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FMEA-TRIZ Analysis of Reused Ti6Al4V Powder in SLM

Baris Ördek[a], Davide Russo[a], Christian Spreafico[a,*]

[a]Department of Management, Information and Production Engineering, University of Bergamo, Via Pasubio 7/b, 24044 Dalmine (BG), Italy

* Corresponding author. Tel.: +39 035/2052031. *E-mail address:* christian.spreafico@unibg.it

Abstract

Selective laser melting (SLM) allows powder reuse in consecutive cycles, a cost-effective and sustainable practice. However, repeated reuse can degrade powder quality, impacting the final product's mechanical properties. This study presents a methodology combining Failure Mode and Effect Analysis (FMEA) with the Theory of Inventive Problem Solving (TRIZ) to address issues in reusing Ti6AL4V powder in SLM. The approach identifies and mitigates potential failures while leveraging an AI-based chatbot to expedite solution-finding. A case study is implemented to demonstrate the FMEA-TRIZ approach proposed in this paper, showcasing the potential benefits of this innovative methodology.

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Keywords: FMEA; TRIZ; reused powde; Ti6AL4V; powder degradation; generative AI

1. Introduction

Generative AI systems are rapidly developing across all parts of industry and research environments. Humans interact with these systems through a phenomenon called prompting, which is defined as an input to a generative AI tool to get the desired output. Prompts can contain images, text, sound, or other media [1]. Prompting in engineering can involve cases, queries, or instructions to leverage AI and machine learning to optimize engineering problems. This method can enhance human-machine interaction, which enables accurate control and deliberate decision-making [2].

Failure Mode and Effect Analysis (FMEA) is a comprehensive and systematic approach used for identifying potential failure modes of a product, system, or process, evaluating the impacts, and highlighting actions to mitigate the risk [3]. It is commonly used in aerospace, automotive, and manufacturing industries to enhance the reliability and safety of products. The FMEA process involves the identification of all possible failure modes, understanding the effects of those failures, and evaluating the occurrence, severity, and detectability of each identified failure mode [4].

Theory of Inventive Problem Solving (TRIZ) is a systematic, innovative problem-solving methodology with a rich history, invented in the mid-20th century [5]. TRIZ aims to solve unconventional problems, forecast technologies and future products, and provide methods to face reliability issues [6].

Integrating FMEA and TRIZ methodologies offers a powerful approach to risk management and problem-solving in manufacturing. TRIZ can enhance FMEA by introducing structured problem-solving tools to address failures proactively before they occur. However, it is crucial to address the limitations of FMEA. For example, [7] stated that the FMEA methodology was time-consuming. According to [8], FMEA methodology does not affect the decision-making and design process since it is usually performed too late. [9] stated that using FMEA to represent a cause-and-effect chain is inefficient since this method alone is not efficient for handling combinations among multiple and simultaneous effects. To overcome these limitations, it is possible to apply a combined FEMA-TRIZ as a complementary approach. By combining these two approaches, the limitations of both methods can be effectively addressed. This approach uses TRIZ to identify solutions to contradictions and inefficiencies identified by the

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FMEA analysis. This hybrid approach can generate more comprehensive and innovative solutions to failures, specifically in complex systems [6].

This study proposes a method to identify solutions to enable the reuse of reused powder on a broad spectrum, i.e., by eliminating the damaged one, preventing it from being damaged or mitigating the harmful effects of its use in the part. The method is based on introducing a pipeline in which problems are reformulated and classified to facilitate the search for solutions. Several tools have been integrated into the method: the FMEA ontology to organize problems, some tools of the TRIZ method for reformulating the problem, and the integration of an AI-based technical chatbot to search for solutions.

The rest of the paper is organized as follows. Section 2 describes the proposed method in three perspectives: during, before, and after problem. Section 3 demonstrates the case study, focusing on the satellite particles failure mode. Finally, in Section 4, the main results are summarized, conclusions are drawn, and future works are presented.

2. Proposed method

The proposed method investigates the failure modes in three perspectives: during problem, before problem, and after problem. Details on these perspectives are provided in the following subsections. Fig. 1 shows details of the proposed method.

2.1. "During problem" perspective

The starting point of the proposed method is the identification of the failure mode, i.e., the reused powder with a certain failure, that is provided by an industrial problem.

The failure mode is reformulated to obtain a well-defined problem to be faced. The problem reformulation is carried out by exploiting two tools of the TRIZ method:

- Object-Product transformation: is used to alter the form or function of an object to solve technical problems and fulfill new objectives. This transformation often involves the application of 40 Inventive Principles of TRIZ [6].
- Element Name Value (ENV) model: to enrich the failure reformulation with parameters and numerical values associated with them, which can have an influence on the search for solutions. Or to describe the position of the powder in the bed in order to identify how/where to use the collection technology [6].

AI-search is used to retrieve solutions to collect powder with failures. AI search exploits prompting techniques and an AI technical chatbot.

- Applying prompting techniques [1,2]
- Prompt reformulation (through Discovery Omnia) technical chatbot [22].

2.2. "Before problem" perspective

In this perspective, after identifying the failure mode, perturbed function analysis is conducted to identify the root

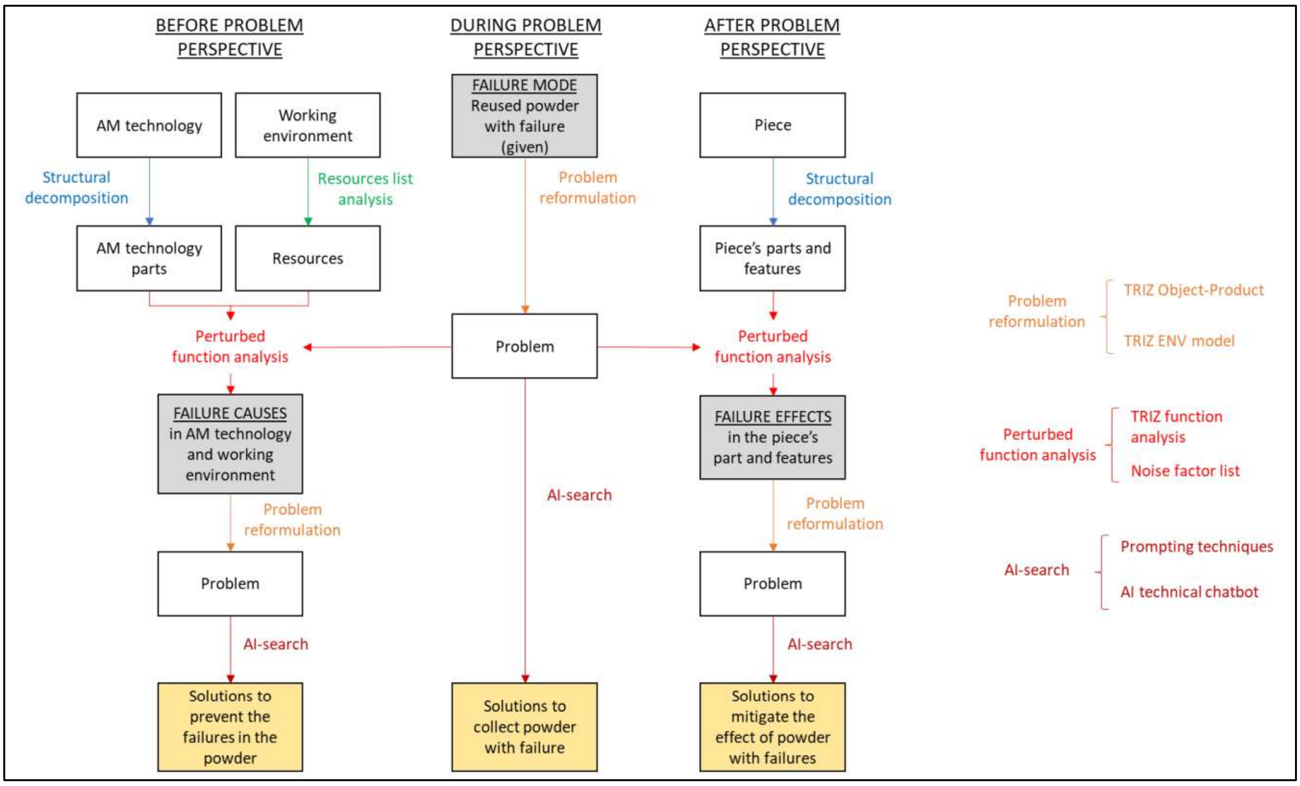

Fig. 1. Proposed Method

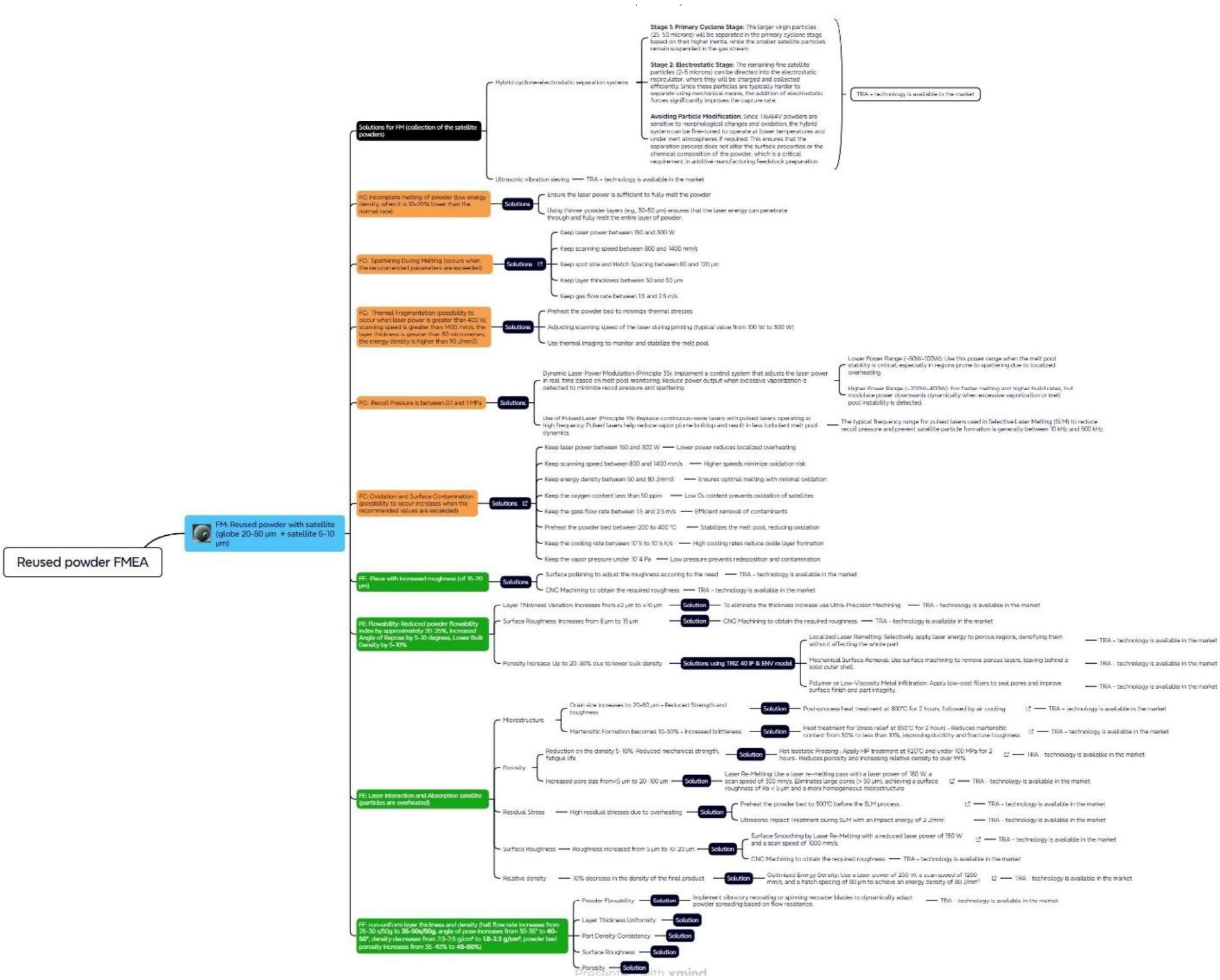

Fig. 2. Mind map including satellite powder failure mode, failure causes, and failure effects

causes of the failure mode by considering the AM technology and the working environment provided by an industrial problem.

Perturbed function analysis (PFA) is a TRIZ tool for identifying and eliminating unnecessary functions in a system by systematically analyzing the effect of small changes on its performance [3]. PFA is used to determine possible causes of failure modes identified in the "during problem" perspective. Then, problem reformulation is conducted using TRIZ object-product transformation and TRIZ ENV model. The problem reformulation is achieved through AI search prompts and an AI technical chatbot. Finally, solutions to prevent powder failures are identified.

2.3. "After problem" perspective

In the "after problem" perspective, the piece is produced with the failure mode identified by an industrial problem (e.g., production using reused powder with satellite particles). PFA is applied to the final product to identify potential failure effects in the piece's parts and features. Then, the problem is reformulated using the TRIZ object-product and ENV models. The result of TRIZ models is generating prompts to mitigate the effects on the final product, e.g., the effect of powder with failures. Finally, these prompts are used to generate solutions, which are evaluated using the Technology Readiness Assessment (TRA).

3. Case study: Satellite particles

Powder degradation occurs during powder reuse in Selective Laser Melting (SLM). Powder degradation modes are particle oxidation, satellite particles, loss of sphericity, agglomeration, irregular size, hollow and porous particles, and elongated or deformed particles.

The focus of the case study is applying the proposed methodology into the satellite particles failure mode. The mind map containing satellite particle failure mode is shown in Figure 2. Satellite particles typically have 20 to 50 µm globe diameter and 5 to 10 µm satellite diameter [10]. An image of a particle with a satellite is demonstrated in Fig. 3.

3.1. "During problem" perspective: Collection of satellite powders

The satellite powder failure mode is identified, and the problem is reformulated using TRIZ Object-product and ENV models. Figure 4 shows the section of the mind map that demonstrates solutions from the "during problem" perspective. Prompting techniques presented in [1, 2] were applied to generate a prompt to find solutions to collect satellite particles. The final prompt was reformulated via a technical chatbot (through Discovery Omnia):

"How can satellite particles of Ti6Al4V, with a

diameter of 2-5 µm, be collected from a virgin powder with a diameter of 20-50 µm?"

Fig. 3. AI generated image of the satellite particles failure mode

By using this reformulated prompt, the following two solutions are identified for collecting satellite particles:

- Ultrasonic vibration sieving: Technology is already available in the market; hence, the technology is mature.
- Hybrid cyclone-electrostatic separation systems: This hybrid process, which includes two separation systems used in order, significantly improves powder quality. The cyclone separation system utilizes centrifugal forces to separate denser and larger particles, while the electrostatic separator further enhances the process by using differences in electrical charge-to-mass ratios among particles.

3.2. "Before problem" perspective: Preventing the occurrence of satellite powders

Fig. 5 shows the mind map for the "before problem" perspective. The TRIZ PFA and TRIZ ENV models are applied to the failure mode satellite powders to identify the main reasons behind the occurrence of satellite particles (e.g., failure causes), which are listed below:

- Incomplete melting of the powder,
- Spattering during melting,
- Thermal fragmentation,
- Recoil pressure is between 0.1 and 1 MPa,
- Oxidation and surface contamination.

For the "before problem" perspective, incomplete melting of the powder failure cause is selected to demonstrate the methodology. The following information is identified as the causes of that satellite powders occur during SLM, specifically focusing on the incomplete melting of the powder failure cause:

- The virgin powders have 20-50 µm diameter.
- The satellite particles have 2-5 µm diameter.
- The observed failure mode is incomplete melting due to having satellite particles.
- The energy density is lower than standard value (10-20%).

This information was given to a chatbot to generate a search prompt using the prompting techniques in [1, 2].

The reformulated prompt is given below (through Discovery Omnia chatbot):

"How do satellite particles in reused Ti6Al4V powder (20-50 µm with 5-10 µm satellites) affect the melting dynamics, heat distribution, and powder bed density in Selective Laser Melting (SLM), leading to incomplete melting at reduced energy densities (10-20% below optimal)? What mitigation strategies can be employed to reduce the risk of incomplete melting when using reused powder with satellites?"

This prompt is used in an AI chatbot to generate solutions to avoid the identified failure cause. The following solutions are provided:

- Improving the particle size distribution: removing particles smaller than 10 µm and maintaining 20-50 µm powder size range can prevent the occurrence of satellite particles [11, 12].
- Adjusting the laser power: this solution suggests using dynamic laser power to ensure equal melting in all areas of the powder. (e.g., laser power increased in the areas where satellite particles are available) [13].
- Melt pool monitoring: real-time process control can dynamically optimize SLM process parameters (such as, laser power is between 150-400 W, melt pool depth is 50-300 µm, scan speed is 600-1200 mm/s, layer thickness is 20-50 µm, and energy density is 50-80 J/mm2) so that the occurrence of satellite particles is mitigated [14].

3.3. "After problem" perspective: mitigating the effect of satellite powders on the final product

The section that presents the "after problem" perspective is shown in Fig. 6. In this perspective, the final product is manufactured using powder with the failure mode satellite particles. Using the TRIZ PFA and ENV models, the possible failure effects are identified:

- Piece with increased roughness of 15-20 µm.
- Poor flowability (piece with increased layer thickness (from 2 µm to 10 µm), piece with increased surface roughness

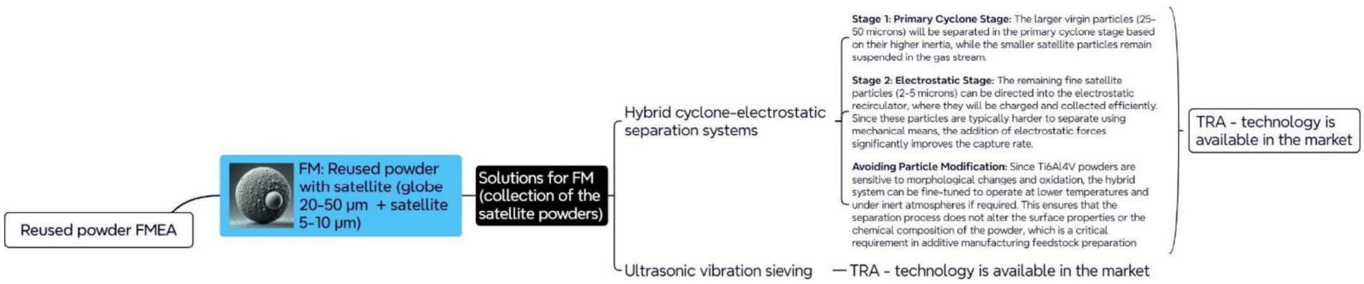

Fig. 4. The section of the mind map focusing on solutions for the satellite particle failure mode from the "during problem" perspective

(from 8 µm to 15 µm), piece with increased porosity (up to 20-30 %)).

- Laser interaction and absorption satellites (happens when particles are overheated). It affects the microstructure, porosity, residual stress, surface roughness, and relative density of the final piece.
- Piece with nonlinear thickness and density happens when the hall flow rate increases from 25-30 s/50g to 35-50s/50g, angle of pose increases from 30-35° to 40-50°, density decreases from 2.3-2.5 g/cm³ to 1.8-2.2 g/cm³, powder bed porosity increases from 35-40% to 45-50%.

Here, the solutions to piece with increased surface roughness failure effect is investigated. The first step is to check if the increased amount of surface roughness meets the requirements of the customer (i.e., the final surface roughness value is within the tolerance range). The second step is to search for solutions to mitigate the effect of the increased surface roughness. To determine solutions for this failure effect, the following prompt is generated using Discovery Omnia chatbot:

> *"What proven post-processing techniques can effectively reduce or eliminate surface roughness in Ti6Al4V parts produced by Selective Laser Melting (SLM) with satellite particles (globe 20-50 µm and satellite 2-5 µm), without compromising material properties?"*

Using the abovementioned prompt, the following solutions are identified:

- Shot peening [15].
- Micro-machining or precision CNC machining can be used to remove the excess surface roughness [16].
- Electropolishing process to reduce surface roughness to the desired value [17].
- Chemical Polishing is used to reduce surface roughness by applying acid bath [18].
- Laser polishing is used to re-melt the surface of the final piece for decreasing the surface roughness [19].
- Isotropic Superfinishing is gradually polishing the surface of a piece by applying vibrations [20].
- Abrasive Flow Machining is employed using a semi-viscous abrasive media through surfaces to reduce the roughness. Typically used to reduce roughness of complex internal surfaces [21].

4. Conclusions

The case study provided has shown how the use of a structured approach and specific tools can be fundamental for a correct reformulation of the starting problem.

FMEA-TRIZ has proven to be useful in highlighting different perspectives with which the problem of powder reuse can be addressed, such as prevention and mitigation, when the identification and collection of dust with particular defects are particularly difficult to achieve.

TRIZ tools for reformulating the problem, such as ENV model, are instead useful for also providing a quantification of the problem, so as to narrow down the field of solutions that one wants to look for. For example, it is one thing to look for a sieve for a grain of dust with a satellite around it, it is another to know what the overall diameter of the grain with the satellite is, in order to identify the solution that is right for us.

Furthermore, reformulating the starting problem is also essential to formulate more effective prompts to search for relevant solutions in the powder reuse problem. One of the strengths of the method and of Discovery Omnia is the reformulation of the problem to be searched for and therefore of the prompt so as to increase the precision and recall of the search, which when it comes to patents, can be particularly difficult, even for AI.

Future works include an interview with a metallurgy expert to conduct a comprehensive FMEA, providing assessments of severity, risk of occurrence, and probability of the identified failures.

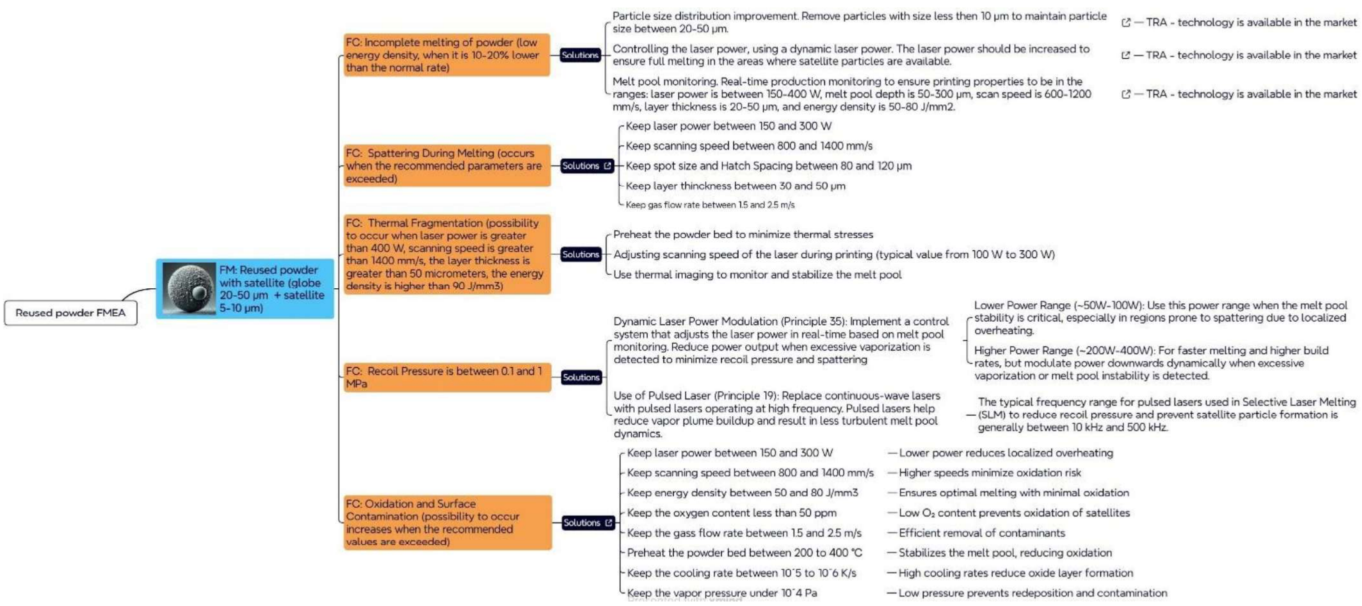

Fig. 5. The section of the mind map with the focus on the failure causes from the "before problem" perspective

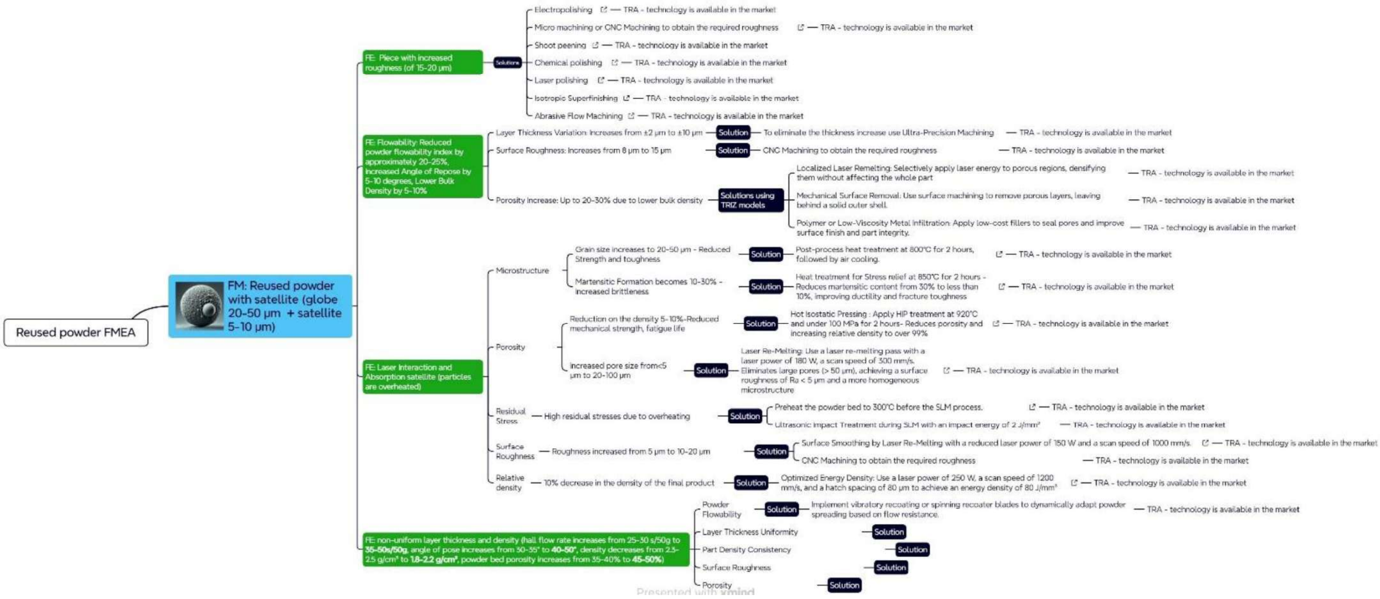

Fig. 6. The section of the mind map with the focus on the failure causes from the "After problem" perspective

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