Using of Taguchi Method to Optimize the Casting of Al–Si /Al_2O_3 Composites

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Abstract

Taguchi method is a problem – solving tool which can improve the performance of the product, process design and system. This method combines the experimental and analytical concepts to determine the most influential parameter on the result response for the significant improvement in the overall performance. In this research Al–Si /Al_2O_3 composites was prepared by vortex technique using three different parameters, stirring time, stirring speed, and volume fraction of the reinforcement particles. A tensile and hardness tests were done for the resulted castings. The primary objective is to use Taguchi method for predicting the better parameters that give the highest tensile strength and hardness to the castings, and then preparing composites at these parameters and comparing them with the randomly used once. The experimental and analytical results showed that the Taguchi method was successful in predicting the parameters that give the highest properties and the volume fraction was the most influential parameter on the tensile strength and hardness results of castings.

Keywords: Al–Si /Al_2O_3, Composites, Taguchi method, Tensile strength, Hardness

استخدام طريقة تاكوجي لايجاد الامثلية في سباكة المواد المتراكبة من Al–Si /Al_2O_3

الخلاصة

تعتبر طريقة تاكوجي اداة لحل المشكلات التي يمكن ان تحسن من اداء المنتج وتصميم العملية والنظام. هذه الطريقة تدمج ما بين المفاهيم التجريبية والتحليلية لتحديد المتغير الاكثر تاثيرا على استجابة الناتج للوصول الى التحسين الملحوظ في الاداء الكلي. تم في هذا البحث تحضير مواد متراكبة من Al–Si /Al_2O_3 بواسطة تقنية الدوامة وباستخدام ثلاث متغيرات مختلفة هي: زمن التحريك وسرعة التحريك والكسر الحجمي لدقائق التقوية، وتم اجراء فحوصات الشد والصلادة للمسبوكات الناتجة. الهدف الرئيسي هو استخدام طريقة تاكوجي للتكهن بالمتغيرات الجيدة التي تعطي اعلى مقاومة شد وصلادة للمسبوكات ومن ثم تحضير مواد متراكبة عند هذه الظروف ومقارنتها بالظروف العشوائية المستخدمة. اظهرت النتائج التجريبية والتحليلية ان طريقة تاكوجي كانت ناجحة في التكهن بالمتغيرات التي تعطي اعلى الخواص وان الكسر الحجمي كان الاكثر تاثيرا على نتائج مقاومة الشد والصلادة للمسبوكات.

1. Introduction

Metal matrix composite materials are advanced materials, which combine tough metallic matrix with a hard ceramic or soft reinforcement [1,2]. These materials have superior properties compared to the monolithic materials and can be tailarable to a specific applications [3,4]. Metal matrix composites show advantages in a great number of specific applications (aircraft, automobile, machines) due to their high specific strength and stiffness,

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wear resistance and dimensional stability [5]. The quality of any composite material is influence by varying processing parameters. Among these parameters, their must be one or two that have the most influence. It has been realized that the full economic and technical potential of any manufacturing process can be achieved only while the process is run with the optimum parameters. One of the most important optimization processes is Taguchi method [6]. Taguchi technique is a powerful tool for the design of high quality systems [7,8]. It provides a simple efficient and systematic approach to optimize design for performance, quality and cost. The methodology is valuable when design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristic through the setting of design parameters and reduce the sensitivity of the system performance to source of variation [9,10]. The Taguchi approach enables a comprehensive understanding of the individual and combined from a minimum number of simulation trials. This technique is multi – step process which follow a certain sequence for the experiments to yield an improved understanding of product or process performance [5].

2. Experimental Work

2.1 Composite Preparation

Commercial eutectic modified (Al – 12% Si) alloy with good bearing properties, good fluidity and low coefficient of thermal expansion is used as the matrix. This alloy is commonly used in the production of pistons. Table (1) shows the chemical composition of the alloy Al_2O_3 powder with (+50 to –75) micron grain size is used as the reinforcement. A measured amount of the matrix alloy was melted at 700 Cº in an electrical furnace shown in figure (1). A measured amount of Al_2O_3 powder was melted at 300 Cº for 30 minutes, then added to the melt. After that, the melt was stirred inside the furnace at different speed and times to make a vortex in order to disperse the particles in the melt. The melt temperature was controlled and checked with thermocouple before pouring into a carbon steel die shown in figure (2). The dimensions of the resulted castings are (15 x 15 x 100) mm. The volume fraction of the particles is calculated by taking its weight and density then dividing its volume on the composite volume which is determined from the inner dimensions of the die.

After some preliminary tests, the experimental conditions shown in table (2) were chosen to study the effects of processing parameters (volume fraction, stirring time, and stirring speed) on the tensile strength and vicker's hardness of the composites. All the composites and tests were done in the laboratories of the Production and Metallurgy Department and Materials Engineering Department at the University of Technology.

2.2 Application of Taguchi Method

In order to observe the influencing degree of process parameters in the composite preparation method, three parameters namely; (1) stirring time; (2) stirring speed; and (3) particles volume fraction, each at three levels were considered and are listed in table (2). Maintaining these processing parameters as constants enabled us to study the effect of stirring time, stirring speed, and volume fraction on the resulted properties. The degrees of freedom for three parameters in each of three levels were and it is calculated as follows [7]:

Degree Of Freedom (DOF) = number of levels -1 ………… (1)
For each factor, DOF equal to:
For (A); DOF = 3 – 1 = 2
For (B); DOF = 3 – 1 = 2
For (C); DOF = 3 – 1 = 2
In this research nine experiments were conducted at different parameters, and then the specimens were machined and tested by Vickers hardness and tensile test. The hardness of each specimen is measured by using Vickers hardness apparatus type Zwick & co., Germany, while the tensile tests were done by using the Instron machine type 1195, England. Figure (3) shows the dimensions of the tensile specimen. Table (3) indicates the used parameters and the result values of hardness and tensile strength.
A three level L_9 3^4 orthogonal array with nine experimental runs was selected. The total degree of freedom is calculated from the following [7]:

Total DOF = no. of experiments – 1 ………… (2)

The total DOF for the experiment is:
Total DOF = 9 – 1 = 8
Taguchi method stresses the importance of studying the response variation using the signal – to – noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter. The tensile strength and hardness were considered the quality characteristic with the concept of "the larger the better". The S/N ratio used for this type response is given by [7]:

$$S/N\ (dB) = -10 \log_{10} \left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Yi^2}\right) \quad \ldots\ldots\ldots\ldots (3)$$

Where dB means decibel and Y_i is the response value for a trial condition repeated n times.

The composite preparation parameters, namely stirring time (A), stirring speed (B), and particles volume fraction (C) were assigned to the 1^{st} , 2^{nd} and 3^{rd} column of L_9 3^4 array, respectively. The 4^{th} column was assigned as error (E), and was considered randomly. The S/N ratios were computed for tensile strength and hardness in each of the nine trial conditions and their values are given in table (4). Computation scheme of pareto ANOVA (ANalysis Of VAriance) for three level factors is shown in table (5). In order to study the contribution ratio of the process parameters, pareto ANOVA was performed for tensile strength and hardness. The details are given in tables (6) and (7) respectively.

3. Results and Discussion

From Table (6), it can be seen that the third level of factor (A) give the highest summation (i.e A3, which is 3 min stirring time). The highest summation for factor (B) is at the first level (i.e B1, which is 50 rpm) and the highest summation for factor (C) is at the third level (i.e C3, which is 15% volume fraction). These predicted parameters are not used in the composite preparation which indicated in table (3). We conducted an experiment at the predicted parameters (A = 3 min , B = 50 rpm, and C = 15 % volume fraction), and tested the resulted specimen by tensile. The resulted tensile strength was 256 Mpa which is greater than the tensile strength values in table (3). These results have proved the success of Taguchi method in the prediction of the optimum parameters for higher tensile strength.
In table (7) it can be seen that the highest summation is at A3 (3 min stirring time), B2 (150 rpm), and C3 (15 % volume fraction). The predicted parameters for giving the highest hardness by Taguchi method is already used in our experiments

and it gave the highest hardness. This also proves the success of Taguchi method.

In both tables (6) and (7), it was found that the particles volume fraction contributes a larger impact on tensile strength and hardness of the composites followed by stirring time then finally stirring speed.

4. Conclusions

This paper has reported a research in which Taguchi's off – line quality control method was applied to determine the optimal process parameters which maximize the mechanical properties of Al–Si /Al_2O_3 composites prepared by vortex technique. For this purpose, concepts like orthogonal array, S/N ratio and ANOVA were employed. After determining the optimum process parameters, one confirmation experiment was conducted. In light of our analysis the following conclusions were drawn:

The optimum level of process parameters to obtain good mechanical properties for the vortex technique cast Al–Si /Al_2O_3 are 15% volume fraction of particles, 3 min stirring time, and 50 rpm stirring speed for tensile strength and 150 rpm for hardness. From the pareto analysis it was evident that the volume fraction is a major contributing factor for improving tensile strength and hardness.

Taguchi method has proved its success in prediction the optimum parameters to reach the best properties.

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Table (1) Chemical composition of commercial Al – Si alloy.

Si	Cu	Fe	Zn	Mg	Mn	Ti	Al
12.1	0.83	0.65	0.45	0.27	0.2	0.02	Rem.

Table (2) Control factors and levels

Factor	Control factor	Level 1	Level 2	Level 3
A	Stirring time (min)	1	2	3
B	Stirring speed (rpm)	50	150	250
C	Volume fraction (%)	5	10	15

Table (3) Experimental observation

Exp. no	A	B	C	Tensile strength MPa	Hardness Hv N/mm^2
1	1	50	5	171	65
2	1	150	10	190	86
3	1	250	15	210	118
4	2	50	15	205	110
5	2	150	5	180	80
6	2	250	10	199	97
7	3	50	10	224	99
8	3	150	15	219	126
9	3	250	5	185	73

Exp. no: Experimental number
A: Stirring time (min)
B: Stirring speed (rpm)
C: Volume fraction (%)

Table (4) S/N ratio for tensile strength and hardness

Exp. no	A	B	C	E	S/N Ratio (Tensile strength)	S/N Ratio (Hardness HV)
1	1	1	1	1	44.66	36.258
2	1	2	2	2	45.575	38.69
3	1	3	3	3	56.444	41.437
4	2	1	3	2	46.235	40.827
5	2	2	1	3	45.105	38.061
6	2	3	2	1	45.977	39.735
7	3	1	2	3	47.005	39.912
8	3	2	3	1	46.808	42.007
9	3	3	1	2	45.343	37.266

Exp. no: Experiment number
A: Stirring time (min.); B: Stirring speed (rpm); C: Volume fraction (%); E: Error

Table (5) Pareto ANOVA for three level factors [7]

Factors		A	B	C	E	Total
Sum at factor level	1	$\sum A_1$	$\sum B_1$	$\sum C_1$	$\sum E_1$	
	2	$\sum A_2$	$\sum B_2$	$\sum C_2$	$\sum E_2$	T
	3	$\sum A_3$	$\sum B_3$	$\sum C_3$	$\sum E_3$	
Sum of squares of differences		S_A	S_B	S_C	S_E	S_T
Degrees of freedom		2	2	2	2	8
(Contribution ratio) / 100		S_A/S_T	S_B/S_T	S_C/S_T	S_E/S_T	1

$T = \sum A_1 + \sum A_2 + \sum A_3$

$S_A = (\sum A_1 - \sum A_2)^2 + (\sum A_1 - \sum A_3)^2 + (\sum A_2 - \sum A_3)^2$

$S_B = (\sum B_1 - \sum B_2)^2 + (\sum B_1 - \sum B_3)^2 + (\sum B_2 - \sum B_3)^2$

$S_C = (\sum C_1 - \sum C_2)^2 + (\sum C_1 - \sum C_3)^2 + (\sum C_2 - \sum C_3)^2$

$S_E = (\sum E_1 - \sum E_2)^2 + (\sum E_1 - \sum E_3)^2 + (\sum E_2 - \sum E_3)^2$

$S_T = S_A + A_B + S_C + S_E$

Table (6) Pareto ANOVA for tensile strength

Factors		A	B	C	E	Total
Sum at factor levels	1	136.679	137.899	135.108	137.445	
	2	137.317	137.489	138.556	137.153	413.153
	3	139.157	137.764	139.488	138.554	
Sum of squares of differences		9.931	0.262	31.936	3.278	45.409
Degrees of freedom		2	2	2	2	8
Contribution ratio		21.87	0.58	70.33	7.22	1
Optimum level		(2)	(3)	(1)		
		A_3	B_1	C_3		
		3	50	15		

Table (7) Pareto ANOVA for hardness

Factors		A	B	C	E	Total
Sum at factor levels	1	116.385	116.998	111.586	118.001	
	2	118.625	118.759	118.338	116.784	354.197
	3	119.186	118.439	124.272	119.412	
Sum of squares of differences		13.174	5.276	241.750	10.378	270.580
Degrees of freedom		2	2	2	2	8
Contribution ratio		0.0486	0.0195	0.8934	0.0383	
Optimum level		(2)	(3)	(1)		
		A_3	B_2	C_3		
		3	150	15		

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Fig. (1) Electrical furnace used for production castings.

Fig. (2) Carbon steel die.

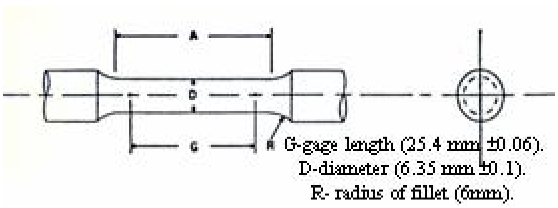

Fig. (3) The dimensions of the tensile.