1. Introduction
With good economic efficiency and high production efficiency, hot forging die is widely used in automobile and other machinery industries. However, with working temperature often higher than 300℃, hot forging die is very easy to crack and wear under repeated action of high temperature and pressure, which reduces its service time. The failure of hot forging die will seriously affect enterprise production, reduce production efficiency and increase production cost. To repair and recycle the retired hot forging can extend its service life, and create greater economic and social benefits.

The repair processes mainly include overlay weld repair, laser cladding repair, brush electro-plating repair, spray welding repair and electric spark repair to retired hot forging die [1]. Zhang et al. [2] used three-coordinate scanner and robot to design crankshaft hot forging die electric-arc additive remanufacturing process. Xia et al. [3] developed 3D print repair equipment for hot forging die, and applied it to repair hot forging die of automotive steering knuckle, which increased its service life by about 4.47 times. Yin et al. [4] repaired Cr12MoV die by laser cladding, and the experiment showed that the hardness of the cladding layer is about 2 times higher than that of the substrate. Mrzyglod B et al. [5] developed a decision support system for durability analysis and prediction of hot forging die surface treatment from automobile transmission shaft seal based on artificial neural network. Jhavar S et al. [6] applied the microwave plasma deposition technology to treatment on surface of hot forging die, and achieved good results.

The repair of retired hot forging dies is a kind of remanufacturing technology. Repairability evaluation before repair is the key to ensure successful repair of hot forging die. Zhao et al. [7]
established a remanufacturing evaluation model based on AHP-GA and triangle fuzzy number for scrap automotive gearbox. Cui et al. [8] adopted hierarchical recursive evaluation model to evaluate remanufacturing, under comprehensive consideration of the relation between failure layer, scrape layer and recycling decision layer of retired crankshafts, and verified the evaluation model through diesel engine crankshaft. Wang et al. [9] used fuzzy TOPSIS method to evaluate the remanufacturing scheme of waste metal cutting machine tools. Ling et al. [10] constructed the remanufacturing feasibility evaluation model of scrape grinding machine, and verified the accuracy of this method combining with the of remanufacturing example of cylindrical grinding machine, which reduced the risk of remanufacturing. Kaustov et al. [11] applied AHP and fuzzy analysis process to calculate the weight of corresponding design criteria, and then used axiomatic design method to evaluate the remanufacturing scheme.

At present, the research on the repair of retired hot forging die mainly focuses on the process and effect, while the research on remanufacturing evaluation mainly focuses on mechanical products such as crankshaft, engine, machine tools, etc., but there is still no repairability evaluation model for retired hot forging die. The process is complicated, and there are many uncertainties to repair retired hot forging die. Therefore, the repairability evaluation index system is constructed in this paper for retired hot forging die, AHP and matter-element extension model is applied to take evaluation, in order to improve the efficiency and success rate of repair, and provide reference for the repair of retired hot forging die.

2. Repairability Evaluation Model for Retired Hot Forging Die

2.1. Evaluation Criteria

Due to the complexity of the actual repair and the difference between repair processes, it’s often difficult to quantify the indexes for the repair of retired hot forging die, and there is a strong ambiguity and uncertainty. Therefore, it is necessary to use expert language variables such as “very good”, “good”, “general”, “bad” and “very bad” to express them, and to use \(N = \{N_1, N_2, N_3, N_4, N_5\}\) to express the evaluation level of the repairability of retired hot forging die, and the evaluation criteria are shown in Table 1.

| Level   | Very good(\(N_1\)) | Good(\(N_2\)) | General(\(N_3\)) | Bad(\(N_4\)) | Very bad(\(N_5\)) |
|---------|---------------------|----------------|-------------------|--------------|-------------------|
| Range   | [1.0,0.8)         | [0.8,0.6)     | [0.6,0.4)        | [0.4,0.2)    | [0.2,0.0)        |

2.2. Evaluation Index

In order to take a comprehensive evaluation on the repairability of retired hot forging die, five indexes including technical feasibility, economic feasibility, environmental feasibility, service life feasibility and timeliness feasibility have been determined according to corresponding domestic and foreign research and engineering practices, combined with expert opinions.

2.2.1. Technical Feasibility

For retired hot forging die, the main element that affects technical feasibility lies in its failure conditions, generally including deformation, collapse, fracture, thermal fatigue, thermal wear and corrosion, etc. [12], which are described in Table 2 in detail. Its actual failure is often caused by a coupling of multiple failure forms, while there is differential of repair effect between different failures from different repair processes. Henceforth, evaluation level should be determined through comprehensive consideration and analysis. In case of serious deformation or fracture, etc., its technical feasibility is 0.0, and the reparable conditions are infeasible.
Table 2 Common Failures of Hot Forging Die

| Failure form | Main Content |
|--------------|--------------|
| Deformation | The surface of high forging die is softened at high temperatures, which reduces strength and causes plastic deformation |
| Collapse     | The surface of hot forging die is softened and the hardness is reduced, which causes collapse in local location of die |
| Fracture     | The bearing capacity of hot forging die itself is not enough to resist the working load, which leads to material cracking, including brittle fracture, ductile fracture, fatigue fracture and corrosion fracture |
| Thermal Fatigue | Due to repeated changes in temperature, large thermal stress occurs on the surface of hot forging die, which causes thermal fatigue cracks under mechanical load and then the cracks expand internally |
| Thermal wear | Under the combined action of thermal load and mechanical load, the surface of hot forging die forms complex wear, mainly including fatigue wear, often accompanied by adhesive wear and abrasive wear |
| Corrosion    | By the physical and chemical effects of liquid metal at high temperatures, the surface of hot forging die will have corrosion, commonly including ablation, corrosion and erosion |

2.2.2.Economic Feasibility
Enterprises can reduce the production cost and improve economic benefit by repairing retired hot forging die and reusing them again, which has a strong advantage compared with manufacturing new die to use. The total cost of repairing retired hot forging die mainly include inspection and pretreatment costs, raw material cost, equipment depreciation cost, labor cost, resource cost (consumption of water, power, gas, etc. during repair) and other cost (such as logistic cost, etc.). The effect of different repair processes on the cost should also be considered when evaluating the repair cost. The literature [13] shows that the enterprise will make a profit when the cost of repairing scrape spare parts is 40% to 70% of manufacturing new one. If the cost of repairing retired hot forging die is more than 70% of manufacturing new one, its economic feasibility is 0.0 and the repair conditions are not available.

2.2.3.Environmental Feasibility
The repair process of hot forging die will produce pollutant emissions, which will have an impact on the environment. Different repair processes have different degrees of impact on environment. The common pollutants include gas, solid, waste, liquid, noise and vibration pollutant. When determining the evaluation level, it should be compared with the pollutant emission from new die manufacturing, and industrial standard permit range should also be taken into consideration. If the pollutant emission of repairing retired hot forging die exceeds that of manufacturing new die or the industrial standard permit range, its environmental feasibility is 0.0, and repair conditions are not available.

2.2.4.Service Life Feasibility
The purpose of repairing retired hot forging die is to extend its service life, and reasonable repair process can enable its service life to reach or even exceed that of new die. The evaluation level is determined according to the length of its service life after repair. If the service life of the repaired hot forging die is 50% less than that of the new one, its service life feasibility is 0.0, and the repair conditions are not available.

2.2.5.Timeliness Feasibility
It will cause great economic losses to enterprises if the production is suspended due to failure of hot forging die. Therefore, it’s required to shorten the repair cycle to least as possible. The repair cycle of retired hot forging die refers to the time required for the whole process from die disassembly to
completion of the installation and commissioning of the die after repair, which is generally compared with the manufacturing recycle of new die to determine the evaluation. If the repair time of retired hot forging die exceeds the manufacturing time of the new one, its timeliness feasibility is 0.0, and the repair conditions are not available.

2.3. Index Weight

The common methods to determine index weight include principal component analysis, entropy method, analytic hierarchy process (AHP), Delphi method, etc. AHP is selected as the analysis method to determine the weights of each index in this paper. The specific steps are shown as below:

Step 1 Study the relationship among the five evaluation indexes including technical feasibility, economic feasibility, environmental feasibility, service life feasibility and timeliness feasibility of the repairability evaluation on retired hot forging die, and build the progressive hierarchy structure of system.

Step 2 Based on the expert opinion of retired die repairing, set up the judgment matrix \( Z \) as below:

\[
Z = \begin{bmatrix}
1 & 1 & 5 & 3 & 4 \\
1 & 1 & 4 & 1 & 3 \\
1/5 & 1/4 & 1 & 1/3 & 1/2 \\
1/3 & 1 & 3 & 1 & 3 \\
1/4 & 1/3 & 2 & 1/3 & 1
\end{bmatrix}
\]

where \( z_{ij} \) means the importance of index \( z_i \) compared with \( z_j \), which is expressed by the integers and their reciprocals from 1 to 9.

Step 3 Calculate the weight of each index \( \omega_i \) \((i=1,2,3,4,5)\) of the repairability evaluation model for retired hot forging die as below:

\[
\omega_i = \frac{1}{s} \left( \prod_{j=1}^{s} z_{ij} \right)^{1/s}
\]

According to equations (1) and (2), calculate the weights of five evaluation indexes including technical feasibility, economic feasibility, environmental feasibility, service life feasibility and timeliness feasibility respectively as 0.3717, 0.2694, 0.0629, 0.2041 and 0.0919.

Step 4 Take consistency test, and the consistency index CR is as below:

\[
CR = \frac{CI}{RI}
\]

\[
CI = \frac{\lambda_{\text{max}} - s}{s - 1}
\]

\[
\lambda_{\text{max}} \approx \frac{1}{s} \sum_{j=1}^{s} z_{ij} \omega_j \omega_i
\]

where \( \lambda_{\text{max}} \) is the maximum eigenvalue, and \( RI \) is the average random consistency index. If \( CR < 0.1 \), the consistency test is passed, and the index weight is reasonable. The consistency test results according to equations (1), (2), (3), (4) and (5) are shown in Table 3.

| \( \lambda_{\text{max}} \) | CI | RI | CR | Result |
|-----------------|----|----|----|-------|
| 5.1339          | 0.0335 | 1.12 | 0.0299 | Passed |
2.4. Matter-element Extension Model

According to matter-element extension model \[14\], define the repairability of retired hot forging die as evaluation matter element \(N\), five evaluation indexes as feature vector \(c_1, c_2, c_3, c_4\) and \(c_5\), the corresponding eigenvalue as \(v_1, v_2, v_3, v_4\) and \(v_5\), and then the repairability evaluation matter element matrix \(R_0\) for retired hot forging die is:

\[
R_0 = \begin{bmatrix}
N_j & c_1 & v_1 \\
& c_2 & v_2 \\
& c_3 & v_3 \\
& c_4 & v_4 \\
& c_5 & v_5
\end{bmatrix}
\]

(6)

Define classical domain matter element matrix \(R_j\) for the repairability of retired hot forging die as:

\[
R_j = \begin{bmatrix}
N_j & c_1 & v_{j1} \\
& c_2 & v_{j2} \\
& c_3 & v_{j3} \\
& c_4 & v_{j4} \\
& c_5 & v_{j5}
\end{bmatrix}
\]

(7)

where \(N_j(i=1,2,3,4,5)\) denotes the \(j\)-th repairability evaluation level of hot forging die; \(V_{ji}(i=1,2,3,4,5)\) denotes the data range of \(i\)-th evaluation index of level \(j\); \(a_{ji}\) and \(b_{ji}\) denote the minimum and maximum values of \(v_{ji}\), respectively.

In the repairability evaluation of retired hot forging die, the range of each characteristic value in different repairability evaluation grades is the corresponding classical domain of repairability.

Define joint domain matter-element matrix \(R_p\) for the repairability of retired hot forging die as:

\[
R_p = \begin{bmatrix}
P & c_1 & v_{p1} \\
& c_2 & v_{p2} \\
& c_3 & v_{p3} \\
& c_4 & v_{p4} \\
& c_5 & v_{p5}
\end{bmatrix}
\]

(8)

where \(P\) denotes the whole retired hot forging die to be evaluated, \(V_{pi}(i=1,2,3,4,5)\) denotes the data range of evaluation index \(i\)-th corresponding to \(P\) about all repairability evaluation level, \(a_{pi}\) and \(b_{pi}\) denote the minimum and maximum values of \(v_{pi}\), respectively.

In the repairability evaluation of retired hot forging die, the value range of each evaluation index about all the repairability evaluation level is joint domain.

Define the relatedness \(k_j(v_i)\) of the repairability evaluation index \(i\) and evaluation level \(j\) of retired hot forging die as:

\[
k_j(v_i) = \begin{cases}
-\rho(v_i, V_{ji})/|V_{ji}|, & v_i \in V_{ji} \\
\rho(v_i, V_{ji})/(|\rho(v_i, V_{ji}) - \rho(v_i, V_{ji})|), & v_i \notin V_{ji}
\end{cases}
\]

(9)
\[
\begin{align*}
\rho(v_i, V_{\mu}) &= |v_i - \frac{(a_{\mu} + b_{\mu})}{2} - \frac{(b_{\mu} - a_{\mu})}{2}|
\rho(v_i, V_{\mu_i}) &= |v_i - \frac{(a_{\mu_i} + b_{\mu_i})}{2} - \frac{(b_{\mu_i} - a_{\mu_i})}{2}|
\end{align*}
\]

Where \( \rho(v_i, V_{\mu}) \) and \( \rho(v_i, V_{\mu_i}) \) denote the distance from \( v_i \) to finite interval \( V_{\mu} \) and \( V_{\mu_i} \), respectively.

Define comprehensive correlative degree \( K_j(N) \) between the evaluation matter element and the evaluation level for the repairability of retired hot forging dies as:

\[
K_j(N) = \sum_{i=1}^{n} \omega_i K_j(v_i)
\]

Where \( \omega_i \) is the weight of five evaluation indexes including technical feasibility, economic feasibility, environmental feasibility, service life feasibility and timeliness feasibility.

According to the principle of maximum correlation degree, determine the repairability evaluation level \( K_{j0}(N) \) of retired hot forging die as:

\[
K_{j0}(N) = \max K_j(N)
\]

3. Process of Repairability Evaluation on Retired Hot Forging Die

Process of repairability evaluation on retired hot forging die is shown in Figure 1. Determine the evaluation level of each evaluation index according to the current situation of retired hot forging die and the proposed repair process. If any evaluation index is "infeasible", the retired hot forging die can not be repaired. If none of the evaluation indexes is "infeasible", the matter-element extension evaluation is carried out. If the result of the final repairability evaluation is “very good” or “good”, it shows the retired hot forging die is reparable, if the repairability evaluation result is “general”, “bad” or “very bad”, then adjust the repair plan, and take second evaluation on the adjusted plan, if the result is “very good” or “good”, it is reparable, otherwise irreparable. The retired hot forging die that cannot be repaired will be mainly recycled or scrapped.
4. Case Verification

Take repairability evaluation on a certain type of retired hot forging die from automotive steering knuckle. Its main failure forms include wear, scratches and erosion, it is proposed to apply arc overlay welding process, and the evaluation result from repair experts is shown in Table 4.

| Index | Technical feasibility | Economic feasibility | Environmental feasibility | Service life feasibility | Timeliness feasibility |
|-------|-----------------------|----------------------|--------------------------|-------------------------|------------------------|
| Result| 0.65                  | 0.86                 | 0.57                     | 0.48                    | 0.55                   |

According equations from (6) to (11), the comprehensive correlation degree between the arc overlay welding repairability and evaluation level of the die is shown in Table 5. According to the principle of maximum correlation degree, the repairability level of this retired hot forging die of automotive steering knuckle is “good”, and it is reparable.

| Level         | Very good | Good    | General  | Bad     | Very bad |
|---------------|-----------|---------|----------|---------|----------|
| Result        | -0.166    | -0.038  | -0.108   | -0.428  | -0.569   |

5. Conclusion

In this paper, the repairability evaluation method of retired hot forging die is studied, and the repairability evaluation model based on AHP and matter-element extension theory is established, with the following characteristics:

1) The influencing factors of repairability evaluation of retired hot forging die were analyzed comprehensively, and five evaluation indexes were determined, including technical feasibility, economic feasibility, environmental feasibility, service life feasibility and timeliness feasibility.
In view of the complexity of hot forging die repair and the fuzziness and uncertainty of evaluation, the matter-element extension theory was used to combine quantitative analysis with qualitative analysis to improve the scientificity of evaluation.

By evaluating the repairability of the hot forging die for a certain type of retired automobile steering knuckle, the rationality of the evaluation method is verified, which provides an auxiliary decision-making tool for the repair of the hot forging die.

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