Jurnal Kejuruteraan SI 6(2) 2023: 249 – 256
https://doi.org/10.17576/jkukm-2023-si6(2)-26

Evaluating the Potential of Additive Manufacturing in Repair for Remanufacturing Using AHP Method: Case Study of Automotive Brake Caliper

(Penilaian terhadap Potensi Proses Pembuatan Aditif bagi Pembaikan untuk Pembuatan Semula Menggunakan Kaedah AHP: Kajian Kes Angkup Brek Kereta)

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Received 30 July 2022, Received in revised form 14 October 2023
Accepted 24 November 2023, Available online 30 December 2023

ABSTRACT

In line with technological advancements in the era of IR 4.0, it is crucial for remanufacturing process to shift towards the more sustainable automated process. One of the remanufacturing activities that is currently gaining significant interest is an additive repair process. The repair processes in remanufacturing are usually conducted conventionally which caused inherent defects on the used part due to the heat generation and residual stress exerted during the process. Therefore, additive repair processes through the metal additive manufacturing should be considered in remanufacturing which offers substantial benefits in terms of efficiency and environmental effects. However, the inclusion of additive repair is still at the infancy stage where thorough investigation is necessary to overcome the issues in the process. The raised issues include the printability, bonding behaviour between two metals and quality of the repaired part. It is important to ascertain the compatibility of the additive repair process with the certain type of defects. This study focuses on the evaluation of defects or failure in an automotive brake caliper component using the Analytic Hierarchy Process (AHP) decision-making method. The main objective is to consider both qualitative and quantitative aspects for selecting the suitable repair process by reflecting the potential defects as the criteria and sub-criteria. Three respondents were participated to provide the priority scores through paired comparisons for each criterion, sub-criterion, and alternative involved. The study found that the Directed Energy Deposition (DED) process is the primary choice of respondents with the potential to be considered as a repair process for additive manufacturing with the score of 0.65. Overall, an AHP method is able to evaluate subjective opinions to select the suitable repair process in remanufacturing application.

Keywords: Additive repair; Additive manufacturing; AHP; Brake caliper; Remanufacturing

ABSTRAK

Selari dengan perkembangan teknologi dalam era IR 4.0, adalah penting untuk proses pembuatan semula bergerak ke arah proses automasi yang lebih mampan. Salah satu aktiviti pembuatan semula yang kini menjadi perhatian adalah proses pembaikan aditif. Proses pembaikan biasanya dilaksanakan secara konvensional yang menyebabkan kecacatan pada komponen terpakai hasil daripada penghasilan haba dan tegasan lampau. Oleh itu, proses pembaikan aditif melalui proses pembuatan aditif logam perlu dipertimbangkan dalam pembuatan semula yang dapat memberikan kelebihan dari segi kecekapan serta kesan terhadap alam sekitar. Namun, pertimbangan bagi pembaikan aditif adalam masih di peringkat awal di mana penilaian terperinci perlu dilaksanakan bagi mengatasi isi yang terdapat dalam proses tersebut. Isu-isu tersebut termasuklah kebolehcetakan, kelakuan lekatan antara dua logam *serta kualiti komponen yang dibaikpulih. Jadi, adalah penting untuk memastikan keserasian antara proses pembaikan aditif dengan jenis kecacatan atau kegagalan. Kajian ini memfokus kepada penilaian kecacatan atau kegagalan bagi komponen angkup brek kereta menggunakan kaedah pembuat keputusan Proses Analisis Berhirarki (AHP). Objektif utama adalah untuk mempertimbangkan aspek kualitatif dan kuantitatif untuk memilih proses pembaikan yang bersesuaian dengan mengambil kira jenis kecacatan yang dijadikan sebagai kriteria dan sub-kriteria. Seramai tiga responden telah terlibat untuk memberikan skor keutamaan melalui perbandingan berpasangan bagi setiap kriteria, sub-kriteria dan alternatif yang terlibat. Hasil kajian mendapati proses DED merupakan pilihan utama responden yang berpotensi untuk dipertimbangkan sebagai proses pembaikan bagi proses percetakan aditif dengan nilai skor 0.65. Secara keseluruhannya, kaedah AHP dapat menilai pendapat subjektif untuk penentuan proses pembaikan dalam pembuatan semula.*

Kata Kunci: Pembaikan aditif; Pembuatan aditif; AHP; Angkup brek; Pembuatan semula

INTRODUCTION

The repair and restoration in remanufacturing process is one of the activities/steps involved to ensure that the functionality of the used part can be restored at the end of its life. The repairing processes are usually conducted conventionally through machining, welding and even the part replacement of new part if necessary. These processes can cause the inherent defects and defects due to the heat generated during the processes, residual stress occurred from machining process and so on. Therefore, with the recent advancements of IR4.0, the initiative to include the automated repair processes in remanufacturing is crucial to ensure the efficient and sustainable processes (Liu et al. 2017; Khalid & Peng, 2021).

Additive manufacturing (AM) process is widely known with its capability of developing new part within seconds without compromising the quality of overall product. Hence, the automated repair process could be adapted through the metal AM process which also called as additive repair process by adding or depositing the additive materials into the defective or damaged areas of the used part during remanufacturing process. In metal AM technology, the process can be divided into two main categories, namely, beam-based metal and beamless metal processes (Vaezi et al. 2020). The beam-based AM, which includes powder bed fusion (PBF) (also known as selective laser melting [SLM]) and directed energy deposition (DED), is known for its wide application in AM, and this process serves as a key that highlights the potential of additive repair that could replace or improve the conventional repair process (Gottwald et al. 2021).

The additive repair process is gaining significant interests among researchers to resolve on upcoming issues related to its capability in terms of printability, bonding or joining between two metals at different states (solid and liquid), the strength and deformation of the repaired parts and the temperature differences between two metals (Li et al. 2022; Zghair et al. 2017). Thus, it is necessary to conduct such analysis at the early stages of the design process to properly plan and mitigate the requirements of the processes and the suitability of the defects or defects that will be repaired using additive repair process.

Some of the design tools can be benefited to evaluate capability and feasibility of the additive repair process even at the beginning stage of the design processes. Thorough investigation is required to assess the suitability of the defects and defects whether to undergo additive repair process or not. He et al. (2020) in their research applied Reverse Engineering (RE) technology to identify the failure feature for adaptive remanufacturing. The failure location and volume of the used part is returned through point-clouds generation based on laser scanning, coordinate measure machine and stereo scanning. The information is further processed to decide on the right remanufacturing strategy and process planning.

On the other hand, the study conducted by Habeeb et al. (2023) focuses on the fuzzy logic model approach as a decision-making tool to evaluate the repair of turbochargers using AM. In addition, previous study by Zhang et al. (2019) highlighted the needs of related failure analysis to assess the remanufacturability of the product (Sherwood & Shu, 2000). The failure analysis was usually performed based on expert and knowledge-based systems, for instance decision-making approach, quality tools like Failure Mode and Effect Analysis (FMEA) and Quality Function Deployment (QFD) (Zhang et al. 2019; Graham-Jones & Mellor, 1995).

The inclusion of multi-criteria decision making (MCDM) like in Analytical Hierarchy Process (AHP) which facilitate the design evaluation of multiple attributes to select the best alternatives based on the established ranking in remanufacturing application (Go et al. 2021). Hence, the evaluation of defects and damages for repair applications using AHP could provide further verification for the selection of repair process by considering several modes of defects and damages as the multiple criteria in the decision-making process.

Previously, Aziz et al. (2022) used FMEA to analyse the potential defects and damages occurred in the remanufacturable brake caliper component The application of FMEA is suitable to assess each type of defects or defects and to consider additive repair as one of the repair options in the corrective action's column. However, the evaluation made in the study was not considering the subjective opinions from the experts and thus, more suitable approach is required. This paper aims to expand the study by considering on both of qualitative and quantitative aspects in order to choose the suitable repair process based on analytical hierarchy process (AHP) decision making model.

METHODOLOGY

The methodology in this study involved several steps as depicted in the following Figure 1.

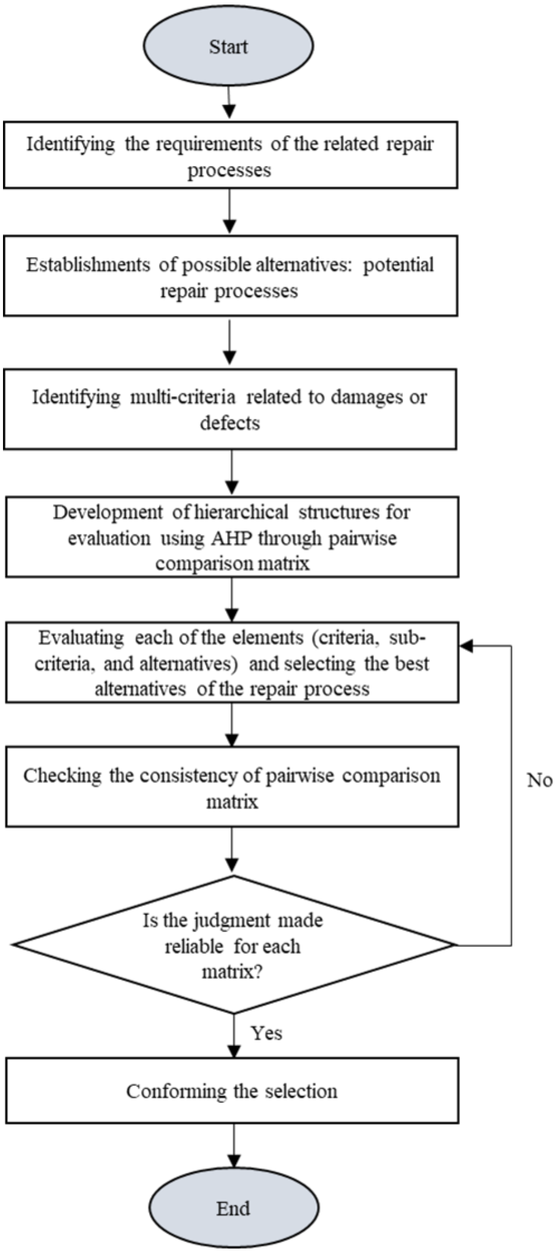

FIGURE 1. Overall methodology

ESTABLISHMENT OF POTENTIAL REPAIR PROCESSES AS THE ALTERNATIVES

The development of hierarchical structure in AHP began with the establishment of alternatives where the potential repair processes for respective defects in brake caliper component will be considered. The repair processes considered in this study include DED process, cold spray process, painting of outer layer process, welding, and part replacement. Based on the listed repair processes, the requirements of each process were identified to facilitate the identification of the criteria of the related defects in the next step as listed in Table 1 as follows.

TABLE 1. List of repair processes as the alternatives

Repair process	Descriptions
DED process	Beam-based metal AM process which uses a focused energy source, such as a plasma arc, laser or electron beam to melt a material and simultaneously deposited by a nozzle.
Cold spray process	Beamless metal AM process that uses solid state thermo-mechanical bonding without the need for a protective print environment for printing mega scale parts (Vaezi et al. 2020).
Painting of outer layer	Coating process for a surface damage like corrosion to protect the surface from harsh environment due to weather changes.
Welding	The joining process of two or more parts which involved the fusion of materials through heating with or without pressure.
5. Part replacement	The part replacement is a final alternative if the repair process is not possible.

IDENTIFICATION OF MULTI-CRITERIA AND DEVELOPMENT OF HIERARCHICAL STRUCTURE OF AHP

The multi-criteria were identified at this stage based on the information gathered from literature surveys which were selected to achieve the main objective of this study which is to select the suitable repair process. The criteria consist of the common type of defects that possibly can occurred to the brake caliper housing, which include corrosion, fatigue, thermal deformation and wear. The fatigue damage was then classified into its own sub-criteria: micro crack, macro crack and fatigue failure. The multi-criteria are usually classified into different levels or stages in hierarchy which depends on the importance of criteria whether to consider as main criteria or sub-criteria. This is one of the advantages of AHP that allows the assessment of multi-criteria at different levels to come out with the most preferred alternatives (Qi & Zhou, 2020). The following Figure 2 shows the hierarchical structure developed in this study.

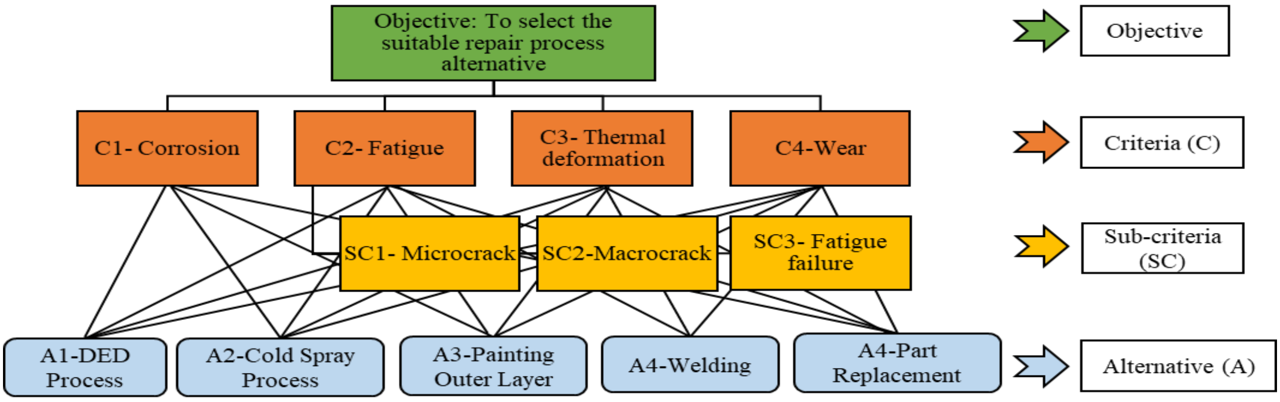

FIGURE 2. Hierarchical structure of multi-criteria and alternatives for the AHP decision making model

EVALUATION AND SELECTION OF THE BEST ALTERNATIVES USING AHP MODEL

The evaluation was then conducted based on the developed hierarchy structure. There were three respondents who participated in this study with experience in repair and service of the brake caliper component. An opened structure of brake caliper components is shown in the following Figure 3. It is noted that only the housing part of brake caliper is suitable to undergo remanufacturing process due to its high durability features that serves as the cover for brake pad and brake disc part.

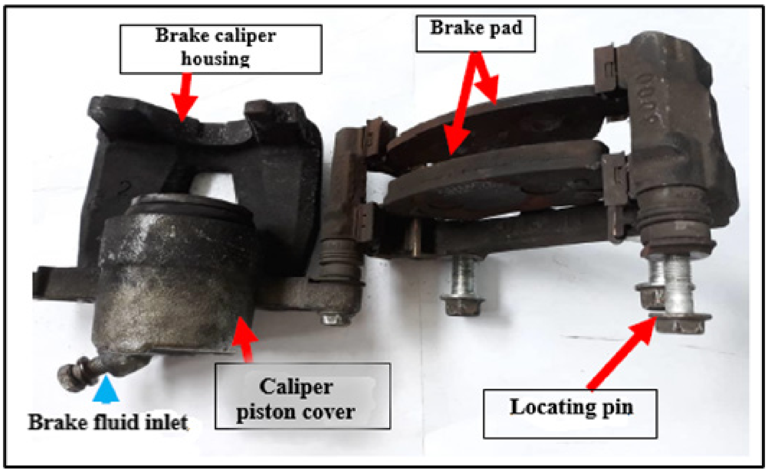

FIGURE 3. An opened structure of automotive brake caliper component

The respondents were required to give the score or rating through pairwise comparison matrix between criteria within the same level for each of the listed alternatives. A pairwise comparison matrix (A) for each of elements (criteria, sub-criteria and alternative can be written as shown in Equation (1):

$$A = (a_{ij})_{n \times m} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

where: a_{ij} represents a rating given by experts on the comparison of element X_i to element X_j; n is the order of matrix A. The pairwise comparison matrix A is reciprocal matrix with $a_{ij} > 0$, $a_{ij} = 1/ a_{ji}$, $a_{ij} = 1 (i = j = 1,2,\ldots,n)$ $a_{ij} > 0$.

AHP uses a numerical scale to express the degree of importance or preference of one criterion or alternative over another. The most common scale used in AHP is a 1 to 9 scale, which is indicated in Table 2.

TABLE 2. Degree of importance in AHP

Scale value	Degree of importance
1	Equally important
3	Moderately important
5	Strongly important
7	Very strongly important
9	Extremely important

Through the pairwise comparison matrix, the example of respondent's preference is described as follows:

"If criterion 1 (C1) is moderately important than criterion 2 (C2), assign a value of a_{ij} = 3 for C1 and a value of a_{ji} =1/3 for C2."

Since there were three respondents involved in this study, the geometric mean in the following Equation (2) will be used to calculate the average mean between all respondent which will be used as the ratings for pairwise comparison matrix (Qi & Zhou, 2020).

$$W_i = \sqrt[n]{\sum_{j=1}^{n} a_{ij}}\,; i, j = 1,2, \dots n \tag{2}$$

where W_i is the geometric mean, n is the total number of respondents, and a_{ij} is the ratings or scales given by each respondent.

The value of each vector W_i was then normalized to obtain the weightage, w_i for each of the criteria, sub-criteria and alternatives as written in Equation (3).

$$w_i = W_i \left(\sum_{i=1}^{n} W_i\right)^{-1} \tag{3}$$

CONSISTENCY OF PAIRWISE COMPARISON MATRIX

It is important to check the consistency of the pairwise comparison matrix to ensure that the results are reliable. This is done by calculating the consistency ratio (CR) of the matrix, which compares the degree of inconsistency in the matrix to that of a randomly generated matrix of the same size. If the CR is less than 0.1, the matrix is considered consistent. The calculation of CR was based on the consistency index (CI) and random consistency index (RI). If the CR and CI are both less than or equal 0.1 (10%), the decisions are acceptable, or else revision is needed. The following Equation (4) and Equation (5) represent the equation for CI and CR respectively.

$$CI = (\lambda_{max} - n)/(n-1) \tag{4}$$

where λ_{max} is the maximum eigenvalue of matrix A and n is number of comparisons.

$$CR = CI/RI \tag{5}$$

where RI values are based on the average random index as shown in Table 3 (Saaty, 1980).

TABLE 3. Standard value of the random consistency index

n	RI
1	0
2	0
3	0.52
4	0.89
5	1.12
6	1.26
7	1.36
8	1.41
9	1.46
10	1.49

RESULTS AND DISCUSSION

The final evaluation that represents the weightage of each of criteria and sub-criteria is presented in the following Table 4. The results show C1- Corrosion criterion has the highest weightage of 0.44 which tells that the corrosion type of damage is the most frequently occurred on the brake caliper housing. While thermal deformation is not commonly occurred to the brake caliper housing with the lowest weightage of 0.06 due to its high thermal resistance of the material that has been designed for the housing to withstand a high temperature environment during braking operation to protect other sub-components: brake disc and brake pad.

TABLE 4. Weightage for each of criteria and sub-criteria

Criteria Level	Weightage	Sub-criteria Level	Weightage
C1	0.44	-	-
		SC1	0.08
C2	0.26	SC2	0.45
		SC3	0.47
C3	0.06	-	-
C4	0.23	-	-

Then, the priority score of each alternative was calculated to obtain the ranking of the alternatives which signify the most preferred alternative based on the multi-criteria considered during the evaluation. The priority score of alternatives is listed in the following Table 5 and presented in Figure 4.

TABLE 5. Final evaluation for priority score of alternatives with respect to main criteria

Criteria	Weightage	Alternative 1 (DED process)	Alternative 2 (Cold spray process)	Alternative 3 (Painting of outer layer)	Alternative 4 (Welding)	Alternative 5 (Part replacement)
C1	0.44	0.51	0.25	0.05	0.1	0.09
C2	0.26	0.37	0.16	0.04	0.17	0.26
C3	0.06	0.37	0.28	0.04	0.19	0.12
C4	0.23	0.43	0.19	0.04	0.18	0.17
Total score		0.65	0.21	0.07	0.28	0.44
Ranking		1	4	5	3	2

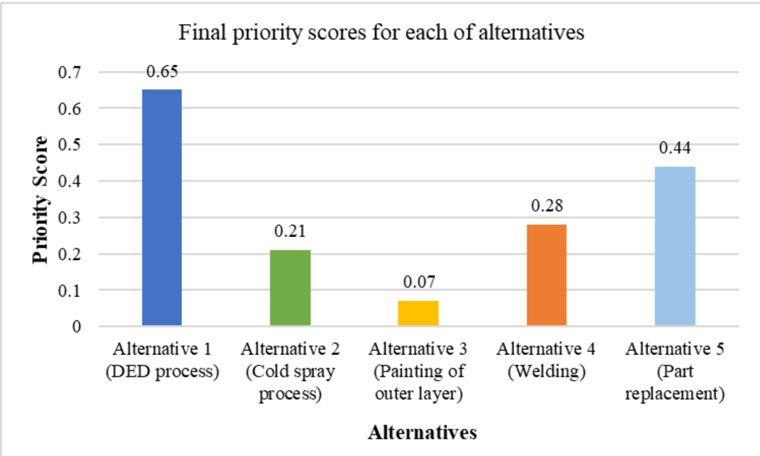

FIGURE 4. Final priority scores for each of alternatives

Based on the priority scores presented in Figure 4, Alternative 1 of DED process possessed higher score in the first rank compared to other alternatives. The experts agreed that most of the listed criteria and sub-criteria were suitable to be repaired through DED process except for corrosion failure. A DED process is capable in repairing certain type of defects which include fatigue failure which cause local failure like cracks as sub-criteria, wear and thermal deformation (Saboori et al. 2019; Gottwald et al. 2021). In addition, the DED process provides significant advantages in repair application, for instance the ability to deposit some wear-resistant and high corrosion-resistant coatings obtaining a strong metallurgical bonding between the deposited material and substrate (Saboori et al. 2019). The DED process is found to be a good candidate for the additive repair process compared to other AM technology and conventional processes due to its lower residual stresses, higher repeatability, and higher precision (Roy et al. 2019; Saboori et al. 2019).

On the other hand, the second rank goes to Alternative 5 (part replacement) due to the strict requirements in remanufacturing to ensure the quality of the remanufactured part is not jeopardized throughout the process (Kandukuri et al. 2021). Hence, the part replacement became the second preferred option if the repair process is not possible.

Finally, the overall judgement made by the respondents in decision-making to select the suitable repair process were then evaluated based on consistency of the pairwise comparison matrix. Both criteria and sub-criteria show the consistent results of pairwise comparison matrix in each level with the value of less than 0.1 (10%). The results of CI and CR are listed in Table 6.

Table 6. CI and CR values for criteria and sub-criteria level

Level	CI values	CR values
Criteria	$0.041 \leq 0.1$	$0.046 \leq 0.1$
Sub-criteria	$0.001 \leq 0.1$	$0.007 \leq 0.1$

CONCLUSION

The DED process has been selected as the most preferred repair process among other listed processes in the evaluation using AHP model. The selection would support the feasibility of additive repair process as one of the viable processes to be applied in remanufacturing process. Besides, the findings were also influenced by the type of defects that are classified as criteria and sub-criteria where most of the defects are potentially can be repaired through DED process. In overall, this study provides a systematic approach to evaluate the suitable process by considering both qualitative and quantitative aspects of the judgments made by respondent by using the AHP decision making model.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Higher Education Malaysia with Geran Konsortium Kecemerlangan Penyelidikan [grant numbers JPT(BKP1)1000/016/018/25 (72), KP/2020/UKM UKM/2/1].

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