Augmentation of ship’s operational availability through innovative reconditioning technologies

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Abstract. Machinery failures have negative impact on ship's technical maintenance, which directly affects her operational availability. Science development allows use of innovative reconditioning technologies in order to increase the ship’s operational availability, and one of the most promising technologies is the Brush Plating. It allows shortening of the recondition time, while minimizing its effect on the base material structure. This technology allows repair using reconditioning with local treatment only in area where is necessary through compact and mobile equipment. Brush Plating technology implementation brings to higher operational availability, less expenditures, and higher profit. Methods used are System Approach, Data Analysis, and Comparative Analysis. In current paper a new method for estimation ship’s operational availability is proposed by the authors. This method in a combination with innovative reconditioning technologies will give an effect on the future ship maintenance program.

1. Introduction

Maritime transportation is the life blood of the global economy, development, and prosperity. Over 80 % of global trade by volume and more than 70 % of its value are transported on board ships. The average annual growth of the maritime transportation remains around 2÷3 %, and its dimensions are shown on figure 1 [1]. Therefore, optimization of the sector means more prosperity and goods.

Maritime transportation is a System of Systems (SoS), and ships are its vital and irreplaceable subsystem. Ships have become technically sophisticated, high value platforms. The world’s cargo fleet is represented of above 50000 ships, with capacity of 1800 million of dead-weight tons (DWT) and total value of all ships is $ 829 billion. The average ship is of age of 20 years, capacity of 36000 DWT, and value of $ 16,58 million [1]. These capable, but sophisticated assets require complex maintenance and multiple planned or unscheduled repairs. Improvement of ship’s maintenance effects on the whole maritime transportation SoS, following to improvement and heightening of its efficiency.

Efficiency of a ship is product of her capabilities and Operational availability (Ao). Ships’ cargo capabilities are designed and they are constant. Therefore, efficiency augmentation is mainly possible by rise of the Ao. There are three types of Ao calculation: for continuous-use, intermittent-use, or impulse systems. Ship’s active operation exploitation is a continuous-use system and it is calculated as follows [2]:

\[ Ao = \frac{MTBF}{(MTBF+MTTR+MSRT+MOADT+MAadmDT)} \]  

where:
MTBF - Mean Time Between Failures (an index of system reliability);
MTTR - Mean Time To Repair (an index of system maintainability);
MSRT - Mean Supply Response Time (an index of system supportability);
MOADT - Mean Outside Assistance Delay Time (an index of system supportability);
MAadmDT - Mean Administrative Delay Time (a collective index of system supportability).

2. Brush Plating Technology
The main practical approach for maintenance and repair are reconditioning procedures to the nominal size of the machine part. This involves application of coating technologies on affected surface. Along with nanotechnology, one of the most promising innovative technologies in this area is the selective Brush Plating Technology (BPT). It allows shortening of maintenance and repair time, while minimizing the risk of heat distortion of the structure and worsening the properties of the base material, from which the machine part is manufactured (table 1). The BPT allows reconditioning using local treatment only in the area where it is necessary, which is provided by compact and mobile repair equipment [4, 6, 7].

Brush plating is a process for electrochemical coating of metals and alloys. It can to be done locally, in strictly defined area for short period compared with conventional methods for maintenance and recondition. The process provides low price of consumables and operations in all spatial positions by provision of a high quality coating with required mechanical characteristics of the repaired machine part.
The principle of Brush Plating technology is depicted on figure 2. The reconditioning process is based on delivery of an electrolytic solution that has a high concentration of active elements, which are subject to deposition on the recovered surface. This delivery can be provided manually by means of a periodic immersion of the absorbing tip of a special device called a “brush” by an operator in the solution tank or entirely mechanized by a circulation pump [4, 6, 8].

This method is particularly suited to perform local recondition procedures with compact and portable equipment. The selective coating equipment is capable to provide an extremely wide variety of scheme options, which are useful for recondition of machine parts in hard-to-reach areas.

The main elements of the BPT are [4]:
- Mobile electric system;
- Tools for application;
- Protective materials;
- Solutions;
- Manual or automatic operated equipment.
- The process of selective repair can be accomplished in two ways:
  - Through formation of a new structure with participation of the basic machine material;
  - By appliance of surface coating of material, that is completely different from the base material. This application is based on the adhesive forces that occur under certain conditions between the base material and the coating applied.

In comparison to conventional reconditioning technologies, such as “Flame spraying” selective "Brush plating” demonstrates numerous of advantages. Most important of them are summarized in table 1.

Results of bending tests of the coating obtained using the BPT show that there is a lack of pores and cracks at the boundary between the substrate and the coating applied. This indicates high bond strength between both layers. It is due to adhesion forces and takes place at atomic level, with bonding forces between the base and the applied layer being 400÷600 N/mm². They are commensurate with the tensile strength of medium carbon steel [6, 7, 8].
Table 1. Comparison between Selective “Brush plating” and Conventional “Flame spraying” Reconditioning Technologies [4, 7]

| Issue                        | Selective Brush Plating                                                                 | Conventional Flame Spraying                                                                 |
|------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Adhesion                     | An atomic bond provides excellent adhesion on all metals used in industry today. Adhesion is not compromised by severe, cyclical temperature fluctuations or by sharp, direct impact. Tests run in accordance with ASTM C633-79 revealed that two commonly used nickel deposits had a bond strength that exceeded the strength of the cement, which failed at roughly 11,000 psi. | Flame spray is a mechanical bond in which molten, semi-molten or solid particles are deposited on a substrate to form a coating. The particles travel at high velocity causing them to flatten on impact. |
| Ability to control deposit thickness | Ampere-hour values to obtain a desired thickness are calculated prior to plating any part. Deposit thicknesses are accurately controlled, allowing parts to be plated to size. | Parts that are built up with flame spray must be machined to a finish dimension. |
| Flexibility                  | Selective plating can be used on a wide variety of shapes and sizes of parts; including holes as small as 1/4” in diameter. | Flame spray is typically limited to outside diameter applications. |
| Deposition Rate              | The solutions are deposited at an average rate of 0.035” / hour.                       | High buildups are rapidly obtained.                                                         |
| Risk of Heat Distortion      | None. Selective plating is carried out at room temperature.                             | Due to the heat involved in the process, flame spray poses a risk of distorting some components. |
| Roughing Up the Surface      | Not required.                                                                          | Grit blasting typically required.                                                           |
| Portability                  | The BP technology is a portable plating process that can be used in the shop or on-site. | Typically limited to the shop.                                                             |
| Safety                       | Water based solutions that are mild acids or alkalines pose minimal risk to the operator. | Toxic fumes require superior ventilation for operator safety. Sound levels associated with thermal spray require additional personal protective equipment. |

Appliance of the brush plating technology allows modifying the operational availability equation, as follows:

\[ A_0 = \frac{MTBF}{MTBF + MTBP} \]  \hspace{1cm} (2)

where:

\[ MTBF \] – Same as equation (1);
\[ MTBP \] – Mean Time for Brush Plating Recondition.

\[ "MTBP=MTET+MTTSP+MTRP" \]  \hspace{1cm} (3)

where:
MTET – Mean Time for Equipment Preparation (working cycle planning, relocation of the brush plating machine and solutions from the vessel’s store to the assigned work place and installation there);

MTSP – Mean Time for treated surface preparation (required preparations like mechanical cleaning, grinding, polishing and etc.).

MTRP – Mean Time for Reconditioning Process (time for reconditioning of the selected detail or surface).

MTET is not applicable for defragmentation because its phases overlap. The MTBP does not include times for dismounting and taking away the brush plating machine and solutions, because these steps can to be conducted while the device is checked and the ship operates.

3. Result Analysis and Discussion

3.1. Operational advantages of innovative recondition technologies

BPT minimizes the effect of repair operations on the structure of the base material and allows processing in required area, only. Application of surface treatment methods ensures maximum performance at minimum cost.

BPT provides variety of recondition options and increases ship’s $A_o$ in three main directions:

- Reduces maintenance and repair duration and cost;
- Provides a compact and mobile equipment for maintenance and recondition, and ensure capabilities to carry out these activities locally, wherever is required;
- Increases capabilities for maintenance and recondition on board in case of emergency.

All three directions cumulatively augment the $A_o$.

![Figure 3. Comparison between $A_o$ When Reliability is Increased and Repair Process is Faster.](image)

Operational availability of a ship is possible to be optimized by augmentation of her reliability or improvement of recondition and maintenance process.

Comparison of Brush Plating and Conventional Repair Technologies is shown on figure 3. There are two ways to augment operational availability: increased reliability of the equipment or shorter repair process.

The $A_o$ is calculated with equation (1) when reliability is significantly increased with 20%. Therefore, MTBF increases with 20%, but the rest of repair processes remain same. Questionnaires with experienced Bulgarian marine engineers working on board of merchant and navy ships, and in naval and civilian shipyards formed a statistic average ship machinery (crankshaft, shaft, piston, cylinder liner, and cylinder unit and similar) MTTR=10 hours, MSRT=24 hours, MOADT=24 hours, and MAdmDR=8 hours.

The $A_o$ for constant reliability and faster repair (BPT) is calculated with equations (2) and (3). The advantages of this technology are that supply of parts and outside assistance and administrative work
are not required. Values for BPT repair for an average ship machinery are MTET=2 hours, MTTSP=2 hours, and MTRP=1 hour.

With these values, the Ao relationship to the MTBF, when the reliability is increased and the repair is faster, are depicted on figure 3. The chart shows that the BPT provides higher value of the Ao than the conventional repair (with spares or Flame Recondition).

Extracted from figure 3 results show that if the MTBF is increased from 3000 to 3600 hours, the Ao will increase from 0.9785 to 0.982. If the MTBF remains 3000 hours, but the BPT is applied, the Ao will be 0.9983. Therefore, appliance of BPT will bring six days more operational time per ship compared to extremely significant increase of the reliability with 20%.

If comparison is done for MTBF=5000, 10000, 15000, and 24000 hours, then the gained operational availability per year is 3, 6, 1.8, 1.2, and 0.75 days.

Comparative analysis of both ways to increase the Ao is not final, precise calculation because it does not include time in ship repair facilities. Repairs in shipyards are unavoidable due to technical and legal requirements of SOLAS and Ship Classification Societies. They are part of ship’s operational cycle, shown on figure 4. In accordance with SOLAS requirements, ships go to a shipyard for a Dock Survey in every five years. The total period while the ship is not operational, when conducts Dock Survey is 4÷8 weeks (for a Panamax class ship). The Dock Survey duration is not fixed and it varies due to the type of the ship, the shipyard, hydrometeorology conditions, actual status of the vessel, etc.

Down time in docks changes Operational Availability and require its recalculation. Recalculated Operational Availability is:

\[ \text{Ao} = \frac{\text{Ao \cdot TOpr}}{\text{TSSY + TOpr}} \]  

where:

- Ao’ – Long Term Ao (recalculated with time in shipyards);
- Ao – Operational Availability calculated by equation (1);
- TOpr – Time when the ship is operational (time between shipyard repairs);
- TSSY – Time Spent in Shipyard (The total time when the ship is not operational for a survey).

| Vessel’s Life Cycle | Type of Time | Shipyard Survey Duration |
|---------------------|--------------|--------------------------|
|                     |              | 4 weeks  | 6 weeks  | 8 weeks  |
| 15 year             | TOpr         | 772      | 768      | 764      |
|                     | TSSY         | 8        | 12       | 16       |
| 30 year             | TOpr         | 1540     | 1530     | 1520     |
|                     | TSSY         | 20       | 30       | 40       |

Presentation of calculations of Ao’ within the entire range of MTBF requires several pages, but a representative extract can be shown below. It is calculated for MTBF=3000 hours, which is a relatively
average value for major part of ship’s mechanisms. The world’s average ship age is 20 years and the selected vessel’s life cycle is 15 years and 30 years. In first case, the company exploits new ships, and utilizes them just before the third dock survey. In second case, the company exploits older than average ships and utilizes them just before the sixth dock survey.

Table 3. $A_o'$ Value for Increased Reliability with 20 % and Faster Repair (BPT)

| Vessel’s Life Cycle | Increased Reliability | Faster Repair (BPT) |
|---------------------|-----------------------|---------------------|
|                     | $MTBF=3000, A_o=0,9785$ | $MTBF=3600, A_o=0,982$ | $MTBF=3000, A_o=0,9983$ |
| Shipyard Survey     | Shipyard Survey        | Shipyard Survey      |
| 4 weeks             | 6 weeks                | 8 weeks              |
| 15 year             | 0.9685 0.9634 0.9584 0.9719 0.9669 0.9619 0.9880 0.9829 0.9778 |
| 30 year             | 0.9639 0.9597 0.9534 0.9694 0.9631 0.9568 0.9855 0.9791 0.9727 |

Figure 5. $A_o'$ Chart for Different Repairs and Vessel’s Life Cycle

Comparison of results in Table 2, visual presented on figure 5, show that 20% higher reliability increases $A_o'$ less than the Brush Plating technology, and duration of the vessel’s life cycle and repairs in shipyards are inversely proportional with $A_o'$ (bigger value of the duration brings to smaller value of the Long Term Operational Availability).

Brush Plating is exactly technology that does not have impact on reliability, but affects to optimization process in reconditioning procedures. It can be conducted without delays for components supply, outside any support with minimal administrative work through its mobility along with simplicity and low price ingredients.

3.2. Resource analysis
BPT brings several financial advantages for ship’s operator. Finances are leading goal for commercial companies, and major limitation for the governmental structures. Therefore, financial advantages are major reason to apply an innovation in an organization.

The main financial advantage is the increased operational availability of vessels, because a daily charter of a cargo ship is above $9000 [10]. The summarized long-term operational availability ($SLTA_o$)
per any ship is a combination of the reliability of all mechanisms, repair organization, and accidental dispersion of technical failures and human caused incidents.

\[ \text{CAo} = \sum_{i=1}^{n} \frac{\text{SLT}_i \cdot \text{Ao}_i}{n} \]  

(5)

where

- \( \text{CAo} \) – the operational availability for the entire organization (company);
- \( n \) – the number of ships, operated by the organization.

Even a small gain of half day more operational availability per year for a single mechanism is important, because it multiplies with the number of all systems on board and the amount of all operated ships.

The second financial advantage is an opportunity for reorganization. Companies create departments that coordinate and manage all maintenance and repair processes and activities. They proceed requirements for repairs and spares, or create and maintain spare parts stock in order to provide faster repair. In this way, companies increase the operational availability by overlapping response time, assistance delay time, and administrative delay time. This kind of operational availability augmentation requires increased number of qualified personnel and stocks of spare parts. BPT will not allow closing these structures and stocks, because it is not a “painkiller” for all kinds of breakdowns, but will allow decreasing the amount of some spares, and less office personnel.

The third advantage is the cheaper repair and maintenance of the ship and its mechanisms. In Bulgaria, conventional reconditioning of a camshaft with length of 4500–6000 mm costs from 750 to 3000 Euros, and requires dismantling, mounting and alignment procedures. The BPT reconditioning of this kind of camshaft is performed much faster on place and price varies from 250 to 700 €. An aspect of the cheaper repairs and maintenance is the higher capability for repair, conducted by the crew, but not by contracted specialists.

There is a minor negative financial effect of the BPT. It will require additional expenses for its purchase and operation. Each ship has in her crew technicians and engineers, operating lathe, welding, cutting and grinding machines on board, and they can qualify in BPT. An average price of Brush Plating equipment is 19000 €, and qualification for operators is 1000 € per trainee (prices are for the Bulgarian market). Therefore, including of Brush Plating equipment in ship’s inventory will cost 19000 € plus 2000 € for operator’s qualification, or it is 0,14% of an average ship value of $ 16,58 million (€ 14,8 million).

4. Conclusion

Selective BPT brings on significant augmentation of ship’s Operational Availability. The technology offers an innovative approach to the technical maintenance and recondition of ship’s machinery by reducing time and expenses of these procedures. This is a result of high quality coating with the required longevity and technical resource of the repaired machine part. The BPT provides compactness and mobility of repair equipment and creates opportunities for on-site work with wide variety of circuit solutions. This allows recondition of machine parts, even in hard-to-reach places, and in all spatial positions. The BPT allows wide variety of repair works on board, even in emergencies. It allows scheduled preventive low cost maintenance to be done when ships are in ports.

Operational result of selective BPT is augmentation of ship’s operational availability. It will not be as simple as described in equations, tables, and graphics above. Equations (2), (3), (4), and (5) provide a basis for broad and precise calculations. When these basic theoretic equations are part of a research with detailed information for a certain ship or fleet, they will provide useful and applicable results. Ship owners, operators, enterprise representatives, and governmental organizations can provide data about their fleets in order to assess Ao and Ao' augmentation. This will assist them to calculate the cumulative financial impact of BPT in different cases like types and number of vessels, life cycle, staffing costs, etc.

The BPT will augment ship’s operational availability cumulatively. The augmentation is a result of cumulative, simultaneously influence of vessel’s machineries and hull maintenance and repair. Augmented operational availability will bring positive financial results for ship operators.
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