J Intell Manuf (2012) 23:629–638
DOI 10.1007/s10845-010-0405-4

Application of fuzzy-based Taguchi method to the optimization of extrusion of magnesium alloy bicycle carriers

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Received: 22 January 2009 / Accepted: 21 April 2010 / Published online: 6 May 2010

Abstract By using fuzzy-base Taguchi method, this study investigates the optimal process parameters that maximize multiple performance characteristics index (MPCI) for hot extrusion of AZ31 and AZ61 magnesium alloy bicycle carriers. The larger-the-better quality characteristics of flattening strength and T-slot fracture strength as well as the smaller-the-better quality characteristic of extrusion load is considered in the MPCI. Through MPCI inference model, a manufacture method with less extrusion load and better mechanical properties under hot extrusion can be obtained. The signal-to-noise (S/N) ratios of the three quality characteristics—flattening strength, T-slot fracture strength and extrusion load—are calculated for the products based on experimental results. And the S/N ratio serves as the input variable to fuzzy control unit, and MPCI is a single output variable. The obtained MPCI is used to analyze optimal process parameters. This study finds combination of process parameters that optimizes MPCI, and conducts confirmatory experiments to prove the accuracy of optimal combination of process parameters thus selected. Finally, mechanical properties of AZ31, AZ61 magnesium alloy and A6061 aluminum alloy bicycle carriers are tested to identify differences among these three materials.

Keywords Magnesium alloy · Bicycle carrier · Extrusion · Fuzzy-based Taguchi method · MPCI

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Introduction

In recent years, bicycle has gradually become an exercise tool of recreational sports. Many people install bicycle carriers on their cars to transport bicycles conveniently. However, the quality of commercially available bicycle carriers varies. In some cases, incorrect installation of bicycle carriers by users, or swinging and vibration of carriers due to wind when cars are travelling at high speed or uneven road surface, can cause bicycle carriers to fall, endangering safety of other cars running on the road. The International Organization for Standardization (ISO) has formulated ISO/PAS 11154 and ISO/DIS15263-4 Standards as inspection standards for safety and reliability of bicycle carriers, requiring static tests, dynamic tests, strap tests, and others. Most bicycle carriers are made of aluminum alloy. However, environmental issues of global warming, carbon emission and energy conservation have become important globally. Some carbon emission reduction methods, such as reducing energy consumption and increasing energy recycling, have slowly become important public topics. A comparison of manufacturing of magnesium alloy parts (with a density of $1.74\ g/cm^3$) with that of aluminum alloy parts (with a density of $2.7\ g/cm^3$), shows that magnesium alloy parts are around 35% lighter for the same volume. Their manufacture consumes less energy, and is therefore more environmentally friendly, and products can be recycled effectively.

The optimal combination of process parameters for Taguchi method varies with the individual quality characteristic, such that optimal combination of parameters for one quality characteristic may contradict those for another. In this study, fuzzy logic is combined with Taguchi method to optimize process parameters for MPCI of hot extrusion of AZ31 and AZ61 magnesium alloy bicycle carriers, as shown in Fig. 1. Through MPCI inference model, a fabrication method

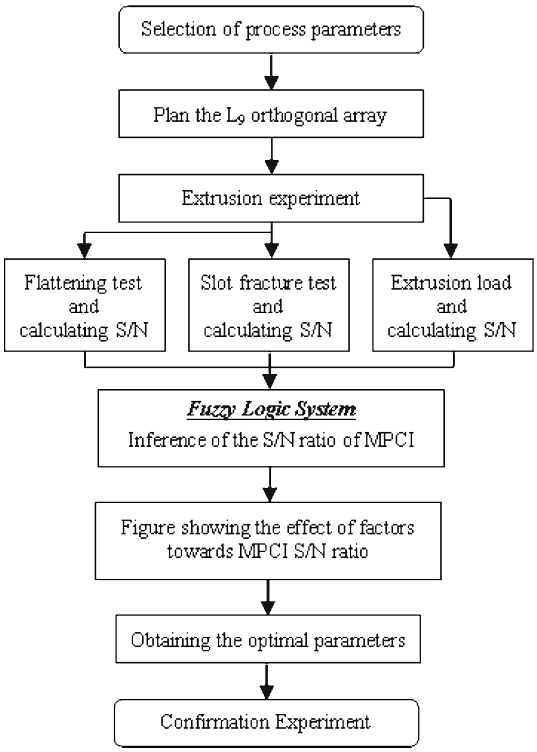


Fig. 1 Research procedures of MPCI

with less extrusion load and better mechanical properties under hot extrusion can be obtained for the maximize MPCI. The obtained MPCI data is used to analyze and find out MPCI of optimal combination of process parameters. The study also investigates the differences among mechanical properties of AZ31 magnesium alloy, AZ61 magnesium alloy and A6061 aluminum alloy bicycle carriers.

Literature review

Magnesium alloy has a hexagonal closed-packed (HCP) crystal structure. Since it lacks slip system that is required by plastic deformation, it has poor elongation properties, and so cannot be easily formed during cold working. The melting point of magnesium alloy is 650°C, making it suitable for die-casting, semi-solid forming and hot working at temperatures of between 300 and 400°C. However, the dominant magnesium alloy forming technology today is die-casting. But, the products made by die-casting had many drawbacks. For example, they had to undergo subsequent manufacturing work, including trimming of finished products, mending of pores on the surface, other surface treatment. The mechanical properties of magnesium alloy die-cast products are not very favorable. However, plastic forming and manufacture of magnesium alloy by rolling, forging and extrusion, markedly improved the mechanical properties, quality and conformance rate of magnesium alloy products. Ogawa et al. studied the influence of heating temperature on limits of forming during precision forging of ZK60 magnesium alloy. When heating temperature of material was below 200°C, the forged object broke. A heating temperature of between 250 and 400°C was optimal for manufacture. When heating temperature exceeded 400°C, oxidization occurred, preventing manufacture (Ogawa et al. 2002). Watanabe et al. examined how temperature affected mechanical properties and microstructure of rolled AZ31 magnesium alloy by differential speed rolling. At low temperature, rolling increased elongation, but change in tensile strength was very small (Watanabe et al. 2007). Hu et al. investigated the cup-rod combined vertical extrusion of AZ31 magnesium alloy, and studied the effects of important process parameters, such as heating temperature of material and lubricant, on mechanical properties of the cup-rod. Extrusion load was the highest when no lubricant was used. When machine oil was used, the load was reduced by 20 kN. When (SW/TM) colorless forge lubricant was used, extrusion load was reduced to a maximum of about 90 kN (Hu et al. 2007). Hsiang and Kuo applied an artificial neural network to predict forming load and mechanical properties following horizontal hot extrusion of magnesium alloy bar (Hsaing and Kuo 2005). Hsiang et al. studied effects of the heating temperature of material on AZ61 magnesium alloy rectangular tube under horizontal hot extrusion. Hot extrusion has a refining effect on the grains. However, when heating temperature of material exceeded 330°C, the grains were enlarged (Hsaing et al. 2006). Some experimental planning methods and predictive theories have often been combined to optimize process parameters. Lin et al. combined the Taguchi method with fuzzy logic and, separately, the Taguchi method with grey theory, to study the multiple performance characteristics index (MPCI) optimization of EDM process, respectively (Lin et al. 2002). Hsiang and Lin combined Taguchi method with fuzzy logic to investigate the MPCI optimization of process parameters for hot extrusion of a magnesium alloy sheet (Hsaing and Lin 2008).

Taguchi method and fuzzy logic system

Taguchi method is an efficient experimental method for measuring quality and analysis of optimal process parameters can find the optimal process parameters based on a single quality characteristic. However, results obtained using different quality characteristics always contradict each other. In this study, Taguchi method will combine with fuzzy logic model to find the combination of process parameters that optimize MPCI.

Taguchi method

Taguchi's orthogonal array emphasized not statistical concepts, but signal-to-noise (S/N) ratio in handling data.

Accordingly, a problem can be solved directly. The controllable factors are combined in a particular manner using an orthogonal array. Retaining accuracy of experimental results, Taguchi method markedly reduces the number of times experiments must be performed by determining the most effective combination of experiments to find parameters that optimize a single quality characteristic. The S/N ratios acquired using larger-the-better and smaller-the-better are used in statistical analysis of factor effects. Therefore, optimal combination of process parameters for a single quality characteristic, such as flattening strength, T-slot fracture strength or extrusion load, can be obtained (Lee 2000).

A smaller quality characteristic, extrusion load, is preferred in this study. Hence, S/N ratio of smaller-the-better quality characteristic is adopted, as shown in Eq. 1. Oppositely, higher values of quality characteristics of flattening strength and T-slot fracture strength are preferred. Thus, S/N ratio of larger-the-better quality characteristic is also adopted, as given by Eq. 2.

$$\mathrm{S/N} = -10 \log \frac{\sum_{i=1}^{n} y_i^2}{n} \tag{1}$$

$$\mathrm{S/N} = -10 \log \frac{\sum_{i=1}^{n} \frac{1}{y_i^2}}{n} \tag{2}$$

In these equations, y_i is the experimental value, and n is number of times doing the same experiment.

Fuzzy logic system

Combining experience of experts with semantic inference rules, fuzzy logic system does not need complicated mathematical equations, so it is commonly used in industry (Chan et al. 2003; Yang et al. 2008; Önüt et al. 2008). Fuzzy logic unit is composed of four main parts—fuzzifier, fuzzy rule base, fuzzy inference engine and defuzzifier. Through fuzzification, a fuzzifier converts the entered crisp value into suitable linguistic fuzzy information to be supplied to the fuzzy set to specify the first part of fuzzy rule. Fuzzy rule base is a database for saving fuzzy rule, which is an if-then expression and a conditional descriptive sentence. These parts together describe the relationship between input and output (Su and Chang 2006). Linguistic fuzzy rule and function fuzzy rule are usually used, in optimization of MPCI, linguistic fuzzy rule is used and called the Mamdani's linguistic fuzzy rule, its rule is as follows.

$$R_i : \text{If } x_1 \text{ is } A_{i1} \text{ and } x_2 \text{ is } A_{i2} \text{ and } \ldots \text{ and } x_n \text{ is } A_{in} \quad \text{then } y \text{ is } B_i \quad i : 1, 2, 3, \ldots, m \tag{3}$$

where A and B are fuzzy sets, and m is the number of fuzzy rules.

The membership functions of input and output variables in this study are triangular-shape and trapezoid-shape. Fuzzy inference engine is the core of fuzzy logic unit. Also called approximate reasoning, fuzzy inference involves calculation of fuzzy output variables from fuzzy input variables using a max-min operation. The inferred fuzzy data must be defuzzified by defuzzifier, and concept of center of gravity is adopted to convert fuzzy output variable to a crisp value, y^*, according to Eq. 4.

$$y^* = \frac{\sum_{i=1}^{L} \mu_B(y_i) \cdot y_i}{\sum_{i=1}^{L} \mu_B(y_i)} \tag{4}$$

where $\mu_B(y_i)$ is degree of membership of y_i to fuzzy set B, y_i is the ith quantization value, and L is quantization levels of output.

Experimental scheme

Extrusion process and material

Figure 2 schematically depicts hot-extrusion process and presents cross-sectional area of bicycle carrier. The forming machine herein is a 500 tons hot extrusion machine. The pre-extrusion operations include preheating of container for 5 h, applying a lubricant to billets and dies, and heating them in a furnace for 3 h. Extruded billets are two magnesium alloys (AZ31 and AZ61). Extrusion ratio is the ratio between cross-sectional area of billets and that of the final product, and is given by Eq. 5. Billets used in this paper is ψ80 mm × length100 mm. After extrusion, the extrusion ratio is 11.43.

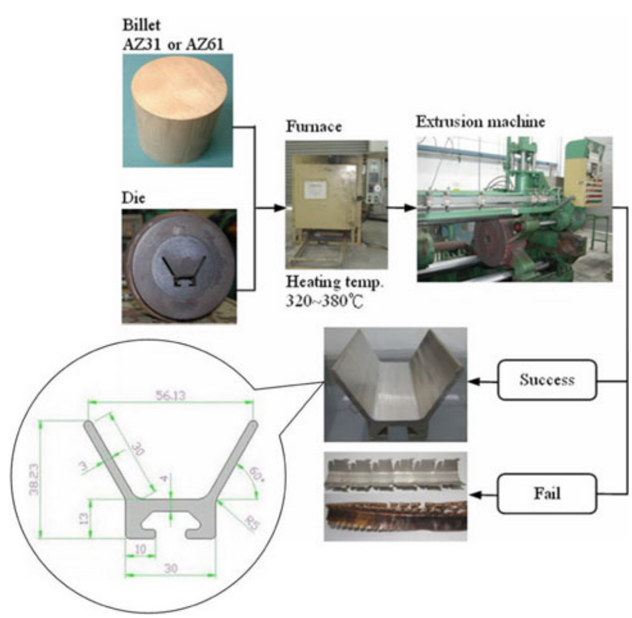


Fig. 2 Schematic diagram of hot-extrusion process

Table 1 Orthogonal array

Controllable factors (Out OA)	Material type				
Level 1	AZ31				
Level 2	AZ61				
	Controllable factors (Inner OA)	A Billet heating temperature (°C)	B Extrusion speed (mm/s)	C Container temperature (°C)	D Lubricant
	1	320	2	300	BN
	2	320	4	350	MoS_2
	3	320	6	400	Graphite
	4	350	2	350	Graphite
	5	350	4	400	BN
	6	350	6	300	MoS_2
	7	380	2	400	MoS_2
	8	380	4	300	Graphite
	9	380	6	350	BN

$$\text{Extrusion ratio} = \frac{A_o}{A_f} \tag{5}$$

where A_o represents cross-sectional area of billets and A_f is cross-sectional area of the final product.

Experimental planning of L_9 orthogonal array (OA)

During hot extrusion process, process parameters of billet heating temperature, extrusion speed, container temperature and lubricant affect extrusion load and mechanical properties of the extruded products. Since study finds the optimal combination of process parameters for bicycle carriers made of two materials of AZ31 and AZ61, both inner and outer OA are adopted. The materials AZ31 and AZ61 constitute outer OA, and process parameter represents the inner OA. Control factors of the four process parameters have three levels, so an L_9 orthogonal array is adopted to set experimental parameters, as shown in Table 1.

Test of mechanical properties

Flattening test is performed mainly to determine the strength on two wings of magnesium alloy bicycle carrier. A sample of length 70 mm is cut from the bicycle carrier, and clipped between two plates of a 30 tons testing machine. In compression test, compression velocity is 7.16 mm/ min. Bicycle carrier is flattened under a preset stroke. The load borne by side wings of bicycle carrier, and whether the wings have any damages or cracking are determined. Figure 3a presents the experimental device of flattening test.

T-slot fracture strength test uses a 30-ton universal testing machine, to design a set of fixtures for fixing finished products, and to put tap bolt into slot at the bottom. In the experiment, bolt associated with screw is locked in a circular bar with an inner screw thread, as shown in Fig. 3b. Results of T-slot fracture strength by experiment are applied to analyze the characteristic of extruded products.

Normalization

S/N ratio ranges of flattening strength, T-slot fracture strength and extrusion load are all different. To ensure that the quality characteristic of the part with smaller S/N ratio can be presented, the S/N ratios are normalized into the range 0–1. The normalized equation is as follows.

$$x_{\text{new}} = \frac{x_{\text{mea}} - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}(D_{\text{max}} - D_{\text{min}}) + D_{\text{min}} \tag{6}$$

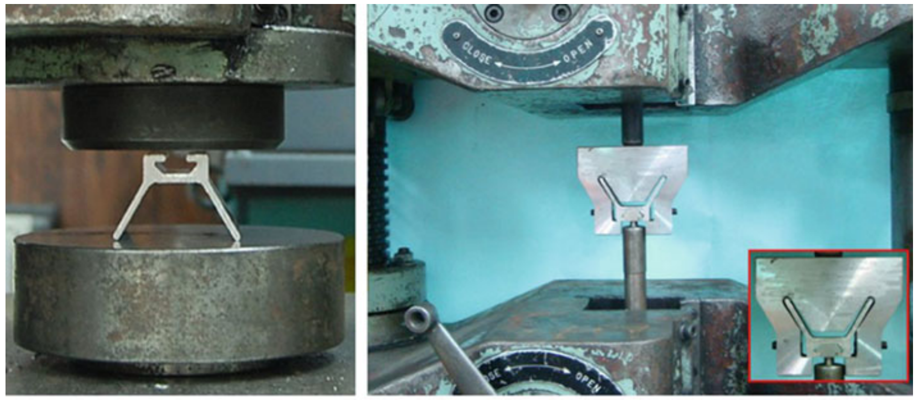
where x_{mea} denotes S/N ratio value, x_{max} and x_{min} denote the maximum and minimum S/N ratio values of quality characteristic respectively, and D_{max} and D_{min} denote the maximum and minimum values of expected normalized value range respectively.

Additive prediction model

In Taguchi method, the additive model of factor effect is applied to calculate predicted S/N ratio value for optimal combination of process parameters. The formula of additive prediction model is as follows.

$$\hat{\eta}_{MPCI} = \overline{\eta}_m + \sum_{i=1}^{s} (\eta_{MPCI_i} - \overline{\eta}_m) \tag{7}$$

where $\hat{\eta}_{MPCI}$ is the predicted value of optimal combination of process parameters of MPCI; $\overline{\eta}_m$ is total average of MPCI



(a) Flattening strength test (b) T-slot fracture strength test

Fig. 3 Test of mechanical properties

values; η_{MPCI_i} is the maximum MPCI value of the ith factor; and s is the most significant process factor in MPCI.

Experimental results and discussion

S/N ratio and normalization of flattening strength, T-slot fracture strength and extrusion load

The extrusion load in hot extrusion process of bicycle carrier is substituted as a smaller-the-better item in Eq. 1 to calculate its S/N ratio. The finished product undergoes testing to determine its flattening strength and T-slot fracture strength. Substituting the obtained values as larger-the-better item of Eq. 2 yields the S/N ratio. Tables 2 and 3 present values and S/N ratios of flattening strength, T-slot fracture strength and extrusion load for AZ31 and AZ61 magnesium alloy bicycle carriers, respectively.

Since S/N ratio ranges of flattening strength, T-slot fracture strength and extrusion load all differ, Eq. 5 is adopted to normalize them. The range of normalized values is set to 0–1. Accordingly, $D_{\max} = 1$ and $D_{\min} = 0$. Tables 4 and 5 present the S/N ratios of three quality characteristics of AZ31 and AZ61 bicycle carriers, respectively, after normalization.

Construction of the fuzzy logic system

This study established two fuzzy logic units to implement the MPCI inference model, as shown in Fig. 4. The fuzzy rule base adopts the Mamdani fuzzy "if-then" rule, and uses Mamdani implication method to perform inference of max-min operation. The defuzzifier uses center of gravity to convert fuzzy data to crisp MPCI values. In fuzzy logic system with two fuzzy logic units, constructed in this study, two quality characteristics must with larger-the-better used as the input variables to same fuzzy logic unit. After output variable of first fuzzy logic unit has been determined, it is combined with a different quality characteristic to yield input variable of the second fuzzy logic unit. Then, an optimal combination of process parameters of correct multiple qualities can be obtained; otherwise, obtained optimal process parameters will be incorrect. Kung applied fuzzy-based Taguchi method to optimize parameters of milling process (Kung 2004). The fuzzy logic system contains three input variables and one output variable, and setting of them is the same as this study.

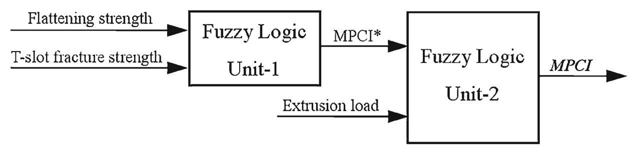


Fig. 4 Fuzzy logic system of 3-input 1-output variables

Fuzzy division is performed on input and output variables using trapezoid and triangular membership functions. Three input variables—flattening strength, T-slot fracture strength and extrusion load—have three set levels, which are small (S), medium (M) and large (L). Input variables of the first fuzzy logic unit (FLU-1) are flattening strength and T-slot fracture strength. Output variable is MPCI*, which is defined as having five levels, which small (S), small-medium (SM), medium (M), medium-large (ML) and large (L). Table 6 presents the nine fuzzy rules of FLU-1. Input variables of the second fuzzy logic unit (FLU-2) are MPCI* and extrusion load. Output variable is MPCI, which is defined as having nine levels, which are tiny (T), very small (VS), small (S), small-medium (SM), medium (M), medium-large (ML), large (L), very large (VL) and huge (H). Table 7 presents the nine fuzzy rules of FLU-2.

Optimal process parameters for MPCI of extrusion process of bicycle carriers

The acquired MPCI is used to perform a statistical analysis of factor effects, optimal combination of process parameters for MPCI can then be acquired. The normalized S/N ratios of flattening strength and T-slot fracture strength of

Table 2 Flattening strength, T-slot fracture strength and extrusion load of AZ31 bicycle carrier

No.	Flattening strength		T-slot fracture strength		Extrusion load	
	Strength (*N*)	S/N ratio	Strength (*N*)	S/N ratio	Load (ton)	S/N ratio
1	3871	71.7562	12531	81.9600	347	−50.8036
2	3724	71.4213	11335	81.0882	304	−49.6557
3	3608	71.1444	11220	81.0000	321	−50.1214
4	3598	71.1221	11123	80.9245	284	−49.0567
5	3569	71.0499	10334	80.2851	255	−48.1349
6	3544	70.9895	10025	80.0217	287	−49.1540
7	3454	70.7668	9589	79.6357	228	−47.1597
8	3475	70.8202	9557	79.6068	248	−47.8972
9	3469	70.8035	9324	79.3924	245	−47.7897

Table 3 Flattening strength, T-slot fracture strength and extrusion load of AZ61 bicycle carrier

No.	Flattening strength		T-slot fracture strength		Extrusion load	
	Strength (*N*)	S/N ratio	Strength (*N*)	S/N ratio	Load (ton)	S/N ratio
1	3998	72.0359	13521	82.6205	357	−51.0484
2	3867	71.7472	13118	82.3571	320	−50.1058
3	3773	71.5332	12956	82.2492	330	−50.3785
4	3752	71.4860	12671	82.0564	301	−49.5850
5	3663	71.2771	12554	81.9759	283	−49.0289
6	3604	71.1354	12567	81.9844	308	−49.7605
7	3549	71.0020	11453	81.1785	251	−47.9838
8	3564	71.0393	11698	81.3625	266	−48.5117
9	3532	70.9613	11241	81.0158	270	−48.6283

Table 4 Normalized value of S/N ratio of AZ31 bicycle carrier and inferred result of MPCI

No.	Normalized S/N ratio			Inference of the MPCI of Fuzzy logic system	
	Flattening strength	T-slot fracture strength	Extrusion load	MPCI* (FLU-1)	MPCI (FLU-2)
1	1.000	1.000	0.000	0.901	0.648
2	0.661	0.660	0.315	0.637	0.593
3	0.382	0.626	0.187	0.504	0.442
4	0.359	0.597	0.479	0.480	0.454
5	0.286	0.348	0.732	0.348	0.405
6	0.225	0.245	0.453	0.301	0.325
7	0.000	0.095	1.000	0.132	0.376
8	0.054	0.083	0.798	0.129	0.327
9	0.037	0.000	0.827	0.099	0.311

bicycle carrier are the input variables of FLU-1. Tables 4 and 5 present MPCI* values of AZ31 and AZ61 bicycle carriers obtained from the FLU-1 inference, as described in the previous section. The acquired MPCI* values and normalized S/N ratio of extrusion load are input variables of FLU-2. Following FLU-2 inference, the MPCI values of AZ31 and AZ61 bicycle carriers can be obtained, as shown in Tables 4 and 5 respectively. Based on the MPCI values in Tables 4 and 5, factor effect diagrams are constructed for analysis, as shown in Figs. 5 and 6, respectively. Maximum S/N ratios in the figures are those associated with optimal combinations of process parameters.

Table 5 Normalized value of S/N ratio of AZ61 bicycle carrier and inferred result of MPCI

No.	Normalized S/N ratio			Inference of the MPCI of Fuzzy logic system	
	Flattening strength	T-slot fracture strength	Extrusion load	MPCI* (FLU-1)	MPCI (FLU-2)
1	1.000	1.000	0.000	0.901	0.648
2	0.731	0.836	0.308	0.714	0.622
3	0.532	0.769	0.219	0.641	0.586
4	0.488	0.648	0.478	0.579	0.588
5	0.294	0.598	0.659	0.456	0.472
6	0.162	0.604	0.420	0.420	0.371
7	0.038	0.101	1.000	0.136	0.379
8	0.073	0.216	0.828	0.216	0.377
9	0.000	0.000	0.790	0.099	0.301

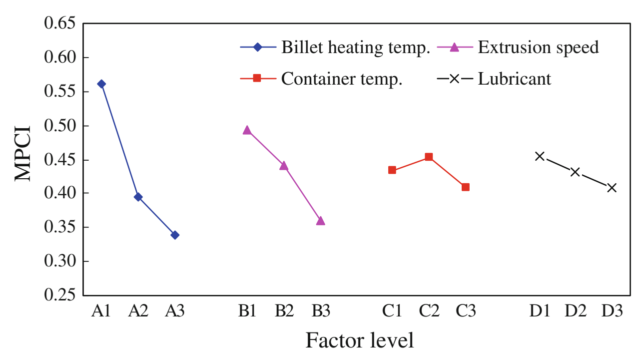


Fig. 5 MPCI factor effects of AZ31 bicycle carrier

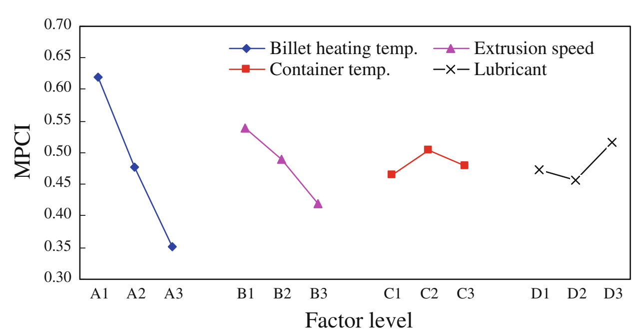


Fig. 6 MPCI factor effects of AZ61 bicycle carrier

Table 6 Fuzzy rules of FLU-1

MPCI*	Normalized flattening strength		
	S	M	L
Normalized T-slot fracture strength			
S	S	SM	M
M	SM	M	ML
L	M	ML	L

Table 7 Fuzzy rules of FLU-2

MPCI	MPCI*		
	S	M	L
Normalized extrusion load			
S	T	VS	S
M	SM	M	ML
L	L	VL	H

The results of Fig. 5 show the parameters that optimizes the MPCI of AZ31 bicycle carrier is heating temperature of billet = 320°C (A1), extrusion speed = 2 mm/sec (B1), temperature of the container=350°C (C2), and a BN lubricant (D1). The results in Fig. 6 reveal that the combination of process parameters that optimize the MPCI of AZ61 bicycle carrier is heating temperature of billet = 320°C (A1), extrusion speed = 2 mm/s (B1), container temperature = 350°C (C2), and a graphite lubricant (D3).

Analysis of variance (ANOVA)

The purpose of ANOVA is to evaluate the significance of factor effect on experimental error. Only when its significance reaches a particular degree will it be cited in the prediction formula. Tables 8 and 9 present the ANOVA table of MPCI for hot extrusion of AZ31 and AZ61 bicycle carriers, respectively. The ANOVA situations of MPCI for AZ31 and AZ61 bicycle carriers are similar. Since each group of experiments has only one MPCI value, factor with small variance are integrated to be non-influential factors in the ANOVA calculations. Since the variances of temperatures of container and lubricant are much smaller than other factors, they are integrated to be non-influential factors. From the contributions presented in Tables 8 and 9, the most significant process

Table 8 ANOVA for the MPCI of extrusion process of AZ31 bicycle carrier

Factor	SS	DOF	Var	F	Contribution (%)
A-Billet heating temperature	0.0806	2	0.0403	26.87	68.00
B-Initial extrusion speed	0.0272	2	0.0136	9.05	21.17
C-Container temperature					
D-Lubricant					
Error	0.0064	4	0.0015		10.84
Total	0.1141	8			100.00

$F = FINV_{(0.001,2,18)} = 10.39$
at least 99.9% Confidence

Table 9 ANOVA for the MPCI of extrusion process of AZ61 bicycle carrier

Factor	SS	DOF	Var	F	Contribution (%)
A-Billet heating temperature	0.1065	2	0.0533	26.64	75.39
B-Initial extrusion speed	0.0215	2	0.0108	5.38	12.87
C-Container temperature					
D-Lubricant					
Error	0.0080	4	0.0020		11.74
Total	0.1360	8			100

$F = FINV_{(0.001,2,18)} = 10.39$
at least 99.9% Confidence

parameters that determine the MPCI of these two materials are heating temperature of billet and extrusion speed.

Verification experiment

Optimal combination of process parameters of the MPCI is experimentally confirmed. Tables 10 refers to confirmatory experiments for AZ31 and AZ61 bicycle carriers, respectively. The optimal combination of process parameters for hot extrusion of AZ31 bicycle carrier is $A_1B_1C_2D_1$, with a predicted MPCI value of 0.622. When this optimal combination of process parameters is set in the confirmatory experiment, flattening strength is 3816 N, T-slot fracture strength is 12115 N, and extrusion load is 316 tons. The experimental MPCI value is 0.636, which is 0.014 higher than the predicted value. Extrusion load for optimal combination of process parameters of MPCI, obtained by fuzzy-base Taguchi inference, is between that of groups 2 and 3 of the orthogonal array, shown in Table 2. However, flattening strength and T-slot fracture strength of bicycle carriers are higher than those of these two groups. The optimal combination of process parameters for hot extrusion process of AZ61 bicycle carrier is $A_1B_1C_2D_3$, with a predicted MPCI value of 0.674. When this optimal combination of process parameters is adopted in the confirmatory experiment, flattening strength is 3934 N, T-slot fracture strength is 13312 N, and extrusion load is 336 tons. The experimental MPCI value is 0.635, which is only 0.039 less than the predicted value. The error of 5.7% is acceptable, and show that Taguchi method can be feasibly combined with fuzzy logic to predict optimal process parameters. The optimal combination of process parameters of MPCI, acquired by the fuzzy-based Taguchi method, reduces extrusion load, and improves mechanical properties.

Comparison of magnesium alloy and aluminum alloy bicycle carriers

The second, fifth and eighth groups of experimental parameters in orthogonal array in Table 1 to extrude bicycle carriers made of AZ31 and AZ61 magnesium alloys, and A6061 aluminum alloy. Figure 7 shows the experimentally extrusion load obtained. The figure reveals that under the same fabrication conditions, extrusion load of A6061 aluminum alloy exceeds those of AZ31 and AZ61 magnesium alloys. As heating temperature of billet decreases, extrusion load of A6061 aluminum alloy increases above those of AZ31 and AZ61 magnesium alloys. Figure 8 shows T-slot fracture strength of A6061 aluminum alloy as well as AZ31 and AZ61 magnesium alloys. The figure reveals that when heating temperature of magnesium alloy and aluminum alloy is low, their T-slot fracture strengths are high. For same heating temperature of billet, T-slot fracture strengths of AZ61 and AZ31 magnesium alloys is higher than that of the A6061 aluminum alloy.

A weight test is performed on AZ31 and AZ61 magnesium alloy, and A6061 aluminum alloy bicycle carriers obtained using the fifth group of orthogonal array. The mass of A6061 aluminum alloy bicycle carrier is 1130.5 g/m, whereas the masses of AZ61 and AZ31 bicycle carriers are 742.1 and 733.0 g/m, respectively. The magnesium alloy bicycle carrier is 1/3 lighter than the aluminum alloy bicycle carrier. Both extrusion load and mass of magnesium alloy are lower than those of aluminum alloy, and mechanical properties of

Table 10 Verification experiment for best suitable process parameter combination

	AZ31 bicycle carrier		AZ61 bicycle carrier	
	Prediction	Experiment	Prediction	Experiment
Setting levels	$A_1B_1C_2D_1$	$A_1B_1C_2D_1$	$A_1B_1C_2D_3$	$A_1B_1C_2D_3$
Flattening strength (*N*)		3816		3934
T-slot fracture strength (*N*)		12115		13312
Extrusion load (ton)		316		336
MPCI	0.622	0.636	0.674	0.635

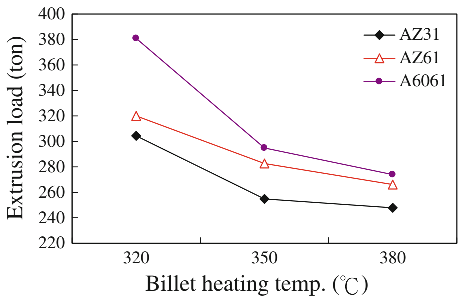


Fig. 7 Extrusion loads of A6061aluminum, AZ31and AZ61 magnesium alloy bicycle carriers under same manufacturing conditions

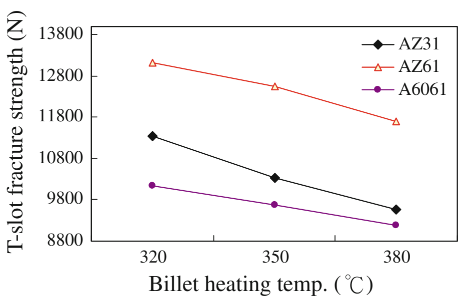


Fig. 8 T-slot fracture strengths of A6061 aluminum, AZ31and AZ61 magnesium alloy bicycle carriers under same manufacturing conditions

magnesium alloy are better than those of aluminum alloy. Accordingly, magnesium alloy should be preferred for manufacturing bicycle carriers.

Conclusions

By combining Taguchi method with fuzzy logic theory, this study investigates optimal process parameters that optimize the MPCI of hot extrusion process of AZ31 and AZ61 magnesium alloy bicycle carriers, through MPCI inference model, a manufacturing method with less extrusion load and better mechanical properties under hot extrusion can be obtained. It overcomes the contradictions among sets of process parameters that optimize different quality characteristics, the limitation is that properties of original billet are not discussed in this study, and it may be considered in the future research. The following conclusions are drawn.

1. The combination of the Taguchi method and fuzzy logic enable to virtually explore a solution space wider than we could with experiments, and higher flattening strength and T-slot fracture strength of bicycle carriers with lower extrusion load can be obtained.
2. A very small difference exists between the predicted and experimental values of optimal process parameters for the MPCI of hot extrusion of bicycle carriers made from two materials. Indicating that the model proposed in this study is available.
3. The aluminum content of AZ61 magnesium alloy exceeds that of AZ31 magnesium alloy, so its mobility is worse, and its forming load is higher. However, in respect of flattening strength and T-slot fracture strength, AZ61 magnesium alloy is the better alloy for bicycle carriers.
4. Extrusion load and mass of magnesium alloy are both lower than those of aluminum alloy, and mechanical properties of magnesium alloy are better than those of aluminum alloy. Accordingly, magnesium should be the preferred material for manufacturing bicycle carriers.

Acknowledgments The authors would like to thank the National Science Council, Taiwan, R.O.C., for financially supporting this research under contract No. NSC-97-2221-E-011-034-MY2.

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