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# Statistical modeling of the mechanical alloying process for producing of Al/SiC nanocomposite powders

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**Abstract**

Mechanical alloying process was modeled by statistical approach for producing of Al/SiC nanocomposite powders. The process variables included two dimensionless variables $TV$ where $T$ and $V$ are milling time and speed, respectively, and $P1/P2$ where $P1$ and $P2$ are balls weight and powders weight, respectively. Responses of the process were crystallite size of the aluminum matrix, lattice strain of the aluminum matrix, and mean particle size of nanocomposite powders. The response variables were obtained by X-ray diffraction patterns (XRD), transmission electron microscopy (TEM), and laser particle size analyzer (LPSA). Two statistical models namely, fixed effects and regression model were developed. Analysis of variance (ANOVA) at 5% levels of significance for fixed effects model and 1% for regression model were performed. Results showed that $P1/P2$ has a significant effect on the crystallite size and lattice strain of the aluminum matrix and $TV$ has a significant effect on the crystallite size, and lattice strain of the aluminum matrix as well as mean particle size of nanocomposite powders. ANOVA for regression model showed that the linear effects of $TV$ and $P1/P2$ variables were significant for crystallite size, lattice strain of the aluminum matrix, and mean particle size of nanocomposite powders. The final regression models were checked and accepted by residual analysis.


*Keywords:* Statistical modeling; Mechanical alloying; Al/SiC nanocomposite; Crystallite size; Lattice strain; Mean particle size

## 1. Introduction

Mechanical alloying is a process for producing of advanced materials [1]. From among the important characteristics of this process it can be pointed to the complexity of the process. There are many variables to participate in this process which are not completely independent. Consequently, modeling of this process is a difficult task. Modeling of the mechanical alloying has been performed as an intricate process by many researchers, and there are many models for description of this process in the literature [2]. Most important modeling approaches can be divided into three categories: (a) phenomenological models such as mechanistic [3–7] and thermodynamic models [8]; (b) microstructural models such as kinetic [9,10] and atomistic models [11,12]; and (c) milling maps models [13,14]. Owing to lack of sufficient knowledge about the deformation behavior of materials at high strain rates, impact velocities, and impact frequencies, one cannot expect absolute prediction, but an only order of magnitude prediction and the general trends from these modeling efforts [15].

Al/SiC nanocomposite as an advanced material was produced by many researchers via mechanical alloying. El-Eskandarani [16] produced Al/SiC nanocomposite by using a high energy ball mill. He investigated microstructural characteristics and mechanical properties of this nanocomposite. Woo and Zhang [17] studied the effect of milling parameters on eutectic temperature as well as sintering rate of the Al–SiC nanocomposite. Lu et al. [18] reported a remarkable improvement in 0.2% YS and UTS via mechanical alloying the elemental powders of Al and Cu together with SiC as reinforcement particulates.

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Hanada et al. [19] has been used mechanical alloying method to disperse fine SiC particulates in an aluminum–lithium matrix powder. Their results showed that the application of this process to the mixing process gave a homogenous distribution of reinforcements and finer grain structure (<1 μm) to the aluminum–lithium nanocomposite. Hong and Kao [20] produced fine SiC particulates of 0.3 μm mean size which incorporated into an aluminum matrix by mechanical alloying. They showed Al–30 vol%-SiC composites had excellent compressive properties namely, yield stress, ultimate strength, and fracture strain.

Since numbers of variables control the process, developing a physical model for mechanical alloying process is very difficult. Simplification of the process in order to generate a physical model causes to deviate the model from the reality and does not give satisfactory results in practice. In these situations, investigators may need to employ statistical modeling to analyze and determine phenomenological models of the process. In the present work, we applied a statistical approach for modeling of mechanical alloying process. Once, a two-factor factorial design was employed to perform experimental procedure. Crystallite size, lattice strain of the aluminum matrix, and mean particle size of the nanocomposite powders were considered as parameters of the nanocomposite and the effects of process variables including milling time ($T$), milling speed ($V$), and ball to powder weight ratio ($P1/P2$) on the parameters of the nanocomposite which were modeled by a statistical approach. The nanocomposite particles in micrometer range include SiC particles which they fracture in nanometer range and incorporate into the aluminum particles. As a result, the mean particle size of the nanocomposite powders is a size of the aluminum particles as matrix of the nanocomposite, that it contains SiC nanoparticles as reinforcement of the nanocomposite. The order of significant effect of every process variables was determined by a fixed effects model. Furthermore, regression analysis has been utilized to analyze the effect of the two dimensionless variables $TV$ and $P1/P2$ on the properties of the Al/SiC nanocomposite. Then, the regression models are checked by residual analysis.

## 2. Modeling procedure

A statistical design of experiment refers to the process of planning the experiment so that appropriate data that can be analyzed by statistical methods will be collected, resulting in valid and objective conclusions [21]. The outline of design of experiment can be divided into seven steps including: (1) Description of the problem; (2) Selection of the response variables; (3) Choices of factors, levels, and range; (4) Selection of experimental design; (5) Performing the experiment; (6) Statistical analysis of the data; and (7) Conclusions.

The aim of this work was investigation and modeling of the effects of dimensionless process variables $TV$ and $P1/P2$ on the characteristic of Al/SiC nanocomposite including: crystallite size, lattice strain of the aluminum matrix, and the mean particle size of nanocomposite powders. The development of the numerical model namely, statistical model has been depended on experimental results. Empirical design, without analysis or careful review of available experimental data, is often high in cost and poor or inadequate in performance. Full size experimental testing for data acquisition for the modeling of the mechanical alloying is either impossible or prohibitively expensive. For this reason, important variables in the mechanical alloying were specified. These variables include: type of mill, milling temperature, milling speed, milling atmosphere, milling time, milling container, type, size, and size distribution of grinding media, weight of balls and powders under processing, extent of filling vial, process control agent (PCA), and type of materials under processing. In the present work, some variables were fixed as a constraint on the experimental procedure. Table 1 shows the characteristics of important variables of the process. The crystallite size and lattice strain of the aluminum matrix as well as the mean particle size of nanocomposite powders were considered as a function of variables of the mechanical alloying. This relationship can be described by:

$$\Psi = f(T, V, D, P1, P2, P3) \quad (1)$$

where $\Psi$ as a dependent parameter can be one of the crystallite size, lattice strain of the aluminum matrix or the mean particle size of nanocomposite powders; and $T$ (milling time), $V$ (milling speed), $D$ (ball diameter), $P1$ (weight of balls), $P2$ (weight of powders), and $P3$ (weight of PCA) are independent variables. Dimensionless variables in the mechanical alloying process were obtained by "dimensional analysis" and the Buckingham Pi theorem [22]. Basically, dimensional analysis is a method for reducing the number and complexity of experimental variables which effect a given physical phenomena. Fig. 1 shows flowchart of dimensional analysis procedure. At the beginning of the procedure, variable parameters were specified. These variables were milling time, speed, ball diameter, weight of balls, powders, and PCA. In the second stage, primary dimensions such as mass, length, and time were determined. In the third stage, dimensions of variable parameters were defined in term of primary dimensions. In the forth to six stages, repeating variables, dimensional equations, and dimensionless variables were obtained. Table 2 shows the dimensionless variables of mechanical alloying process. Finally, the functional relationship between dimensionless variables was obtained by:

$$(\text{Crystallite size}/D, \text{mean particle size}/D \text{ or lattice strain}) = f(P1/P2, P3/P2, TV) \quad (2)$$

For simplifying, $P3/P2$ was taken into consideration as a constant variable in the experimental procedure and the final dimensionless variables were selected as $P1/P2$ (ball