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Production of 93.95Al-5Zn-1.05Sn/ $Al_2O_3.SiO_2$ Particulate Composites and the Establishment of Relationship between Independent Variables and Hardness of the Composites Using MATLAB

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***Abstract*—The ''production of 93.95Al-5Zn-1.05Sn/$Al_2O_3.SiO_2$ particulate composite and the establishment of relationship between independent variables and hardness of the composites using MatLab'' has been done. The work started with the production of the composites. Two independent variables were considered in the production of the composites; and these were the reinforcement and the aging time of the composites. Other variables were kept constant. Using MatLab the production process of the composite was analysed and the relationship existing between the two variables and the hardness of the composite was found to be a polynomial function. Based on the preceding; mathematical models were developed using Matlab that can precisely and accurately predict hardness of the produced composites provided the reinforcement and the ageing time is known.**

Keywords—Matlab; Composite; Independent variables; Hardness; Relationship.

1. INTRODUCTION

Composites combine the attribute properties of the other classes of materials while avoiding some of their drawbacks, they are light, stiff, and strong, and they can be tough. Metal matrix composites (MMCs) reinforced with ceramics or metallic particles are widely used due to their high specific modulus, strength, hardness, and wear resistance. MMCs are considered as an alternative to monolithic metallic materials or conventional alloys in a number of specialized applications. The majority of such materials are metallic matrices reinforced with high strength, high modulus and often brittle second phase in the form of fibre, particulate, whiskers, embedded in a ductile metal matrix [1-2]. The basic structural changes or morphological changes on age hardening are brought together by the different stages of disintegration of the saturated solid solution resulting from hardening of the alloy. Since disintegration of the saturated solution is a diffusion controlled process, the degree of disintegration, type of precipitation from the solution, their dispersion, form, and other structural characteristics depends on the nature of the alloy and its chemical composition. Besides the structure of an age-hardened material, it also depends on impurities, heating temperature, velocity of cooling on hardening, plastic deformation after hardening, duration of weathering of the hardened alloy at room temperature before artificial hardening and many other factors. The effect of all these factors combined makes a study of the process of age hardened alloy and composites difficult [3-6]. Age hardening assists in the distribution of the particles in the matrix and this goes a long way to improve the mechanical properties. In age hardening no phase transformation takes place what happens is precipitation [1-7]. This increases hardness of the material.

The greatest strength in any known aluminium alloy is obtained by the addition of zinc and magnesium (e.g. 8 wt. percent Zn, 1 wt percent Mg), which form zones and intermediate precipitates leading towards the stable $MgZn_2$ compound. The binary Al-Zn system has favourable solubility and zone and intermediate precipitate characteristics but is not a good age hardening system, at room temperature, because the zinc atom is too mobile and the coarse equilibrium precipitate (Zn) forms at quite low temperature by continuous and discontinuous precipitation [1,8-9]. Many commercial alloys are greatly improved by the addition of various elements in trace amounts, which are able to enhance or retard the formation of various structures. For example, Cu-Be alloys soften rapidly by discontinuous precipitation at temperatures above about 300°C, but this can be prevented by the addition of about 0.4 wt. percent cobalt. This trace element retards the formation of G.P. Zones and so delays the age hardening process at room temperature, which gives more time for mechanically fabricating the quenched alloy before it becomes too hard (otherwise the quenched alloy has to be refrigerated to keep it soft); and it speeds up the formation of Θ' and also leads to a greater hardness from this precipitate. This work has used 1.05 wt. percent tin as the trace element in the Al-Zn alloy system. Much effort has gone into the study of trace elements in Al-Zn-Mg alloy [1,8-9]. Although very hard, the basic alloy is plagued by grain boundary weakness due to precipitate-free regions. Small additions of silver have a very beneficial effect in refining the precipitate structure and removing the precipitate-free regions. According to Khanna [1] low tin aluminium alloys possess high fatigue strength and thus can carry fluctuating loads. Literature review has shown that 93.95Al-5Zn-1.05Sn alloy is not a common alloy, therefore the effect of 1.05 wt. percent tin on Al-Zn alloy system will be interesting to investigate. Mg is commonly used but in this work it is replaced by tin. Alloying is used in many different ways to strength metals. The most important general method is to obstruct the movement of dislocations by a fine dispersion of foreign particles distributed throughout the matrix crystal. These particles may be single atoms as in solid solution hardening or some larger clusters or separate phases, as in precipitation hardening and dispersion hardening. Particulate composites derive their strength from dispersion hardening and the use of oxide particulates like Al_2O_3, SiO_2, ZrO_2, and TiO_2 in Al, Mg, Cu, Zn and other metal-matrices have been pointed out by Curran [5] and other researchers [2-4,10-11].

The production of a ternary alloy like 93.95Al/5Zn/1.05Sn as a metal-matrix for a composite material reinforced with a foreign fine dispersion uniformly distributed in the matrix of the ternary alloy is interesting. Particularly from the point of view of the above literature reviews and accompanying discussions, complete analysis of the effects of alloying elements, nature of reinforcement, age hardening treatment and others on the properties of the composite may be a very complex analysis. However, it is important to know the role played by some variables in bringing out certain properties in materials [12-13]. This knowledge will assist in predicting materials properties and also in developing superior materials. The objective of this work is actually to produce 93.95Al.5Zn.1.05Sn/Al_2O_3.SiO_2 particulate composites and to establish the relationship existing between the variables of the composite and its hardness property using MatLab computer software.

2. MATERIALS AND METHODS

The materials used for the work included; alumino-silicate clay, aluminium cables from Cocanaco Cable Company from Kaduna, pure zinc and tin from National Metallurgical Development Centre, Jos stock. The equipment used included cutting saw, weighing balance, mechanical stirrer, oven, Rockwell hardness tester, grinding and polishing machine, ball mill, nest of sieves and sieve shaker, permanent metal moulds and melting furnace. The production of the ternary alloy (93.95Al-5Zn-1.05Sn) was carried out in the foundry shop of the National Metallurgical Development Centre (NMDC) Jos. Different heats were produced. The first heat was without the addition of alumino-silicate. The subsequent heats were produced with the addition of varying percentages of alumino-silicates which were produced by using ball mill and sieving the ground alumino-silicate to 20 microns passing. The alumino-silicate addition was varied from 1-5 wt. percent and stirred at 315 rev/ min using a mechanical stirrer. The different heats were removed and poured into permanent moulds for solidification. The specimens were removed and prepared into test pieces for hardness test using Rockwell tester. They were then subjected to age hardening heat treatment. The treatment involved solutionising at $500^{O}C$, quenching in warm water, drying with air blower, ageing at a constant temperature ($150^{O}C$) and varying the ageing time from 1hr to 6hrs. The details of the hardness test were: Rockwell Hardness 'B' Scale was used, the minor load was 98N (9.8Kgf), the major load was 980N (100Kgf), the indenter was hardened steel ball (1.8mm), the standard test block hardness value was 101.2HRB and the test temperature which was the room temperature was $27^{O}C$. The result of the test is as presented in Table 1. This work was done in NMDC foundry as earlier stated. All other variables were kept constant; alumino-silicate clay particles and ageing time were the only independent variables.

3. RESULTS AND ANALYSIS

3.1 Results

The result of the hardness test is as presented in Table 1. The corresponding independent variables are also shown in the Table.

TABLE 1 HARDNESS VALUES WITH CORRESPONDING AGEING TIME AND REINFORCEMENT.

% Reinforcement	Aging Time (Hours)					
	1	2	3	4	5	6
	Hardness in HRB					
1.00	27.10	25.30	29.50	26.50	24.83	26.00
2.00	27.66	25.30	32.50	26.33	27.33	27.13
3.00	26.33	28.07	31.83	24.67	26.16	27.00
5.00	27.00	31.53	27.66	23.33	25.83	26.40

3.2 Analysis using MatLab

From the experimental data obtained, we seek to have functions that relate the hardness values with the aging time values. Employing Polynomial interpolation Scheme, we assume the form of an interpolating polynomial function to fit the experimental data as,

$$H(\boldsymbol{t}) = a_1 m_1(\boldsymbol{t}) + a_2 m_2(\boldsymbol{t}) + \ldots + a_n m_n(\boldsymbol{t}) = \sum_{i=0}^{n} a_i m_i\,(\boldsymbol{t}) \qquad (1)$$

Where H is the hardness as a function of aging time $\boldsymbol{t}$, a_i are the coefficients of the interpolating polynomial, m_i are the monomials forming the basis function of aging time ***t***.

In order to obtain the best polynomial fit, our chosen polynomial function must be minimized. That is, errors have to be reduced and be confined in the computed hardness values by the determined polynomial. Using the Least-Square approach to reduce error, we have

$$S\,(a_1, a_2, \ldots, a_m) = \sum_{i=0}^{m} \left[H_i - H_i\,(\boldsymbol{t}) \right]^2 \qquad (2)$$

Where S is the Residual function, H_i is the experimental value of hardness, and $H_i(\boldsymbol{t})$ is the computed hardness value at a time ***t***, using the chosen polynomial function.

Substituting the equation (1) into equation (2) and obtaining the derivative of $\partial S/\partial a_k$, we have

$$\partial S/\partial a_k = -2 \left\{ \sum_{i=0}^{m} \left[H_i - \sum_{j=0}^{n} a_j m_j(\boldsymbol{t}) \right] H_k\,(\boldsymbol{t}) \right\} = 0,\ k = 1, 2, \ldots, m \qquad (3)$$

Discarding the constant (-2) and interchanging the summation order and rearranging equation 3, we have

$$\sum_{j=1}^{n} \left[\sum_{i=0}^{m} m_j(\boldsymbol{t}) H_k\,(\boldsymbol{t}) \right] a_j = \sum_{i=0}^{n} H_k(\boldsymbol{t}) H_i\ ] \qquad (4a)$$

Using Matrix notation, equation 4 can be represented as,

$$\boldsymbol{A}a = \boldsymbol{b} \qquad (4b)$$

Where

$\boldsymbol{A} = A_{kj} = \sum_{i=0}^{m} m_j(\boldsymbol{t}) H_k\,(\boldsymbol{t})$, and

$\boldsymbol{b} = b_k = \sum_{i=0}^{n} H_k(\boldsymbol{t}) H_i$

Equation (4b) is a normal equation of the least-squares fit that can be solved using any known method for solving equations system to obtain the coefficient vector matrix *a* [14].

Using Matrices Laboratories (MatLab) software, which has an in-built function that computes a set of coefficients, $c_1, c_2, \ldots, c_{n+1}$ that minimizes any chosen fitting polynomial function of order *n = m - 1*, as described by equation (1) in a least-square sense. Where *m* is the number of data points. The MatLab function coding is

c *= polyfit (**x**,**u**,**n**) % Matlab Code*

Where ***c*** is the output vector of the coefficients of the fitting interpolating polynomial function, ***x*** is the vector of the independent variable, ***u*** is the vector of the dependent variable, and ***n*** is the order of the fitting interpolating polynomial function [15]. The coefficients contained in the variable ***c*** in the MatLab code are arranged in descending order of the exponents of the basis functions $m_i(\boldsymbol{t})$.

Now from the experimental data shown in Table 1, for every percentage of reinforcement used, the hardness values as well as the corresponding aging time values were used in a written little MatLab script, to generate the coefficients of the fitting polynomials relating hardness with aging time obtained.

For every percentage reinforcement used during the experiment, coefficients of the fitting polynomial function relating the Hardness ***H(t)*** and the Aging time ***t***, were obtained and they are presented as follows;

For 1% Reinforcement, we have

$$\boldsymbol{H(t)} = 98.58 - 145.91\boldsymbol{t} + 101.79\boldsymbol{t}^2 - 31.62\boldsymbol{t}^3 + 4.50\boldsymbol{t}^4 - 0.24\boldsymbol{t}^5 \qquad (5)$$

For 2% Reinforcement, we have

$$\boldsymbol{H(t)} = 178.36 - 314.57\boldsymbol{t} + 226.81\boldsymbol{t}^2 - 73.20\boldsymbol{t}^3 + 10.86\boldsymbol{t}^4 - 0.60\boldsymbol{t}^5 \qquad (6)$$

For 3% Reinforcement, we have

$$\boldsymbol{H(t)} = 103.44 - 166.89\boldsymbol{t} + 125.28\boldsymbol{t}^2 - 41.35\boldsymbol{t}^3 + 6.19\boldsymbol{t}^4 - 0.34\boldsymbol{t}^5 \qquad (7)$$

For 5% Reinforcement, we have

$$\boldsymbol{H(t)} = 20.88 - 2.12\boldsymbol{t} + 15.78\boldsymbol{t}^2 - 9.31\boldsymbol{t}^3 + 1.90\boldsymbol{t}^4 - 0.13\boldsymbol{t}^5 \qquad (8)$$

Equation 5 to equation 8 are the interpolating Polynomial functions relating the hardness ***H*** as a function of aging time ***t*** for 1%, 2%, 3% and 5% reinforcement respectively of the material investigated.

The fig. 1 below is the graphical plots of the hardness ***H*** against aging time ***t***.

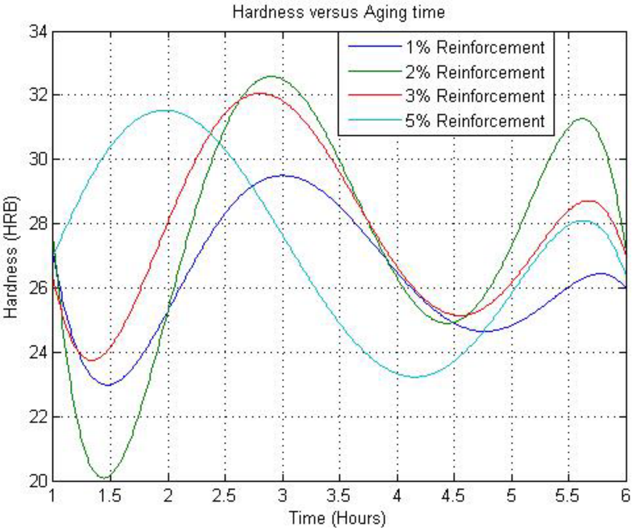

Fig. 1 Plot of Hardness against Aging Time for Different Percentages of Material Reinforcement.

Fig.1 is a plot of hardness against ageing time for different percentages of material reinforcement. The plot has shown that the relationship between the dependent variable (hardness) and the independent variables (ageing time and reinforcement) is a polynomial function and not a linear function. The relationship is nonlinear and this agrees with previous works which were unable to provide adequate model to describe the relationship [12-13, 16]. Those models were developed based on linear regression models and the authors were unable to use them to predict hardness values accurately.

The Table 2 below is the computer hardness values using the interpolating polynomial functions. It can be observed that the computed hardness values have less that 4% error when compared with the empirical values. Also, interpolated hardness values were obtained at aging times of 1.5, 2.5, 3.5, 4.5 and 5.5 hours. This is an indication that the models can be used as a tool for predicting hardness without having to conduct the physical hardness test.

TABLE 2: COMPUTED RESULT

% Reinforcement	**Aging Time (Hours)**					
	1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**
1.00	27.099	22.990	25.300	28.321	29.500	28.539
2.00	27.659	20.175	25.300	31.005	32.500	29.973
3.00	26.329	24.175	28.070	31.441	31.829	29.606
5.00	26.999	30.416	31.530	30.314	27.660	24.901

TABLE 2: COMPUTED RESULT (continues)

% Reinforcement	**Aging Time (Hours)**				
	4.0	**4.5**	**5.0**	**5.5**	**6.0**
1.00	26.499	24.902	24.829	26.025	25.999
2.00	26.330	24.931	27.329	31.012	27.129
3.00	26.670	25.159	26.160	28.408	26.999
5.00	23.330	23.717	25.830	27.952	26.399

TABLE 3: EMPERICAL RESULTS ALONGSIDE CALCULATED RESULTS USING DEVELOPED MODELS

% Rein force ment	**Aging Time (Hours)**											
	1		**2**		**3**		**4**		**5**		**6**	
	Empirical vs. Calculated Hardness in HRB											
	C		**C**		**C**		**C**		**C**		**C**	
1.00	27.10	27.1	25.30	25.3	29.50	29.5	26.50	26.5	24.83	24.83	26.00	25.99
2.00	27.66	27.66	25.30	25.3	32.50	32.5	26.33	26.33	27.33	27.33	27.13	27.13
3.00	26.33	26.33	28.07	28.07	31.83	31.83	24.67	26.7	26.16	26.16	27.00	26.99
5.00	27.00	26.99	31.53	31.53	27.66	27.66	23.33	23.33	25.83	25.83	26.40	26.4

C stands for calculated values of hardness using the developed model equations

Table 3 above shows the empirical results alongside calculated results using developed models (equations 5-8). The accuracy of the models is very high, in-that the values obtained using the models agree with the empirical result with an error of less than 4%. Results in Table 3 indicates that the developed models can be used to predict hardness in 93.95Al.5Zn.1.05Sn/$Al_2O_3.SiO_2$ particulate composite provided the ageing time and amount of reinforcement particles is known. The ageing temperature, nature of reinforcement and other variables must also be the same as those prevailing during the processing of the composite for the model equations to be accurate.

4. CONCLUSION

The work ''production of 93.95Al-5Zn-1.05Sn/ $Al_2o_3.Sio_2$ particulate composites and the establishment of relationship between independent variables and hardness of the composites using matlab'' has been carried out. The conclusions drawn are as follows:

i. The work has successfully produced 93.95Al-5Zn-1.05Sn/$Al_2O_3.SiO_2$ particulate composites of different types (with different reinforcement and ageing time)

ii. The relationship existing between ageing time, reinforcement and hardness of the composite which is the dependent variable is a polynomial function.

iii. The study has confirmed that, against the linear relationship assumed by previous authors the relationship between ageing time, and reinforcement as the independent variables, and hardness of the composite as the dependent variable is not a linear relationship

iv. Using Matlab software, models have been developed which can precisely and accurately predict the hardness of the composites provided the reinforcement percentage and the ageing time (hrs) is known.

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