A novel approach to ensure the quality of 7075 aluminum alloy for green manufacturing

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Abstract. With the rapid development of industrial technology, the most of the traditional industrial materials have been unable to meet the needs of current industry. Aluminum alloys is one of the most popular nonferrous metal materials used in industry. Among them, 7075 aluminum alloy is common applied in aerospace and marine plates because of its corrosion resistance and high strength. To ensure the production quality of 7075 aluminum alloy, reduce the waste of resources, and realize green manufacturing, this paper proposes a product quality inspection method by combining fuzzy Six Sigma process capability index and fuzzy axiom design for the supplier selection in aluminum alloy industry. A case study in Guangdong Province is used to demonstrate the effectiveness and feasibility of the proposed method.

1. Introduction

Aluminum, the most widely used nonferrous metal materials in the industry, has many excellent properties, such as good thermal conductivity and electrical conductivity as well as easy to recycle and reuse. However, pure aluminum is a very soft metal. In order to increase the strength of aluminum, it is necessary to add some elements, such as magnesium (Mg), zinc (Zn), copper (Cu), silicon (Si), to form an aluminum alloy. Aluminum alloy has the characteristics of small specific gravity, good mechanical properties, high strength, and good corrosion resistance, so it is widely used in doors and windows, automobiles, aerospace and electronics industries. As mentioned above, the aluminum ingot is casted into aluminum alloy by adding various alloys or chemical elements required during the smelting process. The fusion casting of aluminum ingot is carried out through the processes of composition analysis, slag removal, filtration, refining and casting, etc., and the product will finally be packaged and shipped to customers.

Table 1 Two important components of 7075 aluminum alloy

| Element | Content (%) | type               |
|---------|-------------|--------------------|
| Mg      | 2.1-2.9     | nominal-the-best   |
| Zn      | 5.1-6.1     | nominal-the-best   |
Similar to steel, aluminum alloys are numbered and divided into various series. Among them, 7075 aluminum alloy is a kind of cold-treated forging alloy, and the major alloying elements are Mg and Zn. The two elements can make 7075 aluminum alloy have the characteristics of high strength, strong corrosion resistance, and good mechanical properties. At present, 7075 aluminum alloy is widely used in mold processing, aerospace, and marine plates. Table 1 shows the international general standard values of two important chemical components (Mg and Zn) of 7075 aluminum alloy. Aluminum alloy manufacturers can control the performance of the aluminum alloy by adjusting the content of each element to meet different customer requirements.

Generally, aluminum alloy processing plants will recast or melt aluminum alloys into other shapes of products using various processing methods. The aluminum alloy is composed of a variety of elements. Once the content of the added elements do not meet the specification standards, the quality of the aluminum alloy products will be affected, thus affecting the safety of users. Therefore, it is necessary to monitor whether the element content of aluminum alloy meets the specification requirements.

Product manufacturing is a conversion of input and output, which is to convert various raw materials, process technology, energy, etc. into a finished or semi-finished product. If the quality of each product is well done, it can reduce the waste and rework, prolong the maintenance interval, and delay the recycling time (Wei et al., 2015). Previous studies have confirmed that the improvement of product quality can bring many benefits to companies and society, such as: reducing costs and losses (Tiwari et al., 2018), low resource consumption (Yang and Chen, 2019a) and waste reduction (Chen et al., 2019). Therefore, a high-quality product can not only improve business performance, but also help reduce pollution problems caused by production and achieve green manufacturing.

Supplier evaluation and selection is an important issue in the business purchasing decision. For most companies, the supplier’s performance can directly affect their operating costs and market competitiveness (Govindan et al., 2017). This study proposes a method to evaluate the product quality of aluminum alloy suppliers. The remainder of this paper is structured as follows. Section 2 introduces the fuzzy axiom theory and fuzzy Six Sigma process capability index, which can be used to solve the supplier selection problem. Section 3 uses an example taken from aluminum alloy industry for demonstration. Conclusions are remarked in the Section 4.

2. Materials and Methods

2.1. Fuzzy axiom design

Axiomatic Design (AD) is proposed by Suh (1990). The aim of the AD is to establish a scientific foundation in the process of design, and to provide designers a useful tool with logical analysis and rational thinking for the product design activities. Moreover, it has the advantages to decrease the lead-time in system design, ensure meet the functional requirements by users, reduce the production costs, and improve the product quality (Suh, 2001).

The principle of AD is to calculate the probability of satisfying the functional requirements (design range) in term of the capacity of the system (system range). Hence, the one with the maximum value of the probability is the best alternative (Earl, 2003). On basis of the AD principles, the probability of realizing functional requirements is determined by the design range and the system range, in which the design range is refer to the range expected by the decision-makers, and the system range is refer to the actual distribution range of the alternatives (Kulak, 2015). According to Suh (2001), the common area \( c \) between the design range \( d \) and the system range \( s \) is the only area that meets the functional requirements. Therefore, the probability of realizing functional requirements \( p \) can be defined as:

\[ p = \frac{c}{s} \tag{1} \]

For a given functional requirement, the information content \( I \) can be defined as:
In many practical decision-making problems, it is difficult for decision makers to express the ranges of design and system using explicit data due to the lack of available information. Therefore, fuzzy data is easier and reasonable. However, the fuzzy data does not have a Probability Distribution Function (PDF); hence, it is impossible to calculate the success probability of the alternative in the AD approach. For this, Kahraman and Selcuk (2009) proposed a Fuzzy Axiomatic Design (FAD) as a powerful tool to provide a complete and accurate way of expressing decision-making information for decision-makers.

In general, fuzzy data can be interpreted in terms of linguistic terms, fuzzy sets and fuzzy numbers. If linguistic terms are used to represent the design range and system range, they should be transformed into fuzzy numbers first. In this paper, we use triangular fuzzy numbers (TFNs) to represent the system range, design range and common area, as follows:

\[
\tilde{s}_i = (s_{i,1}, s_{i,2}, s_{i,3})
\]

\[
\tilde{d}_j = (d_{j,1}, d_{j,2}, d_{j,3})
\]

\[
\tilde{c}_j = (c_{j,1}, c_{j,2}, c_{j,3})
\]

where \(i\) is an index for alternatives, \(j\) is an index for attributes, \(i=1,2,3,...,m\), and \(j=1,2,3,...,n\).

According to Figure 1 and Equation (1), we have:

\[
p_{ij} = \frac{\tilde{c}_{ij}}{\tilde{s}_{ij}}
\]

According to Equation (2), the information content \(I_{ij}\) can be obtained as:

\[
I_{ij} = \log_2 \left( \frac{1}{p_{ij}} \right) = \log_2 \left( \frac{\tilde{s}_{ij}}{\tilde{c}_{ij}} \right)
\]

The total information content \(I_i\) of each alternative can be expressed as:

\[
IV_i = \sum_{j=1}^{s} I_{ij}, i = 1, 2, ..., m
\]

Finally, the best alternative can be determined by finding the minimum value of \(IV_i\) among all alternatives.

![Figure 1 TFNs for the common area of system and design ranges.](image)
2.2. Fuzzy Six Sigma process capability index

Process Capability Index (PCI) is a useful approach to evaluate product quality by monitoring the process mean $\mu$, the process standard deviation $\sigma$, and the consistency of the product specifications. Once there is a problem in the process, it can be immediately reflected in the PCI value. Moreover, the larger the PCI value, the higher the product quality and yield rate will be (Chen et al., 2017b).

Nowadays, a company mostly uses three Sigma (3$\sigma$) as the standard to monitor whether the production process is in a stable state, but it has been unable to meet the requirements of modern companies and customers for high-quality products.

Six Sigma is a quality control and improvement method developed by Motorola in 1986. Many well-known international companies such as SONY, IBM, Nokia have introduced Six Sigma method to improve and reduce manufacturing and operations costs and to ensure that the quality of products and services is maintained at a certain level (Yang et al., 2019b). According to the definition of Six Sigma, considering that the process mean $\mu$ may deviate from the specification center by $\pm 1.5\sigma$, so when the PCI reaches the level of Six Sigma, the yield rate is 99.99966% (Yang et al., 2019b). Many researchers have discussed the issue of PCI with consideration to Six Sigma, see, for example, Chen et al. (2017b); Yang and Chen (2019a). However, these past methods are quite inconvenient in practical application, because it is necessary to evaluate the quality level of products through complex calculation. To detect the quality level and yield rate of 7075 aluminum alloy, this paper use the Six Sigma PCI proposed by Chen et al. (2017a), as follows:

$$Q_{pk} = \frac{1 - \Phi\left(\frac{\mu}{\sigma_p}\right)}{\sigma_p} + 1.5 \tag{9}$$

where $Q_{pk}$ is a two-sided PCI for a product with nominal-the-better (NTB) specifications, $\mu = \sigma / d$ and $\sigma_p = (\mu - T) / d$, $\mu$ is process mean, and $\sigma$ is process standard deviation, $d = (USL - LSL) / 2$ is half the length of the specification interval, $T = (USL + LSL) / 2$, and USL and LSL are the upper and lower specification limits, respectively.

In practice, a company usually set a standard or quality level to judge and analyze the quality of the supplier's products. As mentioned above, 7075 aluminum alloy has two important nominal-the-type quality characteristics. Suppose that the quality level of these two quality characteristics of 7075 aluminum alloy is $y^*$, then it must be greater than total product quality $y$. According to Yang et al. (2019b), the minimum required quality level $y^*$ of two quality characteristics of 7075 aluminum alloy can be obtained as:

$$y^* = \Phi^{-1}\left[1 - \frac{2 - \Phi(y - 1.5) + \Phi(y + 1.5)}{4}\right] + 1.5 \tag{10}$$

For the convenience of application, Table 2 shows the corresponding values of minimum required quality level $y^*$ and yield rate (%) under different quality level. For example, if a company requires the quality level of 7075 aluminum alloy must reach 5 Sigma, then the two quality characteristics of 7075 aluminum alloy must reach at least 5.181 Sigma, so as to meet the requirements of the company.

| quality level $y$ | yield rate % | minimum quality level $y^*$ | yield rate % |
|-------------------|--------------|----------------------------|--------------|
| 6                 | 99.865010197%| 6.286                      | 99.999999984%|
| 5                 | 99.996832876%| 5.181                      | 99.999888945%|
| 4                 | 99.999971335%| 4.236                      | 99.998864844%|
| 3                 | 99.999999901%| 3.333                      | 99.957037721%|
Table 3 Adjusted 7075 aluminum alloy rods’ composition

| Quality characteristic | LSL | USL | d  | T  |
|------------------------|-----|-----|----|----|
| Mg                     | 2.2 | 2.8 | 0.4| 2.5|
| Zn                     | 5.2 | 6.0 | 0.4| 5.6|

The PCI has the advantage of inspecting product quality and yield rate, but there are usually some uncertainties in the production process of products, such as inaccurate data and uncertainty in the production environment, which will affect the accuracy of the PCI to assess the quality level of the product (Montgomery, 2001). For this, the fuzzy Six Sigma PCI proposed by Chen et al. (2019) could be used and is given by

\[
\hat{Q}_{pk} = (\hat{Q}_{pk} \cdot \hat{Q}_{Mpk} \cdot \hat{Q}_{zpk})
\]

where

\[
\hat{Q}_{pk}(\alpha) = \hat{Q}_{pk}(0.01) = (Q_{pk} - 1.5) \times \sqrt{\frac{X^2}{\chi^2_{0.025,n-1}}} - \sqrt{\frac{n-1}{n}} \times \frac{Z_{0.0025}}{\chi^2_{0.5,n-1}} + 1.5
\]

\[
\hat{Q}_{Mpk}(\alpha) = \hat{Q}_{Mpk}(1) = Q_{pk}
\]

\[
\hat{Q}_{zpk}(\alpha) = \hat{Q}_{zpk}(0.01) = (Q_{pk} - 1.5) \times \sqrt{\frac{X^2}{\chi^2_{0.975,n-1}}} - \sqrt{\frac{n-1}{n}} \times \frac{Z_{0.0025}}{\chi^2_{0.5,n-1}} + 1.5
\]

where \( n \) is the total sample size.

3. Results and Discussion

Company H is a processing manufacturer of aluminum alloy products in Guangdong Province, among which 7075 aluminum alloy bar is one of the key materials. As mentioned above, 7075 aluminum alloy has two key quality characteristics, i.e. Mg and Zn. Moreover, Company C required four suppliers to provide 7075 aluminum alloy bars with adjusted the amounts of each chemical element as shown in Table 3, and the quality level should reach 5 Sigma.

This study used the proposed approach to analyze the quality performance of the two quality characteristics of the 7075 aluminum alloy bars produced from four suppliers. First, according to Table 2, we obtained the minimum quality level for two key quality characteristics is 5.181. Then, the total sample size of 100 \( (n = 100) \) was available from each candidate supplier. Finally, the results were shown in Table 4.

Based on Table 4, Supplier C was eliminated since the quality performance of the Mg quality characteristic did not meet the required quality level. Moreover, the ranking of the remaining three suppliers was Supplier D > Supplier B > Supplier A. Therefore, Supplier D was deemed the best candidate for Company C.

Table 4 Results of four suppliers

| Supplier | Quality characteristic | \( \bar{x} \) | \( s \) | \( Q_{pk} \) | \( Q_{pk}^{\alpha} \) | IV | Total | Rank |
|----------|------------------------|----|----|------|-----------|----|------|-----|
| A        | Mg                     | 0.464 | 0.125 | 5.788 | (4.989,5.788,6.701) | 6.816 | 10.036 | 3   |
|          | Zn                     | 0.215 | 0.094 | 5.256 | (4.560,5.256,6.059) | 3.220 |      |     |
| B        | Mg                     | 0.633 | 0.094 | 5.404 | (4.679,5.404,6.239) | 3.896 | 8.987 | 2   |
|          | Zn                     | 0.319 | 0.166 | 5.602 | (4.839,5.602,6.477) | 5.091 |      |     |
| C        | Mg                     | 0.749 | 0.089 | 4.320 | Eliminated |      |      |     |
|          | Zn                     | 0.287 | 0.176 | 5.551 |            |      |      |     |
| D        | Mg                     | 0.428 | 0.148 | 5.365 | (4.648,5.365,6.191) | 3.710 | 8.674 | 1   |
|          | Zn                     | 0.334 | 0.163 | 5.586 | (4.826,5.586,6.457) | 4.964 |      |     |
4. Conclusions
Compared with plastics, aluminum alloy has many advantages, such as high rigidity, high strength, easy recovery and reusable. In order to obtain superior corrosion resistance and good wear resistance, the aluminum alloy must be added alloying elements, such as Mg and Zn, in the production process. However, if the content of elements does not meet the specified requirements, it will affect the product performance and function, and even lead to safety and quality problems in the production process or finished products. Supplier selection is an important issue for a company's sustainability performance since the quality of suppliers' products will directly affect the competitiveness of businesses in the market. Therefore, this paper proposed a novel approach to evaluate the quality of aluminum alloy suppliers. The result showed that the ranking of the four 7075 aluminum alloy suppliers for Company H is: Supplier D > Supplier B > Supplier A > Supplier C. Among them, Supplier C was eliminated because the Mg did not meet the quality requirements. Since the Mg will affect the strength and corrosion resistance of 7075 aluminum alloy, Supplier C should implement quality improvement activities to improve product quality, reduce the waste generation for green manufacturing.

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