| C, %     | Si, %    | Mn, % | S, %  | P, %  | Fe, % |
|----------|----------|-------|-------|-------|-------|
| 0.15–0.25| 0.2–0.4  | 1.2–1.6| <0.04 | <0.04 | other |

An experimental test rig of a jet-abrasive type based on a sandblasting machine was used for the research. The test rig simulated various interactions of between solid particles and the surface of structural materials. Purified air, free of impurities and moisture, was used as a carrying medium in the test rig. The flow and sample surface temperature were kept constant and equal to 25 °C. Al₂O₃ particles (electrocorundum, average particle size 250–300 µm) were used as the abrasive material. Series of tests of steel 20GL samples without modification and with boriding at a speed of air-abrasive flow of 170 m/s and at an impact angle of 30° and 90° were carried out. As a result, kinetic curves of solid particle erosion process were obtained (see Figure 1). Additionally, the resistance of borided steel in relation to steel 20GL without modification was evaluated.
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Additionally, the resistance of borided steel in relation to steel 20GL without modification was evaluated. The research results [35] demonstrated that boriding at an impact angle of 90° does not worsen the solid particle erosion resistance of steel 20GL samples, while at an impact angle of 30° it increases it by eight times at least. The increase of solid particle erosion resistance indicates the change of wear type when decreasing the impact angle from 90° to 30°. This fact is related with the appearance of transition from brittle to prevailing ductile fracture. This is due to the embrittlement of the steel 20GL surface after the boriding process. Indirectly, this fact is confirmed by the obtained high results of boride layer microhardness measurements up to 1500–2200 HV0.01.

The results in [35] indicate that the boriding process of hydraulic machine parts made of steel 20GL will improve their solid particle erosion resistance and extend their overhaul period.

This study aimed to investigate the corrosion resistance of cast steel 20GL with boriding and to identify, on the basis of new and previously obtained data, the potential for resistance to the combined solid particle erosion and corrosion effects that arise from the use of this method of hardening.

2. Materials and Methods

Samples of cast steel 20GL (plates with dimensions of 20 mm × 30 mm × 2 mm) were surface hardened by boriding. The boriding was carried out in a melt based on sodium tetraborate, sodium fluoride and sodium chloride salts in an STC 35/50 shaft furnace with external heating.
Several processes were carried out, including the following steps:
- Heating and soaking the samples at 350 °C for 2 h;
- Boriding bath treatment at 880 °C for 3 h (boriding type I) and 6 h (boriding type II);
- Quenching samples in an oil bath heated to 90 °C.

After boriding, the surface roughness, microhardness, composition and microstructure of the boride layer were determined for the samples.

The surface roughness was measured using a stylus method using a portable contact surface profiler over five surface profiles. The microhardness of the hardened surface was measured using Vickers hardness test at a load of 0.01 kgf (0.098 N).

The composition and the microstructure of the boride layer were examined on cross-sectional metallographic specimens using a scanning electron microscope. The metallographic specimen from a steel 20GL sample without modification was also made for reference.

The scanning electron microscope images were acquired in backscattered electron mode (BSE), which provides contrast by atomic number where lighter areas correspond to heavier phases and darker areas to lighter phases to evaluate the boride layer thickness and the presence of different phases in it.

Corrosion tests of the samples were conducted by two methods: electrochemical and gravimetric [36].

An electrochemical method using potentiostat/galvanostat in a three-electrode cell with a silver chloride reference electrode was used to measure the free corrosion potential in a naturally aerated 3% NaCl solution and a 0.7% Na$_2$SO$_4$ solution. After immersion of the sample in the solution, an open-circuit potential was recorded, assuming the corrosion potential at the end of exposure, provided that the change in potential during the last 0.5 h did not exceed 30 mV. The solutions used were chosen based on the minimum (0.7% Na$_2$SO$_4$ solution) and maximum (3% NaCl solution) corrosion effects in an aqueous environment.

The tendency of the samples to continuously corrode was evaluated by a gravimetric method. To this end, degreased samples were immersed in a 3% NaCl solution and a 0.7% Na$_2$SO$_4$ solution, with ventilation provided (temperature of 23–25 °C). Samples were maintained in the solutions for 10 days. Samples were weighed before and after tests on electronic analytical scales with the accuracy of ±0.0001 g. Before weighing, the samples were dried and corrosion products were removed from them. The working area of the sample was calculated using special software.

The corrosion rate $V_k$ (g/(m$^2$·h)) was calculated according to the formula:

$$ V_k = \frac{m_0 - m_1}{S \cdot \tau} \times 10^4, $$

where $m_0$ is the sample mass before the test (g); $m_1$ is the sample mass after the test (g); $S$ is the sample surface area (cm$^2$); $\tau$ is test duration (h).

The protection ratio ($\gamma$) was calculated according to the formula:

$$ \gamma = \frac{V_{kk}}{V_{kp}}, $$

where $V_{kk}$ is the corrosion rate of the control sample; $V_{kp}$ is the corrosion rate of the coated sample.

Coating defects were determined by the penetrant testing [37]. The penetrant testing is based on the capillary (uncontrolled) action of liquid penetrants into the cavities of the surface and through imperfections of the material of objects under test and visual registration of the traces formed by the penetrant. The detection of defects was performed in the visible spectrum. The depth of penetration of defects was evaluated by metallographic methods. For this purpose, cross-sectional metallographic specimens were made and examined on a scanning electron microscope in backscattered electron mode (BSE), which provides contrast by atomic number, where lighter areas correspond to heavier phases and
darker areas to lighter phases to evaluate the boride layer thickness and the presence of different phases in it.

3. Results and Discussion

The results of the determination of the roughness and microhardness parameters of steel 20GL samples with boriding, as well as without surface modification, are given in Table 2. These results indicate that the boriding process does not affect the initial roughness of cast steel 20GL but increases the surface microhardness by more than six times.

Table 2. Results of microhardness and surface roughness measurements of top and surface damage of samples with different types of surface modification in 600 min of testing.

| Description of Sample | Ra, µm  | Rz, µm  | HV0.01    |
|-----------------------|---------|---------|-----------|
| Steel 20GL with boriding of type I | 2.3 ± 0.4 | 15 ± 3  | 1860 ± 180 |
| Steel 20GL with boriding of type II | 2.1 ± 0.3 | 12.8 ± 1.1 | 1940 ± 140 |
| Steel 20GL without modification | 2.0 ± 0.3 | 13.9 ± 1.7 | 280 ± 10  |

$R_a$ is the arithmetic mean deviation of the profile; $R_z$ is the height of profile irregularities at ten points.

A representative view of the structure of the steel 20GL surface layer after boriding is shown in Figure 2.

The images of the obtained metallographic specimens in Figure 2 show that the boride layer has a needle-shaped structure. We can also see two phases in the layer. The analysis of the elemental composition of the boride layer shows that the upper (darker) phase corresponds to the FeB phase and the lower (lighter) phase corresponds to Fe$_2$B phase (see Figure 3).
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Figure 3. Analysis of the elemental composition of the boride layers: (a) map of analysis of elemental composition; (b) SEM elemental map.

The thickness of the layer consisting of the FeB phase averages 25 µm for boriding of type I and 60 µm for boriding of type II. The total layer thickness after the boriding process for 3 h (type I) was 80 ± 5 µm and after boriding for 6 h (type II) was 150 ± 5 µm. The measurement of the corrosion potential of steel 20GL in the initial state and with boriding in investigated environments testifies about its insignificant shift in the positive side (see Figure 4) depending on the thickness of the boride layer. Such a change of potential can be explained by small anodic polarization, which is the main factor controlling the course of the corrosion process. There is no sudden inhibition of iron ions entering the solution in this case.
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Figure 4. Typical relationship between the thickness of the boride layer and the corrosion potential of steel 20GL: (a) medium of 3% NaCl; (b) medium of 0.7% Na₂SO₄; \( \tau \) is time of exposure (s).

In the medium of the 3% NaCl solution and the medium of the 0.7% Na₂SO₄ solution, samples are in the active state (because the values of potentials are in the negative range). This is confirmed by the gravimetric tests. After 10 days on the surface of the control samples without modification and on the samples with boriding, corrosion products are formed in large quantities. Iron ions transferred into the water are hydrolyzed and form a loose residue at the bottom of the tank (Figure 5a).

With an increasing thickness of the boride layer, the transfer of iron ions into the solution (change in colour of solutions) decreases (Figure 5b). The appearance of the samples after the removal of deposits is shown in Figure 5c. The corrosion properties of the samples are shown in Table 3.

Boriding of type I turns steel 20GL from a low-resistant class (score 6) to a resistant class (score 5) on a 10-point scale of corrosion resistance of metals [38], and boriding of type II turns to a resistant class (score 4).

Penetrant testing shows that defects are present in the samples for both boriding types. The defects are localized throughout the surface, have no predominant orientation and are shaped predominantly as dots.
Figure 5. Pictures of samples during corrosion tests by the gravimetric method in media of 3% NaCl solution and 0.7% Na₂SO₄ solution, exposure time of 10 days: (a) placement of samples in vessels; (b) colour of solutions after tests; (c) appearance of samples after removal of deposits.

Table 3. Corrosion properties of samples.

| Description of Sample | Corrosion Potential, mV (Relative to Silver Chloride Electrode) | Corrosion Rate, g/(m²·h) | Protection Ratio, γ |
|-----------------------|---------------------------------------------------------------|--------------------------|---------------------|
| **Medium of 3% NaCl solution** | | | |
| Without modification | −669 | 0.1062 | - |
| Boriding of type I | −641 | 0.0751 | 1.4 |
| Boriding of type II | −634 | 0.0378 | 2.8 |
| **Medium of 0.7% Na₂SO₄ solution** | | | |
| Without modification | −657 | 0.1550 | - |
| Boriding of type I | −649 | 0.0705 | 2.2 |
| Boriding of type II | −643 | 0.0376 | 4.1 |
Figure 6 shows a representative view of the surface layer of steel 20GL with boriding of type I (Figure 6a) and type II (Figure 6b), having different thicknesses of the boride layer. As can be seen, cracks are observed in the borided layer, many of which begin on the surface and end in the base material in the transition zone in which the base material is interspersed with grains of Fe₂B phase, reaching a depth of 47–76 μm for boriding of type I and 73–152 μm for boriding of type II. The cracks propagate mainly along the grain boundaries. The crack width varies from 1–2 μm to 4–6 μm. On the surface of the samples, there are also defects in the form of broken FeB grains. The depth of defects ranges from 4–7 μm to 15–20 μm.

Figure 6. Picture of cross-sectional metallographic specimen of steel 20GL sample with boriding of type II after penetrant testing of surface defects: (a) boriding of type I; (b) boriding of type II.

4. Conclusions

Studies of the corrosion resistance of cast steel 20GL show the positive effect of boriding. The boriding at a depth of 150 ± 5 μm reduces the corrosion rate in the environment of a 3% NaCl solution by 2.8 times and in the environment of a 0.7% Na₂SO₄ solution by 4.1 times, compared with the initial material without modification. A reduction in boriding depth leads to a decrease in corrosion resistance in the considered media. The results indicate that the boriding of hydraulic machine parts made of cast steel 20GL will increase their corrosion resistance and extend the overhaul period. Present and previous studies show that boriding may be a promising passive method of protecting hydraulic machine elements from hydro-solid particle erosion and corrosive effects.
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References

1. Vasiliev, A.A.; Igoshin, D.N.; Gorin, L.N. Influence of cavitation-abrasive wear on screw pumps. Young Sci. 2015, 22, 135–137.
2. Bregliozzi, G.; Di Schino, A.; Ahmed, S.I.-U.; Kenny, J.M.; Haefke, H. Cavitation wear behaviour of austenitic stainless steels with different grain sizes. Wear 2005, 258, 503–510. [CrossRef]
3. Steller, J. Erosive wear modelling by means of the fractional approach. Wear 2021, 484–485, 204015. [CrossRef]
4. Yi, J.Z.; Hu, H.X.; Wang, Z.B.; Zheng, Y.G. On the critical flow velocity for erosion-corrosion in local eroded regions under liquid-solid jet impingement. Wear 2019, 422–423, 94–99. [CrossRef]
5. Pang, X.; Zhang, B.; Li, S.; Zeng, Y.; Liu, X.; Shen, P.; Li, Z.; Deng, W. Machining performance evaluation and tool wear analysis of dry cutting austenitic stainless steel with variable-length restricted contact tools. Wear 2022, 504–505, 204423. [CrossRef]
6. Pang, J.; Liu, H.; Liu, X.; Yang, H.; Peng, Y.; Zeng, Y.; Yu, Z. Study on sediment erosion of high head Francis turbine runner in Minjiang River basin. Renew. Energy 2022, 192, 849–858. [CrossRef]
7. Hamilton, A.; Sharma, A.; Pandel, U. Effect of impingement velocity on solid particle erosion behaviour of CA6NM hydroturbine steel. Mater. Today Proc. 2018, 5, 17325–17332. [CrossRef]
8. Steller, J. Cavitation damage as a result of polyfractional erosion process. Wear 2020, 456–457, 203369. [CrossRef]
9. Gohil, P.P.; Saini, R.P. Investigation into cavitation damage potentiality using pressure pulsation phenomena in a low head Francis turbine for small hydropower schemes. Ocean Eng. 2022, 263, 112230. [CrossRef]
10. Leguizamón, S.; Jahanbakhsh, E.; Maertens, A.; Alimirzazadeh, S.; Avellan, F. A multiscale model for sediment impact erosion simulation using the finite volume particle method. Wear 2017, 392–393, 202–212. [CrossRef]
11. Lazzerini, G.; Coiro, D.P.; Troise, G.; D’Amato, G. A comparison between experiments and numerical simulations on a scale model of a Horizontal-Axis current turbine. Renew. Energy 2022, 190, 919–934. [CrossRef]
12. Liu, X.; Luo, Y.; Karney, B.W.; Wang, W. A selected literature review of efficiency improvements in hydraulic turbines. Renew. Sustain. Energy Rev. 2015, 51, 18–28. [CrossRef]
13. Natsume, M.; Hayashi, Y.; Akebono, H.; Kato, M.; Sugeta, A. Fatigue properties and crack propagation behavior of stainless cast steel for turbine runner of hydraulic power generation. Procedia Eng. 2010, 2, 1273–1281. [CrossRef]
14. Nguyen, Q.B.; Nguyen, D.N.; Murray, R.; Ca, N.X.; Lim, C.Y.H.; Gupta, M.; Nguyen, X.C. The role of abrasive particle size on erosion characteristics of stainless steel. Eng. Fail. Anal. 2019, 97, 844–853. [CrossRef]
15. Ghiban, B.; Safa, C.-A.; Ion, M.; Crângășu, C.E.; Grecu, M.-C. Structural aspects of silt erosion resistant materials used in hydraulic machines manufacturing. Energy Procedia 2017, 112, 75–82. [CrossRef]
16. Saad, J.; Ghahramani, E.; Neuhauser, M.; Bourgeois, S.; Bensow, R.E.; Pooima, C. Experimental investigation of cavitation-induced erosion around a surface-mounted bluff body. Wear 2021, 480–481, 203917.
17. Babu, A.; Perumal, G.; Arora, H.S.; Grewal, H.S. Enhanced slurry and cavitation erosion resistance of deep cryogenically treated thermal spray coatings for hydroturbine applications. Renew. Energy 2021, 180, 1044–1055. [CrossRef]
18. Grewal, H.S.; Arora, H.S.; Agrawal, A.; Singh, H.; Mukherjee, S. Slurry erosion of thermal spray coatings: Effect of sand concentration. Procedia Eng. 2013, 68, 484–490. [CrossRef]
19. Goyal, D.K.; Singh, H.; Kumar, H.; Sahni, V. Slurry erosion behaviour of HVOF sprayed WC-10Co-4Cr and Al2O3 + 13TiO2 coatings on a turbine steel. Wear 2012, 289, 46–57. [CrossRef]
20. Amarendra, H.J.; Prathap, M.S.; Karthik, S.; Darshan, B.M.; Girish, P.C. Combined slurry and cavitation erosion resistance of HVOF thermal spray coated stainless steel. Mater. Today Proc. 2017, 4, 465–470. [CrossRef]
21. Nowakowska, M; Łatka, L; Sokolowski, P; Szala, M; Toma, F.-L.; Walczak, M. Investigation into microstructure and mechanical properties effects on sliding wear and cavitation erosion of Al2O3-TiO2 coatings sprayed by APS, SPS and S-HVOF. Wear 2022, 508–509, 204462. [CrossRef]
22. Belov, D.S.; Blinkov, I.V.; Sergevnn, V.S.; Smirnov, N.I.; Volkonskii, A.O.; Bondarev, A.V.; Lobova, T.A. Abrasive, hydroabrasive, and erosion wear behaviour of nanostructured (Ti,Al)N-Cu and (Ti,Al)N-Ni coatings. Surf. Coatings Technol. 2018, 338, 1–13. [CrossRef]

23. Alidokht, S.A.; Vo, P.; Yue, S.; Chromik, R.R. Erosive wear behavior of Cold-Sprayed Ni-WC composite coating. Wear 2017, 376–377, 566–577. [CrossRef]

24. Sergeyev, S.V.; Al-Bdeiri, M.S.H.; Kolesnikov, D.A.; Baranov, S.O. Analysis of physical and mechanical properties of Galvanic-plasma wear-resistant coatings. Mater. Today Proc. 2021, 45, 6386–6392. [CrossRef]

25. Doddamani, M.; Mathapati, M.; Ramesh, M.R. Microstructure and tribological behavior of plasma sprayed NiCrAlY/WCCo/ cenosphere/solid lubricants composite coatings. Surf. Coatings Technol. 2018, 354, 92–100. [CrossRef]

26. Singh, R.; Kumar, D.; Mishra, S.K.; Tiwari, S.K. Laser cladding of Stellite 6 on stainless steel to enhance solid particle erosion and cavitation resistance. Surf. Coatings Technol. 2014, 251, 87–97. [CrossRef]

27. Ordoñez, M.F.C.; Amorim, C.L.G.; Krindges, I.; Aguzzoli, C.; Baumvol, I.J.R.; Figueroa, C.A.; Sinatara, A.; Souza, R.M.; Farias, M.C.M. Microstructure and micro-abrasive wear of sintered yttria-containing 316L stainless steel treated by plasma nitriding. Surf. Coatings Technol. 2019, 374, 700–712. [CrossRef]

28. Voroshnin, L.G. The structure of alloys of the Fe-B system. Met. Sci. Heat Treat. 1970, 9, 14–17.

29. Nath, G.; Kumar, S. Slurry erosion behaviour of pack boronized 13-4 martensitic stainless steel for hydro turbine blades. Mater. Today Proc. 2018, 5–9, 17380–17388. [CrossRef]

30. Formanek, B.; Swadźba, L.; Maciejny, A. Microstructure wear resistance and erosion resistance of plasma-sprayed boride coatings. Surf. Coatings Technol. 1993, 56, 225–231. [CrossRef]

31. Voroshnin, L.G.; Lyakhovich, L.S. Steel Boriding, 1st ed.; Metallurgy: Moscow, Russia, 1978; pp. 154–172.

32. Zhang, D.; Li, Y.; Du, X.; Fan, H.; Gao, F. Microstructure and tribological performance of boride layers on ductile cast iron under dry sliding conditions. Eng. Fail. Anal. 2022, 134, 106080. [CrossRef]

33. Ma, S.; Xing, J.; Fu, H.; Yi, D.; Zhang, J.; Li, Y.; Zhang, Z.; Zhu, B.; Ma, S. Interfacial morphology and corrosion resistance of Fe-B cast steel containing chromium and nickel in liquid zinc. Corros. Sci. 2011, 53, 2826–2834. [CrossRef]

34. Zhang, X.; Chen, W.; Luo, H.; Li, S.; Zhou, T.; Shi, L. Corrosion resistance and interfacial morphologies of novel Fe-Cr-Mo-B cast steels in molten aluminum. Corros. Sci. 2017, 125, 20–28. [CrossRef]

35. Tkhabisimov, A.B.; Zilova, O.S.; Kalakutsikaya, O.V. Research results of solid particle erosion resistance of 20GL steel with boriding. J. Phys. Conf. Ser. 2021, 2124, 012012. [CrossRef]

36. GOST 9.506-87; Unified System of Corrosion and Ageing Protection. Corrosion Inhibitors of Metals in Water-Petroleum Media. Methods of Protective Ability Evaluation. Standards Publishing House: Moscow, Russia, 1988; pp. 1–17.

37. ISO 3452-1:2008; Non-Destructive Testing—Penetrant Testing—Part 1: General Principles. 1st ed. Standartinform: Moscow, Russian, 2012; pp. 1–20.

38. GOST 9.908-85; Unified System of Corrosion and Ageing Protection. Metals and Alloys. Methods for Determination of Corrosion and Corrosion Resistance Indices. Standards Publishing House: Moscow, Russia, 1989; pp. 1–22.