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Research Paper

Development of a mathematical model describing the effects of SiC content, sintering temperature, and compaction pressure on the strength of Cu-SiC composites

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Abstract
Silicon carbide (SiC)-reinforced metal matrix composites, owing to their advantages such as high hardness and excellent wear resistance, have wide potential applications in various industrial fields, including mining and cutting tools. In this study, the linear regression method was employed to develop a mathematical model describing the influence of technological parameters (SiC content, compaction pressure, and sintering temperature) on the compressive strength of Cu–SiC composites. The SiC content was varied within the range of 10÷30 wt.%. After mixing for 1 h, the powder mixtures were hot pressed at temperatures of 950÷1000 °C under a compaction pressure of 20÷60 MPa. The composite samples were evaluated for compressive strength using a universal compression testing machine.

Keywords: *Metal matrix composite; Powder metallurgy; Hot pressing; Linear regression*.

I. Introduction

Metal matrix composites (MMCs) have been extensively investigated and fabricated by many researchers (Mei et al., 2003 [1]; Panchal et al., 1990 [2]; Robisch & Slagle, 1989 [3]; Dogan & Hawk, 1995 [4]). Previous studies have shown that the hardness and strength of composites are superior to those of the metallic matrix. The enhancement in hardness and strength is mainly attributed to the uniform dispersion of hard particles such as TiC and SiC within the metal matrix.

Composites can be fabricated using either solid-state synthesis or melt-casting methods [5–7]. Solid-state synthesis offers the advantage of lower fabrication temperatures and includes powder metallurgy, self-propagating high-temperature synthesis, mechanical alloying, and carbothermal reduction methods [8–16]. Melt-casting methods are advantageous for producing large and complex-shaped components; however, they require high processing temperatures and are prone to microstructural segregation [17]. Since the starting materials are in powder form, powder metallurgy has become the most commonly used technique for fabricating metal matrix composites.

In the present study, Cu–SiC composites were fabricated by the powder metallurgy method. Cu and SiC powders were uniformly mixed and subsequently consolidated by hot pressing to produce composite specimens. The compressive strength results were employed to develop a mathematical model, in which the selected influencing parameters were SiC content, compaction pressure, and sintering temperature.

II. Experimental Procedure

In this study, Cu powder (99.5% purity, average particle size of 100 μm) and SiC powder (99% purity, average particle size of 150 μm) were used to fabricate Cu–SiC composites.

The fabrication process of the Cu–SiC composites is illustrated in Figure 1. Cu and SiC powder mixtures (10÷30 wt.% SiC) were homogeneously mixed in a hexane medium using a planetary ball mill for 1 h, with a ball-to-powder weight ratio of 3:1 and a rotational speed of 100 rpm. After the milling process, the powder mixtures were consolidated in a graphite mold with dimensions of Φ15 × 80 mm under a pressure of 20÷60 MPa by hot pressing. The obtained hot-pressed specimens were subsequently evaluated for compressive strength.

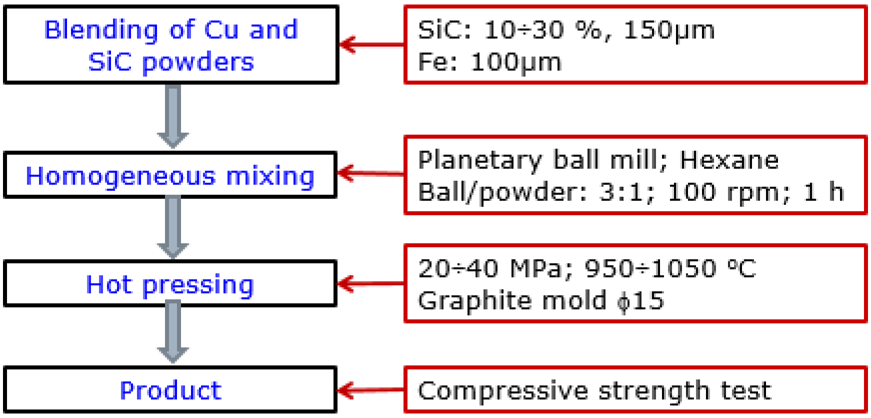

Figure 1. Processing route for the fabrication of Cu - SiC composites

III. Development of a Mathematical Model

3.1. Selection of influencing parameters

Based on literature review and the results obtained from preliminary experiments, the main influencing parameters were selected as follows:

- SiC content, %: Z_1
- Compaction pressure, MPa: Z_2
- Pressing temperature, °C: Z_3

The ranges of the influencing parameters selected are listed in Table 1. The investigated response parameter was selected as compressive strength (Y, MPa). A first-order full factorial two-level experimental design was employed to determine the relationship: Y=f(Zj)

Table 1. Survey values for influencing parameters

	SiC content Z1, %	Compaction pressure Z2, MPa	Temperature Z3, °C
Central value , Z^0_j	20	40	1000
Variation interval, ΔZ_j	10	20	50
Upper limit	30	60	1050
Lower limit	10	20	950

3.2. Coding and construction of the experimental matrix

To establish the experimental matrix, the variables Z_j were first transformed into dimensionless variables x_j according to the following equation:

$$x_j = \frac{Z_j - Z_j^0}{\Delta Z_j} \tag{1}$$

The general equation can be expressed as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_{12} + b_{13}x_{13} + b_{23}x_{23} + b_{123}x_{123} \tag{2}$$

Total number of experimental runs: $N = 2^k + n_0$ (3)

k = 3 is the number of influencing parameters,

$n_0 = 4$ is the number of center-point experiments, at which the coded values of all parameters are equal to zero.

Therefore, the total number of experiments is given by: $2^3 + 4 = 12$, where 2^3 experiments were used to calculate the coefficients of the regression equation, while 4 replicated experiments at the center point were conducted to evaluate the significance of the coefficients. The experimental design matrix is presented in Table 2.

Table 2. Values of the coded variables Z_j and x_j

N^0	x_0	x_1	x_2	x_3	Z_1	Z_2	Z_3
1	+	-	-	-	10	20	950
2	+	+	-	-	30	20	950
3	+	-	+	-	10	60	950
4	+	+	+	-	30	60	950

5	+	-	-	+	10	20	1050
6	+	+	-	+	30	20	1050
7	+	-	+	+	10	60	1050
8	+	+	+	+	30	60	1050
9	+	0	0	0	20	40	1000
10	+	0	0	0	20	40	1000
11	+	0	0	0	20	40	1000
12	+	0	0	0	20	40	1000

3.3. Results and Discussion

All experiments were conducted by hot pressing for 3 min. The obtained specimens were evaluated for compressive strength. The results are presented in Table 3.

The coefficients were calculated as follows:

$$b_j = \frac{1}{N}\sum_{u=1}^{N} x_{ju} y_u \qquad (4) \qquad\qquad b_{ij} = \frac{1}{N}\sum_{u=1}^{N} x_{iu} x_{ju} y_u \text{ , với mọi } i \neq j (5)$$

$$b_{ijk} = \frac{1}{N}\sum_{u=1}^{N} x_{iu} x_{ju} x_{ku} y_u \qquad (6) \qquad\qquad t_{bi} = \frac{|b_i|}{S_b} \qquad (7)$$

Table 3. Experimental results

N^0	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	Y
1	+	-	-	-	+	+	+	-	502
2	+	+	-	-	-	-	+	+	405
3	+	-	+	-	-	+	-	+	531
4	+	+	+	-	+	-	-	-	422
5	+	-	-	+	+	-	-	+	621
6	+	+	-	+	-	+	-	-	465
7	+	-	+	+	-	-	+	-	649
8	+	+	+	+	+	+	+	+	615
9	+	0	0	0	0	0	0	0	538
11	+	0	0	0	0	0	0	0	542
12	+	0	0	0	0	0	0	0	535

The Student's t-values of the coefficients were determined according to Equation (7) and compared with the critical $t_{0.05;3} = 3.18$ (At a significance level of p=0.05 and the degree of freedom of replication f2= 4−1=3).

Based on the calculated results, the experimental regression equation was obtained as follows:

$$y = 526{,}3 - 49{,}5\, x1 + 28{,}0\, x2 + 61{,}3\, x3 + 13{,}8\, x1x2 + 16{,}5\, x2x3 + 16{,}8\, x1x2x3 \qquad (8)$$

By transforming Equation (8) into the form expressed in terms of the Zj variables, the relationship between the compressive strength and the technological parameters can be written as follows:

$$Y = -1285{,}5 + 59{,}49\, Z_1 + 17{,}12\, Z_2 + 1{,}91\, Z_3 - 1{,}611\, Z_1Z_2 - 0{,}0672\, Z_1Z_3 - 0{,}0171\, Z_2Z_3 + 0{,}00168\, Z_1Z_2Z_3 \qquad (9)$$

IV. Conclusion

The effects of the composition parameters (%SiC) and technological conditions (compaction pressure and pressing temperature) on the strength, wear resistance, and porosity of the Cu-SiC material were determined, and the mathematical relationships among these parameters were established as follows:

$$\mathbf{Y = -1285{,}5 + 59{,}49\, Z_1 + 17{,}12\, Z_2 + 1{,}91\, Z_3 - 1{,}611\, Z_1Z_2 - 0{,}0672\, Z_1Z_3 - 0{,}0171\, Z_2Z_3 + 0{,}00168\, Z_1Z_2Z_3}$$

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References

[1] Z. Mei, Y.W. Yan, K. Cui, "Effect of matrix composition on the microstructure of in situ synthesized TiC particulate reinforced iron-based composites" - Materials Letters, vol. 57, pp. 3175–3181, 2003.

[2] J.M. Panchal, T. Vela, T. Robisch, "Ferro-TiC metal matrix composites for high performance tooling and engineering applications"- Fabrication of Particulates Reinforced Metal Composites, Montreal, Quebec, Canada, pp. 245–260, 1990.

[3] T. Robisch, P. Slagle, "Steel-bonded carbides for wear problems" - Materials and Design, vol. 10, pp. 258–261, 1989.

[4] O.N. Dogan, J.A. Hawk, "Abrasion resistance of in situ Fe–TiC composites" - Scripta Metallurgica et Materialia, vol. 33, pp. 953–958, 1989.

[5] F. Akhtar, S.J. Askari, J.A. Shah and S.J. Guo, "Processing, microstructure and mechanical properties of TiC-465 stainless steel/465 stainless steel layer composites" - J. Alloys Compd, vol. 493, pp. 287-293, 2007.

[6] J.J. Park, S.M. Hong, M.K. Lee and C.K. Rhee, "Effects of metal additions on refinement behavior of TiC particles during a very high speed milling process" - Powder Technol, vol. 249, pp. 126-133, 2013.
[7] R. Mansour, S.Y. Maziar, R.R. Mohammad and S.R.T. Seyed, "The effect of production method on Fe-TiC composite" - Int. J. Min. Process, vol. 94, pp. 97-100, 2010.
[8] B.H. Li, Y. Liu, J. Li, H. Cao and L. He, "Effect of process on the microstructures and the properties of in situ TiB2-TiC reinforces steel matrix composites produced by spark plasma sintering" - J. Mater. Process. Technol, vol. 210, pp. 91-95, 2010.
[9] C.L. Han and M.G. Kong, "Fabrication and properties of TiC-based cermet with intra/intergranular microstructure" - Mater. Des, vol. 30, pp. 1205-1208, 2009.
[10] D.H. Bacon, L. Edwards, J.E. Moffatt and M.E. Fitzpatrick, "Fatigue and fracture of a 316 stainless steel metal matrix composite reinforced with 25% titanium diboride". Int. J. Fatigue, vol. 48, pp. 39-47, 2013.
[11] F. Akhtar and S.J. Gu, "Microstructure, mechanical and fretting wear properties of TiC-stainless steel composites" - Mater. Charact, vol. 59, pp. 84-90, 2008.
[12] H. Kwon, C.Y. Suh and W. Kim, "Microstructure and mechanical properties of (TiW)C-Ni cermet prepared using a nano-sized TiC-WC powder mixture" - J. Alloys Compd, vol. 639, pp. 21-26, 2015.
[13] O.R. Wiedemanm, C. Weck, U. Martin, A. Muller and H.J. Seifert, "Spark plasma sintering of TiC particle-reinforced molybdenum composites. Int" - J. Refract. Met. Hard Mater, vol. 32, pp. 1-6, 2012.
[14] R.H. Md, Z. Hussain and R. Sivakumar, "Mechanism and optimization of titanium carbide-reinforced iron composite formation through carbothermal reduction of hematite and anatase" - J. Alloys Compd, vol. 587, pp. 442-450, 2014.
[15] W.F. Zhang, X.H. Zhang, J.L. Wang and C.Q. Hong, "Effect of Fe on the phases and microstructure of TiC-Fe cermets by combustion synthesis/quasi-isostatic pressing" - Mater. Sci. Eng, vol. 381, pp. 92-97, 2004.
[16] Y. Yang, H. Wang, R. Zhao, Y. Liang, L. Zhan and Q. Jiang, "Effects of C particle size on the ignition and combustion characteristics of the SHS reaction in the 20 wt%Ni-Ti-C system" - J. Alloys Compd, vol. 460, pp. 276-282, 2008.
[17] O.N. Dogan, J.A. Hawk, and K.K. Schrems, "TiC-Reinforced Cast Cr Steels" - JMEPEG, vol. 15, pp. 320-327, 2006.
[18] Nguyễn Minh Tuyển, "Quy hoạch thực nghiệm", Nhà xuất bản Khoa học và kỹ thuật, Hà Nội, 2005 (Vietnamese).