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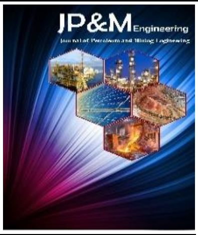

Fabrication of Al Alloy-Based Metal Matrix Composites and Use the Interpolation Approach for Mechanical Properties Estimation

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Abstract

Aluminum alloy-based metal matrix composites (AMMCs) are extensively utilized due to their distinctive mechanical properties. Al-6%Si alloy was reinforced with different contents of alumina (Al_2O_3) particles (0, 1.5, 3, 4.5, 6, 7.5, 9, 10.5 and 12% wt.) and the MMCs were prepared by stir casting at 800°C. Microstructural characterization of AMMCs was studied using optical microscopy, to emphasize the homogeneous distribution of the reinforcement particles (Al_2O_3) in the Al alloy matrix. Hardness and wear tests were used to study the influence of Al_2O_3 addition on the mechanical properties of the prepared composites. The interpolation method is applied as a perfect alternative approach for saving the consumed time during the experimental work. The used mathematical expression can be utilized for an early prediction of the mechanical properties of AMMCs at different contents of Al_2O_3 particles without carrying out much experimental analysis. The current study shows that the linear interpolator is the optimal one where it achieved Mean square error (MSE) equals 0.1875, and 0.0119 for hardness and wear loss tests, respectively.

Introduction

The composite materials possess enhanced mechanical properties; good ductility, high strength, high corrosion resistance, excellent wear resistance, better fatigue strength and good creep resistance [1,2]. Metal-Matrix Composites (MMCs) have distinctive characteristics over the other types of composites and can achieve superior mechanical properties [2-4]. Aluminum-matrix composites (AMCs) are applied in high efficiency applications as aerospace, automotive, electricity industries, military equipment, due to their unique mechanical properties [4-6]. AMMCs gained a great interest for their high strength, wear resistance, fracture toughness and are very suitable for high temperature applications when reinforced with ceramics [7,8]. Al-Si alloys are considered a remarkable type of aluminum alloys. So, their predominant usage compared with other aluminum alloys types is attributed to their perfect physical and mechanical properties [9,10].

Aluminum alloys reinforcement with alumina has a commercial value due to the improved mechanical properties of the created composites especially which used at elevated temperatures. Enhanced mechanical properties of MMCs are attributed to the content of ceramic particles which enforce the metal matrix [7,8,9]. The composites of aluminum alloy matrix which reinforced with ceramics, have an enhancement in the mechanical properties (hardness, wear resistance) with the increase in the particle content [7,8]. There are different methods for AMMCs fabrication as liquid state fabrication [11]. The simplest method and cost-effective process of the liquid fabrication is the stir casting method [3,12].

The mathematical expression is used as an appropriate alternative technique for saving experimental work, cost, and time. In connection with the development of artificial intelligence (AI), researchers have great interest for solving nonlinear problems of synthesis and characteristics of metal alloys and composites [13]. The interpolation technique is excessively applied as a valuable method in science and technology. Linear interpolation (LI) is a useful tool for predicting data points, which is involved in reducing the time spent on experiments. A suitable linear interpolation technique is important for correcting errors in the target case that are based on the error status of neighbouring points of the study grid [14]. Recently, different researchers designed and developed various progressing interpolation algorithms [15,16].

The aim of the present work is to prepare Al-6%Si-xAl2O3 composites by reinforcing the Al alloy matrix with Al2O3 particles, using the stir casting method.

Also, to study the prediction of behavior of mechanical properties for the obtained composites, by a mathematical approach (interpolation method) using the MATLAB software, that is the main object of the present study.

Interpolation methods

Interpolation is considered a mathematical technique for determining values of unknown points based on the values of known data points. Linear interpolation is the most commonly used interpolation technique that defines the linear relationship between the well-known points. Simply, it can be considered as the average for two rates through the interpolation period [17]. The coordinates of any two points in 2D-plane are x1, y1 and x1, y2. An unknown point (x, for example) can be determined for a known (y) value using the concept of (Li), which can be formulated by equation (1):

$$(y-y1)/(y2-y1) = (x-x1)/(x2-x1) \qquad (1)$$

Among the interpolation methods, popular and widely used are those that applied MATLAB Curve Fitting Toolbox. Various Interpolation techniques were supported in MATLAB, within the curve fitting toolbox, including (LI), Spline Interpolation (cubic spline), Pchip Interpolation (piecewise cubic Hermite interpolation) and Nearest Neighbor interpolation [18]. Linear and cubic spline interpolation techniques provide reasonable interpolation data for the calculation and calibration processes [19]. The cubic spline technique also assumes that the target pose error is within the cubic curve, which is organized from the pose errors of 8 neighboring grid points round the target [20]. Pchip is used initiated by Fristch and Carlson [21] and subsequently it has been extended by Fristch and Butland [22] for convenient control of the interpolating curves. Nearest neighbor interpolation (known as proximal interpolation), and it is a simple method in interpolation. Its algorithm takes the value of the nearest point, and does not nearly estimate the values of neighboring points [23]. The interpolation process helps us to predict the values of mechanical properties as hardness and wear loss tests at which were not performed in the laboratory based on that values obtained previously.

Experimental Work

Materials

In this work, an aluminum alloy (Al-6% Si) was utilized as the matrix for the synthesis of the composites which were reinforced with (0, 1.5, 3, 4.5, 6, 7.5, 9, 10.5 and 12 wt.%), of Al_2O_3 particles. The particle size distribution of alumina particles is determined using sieve analysis and the average size was 80 µm. Table 1 displays the chemical analysis for the composite matrix (Al-Si alloy) which shows that the Al-Si alloys have little total impurities.

Table 1 Chemical analysis of Al-6Si alloy

Component	%
Al	Rem.
Si	6
Fe	0.17
Mg	0.001
Mn	0.003
Cu	0.006
Ti	0.004
Zn	0.003
V	0.004
Na	0.005

The ceramic element (Al_2O_3) was chosen as the reinforcement material because it can be used at elevated temperatures, and also with benefits of creep resistance [24]. The chemical analysis of the as-received Al_2O_3 particles is presented in Table 2.

Table 2 Chemical composition of Al_2O_3 particles

Compound	Wt.%
Alumina	± 93
Fe_2O_3	± 0.8
TiO_2	± 1.7
CaO	± 1.2
Other magnetic materials	± 0.3

Synthesis of the Composite

AMMCs were synthesized by the stir casting method because it is a simple and cost-effective method [11,12]. In the stir casting method, a reinforcement material (alumina) is distributed in a molten matrix (Al-6% Si alloy) using mechanical stirring (Figure 1) [1,3,12]. The obtained Al-6%Si alloy was melted in a graphite crucible in an electrical laboratory furnace, at temperature of 800 °C. The alumina powder was heated at about 250 °C to remove moisture, and was put with different percentages (0, 1.5, 3, 4.5, 6, 7.5, 9, 10.5 and 12 wt.%). The addition of alumina was carried out under mechanical stirring of 400 rpm speed for 3 min rotation period, for achieving a well distribution of reinforcement (alumina) in the matrix (melt Al-Si alloy). The molten was poured into a metal mold and kept at room temperature for complete solidification

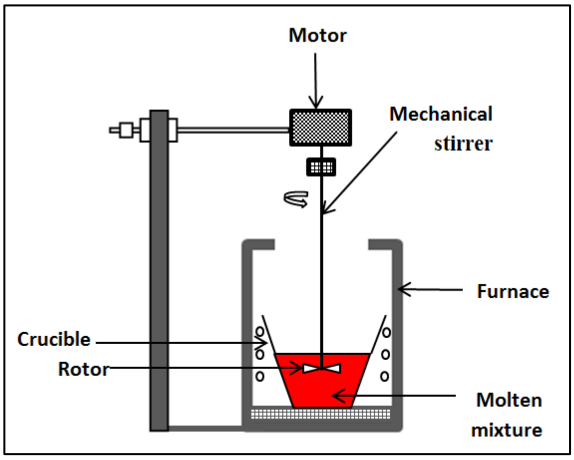

Figure 1 Schematic illustration of the stir casting process

The samples of the prepared composites are metallography prepared by grinding, polishing, and etching (0.5% diluted solution of HF, 2 second), for microstructure observation using optical microscope (Olympus BX51). For measuring the hardness of the synthesized composites, a Vickers hardness tester was used. Several indentations were made on each sample to obtain an average value of hardness. A wear test (pin on disc) was used to study the behaviour of the prepared composites for dry sliding wear. The wear test conditions were; 0.886 kg used load, 250 rpm sliding speed, and 30 min sliding time. The primary weight of the composites samples was determined and after the running of the test, the samples were reweighed to calculate the loss of weight due to wear. So, from the weight difference the average wear weight loss for the tested samples can be determined [6].

Interpolators simulations for the studied cases

Hardness and wear tests were carried out for aluminum-based alloys reinforced with Al_2O_3 particles at different contents of Al_2O_3 (0 to 12%). Determined values of Al_2O_3 contents (1.5, 4.5, 7.5 and 10.5 %) are applied in interpolation method to predict the hardness and wear loss of the AMMCs at various Al_2O_3 ratios. The flowchart in Figure 2 describes the process of interpolation, where four different cost functions were used in order to find the most optimal interpolator.

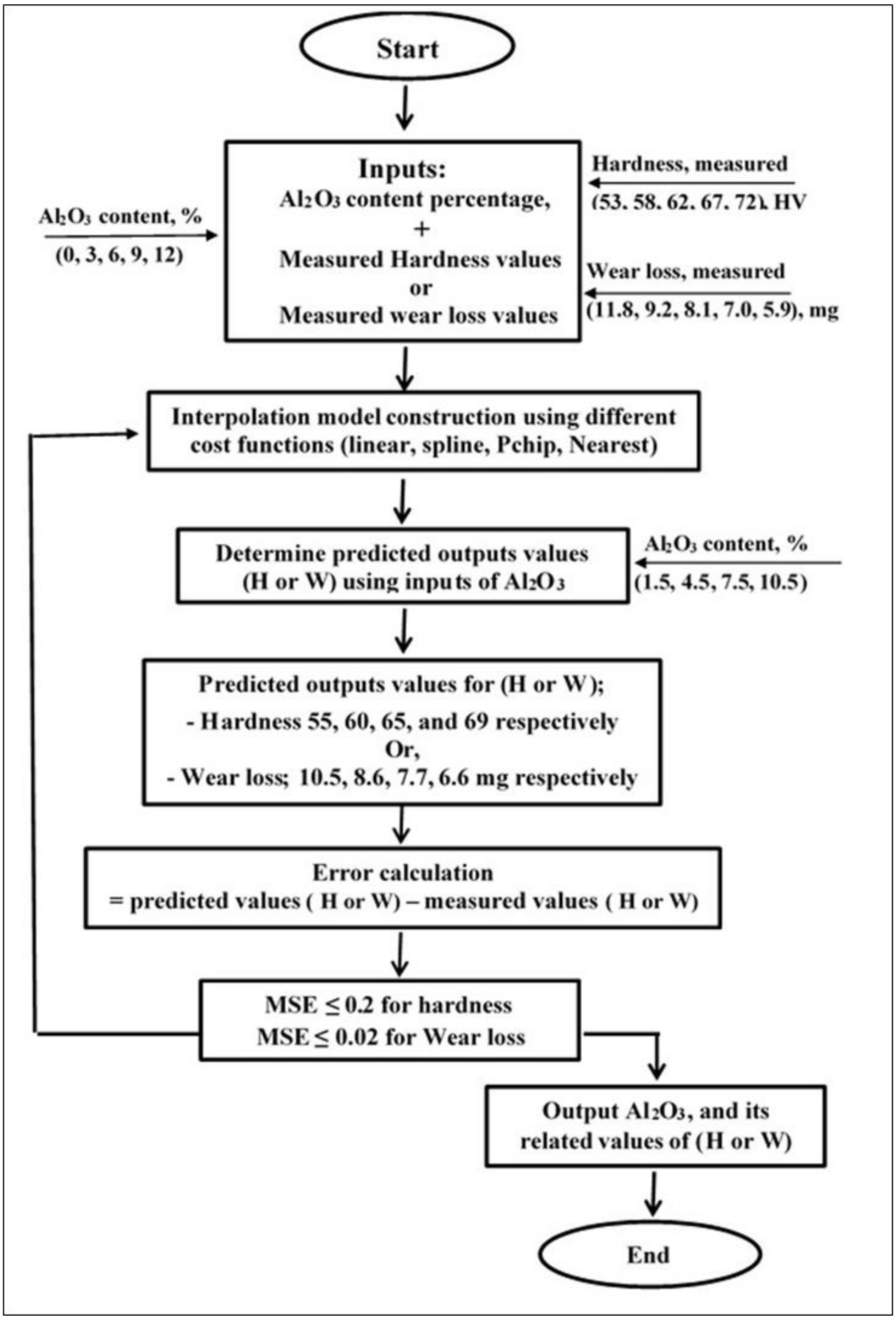

Figure 2 Flowchart for interpolation process, using four different cost functions to predict the hardness and wear loss of the AMMCs at various alumina contents.

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The optimum interpolator is the one that achieves more precise predictions and hence the most minimum error in terms of mean square error (MSE). In accordance with the minimum error values that are required at the end of the learning process, the standard (MSE) error measure function is a good scale for achieving good performance of the examined interpolators [25]. In order to compare the characteristics of all the studied interpolators, the MSE was used for each, which is determined by the following equation (2)

$$\text{MSE} = \left[\frac{\sum_{i=1}^{N} (O\ exp_i - O\ int_i)}{N}\right] \quad (2)$$

Where:

($\mathbf{O}\ \boldsymbol{exp_i}$): the experimental value,

($\mathbf{O}\ \boldsymbol{int_i}$): the interpolator output

N: a total number of data.

Results and Discussion

Composites Characterization

Aluminum alloy-based metal matrix composites were synthesized by the stir casting method, through which the reinforcement material (alumina) is distributed in a molten matrix (Al-6%Si alloy). Hardness and wear tests were applied to investigate the influence of Al_2O_3 addition on the mechanical properties of the synthesized composites. The interpolation method is utilized as a perfect alternative approach for early prediction of the mechanical properties of the composites at different contents of Al_2O_3 particles without performing much experimental work. The homogeneous distribution of the Al_2O_3 in the matrix is fundamental to produce a composite with uniform mechanical properties. The microstructure of the prepared composites was studied by optical light microscope (Figure 3 (a-b)). The uniform distribution of the alumina particles in the Al alloy matrix and the homogeneity of the cast composites is displayed in Figure 3a [7,8]. While the agglomerations of Al_2O_3 particles in the alloy matrix are shown in Figure 3b. This can be attributed to the fact that Al melt have a higher thermal conductivity and heat diffusivity than alumina and thus, Al_2O_3 particles are incapable to cool down with the melt. As a result, the temperature of the alumina particles is higher than that of the liquid alloy, and therefore retard solidification of the surrounding liquid Al alloy [7,8, 26,27].

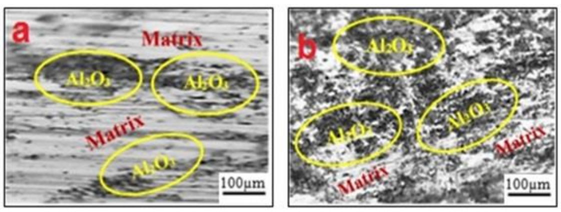

Figure3 Composites microstructure (X= 100); a) 3% Al_2O_3 b) 12% Al_2O_3

Mechanical Properties

Table (3) illustrates the values of hardness Vickers and Wear weight losses, of the synthesized composites under different contents of alumina.

Hardness

The hardness values for the prepared composites increase with increasing the addition of alumina particulates. This attributes to the hardness of alumina particles which dispersed in the alloy matrix and resulted in increasing the strength [5,8].

Wear test

Table (3) shows the average weight losses for the tested samples of the synthesized composites with different Al_2O_3 contents. The results illustrate that the wear resistance of the prepared composites is clearly improved for alumina particles addition and increases with the increasing of Al_2O_3 content. The hardness of the alumina is greater than the hardness of the matrix (Al alloy) [6,26,27]. So, the wear resistance of the fabricated composites is attributed to the wear resistance and hardness of the distributed reinforcement material [6,26,27].

Table 3 The hardness and Wear weight losses values of the MMCs

Al_2O_3, %	Hardness, HV	Wear wt. loss, mg
0	53	11.8
1.5	55	10.5
3	58	9.2
4.5	60	8.6
6	62	8.1
7.5	65	7.7
9	67	7
10.5	69	6.6
12	72	5.9

Prediction of the mechanical properties using interpolation methods

The interpolation techniques can be used as efficient alternative approaches for saving efforts, time and costs of the experimental work. Based on the previous obtained experimental data sets, the interpolation techniques have been used as predictors (estimators) in many scientific and engineering fields. Herein, the interpolation technique is applied to get the predicted values of both the hardness and wear loss of Al-Si alloys reinforced by Al_2O_3 particles. The interpolation techniques (interpolators) agree with the experimental values, which in turn confirm the functionality of interpolators as predictors. Four interpolation methods are compared namely, spline, linear, pchip and nearest method, by the mean square errors obtained from each method applied to a sample data. The mean square error that obtained by the linear method is much lower than the spline, pchip and nearest interpolation methods.

Prediction of hardness values

The experimental data and the interpolation outputs for hardness results are shown in Table (4).

Table 4 The experimental results and interpolators algorithms outputs for hardness test

Experimental work		Interpolators Outputs			
input	Output				
Al_2O_3 %	Hardness (HV)	"spline" method	"linear" method	"pchip" method	"nearest" method
1.5	55	55.7969	55.5000	55.6319	58.000
4.5	60	59.9531	60.0000	60.0000	62.000
7.5	65	64.3906	64.5000	64.4306	67.000
10.5	69	69.6094	69.5000	69.5000	72.000
MSE		0.3450	0.1875	0.2434	6.5000

The tabulated values show that the increase of the proportion of alumina (1.5 to 10.5%) increases the hardness from 55.7969 to 69.6094 for the first cost function (spline, Figure 4), from 55.5000 to 69.5000 for the second cost function (linear, Figure 5), from 55.6319 to 69.5000 for the third cost function (pchip, Figure 6) and from 58.000 to 72.000 for the last cost function (nearest, Figure 7).

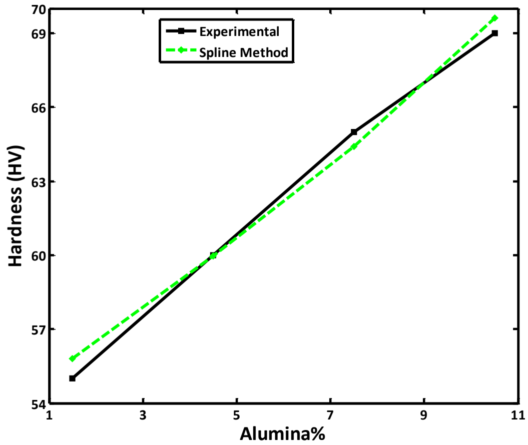

Figure 4 Interpolation outputs for hardness test using spline cost function

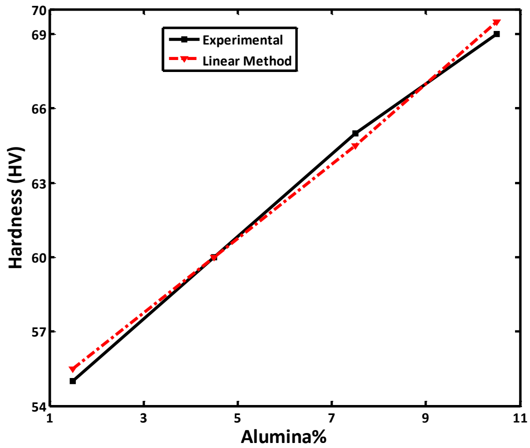

Figure 5 Interpolation outputs for hardness test using linear cost function

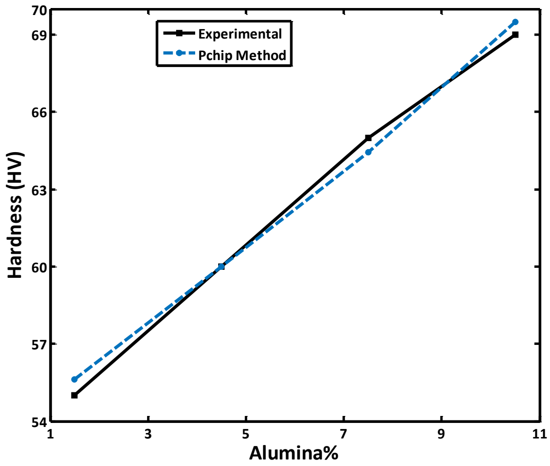

Figure 6 Interpolation outputs for hardness test using pchip cost function.

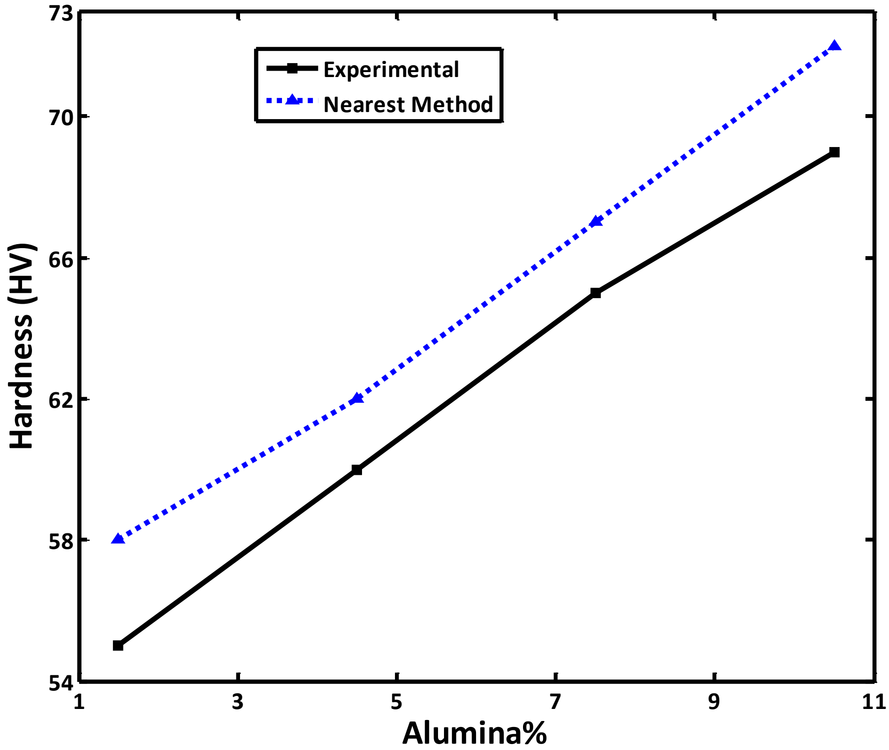

Figure 7 Interpolation outputs for hardness test using nearest cost function

Figure (8) represents the alumina addition effect on the hardness values of the Al-Si alloys reinforced by Al_2O_3 for the four interpolation methods compared with the experimental data.

From Figure (8), it is clear that experimental and predicted curves obtained using interpolation algorithms for hardness (HV) are close to each other. The superior performance of the interpolation algorithms can be indicated by mean square error MSE equals 0.3450 for spline method, 0.1875 for linear method, 0.2434 for pchip method and 6.5000 for nearest method respectively are shown in Table 4. From MSE values, it is obvious that the linear method has better predictions because it has the less error.

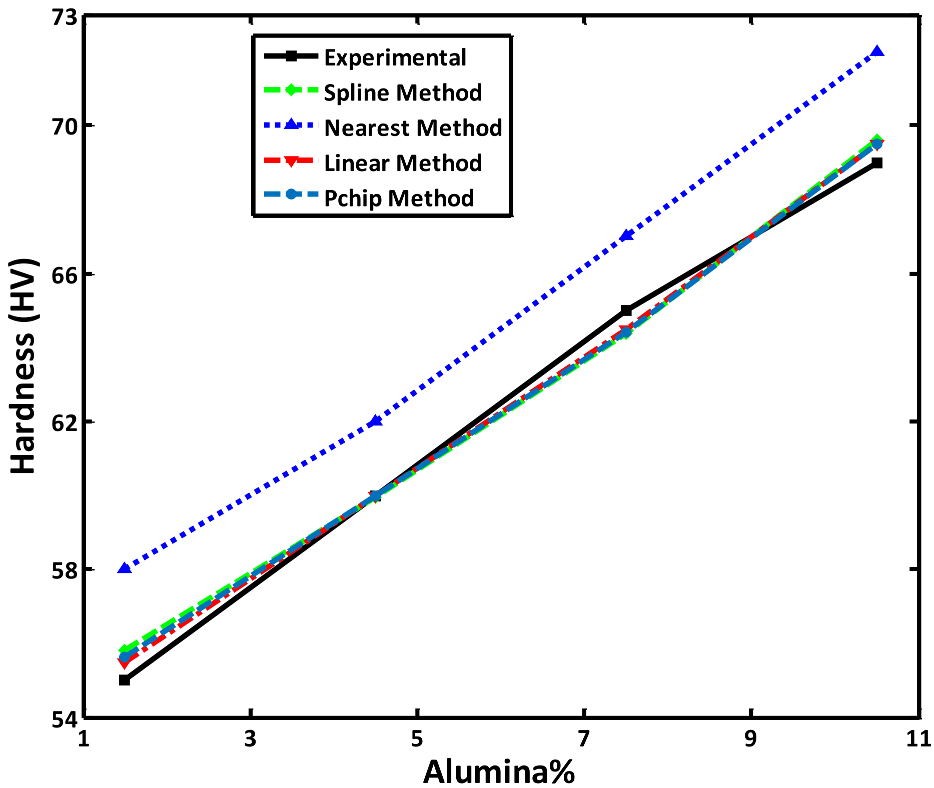

Figure 8 Experimental and predicted results of the hardness of AMMCs with various Al_2O_3 content by the four interpolation methods

Prediction of wear weight loss values

The experimental data and the interpolation outputs values for wear loss results are illustrated in Table 5. The results show that the increase of the proportion of alumina (1.5 to 10.5%) decreases the value of wear loss from 10.1953 to 6.4266 for the first cost function (spline, Figure 9), from 10.5000 to 6.4500 for the second cost function (linear, Figure 10) and from 10.2745 to 6.4500 for the third cost function (pchip, Figure 11) and from 9.2000 to 5,9000 for the fourth cost function (nearest, Figure 12).

Table 5 Experimental results and interpolators algorithms outputs for wear weight loss test

Experimental work		Interpolators Outputs			
input	Output				
Al_2O_3, %	Wear loss, mg	"spline" method	"linear" method	"pchip" method	"nearest" method
1.5	10.5	10.1953	10.5000	10.2745	9.2000
4.5	8.6	8.5797	8.6500	8.5943	8.1000
7.5	7.7	7.5734	7.5500	7.5500	7.0000
10.5	6.6	6.4266	6.4500	6.4500	5.9000
MSE		0.0348	0.0119	0.0240	0.7300

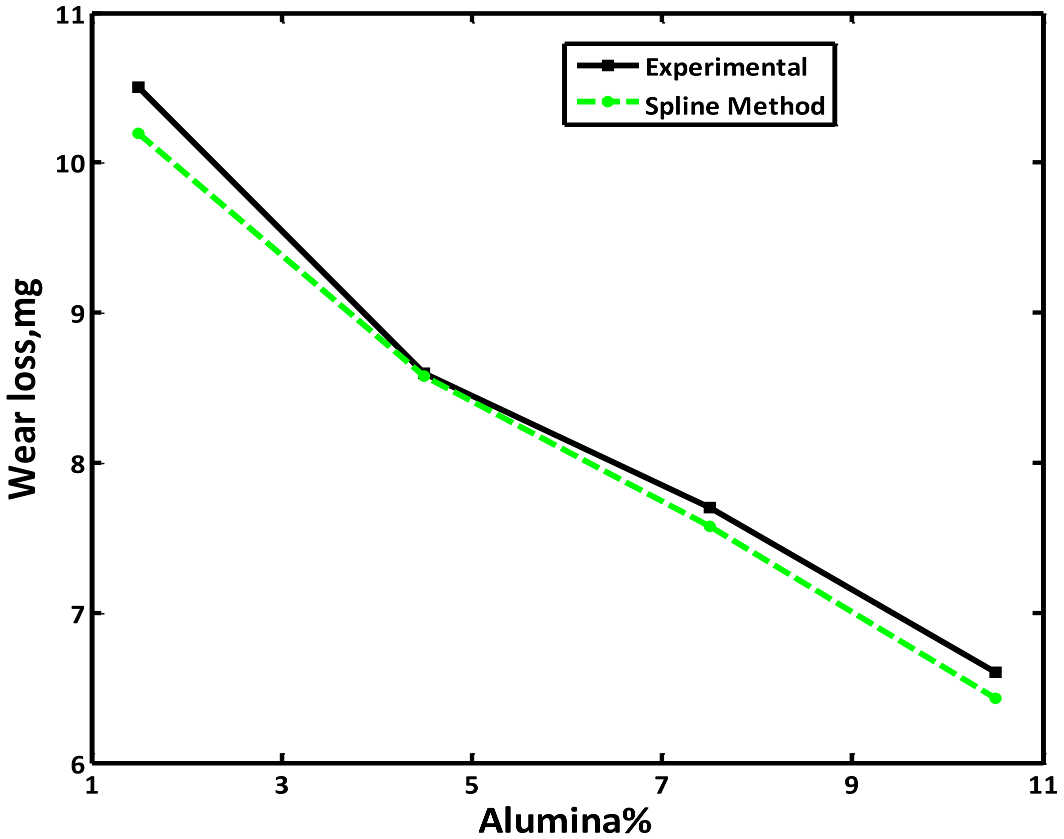

Figure 9 Interpolation outputs for wear weight loss test using spline cost function

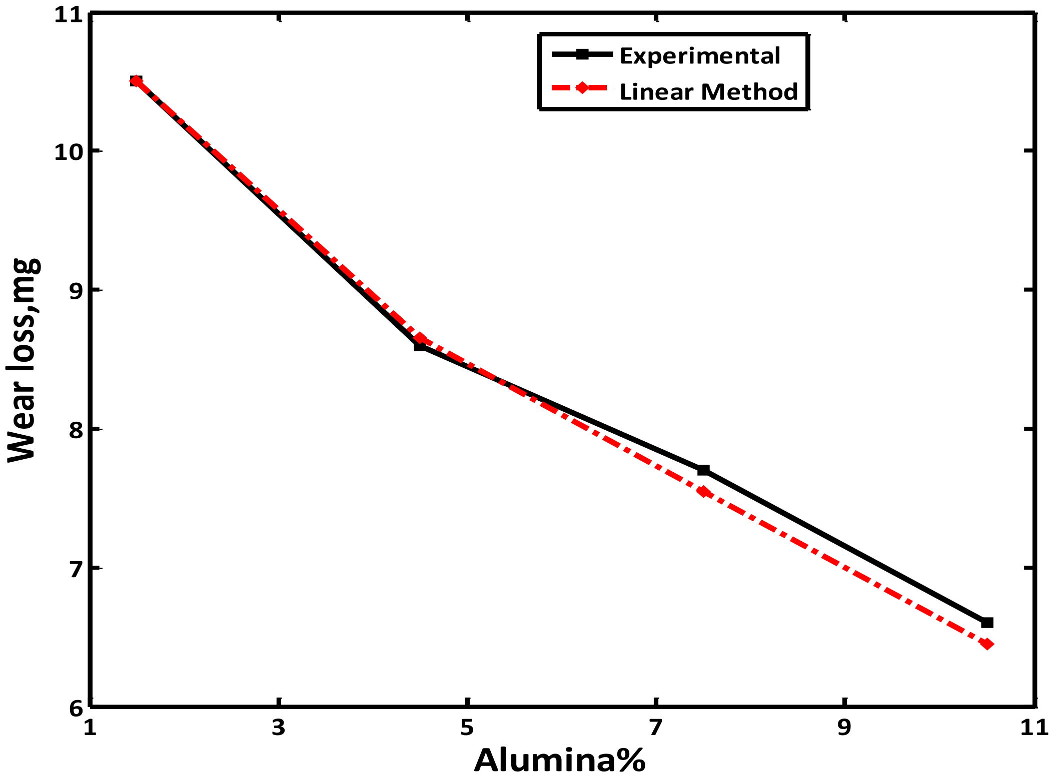

Figure 10 Interpolation outputs for wear weight loss test using linear cost function

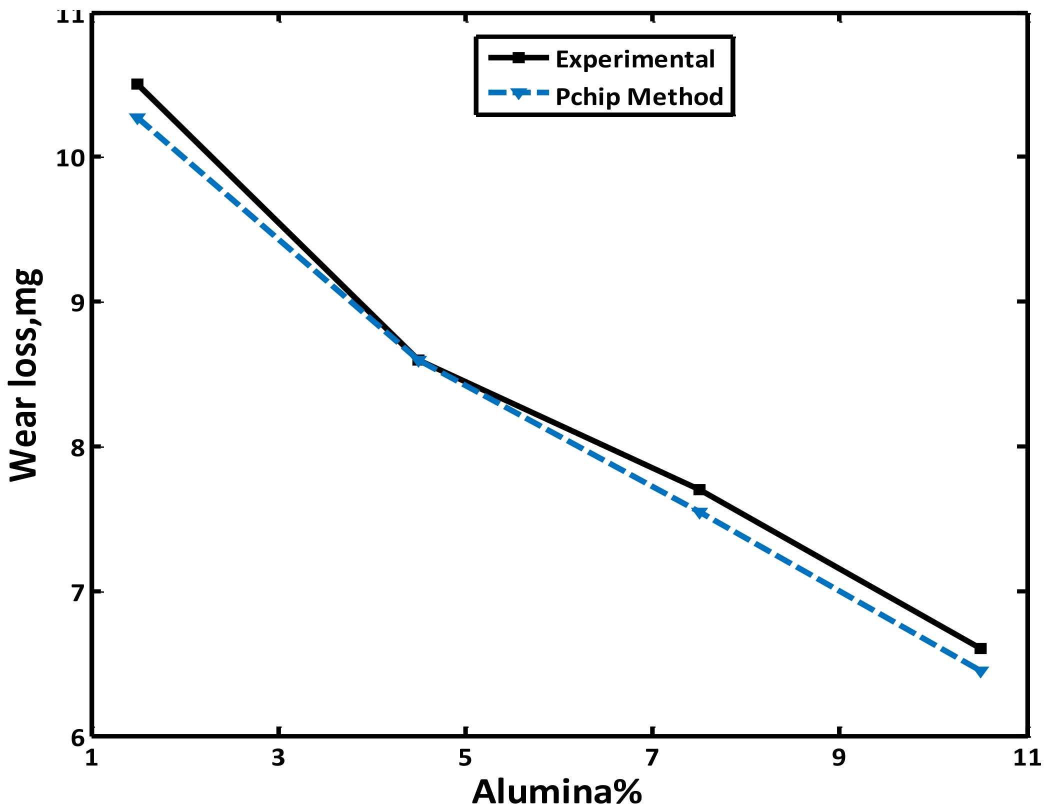

Figure 11 Interpolation outputs for wear weight loss test using pchip cost function

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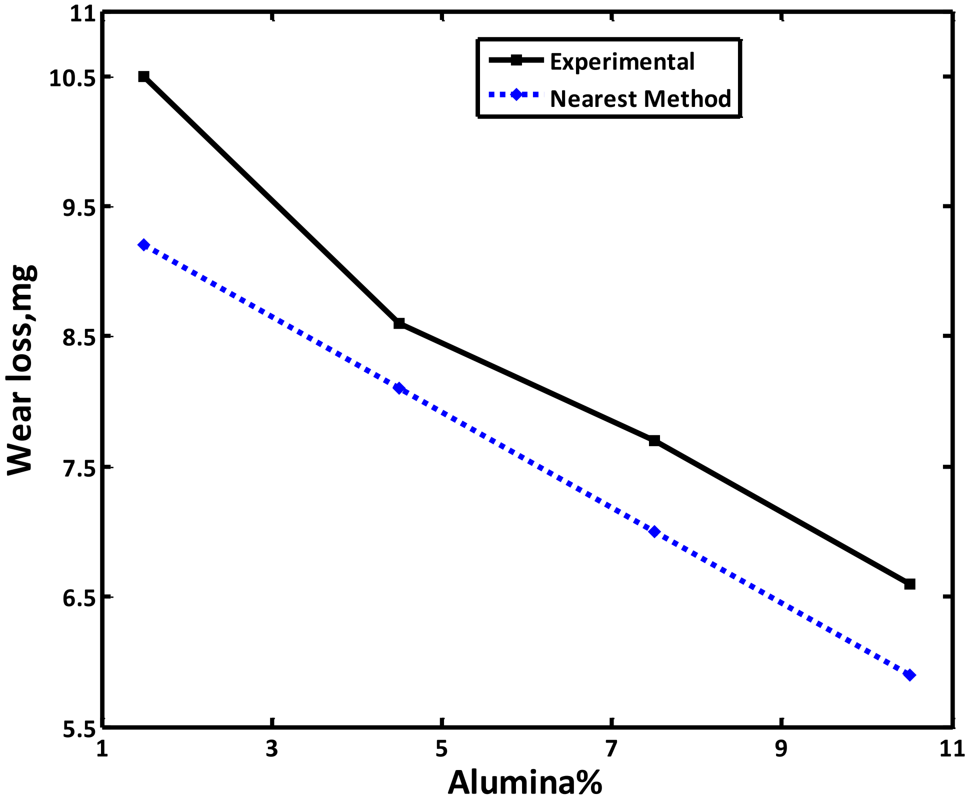

Figure 12 Interpolation outputs for wear weight loss test using nearest cost function

Figure 13 represents the influence of alumina content on the wear loss values of Al-6Si alloys reinforced by Al_2O_3 using different interpolation algorithms. From Figure 13, it could be seen, clearly that experimental data and predicted curves obtained from interpolation algorithms for wear loss test are close to each other. The superior performance of the interpolation algorithms can be indicated by mean square error MSE equals 0.0348 for spline method, 0.0119 for linear method, 0.0240 for pchip method and 0.7300 for nearest method are shown in table 5. From these values we note that the linear method has better performance because it has the less error.

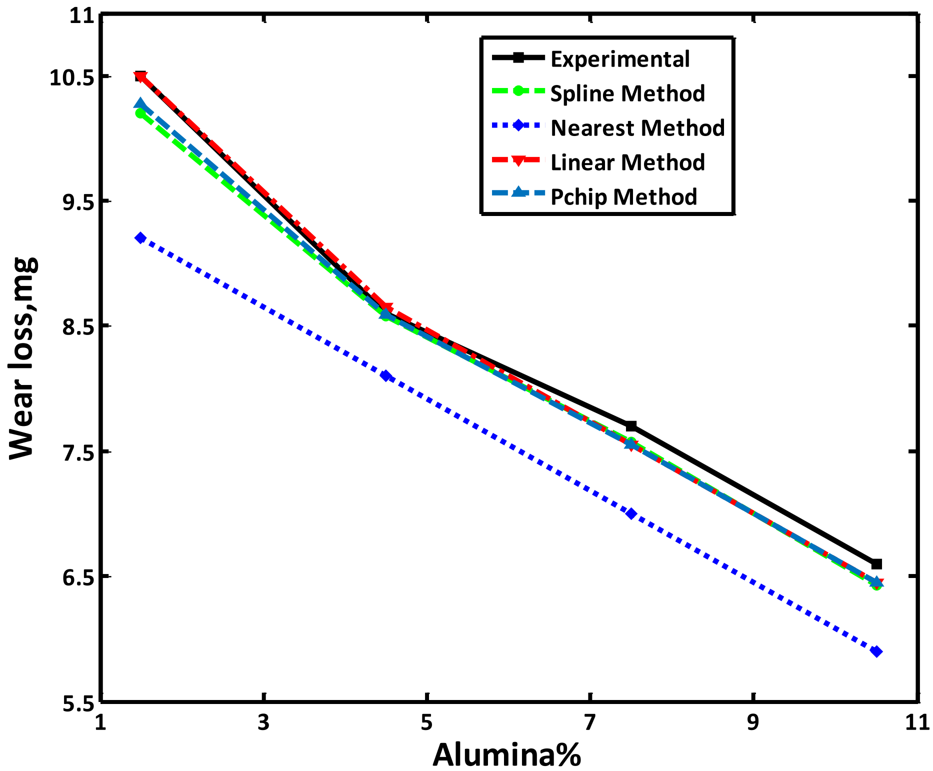

Figure 13 Experimental and predicted results of the wear of AMMCs with various Al_2O_3 content by the four interpolation methods

Conclusions

- Using stir casting method, the Al-6%Si composites reinforced with different alumina particles can be fabricated with improved mechanical properties.
- The hardness obtained values (HV) of the synthesized AMMCs increase due to the increase of alumina weight fraction.
- The synthesized AMMCs have an improvement in wear resistance with Al_2O_3 particles addition, and with increasing Al_2O_3 content the wear resistance increases.
- Experimental results of hardness and wear loss tests of composite material have shown a good agreement with predicted results of interpolation algorithms.
- The linear interpolation is the optimal one in comparison with its peers, where it achieved MSE equal 0.1875, and 0.0119 for hardness and wear loss tests respectively

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Conflicts of interest

There are no conflicts to declare.

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