RISK REDUCTION OF COPPER-NICKEL-INDIUM COATED HARDWARE FAILURE VIA IMPROVEMENT OF THE REJECTION INDEX OF THERMAL SPRAY COATINGS APPROVAL TESTS BY USING LEAN MANUFACTURING – A CASE STUDY

Matheus Ribeiro
Graduation Student - Production Engineering – UCP
matheus_ribeiro-dias@hotmail.com

José Cristiano Pereira
Professor - Post Doctor Fellow at the National Laboratory for Science Computing – LNCC
josecristiano.pereira@ucp.br

ABSTRACT

The present study has as main objective the application of the Lean methodology Manufacturing during Copper-Nickel-Indium thermal spray test run targeting to reduce the failure rate and identify the contributing factors that cause failure to reduce part waiting time and rework expenses, thus increasing the operational effectiveness in the workshop. The challenge and practical problem of this study are to propose a solution by implementing the Lean Manufacturing methodology to minimize failures in this test.
Applying the methodology becomes necessary to reduce hardware failure risks and identify opportunities for cost reduction and transformations in the process. A high rejection rate of thermal spray coatings test samples representing specific hardware *(Fan disk)* has been observed in the operational processes of an aeronautical company, leading to waste, high costs, and risk of hardware failure. The authors conducted a case study using Lean tools in the Thermal Spray process in this company to minimize the risk of hardware failure, rework costs, and speed up the delivery time for repaired parts. The results show that the implemented actions reduced the rejection rate, increasing the process's quality, safety, and reliability. The contribution is relevant since the method applies to other industries, such as automotive, metallurgical, and even administrative areas. This study is critical because understanding the significant risks in the process can influence companies' operational managers, maintenance engineers, and decision-makers. As expected, the contribution is substantial; it is believed that the present study will augment the knowledge of maintenance engineers, mechanics, and operation engineers concerning the risk factors to be addressed to improve the quality and effectiveness of the thermal spray coating process.

1. INTRODUCTION

Industries nowadays are looking for innovative solutions for being increasingly competitive in the market. They are looking for ways to reduce their costs and increase productivity without leaving aside a safe and secure work environment. The aeronautical industry has been standing out for its rapid development in recent years, as the growing demand for flights for transporting people as freight transport has required it. However, these planes need to carry out periodic maintenance, mainly on their engines like all the machines. Aeronautical maintenance companies always seek quality and speed in their services so they can serve their customers. Fulfilling the regulatory requirements and seeking their satisfaction is vital. For these companies, Lean Manufacturing has been used for cost reduction, organization, and engagement tools for employees with the company's goals.
The processes necessary to carry out the maintenance of an engine are expensive and need to be well controlled. The Thermal Spray can be highlighted among the repair processes, which uses technology to spray coatings on parts. These coatings can be metallic, abrasive, carbide, or ceramic. Each class of coatings has a purpose: dimensional recovery of parts worn with the engine's rotation, corrosion protection, or serve as an anchorage for another material to be applied. The Thermal Spray process has its quality measured through metallographic

1 Estudante de Engenharia Mecânica – Universidade Católica de Petrópolis
2 Prof Doctor - Universidade Católica de Petrópolis e LNCC

tests that verify that the coating characteristics are following pre-established standards. This analysis comes from tests performed periodically, and depending on the characteristics that the coating has, it can lead to acceptance or disapproval. As the process is expensive, each test failure is considered a cost for the company, as the test must be rerun until it is approved to be applied to the parts. This study proposes an approach to reduce the rates of rejection of the test representing a part using Lean Manufacturing tools. The Thermal Spray process used to repair parts in a manufacturing company's aeronautical maintenance has strict quality control. All applied coatings are previously subjected to analysis in a laboratory of materials. The characteristics observed are stress test analysis (disruption by traction), micro and macro hardness analysis, and metallographic analysis of the specimen with coating. To maintain the required quality level for the Thermal Spray, process these tests are performed frequently. However, when the coating does not reach the desired characteristics, it fails and must be redone until it reaches features, but this is costly for the company since the repair of the parts depends on the test approval. In addition, there is the expense of consumable material and labor. In the company where the study was conducted, it has been observed that a high rejection rate of test sample occurs, and there is no clear definition of how the thermal spray process could be improved to decrease the rejection rate.

This study aims to improve the performance of a specific test of a part whose failure can lead to delay and additional expense in repair; this study's great challenge and practical problem is to propose a solution through the implementation of the Lean Manufacturing methodology to minimize failures in this test. The present work has as main objective the application of the Lean methodology Manufacturing during Copper-Nickel-Indium Thermal Spray Test Run targeting at reducing the failure rate and identifying the contributing factors that cause failure to reduce part waiting time and rework expenses, thus increasing the operational effectiveness in the workshop.

None of the researched previous studies presented information for thermal process optimization. Some of these researched papers are listed herein in section 2. The study responds to the following important research questions:

Research Question 1: How can the Lean Manufacturing methodology be applied to Thermal Spray's process to increase its efficiency and reduce the risk of hardware failure?

Research Question 2: What benefits a process controlled by Lean tools manufacturing can bring to the company?

The paper is structured as follows: Section 2 describes the methodology and previous Thermal Spray and Lean Manufacturing studies. Section 3 presents the discussion, and section 4 the conclusion. In the end, the list of references used in this paper is provided.

2. DESCRIPTION

2.1 Methodology

The study was conducted following these steps: 1 – Research on the theoretical framework and updated literature using the keywords: Thermal Spray, Lean Manufacturing and Aeronautical Maintenance; 2 – Collection data and records of past and recent tests to confirm the need to apply the Lean Methodology to improve the process. Data were collected from the company's Materials Laboratory records; 3 - Conversation with operators to gather ideas and kaizens focused on reducing the test rejection rate; 4 - Execution of proposed kaizens and devices; 5. Application of kaizens and developed devices; 6. Test execution after improvements. 7. Test results analyzed by the laboratory collected and processed. 8. Elaboration and recording of a standard procedure for carrying out the test. Fig. 1 shows the flowchart with these steps.

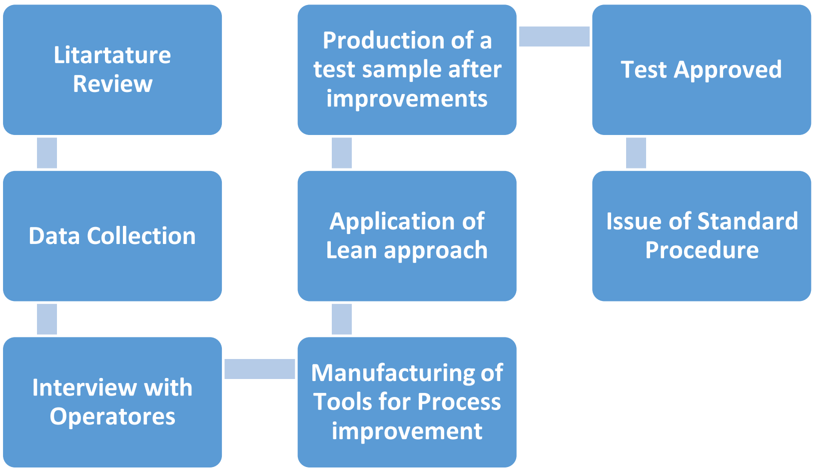

Fig. 1 – Methodology flowchart

The study focused on executing the Thermal Spray test on test panels processed simultaneously with the Fan Disk part from an aeronautical engine, as shown in Figure 2, where the Plasma Spray process applies the Cu-Ni-In coating. For the test, three specimens are needed that simulate the coating application locations on the part; these are the pressure faces located inside the slot.

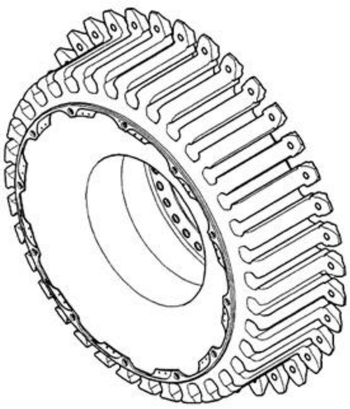

Fig. 2 – Blueprint of the Fan Disk

2.2 Thermal Spray

Thermal Spray is a generic term commonly used to define processes for applying metallic or non-metallic coatings. Heated particles are then carried by the process gas or compressed air jets and sprayed against a prepared surface. For Davis [1], when particles reach the surface, they form a bond, and subsequent particles overlap, forming the coating. Fig. 3 shows a schema with Therma Spray Process.

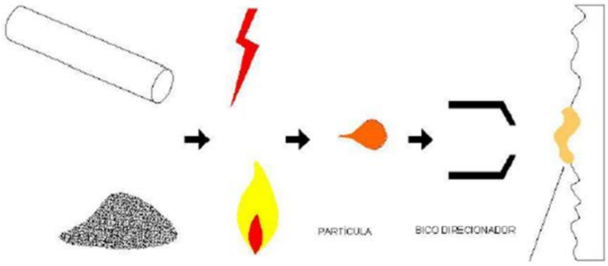

Fig. 3 –Thermal Spray Process

The industry's application began with the combustion process (oxygen-fuel), where molten metal particles with jets of steam or compressed air are projected [2]. A patent was registered with the use of electric energy as the heat-producing source [3]. However, the use of the process intensified, and over the years, the concept of reducing raw material and reusing parts was created [2]. During application, the particles deform and adhere to the base material [4]. The coating feed into the flame is done by gravity through a container with the coating in powder form or equipment that pressurizes a container. Some advantages that can be observed in the process by Cortés [5]: 1 - No cure time required, providing immediate corrosion protection, 2 - Good adhesion to subsequently applied sealants and paints, which makes a process easy to maintain, 3 - Possibility of application at temperatures close to 0°C. In the process, argon or nitrogen is used for ionization and hydrogen, or helium is added to increase power and speed [7]. Surface preparation is the most critical phase of the Thermal Spray application operation; the adhesion of the coating to the surface is directly linked to cleaning and roughness.
Besides the studies mentioned above, other works about Therma Spray are as follows: The type of coating applied and the substrate material is also determining factors in ensuring the quality of the process [6]. The initial step in surface preparation is cleaning, removal of contaminants such as rust, moisture, dust, oil, grease, paint, etc. [8]. After cleaning, abrasive blasting must be done to obtain surface roughness. Blasting must be done with sharp edges. According to Menezes [9], the angle of the abrasive jet must be between 75° to 90°.
In recent years, some studies about Thermal Spray and Cu-Ni-In coating are as follows: Fridrici et al.[10] studied the influence of the Cu–Ni–In coating on the cracking of the Ti–6Al–4V counter body and concluded that the presence of the coating changes the situations for which cracks nucleate and lowers the length of the cracks in the Ti–6Al–4V test sample for given conditions. Zhiqiang et al. [11] studied the fretting wear mechanism of plasma-sprayed Cu-Ni-In coating on Ti-6Al-4V substrate under plane/plane contact conditions systematically using a bench level test. J. Cizek et al. [12] used a combination of recently developed techniques, a simultaneous assessment of mechanical properties, fatigue crack growth rates, as well as fracture toughness in their study about this coating. They conclude that the behavior changes at higher loads: the particle interfaces in the cold sprayed deposits turn into the weak point, and the cracks grow at high rates by inter-particle lack of cohesion. At the same time, the sheet materials generally fail by striation mechanism at much lower rates. Fayegh et al. [13] studied the microstructure of the bonding zone by using optical and scanning electron microscopes, spectroscopy, and X-ray diffraction. Shear and microhardness tests were also used to evaluate the mechanical properties of the TLP joints. The results indicated that α-Ti, Ti2Cu, and Ti2Ni phases were formed in the thermally solidified zone of the joints.
The previous studies listed here dealt with Cu-Ni-In coatings by using different approaches. This paper aims to fill this gap by proposing and describing a method to optimize the coating application and define actions for improvement. This study brings a significant contribution by responding to two relevant research questions proposed previously.

2.3 Lean Manufacturing

According to Liker [14], Lean Manufacturing is a management philosophy that aims to identify and eliminate waste in the production system, which does not add value. The post-war destruction and lack of money and resources brought the need to provide consumer products so that the population could return to everyday life [15]. The term "Lean" emerged and was associated with Toyota's Production System. Kaizen means continuous improvement; the word has Japanese origin Kai (change) and Zen (good) and aims to add value to the finished product by eliminating waste [17]. The basis of Kaizen is to eliminate waste with quick, creative, and cheap solutions using the motivation and creativity of employees, thus improving work processes and directly impacting productivity [18]. The pattern is the starting point for improvement. According to Dennis [19], the basis of production is the standard to achieve operational excellence. However, the concept of pattern is suggested something complicated or complex to execute. However, in the Lean manufacturing approach, the pattern is a clear result that must be achieved at the end of processing. The result must be transparent so that abnormalities can be identified immediately and taken corrective actions.
In recent years, some studies about Lean Manufacturing, Thermal Spray, and Cu-Ni-In coating are as follows: Tagesson and Karlsson [20] stated an industrial culture related to the case that hampers efficiency, which the cornerstones of Lean manufacturing can explain. Monetary gains and environmental savings are achievable by measuring, including, and involving personal combined with dedicated management. Das et al. [21] also proposed many Kaizens methods to simplify the setup procedure by eliminating waste (muda) from the expander setup. Other benefits were obtained by reducing work-in-process inventory, shop floor congestion and coil damage due to extra coil handling, and improved workplace safety. Saito et al. [22] stated that the art of making things with excellence, skill, spirit, zeal, pride requires education and training. Sordan et al. [23] suggested implementing industrial robotics with balancing studies highlighting efficiency gains and idle reduction. Further, it also addresses some concepts directly related to industry 4.0, such as collaborative robotics, artificial intelligence, and lean automation.
The previous studies listed here dealt with applying Lean Manufacturing on coatings applications by using different approaches. This paper aims to fill this gap by proposing and describing a method to optimize coating application and define actions for improvement using kaizens. This study brings a significant contribution by responding to two relevant research questions proposed previously.

3. DISCUSSION

.

For this study, data on test rejections were first collected; these data were provided by the company's materials laboratory and were placed in an electronic spreadsheet. Thus, the First Time Yield (FTY) indicator was chosen to measure the efficiency of the process. FTY can be obtained by dividing the number of tests accepted by the number of tests done. The FTY of the process was 63.3%; that is, 36.7% of the tests that were made failed. This demanded a new execution of the tests, costing time and resources for the company. Through the study of the process and an exchange of ideas with the operators, it was possible to identify the main points and susceptible to failure, and that would be causing a test failure. For this, the Cause-and-Effect Diagram and the Cause-and-Effect Matrix were used, identifying action points for implementing improvements, as shown in Tab. 1. A total of 7 operators participated in the survey. The matrix was created by asking operators to assign weights to each item; the weights could be 0, 1, 3, or 9. After the assignment, the sum of the weights was performed, and it was possible to identify probable causes that influenced the test to fail.

Tab.1 – Initial Weights provided by operators

Cause and Effect Diagram Results									
Test Execution Process		Weights 0 – 1 – 3 – 9							
Process Steps	Input Variables	operator 1	operator 2	operator 3	operator 4	operator 5	operator 6	operator 7	Total Weight
Equipment Preparation	Gun Centering	9	9	9	9	9	9	9	63
	Air jet Convergency	9	9	9	9	9	9	9	63
	Gun Position	9	9	9	9	9	9	9	63
Equipment Parameters	Flame Temperature	3	3	9	3	3	9	3	33
	Gas Flow	3	9	9	3	1	9	3	37
Test Sample Preparation	Blasting and Roughness	9	9	9	3	3	9	3	45
	Substract Cleanleness	9	3	3	3	9	9	3	39

With the result of the matrix, it is possible to identify three main factors (in red) that, if not controlled, lead to test failure: 1 - Gun Centering – There was no tool to ensure the centering of the nozzle; it was done visually; 2 - Air Jet Convergence – There was no device to measure cooling air convergence. By the standard procedure, the air should converge at a specific value. It was uncontrolled; 3 - Gun Position – The spray gun has many moving parts, and if these parts moved, it would not be able to identify such movement.

Then the Kaizen tool was applied to each of the topics identified to remedy these failures. Four Kaizens were developed: a device to center the nozzle, a device to check the convergence of air, two marks on the gun body that are used as a reference to identify if any part of the gun moved during assembly. Fig. 4 shows the gun used and the places where the kaizens were implemented

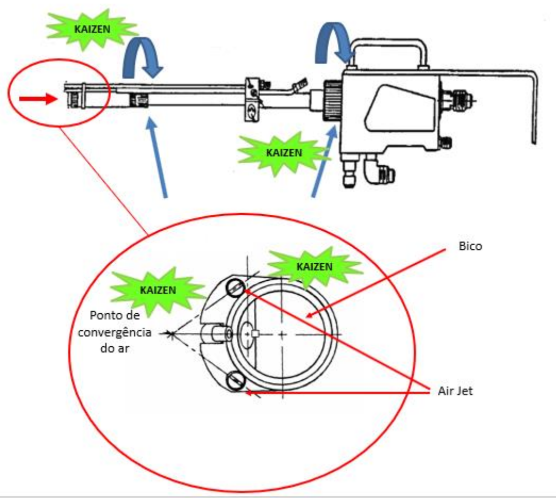

Fig. 4 –Thermal Spray Process Gun

After implementing the improvements, a new test was carried out to verify the immediate effectiveness of the process. First, the specimens for the coating application were prepared; the dimensions of the specimens were the ones required to simulate the left and right sides and the center. The specimens are made of the same alloy as the parts. They were previously prepared with a blasting process that improves the surface resistance of the material. The equipment used for the Plasma Spray coating application process was a robot, as shown in Fig.5.

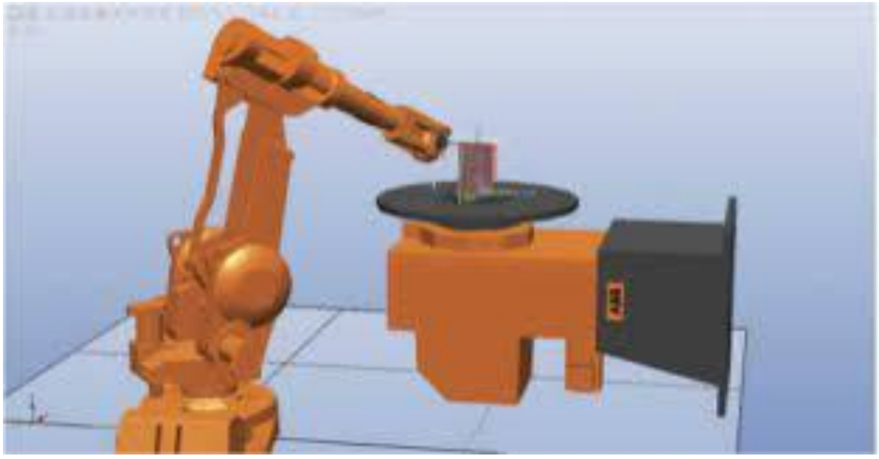

Fig. 5 –Thermal Spray Process robot

After applying the coating, the specimens were submitted to metallography analysis. Fig. 6 shows the microstructure of the coating obtained.

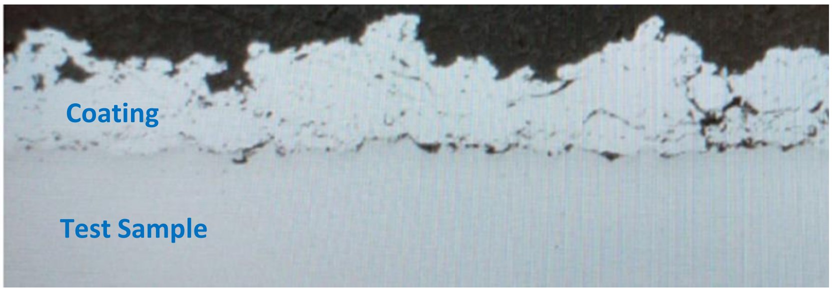

Fig. 6 – Microstructure of the coating

The test was carried out after the improvements were approved, but the data collection remained for one month to conclude that the process was impacted. Moreover, during the process, only one piece of evidence was rejected. The reason for rejection was studied. It was concluded that the operator did not follow a step of the procedure that was created, which is verifying the robot tool angle with a digital goniometer to ensure that the gun does not rotate during the execution of the program. If the operator performed this step, he would identify that the gun was rotating, and possibly the test would not have failed.

Tab.2 – Final Weights provided by operators and improved FTY

Calculation of the new FTY of the process and perception of operators					
Input Variables	**Initial Weights**	**Failure percentage**	**Condition**	**Final Weights**	**New Failure Percentage**
Gun Centering	63	18,4%	Controlled	13	6,6%
air jet convergence	63	18,4%	Controlled	13	6,6%
Gun position	63	18,4%	Controlled	17	8,6%
Flame temperature	33	9,6%	Not Controlled	33	16,8%
Gas flow	37	10,8%	Not Controlled	37	18,8%
Sandblasting and roughness	45	13,1%	Not Controlled	45	22,8%
Cleaning the substrate.	39	11,4%	Not Controlled	39	19,8%
Sum of process perception indicator	343	100,0%	Sum of process perception indicator	197	100,0%
Initial FTY: 63.7% (approximately 3 years)			**Final FTY: 93,7% (2 months)**		

Tab 2 shows the Final Weights provided by operators and the improved FTY. The new process after the change had FTY is 93.7%, a 30% improvement over the previous FTY. This reduction in the test rejection rate generated savings in materials, labor, and supplies spent on reworking the test and prevented the part from being stopped waiting for a new test to be applied.

4. CONCLUSION

As initially proposed, the results show, through a case study, the application of Lean Manufacturing to optimize the Thermal Spray process to reduce the risks of hardware failure. The study also shows the benefits to the company. The result is significant compared to previously published studies, as it contributes to thermal spray optimization and reduction of risks. As an implication, other companies can use the results of this study to obtain improvements in the quality of Cu-Ni-In coatings. Researchers may also use this study to develop additional studies in coating applications. Considering the guidelines methods and analyzing the literature, it was possible to validate the hypothesis that Lean Manufacturing can be implemented in the Thermal Spray process through quality tools.

In response to the first question: How can the Lean Manufacturing methodology be applied to the Thermal Spray process to increase its efficiency and reduce the risk of hardware failure? With the study and analysis of the process and especially the involvement of operators that work with the process, it was possible to implement tools provided by Lean Manufacturing methodology to the Thermal Spray process such as Kaizen, Cause and effect matrix, cause and effect diagram, and the concept of standardization. The observation and data processing and the study of failures significantly contributed to the analysis of the process, thus ensuring an increase in process efficiency.

In response to the second question: What benefits can a process controlled by Lean Manufacturing tools bring to the company? The application of the tools reduced the rejection rate to the process of the tests and thus avoided additional costs with the rework of the tests and the expressive gain in hours of machine use. During the project implementation, it could be noticed how important it is for the companies to evaluate their processes to seek continuous improvement reducing their operating expenses and service delivery time, which continue competitively in the market

As expected, the contribution is significant since the proposed process optimization and risk reduction in the thermal spray process permit decision-makers to assign funds for critical activities that can impact the quality of the process. It is believed that the present study will augment the knowledge of process engineers and managers and help in the decision-making process.

1. REFERENCES:

[1] DAVIS, JOSEPH R. Handbook of thermal spray technology. 1. ed. ASM International (20040. disponível em: < https://books.google.com.br/books > acesso em April de 2021.

[2] LIMA, C. TREVISAN, R. Aspersão Térmica: fundamentos e aplicações. 2ª ediçao revisada e ampliada, Editora Art. Liber. (2007).

[3] COUTO, L. C. O. Aspersão Térmica na construção metálica- Ciência e Arte: Trabalho Técnico apresentado no Congresso Latino-Americano da Construção Metálica, (20060. ed. São Paulo: [s.n.], available at <http://metalizacao.eng.br/data/documents/Aspersao-Termica-na-Construcao-Metalica-Construmetal-Consultoria-metalizacao.eng.br.pdf> acessed in April de 2021.

[4] AWS - American Welding Society, Inc. Thermal Spraying. Practice, Theory, and Applications, (1985).

[5] CORTÉS, R. S., PIZA, M. T., BUSCHINELLI, A. J. A., Sistemas Dúplex de Revestimentos para Meio Offshore (Aspersão Térmica do Alumínio + Selante Orgânico) – Proteção Anticorrosiva Superior a 20 anos com Manutenção Mínima, X EBRATS, São Paulo, SP, (2000). Available at< http://www.metalmat.ufrj.br/index.php/br/pesquisa/producao-academica/teses/2007/46--37/file> acessed in April 2021.

[6] MARQUES, P. V. Aspersão Térmica. Infosolda. Disponivel em: <http://www.infosolda.com.br/artigos/processos-de-soldagem/231-aspersaotermica. html>. Acesso em: 22 Abr 2021.

[7] SANTOS, A. O., Estudo da resistência a corrosão em aço e revestimentos visando a aplicação em hastes de bombeio de petróleo. Dissertação de Mestrado, UNIT, Aracaju, SE. (2008). Available at < http://www.dominiopublico.gov.br/pesquisa/DetalheObraForm.do?select_action=&co_obra=109332> Accessed in April de 2021.

[8] PADILHA, H. Estudo sobre revestimentos depositados por aspersão térmica para melhorar o desempenho de conexões elétricas. Dissertação de mestrado., PIPE/UFPR, Curitiba, Brasil. (2005) Available at < https://acervodigital.ufpr.br/handle/1884/4681> Acesso em April 2021.

[9] MENEZES, D. D., Avaliação da resistência a corrosão de revestimentos de alumínio aplicados pelas técnicas de arco elétrico e chama convencional, em meio cloreto. Tese de Doutorado, COPPE/UFRJ, Rio de Janeiro, RJ, Brasil. (2007). Available at < http://www.metalmat.ufrj.br/index.php/br/pesquisa/producao-academica/teses/2007/46--37/file#:~:text=D.Sc.)> Accessed in April 2021

[10] Fridrici, S Fouvry, Ph Kapsa, Fretting wear behavior of a Cu–Ni–In plasma coating, Surface and Coatings Technology, Volumes 163–164, (2003). Pages 429-434, ISSN 0257-8972, https://doi.org/10.1016/S0257-8972(02)00639-4.

[11] Zhiqiang Niu, Wenlong Zhou, Chenglin Wang, Ziwen Cao, Qi Yang, Xuesong Fu, Fretting wear mechanism of plasma-sprayed CuNiIn coating on Ti-6Al-4V substrate under plane/plane contact, Surface and Coatings Technology, Volume 408, (2021). ISSN 0257-8972, https://doi.org/10.1016/j.surfcoat.2020.126794.

[12] J. Cizek, O. Kovarik, J. Cupera, J. Kondas, T. Bajer, F. Siska, M. Janovska, H. Seiner. Measurement of mechanical and fatigue properties using unified, simple-geometry specimens: Cold spray additively manufactured pure metals, Surface and Coatings Technology, Volume 412, (2021). ISSN 0257-8972, https://doi.org/10.1016/j.surfcoat.2021.126929.

[13] Fayegh, A., Aghaie-Khafri, M. & Binesh, B. Interfacial microstructure and mechanical properties of transient liquid phase bonded IN718/Ti-6Al-4V joints. Weld World (2021). https://doi.org/10.1007/s40194-021-01134-y

[14] LIKER, J. K. O modelo Toyota: 14 princípios de gestão do maior fabricante do mundo (2005). São Paulo: Bookman,. 316 p.

[17] OHNO, T O sistema Toyota de Produção: Além da produção em larga escala. Porto Alegre: Bookman,. 150p. (1997).

[18] SLACK, N. et al Nigel Slack_ Alistair Brandon Jones_ Robert Johnston - Administração da Produção-Atlas. (2018).

[19] DENNIS, P (2008). Produção Lean Simplificada. Porto Alegre: Bookman. FERRO, J. R. Efetiva solução de problemas: o que está faltando? Lean Institute Brasil (2006). Available at https://www.lean.org.br/artigos/938/efetiva-solucao-de-problemas--o-que-esta-faltando.aspx, accessed in May 2021.

[20] Tagesson, D., & Karlsson, I. Implementation of Green and Lean manufacturing in post processing activities : A qualitative case study at a barrier coating facility (Dissertation). (2021) Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kau:diva-85080

[21] Das, B., Venkatadri, U. & Pandey, P. Applying lean manufacturing system to improving productivity of airconditioning coil manufacturing. Int J Adv Manuf Technol 71, 307–323. (2014). https://doi.org/10.1007/s00170-013-5407-x

[22] Saito K., Salazar A.J., Kreafle K., Grulke E. Hitozukuri and Monozukuri in Relation to Research and Development in Surface Coating. In: Toda K., Salazar A., Saito K. (eds) Automotive Painting Technology. Springer, Dordrecht. (2013) https://doi.org/10.1007/978-94-007-5095-1_6

[23] Sordan, J.E., Oprime, P.C., Pimenta, M.L., Lombardi, F. and Chiabert, P. (2021), "Symbiotic relationship between robotics and Lean Manufacturing: a case study involving line balancing", The TQM Journal, Vol. ahead-of-print No. ahead-of-print. (2021), https://doi.org/10.1108/TQM-03-2021-0073