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Remanufacturing Process Planning

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Abstract

Remanufacturing is an active area of research due to its cost saving capabilities and emission-reduction benefits. After being disassembled, cleaned and inspected, the core components go through a series of reconditioning operations before being reassembled into the final remanufactured product, and tested to ensure quality. However, used core components have varying conditions, different defects, etc., which result in reconditioning process paths being specific to each component in the core. The reconditioning process sequence for a core component depends on its conditions. This paper analyses the conditions of the core components to determine an optimal reconditioning process sequence for these components

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Keywords: Remanufacturing, Reconditioning, Process sequence

1. Introduction

In the recent decades, with the development of climate change and increased pollution, there has been a global rising concern about the environment, matched with tighter legislations to control the ecological impact of human products through their use and manufacturing. Production businesses go “green” by incorporating sustainable manufacturing and end-of-life (EOL) strategies to meet regulations, and attract the now environmentally conscious consumers. Besides recycling, repair and refurbishing, remanufacturing is another EOL strategy where a used product is brought, through a series of industrialized processes, to “like-new” conditions with warranty and performance at least matching the OEM level [1], and offers the used product another complete lifecycle.

One of the complicating characteristics in remanufacturing is the stochastic and sporadic nature in the condition and quantity of the returned cores which impacts on many levels in the planning and control [2, 3]. Returned products can range from minor scratches to extensive damage and thus inspection and sorting procedures are required to filter the valuable cores. High quality returns are preferred as the quality of the returns determines the level of the remanufacturing effort required, the processing time, the rate of remanufacturing success, the process sequence used, the amount of cost savings, and the amount of cores being scrapped [4, 5]. The extent to which remanufacturing is done and the definition of sufficient quality depend on the type of remanufacturers and the business model; independent remanufactures try to repair as many parts as possible, whereas OEM remanufacturers can be more selective on the cores to accept [6]. Inspection therefore plays an important role in order to sort the cores. During inspection, the remanufacturing suitability of a core is estimated and the processes to be used are evaluated based on the inspector’s knowledge and scheduling constraints. The decision-making process and the ability to restore a core reliably have a strong influence on the success rate and profit of the remanufacturing initiative. Despite all the technical challenges and scheduling difficulties, the remanufactured product must be of high reliability and quality while being price competitive to be successful.

Reliable engineering expertise and capabilities is the backbone to a successful remanufacturing facility. Remanufacturing depends extensively on the skills of the technicians and the knowledge base related to the cores and their restoration [7]. However, OEMs who wish to maintain their competitive edge will not divulge their product design information to the independent remanufacturers who would have to rely on their own experience [2, 8, 9] combined with industry guidelines, such as QS9000[10].

Through the inspection and sorting process, cores are classified as to whether they can be reused, remanufactured, scrapped and recycled. In this paper, the cores that can be remanufactured are of concern. A conceptual framework and methodology are proposed to aid in the selection of the reconditioning process sequence based on the conditions of the cores and their engineering functions, which will be the guiding factor during the decision making processes.

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2. Literature review

2.1. FMEA

Parkinson [10] proposed a systematic approach to the planning based on the failure mode effect analysis (FMEA) method in order to increase the reliability of the remanufactured product. FMEA is used for risk management and the prevention of catastrophic failure of the product by first performing a product FMEA to identify the critical core components which need to be focused on. Second, the remanufacturing processes to treat them are established. Next, a process FMEA is used to determine the remanufacturing processes among inspection, cleaning, manufacturing operations that are most critical and the ways to diminish their risk priority number (RPN) are decided by a consensus of the technical team and the management. Finally, a cost benefit analysis using the RPN/cost ratio serves as a guide on where more resources should be allocated. This four-step approach can be applied repeatedly to improve the reliability of the remanufacturing system. Shu et al. [11] performed waste stream FMEA analysis to identify the failure and scrap modes of automobile parts against which Design for Remanufacture must cater for to facilitate remanufacturing.

2.2. Process planning

Kernbaum et al. [12] presented an approach for the design and evaluation of the remanufacturing processes for a facility. A mixed integer programming approach is used for the optimization of a remanufacturing process plan from cleaning to reassembly; they assessed the economic viability by considering all the relevant costs. The reconditioning process planning, however, is still performed by the user who inputs the process in the software through graphical user interface (GUI), which helps the users to visualize the sequences and types of operations.

Jiang et al. [13] defined reconditioning system planning as being made up of three closely related aspects, namely, restoration planning, process planning and technology planning. Assuming that the restoration and process planning have already been performed, they formulated a multi-criteria decision-making method that considers the economic and environmental aspects for the selection of the manufacturing technology portfolio. The analytical hierarchy process (AHP) was used to assign weights to the various criteria, and capture the singular and synergistic benefits of each technology for decision making.

2.3. Product design and remanufacturing

A valuable core is remanufactured such that its quality is at least as good as a new one. Fig. 1 depicts the technical factors influencing the reconditioning operations. Analogous to the case of new product development where manufacturing processes need to meet design requirements in order for the product to fulfill satisfactory functional capabilities with reliability, remanufacturing reconditioning operations, too, have the objective to restore the core to meet the performance criteria of the product in order that it can successfully perform its intended purpose. As such, product design considerations are important in the selection of the reconditioning processes so as to ensure that the remanufactured product will be of high quality.

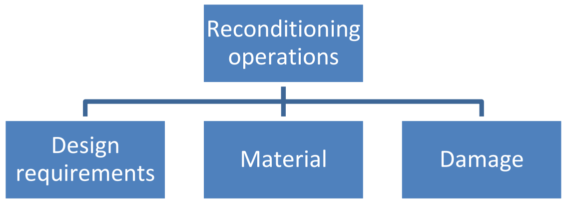

Fig. 1: Technical factors driving reconditioning operations.

Process planning is the specification of the manufacturing operations to be performed, the parameters of these operations and the order in which they will be executed. In the case of remanufacturing, the “raw” materials are the returned cores where the design and material have already been fixed. The reconditioning process can be defined in two interlinked stages, namely, restoration of defects and remanufacture to high quality.

2.4. Types of reconditioning operations

The remanufactured core should be ideally free from any damage from its previous use phase, as well as from secondary effects from the reconditioning processes. Therefore, in selecting the process sequence, the side effects of each step on the part need to be taken into consideration to avoid reworking. Hence, the types of reconditioning processes can be classified into five main categories as follows:

A. Remove surface and shape defects
B. Material addition or surface replacement
C. Restore material properties
D. Assembly and fastening manipulation
E. Surface finish

a) *Remove surface and shape defects*

Defects, such as cracks, scratches, nicks and burrs, burnt or corroded regions, and inclusions are removed by machining processes such as turning, milling, drilling, grinding, etc. Surface finish and tolerances are not of top priority but rather the removal of all stress raisers. However, if a part is in good condition and does not need to be further treated, machining with the final surface quality can be performed if technically feasible. When surface defects such as cracks are deep, the material around the defect is gouged out if refilling of such cut-out does not impair the strength and safety requirements of the part. Shape defects, such as bends, warps and dimples, are also removed if technically feasible and design considerations allow.

b) *Surface addition or surface replacement*

A part with "cavities" can be restored to its intended shape and gross dimension through material additive processes, such as welding, powder coating, laser cladding. Depending on the requirements and nature of the surface, the appropriate method is selected. Due to the application of high temperature, pre-heating is required to avoid cracking. Stress relief grooves may be applied when necessary.

In some cases, inserts and sleeves may be used to provide new surfaces, such as valve guides in cylinder heads, after the original surface has been initially bored to fit the insert. This approach is used in cases where the required surface/material condition cannot be restored through the normal conditioning processes, and therefore providing a new surface would be more practical and offer better performance. Finishing processes are applied subsequently to the inserts to match specifications.

c) *Restore material properties*

Desired material properties are restored through conditioning processes, such as heat treatment, which either remove unwanted residual conditions (annealing, normalizing, demagnetization), or prepare the part to be more resistant to its loading and environmental operating condition. Such treatments can be either throughout the whole material or up to a layer below the surface, such as in case hardening (carburizing, nitriding, induction hardening, shot peening). For example, in design against wear, it is generally accepted that a hard surface is beneficial [14], whereas for fatigue resistance, the bulk needs to be tough and the surface shall contain compressive residual stresses.

d) *Assembly and fastening manipulation*

In the case of sub-assemblies with many constituent parts, assembly manipulation is needed as the parts are put together. Such manipulation may alter dimensions which require specific tolerances, and cause them to be out of dimensions. For example, in the remanufacturing of a connecting rod, the big end journal surface needs to be honed after the rod bolts have been tightened, otherwise the tightening would result in concentricity issues. The assembly and fastening activities should therefore be prior to processes that restore any region to the final dimension.

e) *Surface finishing*

Fine surface finishing where final high quality finish or dimensional tolerances are required, can be achieved using processes, such as grinding, reaming, honing, hard turning, and burnishing. In other types of surfaces, painting, coating, polishing and similar operations relevant to the part are performed. This step is performed last because any subsequent process will affect the quality of the surface.

3. Methodology

The key features of the conceptual framework are:

1. Use of product design engineering requirements to determine the reconditioning processes.
2. Regionalization of defects per engineering surface.
3. Rank criticality assessment of the defects.

The proposed framework of the reconditioning processes is illustrated in Fig. 2, and the sequence is as follows:

1. Identify defects and their locations
2. Assess and rank defect criticality
3. Identify reconditioning operations for each defect
4. Identify precedence relationships
5. Devise reconditioning process sequence
6. Risk and reliability assessment
7. Preliminary selection

Step 1: Identify defects and their locations

All the defects present in the core component have to be identified, and one of the ways is by analyzing the waste stream data. The locations and occurrences of the defects are mapped out over the core's shape. The engineering surfaces which are subject to the same kind of loading and having the same design requirements are delineated.

Step 2: Rank and assess defect criticality

In this stage, a full product FMEA is performed. The different types of defects which have been grouped are scored using the FMEA indicators of occurrence (OCC), severity (SEV) and detectability (DET) and then ranked based on the risk priority number (RPN) where RPN= OCCxSEVxDET. This assessment is performed by comparing the location of the defect to the product's intended engineering function, loading capacity and environmental condition. For example, a crack at the external surface of an engine is less critical than in the cylinder bore, which is subjected to contact pressure, sliding motion and higher heat.

The specific engineering requirements which determine criticality of the defects must be clearly noted. The higher ranked defects will be given higher priority during the reconditioning process. This will ensure that the quality and reliability of the final remanufactured product will be at the desired level. At the same time, the criticality of each defect will affect the selection of the reconditioning technologies.

Step 3: Identify the type of reconditioning operations for the defects

The type of operations required can be identified from the five main classifications elaborated in the previous section. The final necessary properties of the core product with respect to its material properties, condition and surface tolerances, such as surface roughness and hardness specifications, are determined from the engineering product attributes. From the product design information, the desired engineering attributes for each surface are identified and translated into product attributes. These will set the objectives of the reconditioning operations.

Since the defects have already been grouped according to their engineering surfaces, the selection of the feasible methods from the clearly inappropriate ones can be achieved more effectively. This will be evaluated from the perspective of tool accessibility, geometrical, shape and surface finish tolerances. Higher priority defects will require reconditioning operations of higher performance characteristics.

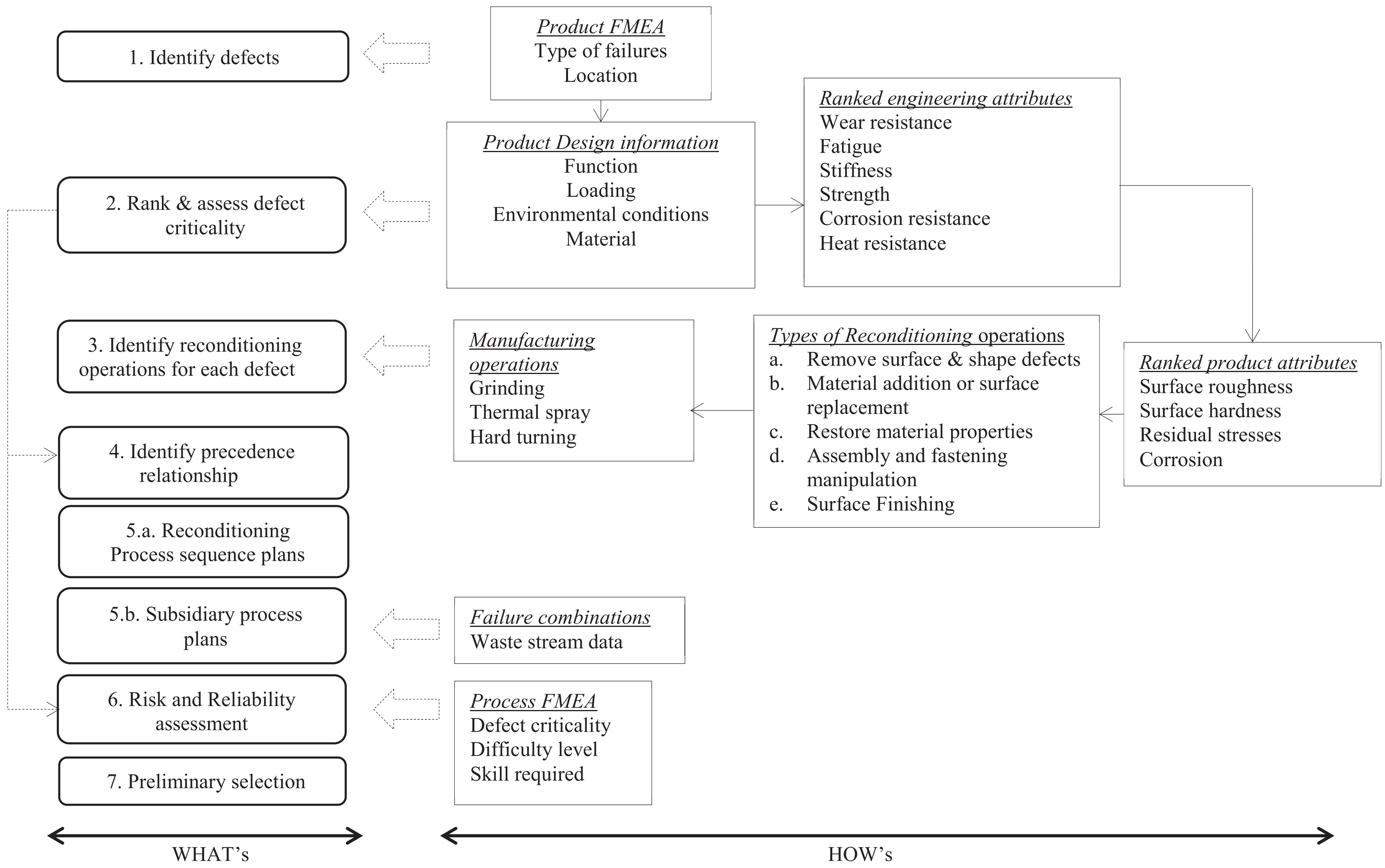

Fig 2. Steps for reconditioning process sequence planning.

Step 4: Identify precedence relationships

Precedence relationships are established on the basis of three factors, which are defect priority, finish quality and the secondary effects of each reconditioning operation.

The defect with the highest RPN obtained from step 2 is treated first. The rationale behind is that it is better for the whole reconditioning effort to fail in the first step rather than last step, so as to minimize costs. If the restoration of the critical defect is not successful, subsequent operations will not be performed to bring the core back to quality since the item will no longer be safe for utilization.

The conditions of the surface before and after each operation determine the precedence relationships of the operations. It is well established that material removal processes can induce changes to the surface conditions of a workpiece [15]. The usual alterations that have been identified as plastic deformation, micro-cracks, residual stress distributions and hardness among others, can vary in depth and profiles depending on the material and the process characteristics, such as cutting speed, force cutting angle, etc. For machining operations, the sequence follows standard precedence requirements and heuristics, such as dimensions with datum are machined first, roughing operations are performed before surface finishing, etc.

Most importantly, besides the mechanical and thermal loads of the manufacturing processes, the final stress state of the surface will also depend on its pre-existing stress condition. Positive and negative synergistic effects of each reconditioning process need to be taken into account for each type of core. The finish quality specifies the last operation to be performed on the core. Generally, the order illustrated in Table 1 below can serve as a guideline.

Table 1. General order of reconditioning processes.

Order	1	2	3	4	5	6
B1 Only	A	C	B1	E		
B2 Only	A	C	E	B2	E	
B1 and B2	A	C	B1	E	B2	E

Three cases are considered depending on whether the material addition (B1) or surface replacement (B2) method is selected, or both are selected. Category A processes come first because any material with compromised strength needs to be removed for failure prevention. Category C is performed before B. If otherwise, the treatment operations from C may affect the bonding (B1) or fitting quality (B2). Category E is performed before B2 to ensure the fitting requirements. As for category D the assembly manipulations, where the nature and effect of the manipulation are specific to the product and must be determined first before the precedence relationship for this type is defined.

Step 5: Devise reconditioning process sequence

The reconditioning processes are sequenced using the precedence relations from step 4. Further information about the limitation, capabilities and effect of each operation provide further direction on which is the best order and combination. Further sequences are developed to accommodate the different combinations of defects which can affect the core product. Steps 2-5 are repeated to formulate the sequence where the hierarchy of defects and the synergistic effects of the operations apply.

Step 6: Risk and reliability assessment

A process FMEA is performed to increase the reliability of the processes. Potential failure of the operations is identified through their high OCC and SEV and appropriate control measures are identified. If deemed insufficient, the operation is aborted. In reference to reliability-based maintenance, the types of control which can be applied to remanufacturing are operational visual control, inspection of defects after processing, and repair of the core. The latter would mean a re-entrant loop in the process sequence. Additionally, the difficulty level of the process and the required skill level of the workmen can be included in the evaluation using the same scoring method. For example, manual welding is least accurate and therefore requires a higher level of technician skill than in laser welding.

Step 7: Preliminary selection

The optimal reconditioning sequence satisfies scheduling needs, and reliably delivers cores of high quality while being cost effective and environmentally benign. Multi-criteria decision making techniques, such as AHP, quality function deployment (QFD) and Fuzzy Logic have been successfully applied in remanufacturing [13, 16, 17] and can be used to score and compare the processes based on the performance criteria of cost, resource consumption, cycle time, and process emissions. However, the final decision will be related strongly to the local factors of the remanufacturing company. Available skill personnel, business models and company policies will influence the selection process.[18] Therefore, the weights of the different criteria will have to be evaluated by the relevant key persons of the company for the selection of the reconditioning sequence.

4. Case study

Camshafts are one of the remanufactured parts in the automotive industry [11]. The lobe surface of the camshaft is considered for remanufacturing. The profile of the lobe controls the engine air valve opening to optimize fuel burning. During operation, it is subjected to Hertzian contact stress and friction. Defects that can be found on a used camshaft are wear, burnt surface and corrosion. Due to their effects on the core and the same needs for wide surface material removal, similar processes can be applied to these defects. The remanufacturing requirements are surface roughness and hardness for wear resistance, and, dimensional accuracy for geometric needs. Table 2 shows the process candidates.

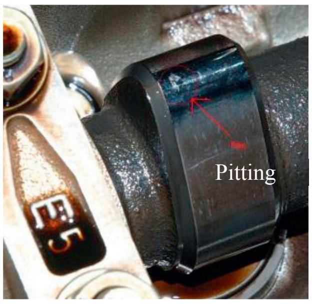

Fig 3: A camshaft lobe with surface wear [19].

Table 2. Process candidates for camshaft lobe remanufacturing.

Processes	A	B	E
Wear	Grinding	Laser cladding	Fine Grinding
Corrosion	Milling	Thermal spraying	Milling
Burnt		Welding	

5. Conclusion

A conceptual methodology has been proposed to aid in the selection and planning of the reconditioning processes based on the conditions of the products. Engineering requirements have been included in the selection of the reconditioning processes. The ranking of the defects and the precedence relationships which consider the criticality of the defects, the synergistic effects of the operations and the necessary end results are crucial steps in the reconditioning process sequence planning. Process FMEA and ranking provide reliability to the remanufactured products. Optimization of the selection process through computational methods can be explored for evaluating the process plans in greater detail.

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