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Fuzzy Logic Modelling for Microwave Heat Treatment of Aluminium Sheet

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Abstract. Microwave energy heating is one of the methods to improve product quality, faster processing, eco-friendliness, and cost and energy savings. The unique heating ability leads to explore this heat treatment method by exploiting its process parameters to improve its effectiveness. This research aimed to predict the effect of microwave heat treatment on aluminium alloy 6063-T6 sheets using fuzzy logic. Microwave heat-treatment trials are designed using the Design of Experiment (DOE) method. The input parameters are heating time, susceptor, and insulator. The non-heated and heated aluminium 'specimen's mechanical properties have been tested using a hardness and tensile testing machine. The experimental results are used to develop a Mamdani fuzzy logic model system. The results indicate that the mechanical properties in terms of tensile Load, and hardness of the specimen have improved after being microwave heat-treated for a short time. The susceptor material and insulator can assist in the microwave processing of materials. The percentage difference between the experimental and simulation values are 0.27 and 6.31%, respectively, for tensile Load and hardness. The experimental and predicted results are still compatible with a small percentage of errors. The fuzzy model can be used to predict the parameters.

Keywords: Aluminium 6063; Fuzzy logic; Hardness; Insulator; Microwave heating; Susceptor; Tensile strength

1. Introduction

Heating using microwave energy is a faster, eco-friendly, cost effective and energy-saving method. Many studies have discovered that microwave heat treatment can be used to enhance metals' physical and mechanical properties. However, several significant parameters must be considered when applying the method to achieve optimum microwave heating. Consequently, sparking and arcing that looks like a miniature bolt of lightning will occur when the microwave heats the metal. One of the numerous effective ways to heat treat metals using microwave heating is the use of microwave susceptor. Susceptors and insulators are critical in optimizing microwave energy conversion and heating process (Bhattacharya and Basak, 2016). Absorbent, also known as a susceptor, effectively enhances microwave heating characteristics. Since metal will reflect the microwave's energy, the susceptor can uniformly distribute microwave energy and minimize escaping heating (Muhammad, Idris, and Mohamad, 2016).

The dielectric properties of the susceptor, namely graphite, silicon carbide, and

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charcoal, determine the material's ability to heat in microwave fields. Seo et al. (2011) used DOE to establish relationships between design factors and response values of micro milling processes. Pavani, Rao, and Prasad (2017) studied the tribological properties using the design of an Experiment (DOE). Butdee and Khanawapee (2021) did a quality prediction using a fuzzy inference system with multi-factors and developed a model to predict quality. Design of experiments and simulations, such as the fuzzy logic model, is suitable to analyze and predict the outcomes of a study depending on the input parameters (Sengottuvel Satishkumar, and Dinakaran, 2013). In this research, a fuzzy logic model is developed to predict the effect of microwave heat treatment on the aluminium sheets mechanical properties under the studied parameters of microwave heating time, susceptor material, and the amount of insulator. The accuracy of the fuzzy model will be determined by comparing the measured values to the predicted output values. Studies have proven that the fuzzy logic model is reliable since it can produce accurate output values. Therefore, this research aimed to investigate the effect of microwave heat treatment on the mechanical properties of aluminium sheets and to develop a fuzzy logic model to predict the factors affecting the microwave heat treatment process.

2. Methods

The microwave heat treatment experiment was carried out in the home microwave oven with 950 W of power and a 2.45 GHz frequency (Palanisamy and Krishnan, 2021). The experimental setup is shown in Figure 1. An Aluminium 6063-T6 sheet with a 1.5 mm thickness was used in this experiment, which was purchased from Uniware Machinery Sdn. Bhd. The material is prepared with a dimension of 25x25 mm and an ASTM E-8 standard specimen. To prevent damage to the microwave turntable from direct heating, a layer of alumina boat and fiberglass was used as protection between the turntable and the specimens. An alumina boat with a 100 x 30 x 20 mm dimension is used. Aluminium oxide (Al_2O_3) powder was used as the insulation material. Different amounts of aluminium oxide were measured and used during the experiment to determine the optimum insulation thickness during the microwave heating process on the aluminium specimen. The amount of aluminium oxide (Al_2O_3) used for the experiment is 20 g, 30 g, and 40 g, while the susceptor powder (charcoal and silicon carbide) used is 1 g only. An electronic digital scale was used to measure the amount of alumina and the susceptor. The materials that were the chosen susceptors for this study include graphite, silicon carbide, and charcoal. The number of tests conducted is based on the Central Composite Designs (CCD) method. Input materials and their levels are given in Table 1. The experiment was conducted according to Table 2. Figure 1 shows the experiment setup before placing the aluminium oxide as the last layer.

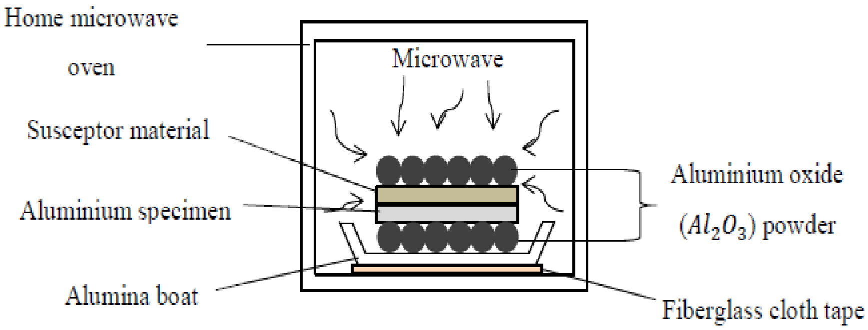

Figure 1 Microwave heat treatment setup

The Mamdani inference system was used to predict the output responses. all variables were numerically divided into several fuzzy sets and labeled using appropriate linguistic terms. The input variables were divided into three levels, while the output variables were set to five levels. To achieve more accurate results, the output membership functions were given more levels than the input membership functions due to the variability of the experimental output results.

Table 1 Levels and code for input parameters

Parameter	Levels		
Level and code	Low (-1)	Middle (0)	High (1)
Susceptor	Graphite	Silicon Carbide	Charcoal
Timing	7	14	21
Insulator	20	30	40

3. Results and Discussion

The tensile and hardness test results are given in Table 2. Test specimen 8 recorded the highest tensile Load among all specimens, which is 2.065 kN, where the difference is 1.68%.

Table 2 Experimental table and output

No	Input parameters			Output	
	Susceptor	Time (s)	Al_2O_3 (g)	Hardness (HV)	Tensile Load (kN)
0	-	-	-	93.53	2.063
1	Graphite	7	20	91.77	2.065
2	Charcoal	7	20	88.17	2.087
3	Graphite	21	20	87.27	2.071
4	Charcoal	21	20	88.13	2.031
5	Graphite	7	40	95.53	2.064
6	Charcoal	7	40	90.70	2.095
7	Graphite	21	40	89.73	2.028
8	Charcoal	21	40	87.83	2.098
9	Graphite	14	30	88.23	2.035
10	Charcoal	14	30	86.70	2.091
11	Silicon Carbide	7	30	94.17	2.024
12	Silicon Carbide	21	30	86.90	2.091
13	Silicon Carbide	14	20	88.43	2.035
14	Silicon Carbide	14	40	87.30	2.028
15	Silicon Carbide	14	30	95.10	2.078

Specimen 8 was heated with 40 g of alumina powder and charcoal powder for 21 seconds, as compared to the unheated specimen. On the other hand, the lowest tensile Load is for specimen number 11, which is 2.024 kN, which is 1.91% lower than the unheated specimen. This specimen was heated with a silicon carbide susceptor and a 30 g insulator for 7 s. The hardness test for each aluminum specimen was conducted under the same load and repeated three times to average the values for accuracy. The hardness value of the unheated specimen will be compared to that of the heated specimen. Based on the data in Table 2, the hardness values between the specimens have slight differences. Some of them have higher or lower hardness than the non-heated specimen, named specimen 0, with a hardness value of 93.53 HV. The hardest specimen, 95.53 HV, was heated for 7 seconds and mixed with graphite susceptor and 40 g of alumina powder. Its hardness value has increased by 2.14% compared to the unheated specimen. Furthermore, the hardness values of specimens 11 and 15 were higher than that of the non-heated specimen by 0.68% and 1.67%, respectively, with hardness values of 94.17 HV and 95.10 HV. During the microwave heating, the specimens were mixed with silicon carbide susceptor and 30g alumina powder, but specimen 11 was only heated for 7 s and specimen 15 for 14 s. Meanwhile, specimen 10 was heated for 14 s with a charcoal susceptor, and 30 g of alumina powder, had the lowest hardness value, 86.70 HV. The hardness of the specimen has dropped by 7.31% compared to the unheated specimen. Among the specimens with decreased hardness value, all heated specimens with added charcoal susceptor have a low hardness value. These specimens are 2, 4, 6, 8, and 10, with a hardness value that dropped to 5.74% (88.17 HV), 5.77% (88.13 HV), 3.03% (90.70 HV), 6.09% (87.83 HV), and 7.31% (86.70 HV), respectively. Moreover, except for specimen 5, other specimens with graphite sheets, such as 1, 3, 7, and 9, have a lower hardness value than the non-heated specimen. The reduction in hardness value of these specimens is 1.89%, 6.70%, 4.06%, and 5.67%, where their hardness is 91.77 HV, 87.27 HV, 89.73 HV, and 88.23 HV. Finally, the specimen's heat treated with silicon carbide decreed in hardness compared to the unheated specimen is 12, 13, and 14, with a value of 86.90 HV, 88.43 HV, and 87.30 HV. These specimens differ from the non-heated specimen by 7.09%, 5.45%, and 6.66%, respectively.

Table 3 Linguistic terms of range for output variable**s**

Output Parameter	Range	Linguistic Terms
Tensile load (kN)	2.024-2.041	Lowest
	2.034-2.056	Low
	2.049-2.071	Middle
	2.064-2.094	High
	2.079-2.1	Highest
Hardness (HV)	9.69-13.1	Lowest
	11.13-15.26	Low
	13.28-17.42	Middle
	15.44-19.57	High
	17.6-21.1	Highest

Based on the tensile and hardness test results, AL-Qaisy, Hasan, and Mahmood (2017) developed a fuzzy logic model for the microwave heat treatment of the aluminum sheet using "if-then" rules. These fuzzy rules are evaluated and combined to generate a set of fuzzy outputs. The input variables and their terms are shown in Table 1. The output variables were categorized into five linguistic terms, as shown in Table 3, and Table 4 shows the fifteen fuzzy rules. Finally, the model is used to predict the output. The fuzzy prediction values for all 15 runs are shown in Table 5. The accuracy of the fuzzy logic values was investigated by calculating the percentage errors.

Table 4 List of fuzzy rule base for input and output parameters

No	Input Parameter			Output
	Susceptor	Timing	Insulator	Tensile Load
1	Graphite	Short	Small	High
2	Charcoal	Short	Small	Highest
3	Graphite	Long	Small	Middle
4	Charcoal	Long	Small	Lowest
5	Graphite	Short	High	High
6	Charcoal	Short	High	Highest
7	Graphite	Long	High	Lowest
8	Charcoal	Long	High	Highest
9	Graphite	Middle	Average	Low
10	Charcoal	Middle	Average	Highest
11	Silicon Carbide	Short	Average	Lowest
12	Silicon Carbide	Long	Average	Highest
13	Silicon Carbide	Middle	Small	Low
14	Silicon Carbide	Middle	High	Lowest
15	Silicon Carbide	Middle	Average	High

Table 5 shows that the majority of percentage errors are less than 10%, except the hardness outputs of specimens 1 and 2, which have 14.26% and 14.20%, respectively. This might be due to errors in the hardness test on specimen 1 since the specimen's hardness value was set as the upper limit of the range for hardness output in the developed fuzzy model. Thus, the error has affected the rest of the predicted hardness output values, as most have more than 1% error. However, the fuzzy logic results for tensile load are reliable since it is no higher than 10%, according to the claim by (Vasudev *et al.*, 2019; Tanyildizi, 2009). Figure 2(a)-(b) depict the predicted fuzzy logic values of output parameters alongside experimental results. We can determine the absolute percentage errors between the experimental and estimated results by averaging the individual percentage errors. It has been observed that the error is 0.27%, 0.35%, 1.23%, and 6.31% for a tensile load. The output is small despite a few significant individual percentage errors for the hardness test. Therefore, the fuzzy logic model predicted values are close to the experimental data. This shows that the developed fuzzy logic model can predict the output values of tensile load and hardness within the considered range of input parameters.

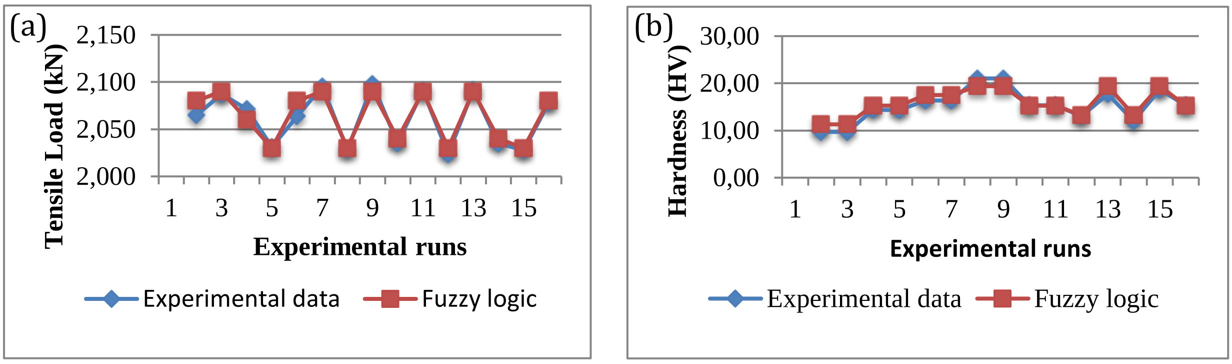

Figure 2 Experimental with fuzzy predicted results comparison (a) Tensile load (b) Hardness

Table 5 Experimental and fuzzy predicted values

No	Experimental		Fuzzy		Errors (%)	
	Tensile (kN)	Hardness (HV)	Tensile (kN)	Hardness (HV)	Tensile	Hardness
1	2.065	9.69	2.080	11.30	0.73	14.26
2	2.087	9.70	2.090	11.30	0.13	14.20
3	2.071	14.36	2.060	15.30	0.55	6.16
4	2.031	14.34	2.030	15.30	0.05	6.25
5	2.064	16.35	2.080	17.50	0.77	6.54
6	2.095	16.37	2.090	17.50	0.26	6.48
7	2.028	21.01	2.030	19.40	0.09	8.30
8	2.098	21.03	2.090	19.40	0.37	8.42
9	2.035	15.35	2.040	15.30	0.24	0.29
10	2.091	15.36	2.090	15.30	0.05	0.42
11	2.024	13.01	2.030	13.20	0.31	1.46
12	2.091	17.70	2.090	19.40	0.06	8.78
13	2.035	12.01	2.040	13.20	0.25	9.00
14	2.028	18.68	2.030	19.40	0.11	3.73
15	2.078	15.36	2.080	15.30	0.09	0.39

The response plot developed by the fuzzy logic system depicts the changes in mechanical properties in the specimen due to the microwave heat treatment's independent variables. Figure 3 (a) shows that the most favorable tensile load is achieved with a heat timing range of 14 to 21 s and a susceptor value of 1.25 to 1.5. This suggests that the highest tensile load is obtained at the maximum heat timing, while using a susceptor made of silicon carbide or charcoal. Simultaneously, using 30g of insulator increased the specimen's tensile load, as shown in Figure 3(b). In addition, a susceptor can increase the tensile load of the specimen when heated for a longer period of time, specifically in the range of 14 to 21 seconds. Each rise or fall in the tensile and hardness is related to one another depending on the microwave parameters. According to the experimental results, the addition of a susceptor and insulator can improve the aluminium specimen's mechanical properties as the microwave heating process takes longer (Leong-Eugene and Gupta, 2010). The experimental results supported the finding as they showed an increase of 0.08% in the tensile load and tensile stress of specimen 1.

The experimental results also show that using charcoal as a susceptor is better than using graphite during the microwave heating. It can produce a higher tensile load, and tensile stress than a specimen made using graphite. Specimen 2 used the same amount of insulator and heated for the same amount of time as specimen 1 but used charcoal as the susceptor. Charcoal material has proven to be a good electromagnetic absorber due to its lower range of loss tangent factor, 0.14 to 0.38, with a penetration depth of 6–11 cm (Bhattacharya and Basak, 2016). The material's ductility also increases as the hardness value has dropped 5.74% with an 88.17 HV value. The hardness value of specimen 2 is lower than that of specimen 1. In other words, charcoal powder is a more effective susceptor material compared to graphite sheet. Moreover, charcoal powder is commonly used in cladding and joining applications. During the microwave heating process, some of the specimens developed cladding on their surfaces as a result of using charcoal powder as the susceptor.

The higher amount of insulator used during microwave heat treatment also improved the material's mechanical properties. By taking an example case of the highest amount of insulator but still using the same susceptor material and heated in the same short time as specimen 2, the tensile load of specimen 6 is higher than the former specimen. The tensile load of the material has improved by 1.17%, with a value of 2.087 kN. The specimen used the highest amount of aluminium oxide powder, 40 g, which caused the insulator's thickness that covered the specimen to be increased. As the insulator's quantity increases, the thermal heat loss rate will decrease. Aluminium oxide is considered one of the electro-conductive materials that can resist high temperatures from microwave energy. Therefore, more microwave heat can be generated and transferred to the specimen in a short time. Furthermore, a higher amount of insulator can cover more metal surfaces to prevent the microwave's electromagnetic energy from contacting the heated specimen. Subjecting a wrapped specimen with sufficient insulator thickness can cause a non-sparking microwave heating process, preventing the microwave furnace from damage and saving time and money.

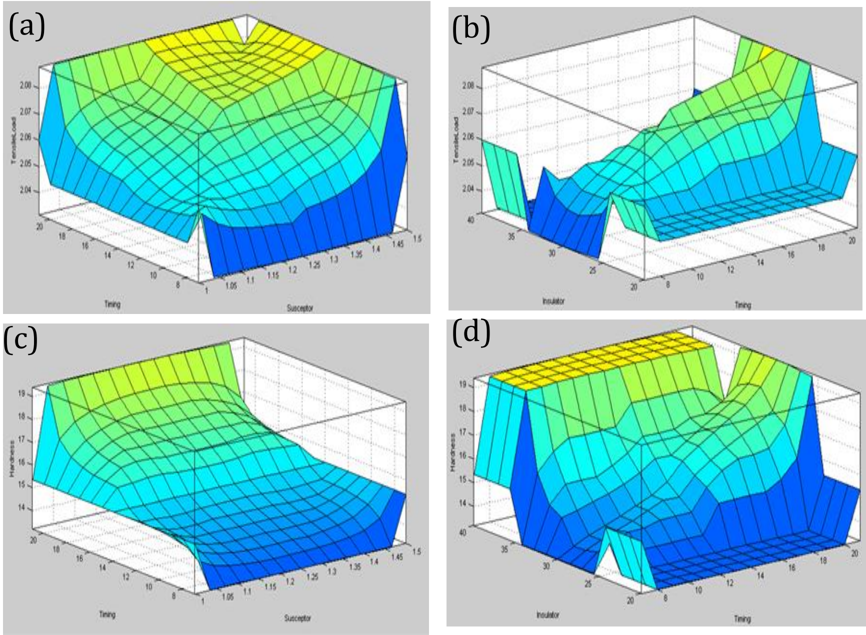

Figure 3 The Surface plots (a) timing and susceptor for tensile load (b) insulator and timing for tensile load (c) timing and susceptor for hardness (d) insulator and timing for hardness

A brittle material can be produced from the microwave heat treatment by the increased material hardness , leading to a lower tensile load in the heated specimen (Padmavathi, Upadhyaya, and Agrawal, 2011). The susceptor can increase the specimen's toughness due to the higher value of hardness, 13.01 HV, with a difference of 0.68% to the non-heated specimen (Meunier *et al.*, 2017). Brittle aluminium is suitable for high strain-rate construction and military applications. The material has a higher resistance to bending and wear. From the data, specimen 8 has the highest tensile load and tensile strength with low hardness. Thus, microwave heat treatment's optimum input parameters are charcoal susceptor, 21-second heating time, and 40 g of the insulator. In addition, specimen 11 has the lowest tensile load with high hardness. This demonstrates that the input parameters of silicon carbide susceptor, 7 s heat timing, and 30 g insulator are the least suitable parameters to achieve optimum microwave heat treatment effectiveness. The changes in these specimens' mechanical properties depend on the input parameters: heat timing and susceptor material. In a short heating time, the charcoal susceptor will increase the tensile load.

4. Conclusions

Aluminium alloy 6063-T6 has been heat treated by a microwave heating process and the heat treatment trials were conducted based on a central composite design. The input parameters are susceptor material, heat timing, and amount of aluminium oxide. A tensile and hardness test was conducted on both non-heated and heat-treated aluminium specimens to compare the results of mechanical properties such as tensile load and hardness. The experimental results were used to develop a fuzzy model. It is proven that the fuzzy model is highly reliable as the experimental and predicted results are compatible with each other. The absolute errors between the experimental and predicted values are 0.27 and 6.31%, respectively, for tensile load and hardness. The experimental results show an improvement in the mechanical properties of the microwave heat-treated aluminium specimen. The material's mechanical properties increased as the susceptor absorbed and transferred a high density of microwave heat to the specimen. Under the same amount of insulator case, the changes in the mechanical properties depend on the heating time and susceptor material parameters. An insulator helps prevent sparks or flames from occurring during microwave heat treatment. It was found that the susceptor and insulator could improve the mechanical properties of the microwave heated aluminium material. The experimental and predicted results are still compatible with each other because of the relatively small percentage of errors between both values. Thus, the fuzzy model can be used in the industries in microwave heat treatment applications to predict the effect of microwave heat treatment on aluminium sheets.

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