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Modeling and Study of the Effect of Weakening Factor on Elastic Property of Particulate Metal Matrix Composites

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Abstract

Metal matrix composites materials have emerged as potential candidate for a variety of structural applications in the aeronautical / aerospace, transportation, defence and sports industries because they are considerably cheaper and easier to process. A MMC is normally fabricated using a ductile metal (e.g., Al, Ti or Ni) as the matrix material and a ceramic material (e.g., alumina, SiC or graphite) as dispersoids. Combining the metallic properties such as good ductility and toughness of the matrix with ceramic properties such as high strength, hardness and elastic modulus of the dispersoids, the composites exhibit high toughness; specific strength, stiffness and good wear resistance. Particulate metal matrix composites (PMMCs) are a class of composites that have evoked keen interest, largely due to the promise of improved properties over conventional metals and alloys. Among the many ceramic reinforcements SiC has been found to have excellent compatibility with the Al-matrix. Conventional liquid metallurgy and powder metallurgy are the two commonly employed methods by which these composites are processed. The test specimens used in these experiments are processed through liquid metallurgy. Hence these composites exhibit the conventional casting defects as well as the composite defects. The presence of fine porosity in MMC causes a reduction in mechanical property of metal matrix composites products. These porosities are bound to come, as it is a cast product.

A theoretical model to predict the elastic property of metal matrix composites is derived in this paper. A factor that represents the weakening caused by the presence of porosity is also included in the model. The elastic modulus of the product based on theoretical models are also calculated and compared with the experimental values. For the experimental elastic property estimation ultrasonic velocity measurements are made use of. Results indicated that ultrasonic testing is more appropriate technique to evaluate the quality of composite as the elastic properties derived by ultrasonic velocity values of defective specimens are deviating with predicted values.. In this paper an attempt has been tried to standardize an ultrasonic method for evaluating the quality of the composite specimens. Primarily ultrasonic techniques are selected, as the velocity of ultrasonic is much influenced by the constituent elements and its composition in the medium through which it travels.

Keywords: *Metal matrix composites, Elastic modulus, and Ultrasonic velocity*

1. Introduction

Metal matrix composites materials have emerged as potential candidate for a variety of structural applications in the aeronautical / aerospace, transportation, defence and sports industries because they are considerably cheaper and easier to process

[1-3]. A MMC is normally consists of a ductile metal as the matrix material and a ceramic material as dispersoid. Hence the MMC will exhibit a combination of metallic properties and ceramic properties. Resulting in high toughness; specific strength, stiffness and good wear resistance. Among the many ceramic reinforcements SiC has been found to have excellent compatibility with the Al-matrix. Conventional liquid metallurgy and powder metallurgy are the two commonly employed methods by which these composites are processed [4,5]. The test specimens used in these experiments are processed through liquid metallurgy.

2. Theoretical Model for Prediction of Young's Modulus

In order to estimate the elastic property of the MMC initially a theoretical model is to be derived Our earlier works on MMC for finding out Young's modulus of composites resulted in deriving a model (R6)

$$E_c = E_m (1- V_r) + X E_r V'_r \qquad (1)$$

Where E_c, E_m and E_r are Young's modulus of composite, matrix and reinforcement respectively, V_r the volume fraction of the dispersoid, V'_r is effective volume fraction of dispersoid and it given by

$$V'_r = V_r . e^{(b. V_r)}$$

Where 'b' is a characteristic constant and a function of l/d ratio and given by

$$b = 0.9 + 0.02 \{23.04-[5-0.2(l/d)^2]\}^{1/2}$$ for $1 \le l/d \le 25$

$b = 1$ for $l/d > 25$

and X is the weakening factor and is given by

$$X = a. e^{(b. V_r)}$$

Where 'a' is a factor indicating the effectiveness resulted by the orientation of dispersoid and it is 0.385 for discontinuously dispersoids used in processing these specimens. Though the above-explained model could fairly concur with the experimental values, voids are not taken into account in deriving this model, as they are not desirable in the final product. But in actual practice it can be seen that voids could not be eliminated totally. Hence it is imperative to consider the effect of voids on mechanical properties. This necessitates modifying equation (1) taking into account the effect of porosity on elastic properties of the matrix material. Accordingly the factor E_m requires a correction. For adding a correction to E_m it is assumed that the reinforcement particles of volume fraction V_r are uniformly distributed in porous matrix material. Thus, the effective elastic modulus of the matrix, E_{eff}, containing porosity of volume fraction f can be determined by using Eshelby model [17]. In this model the effective bulk modulus K_{eff}, and shear modulus μ_{eff}, are calculated for an isotropic material with bulk modulus K and shear modulus μ containing a volume fraction of randomly distributed, non-interacting, spherical voids.

$$K_{eff} = K / 1+Af$$

where A = constant and is given by

$$A = 1+ 3K/4 \mu \text{ and}$$

$$\mu_{eff} = \mu / 1+Bf$$

where B = constant and is given by

$$B = 5(3K + 4 \mu) / (9K + 8 \mu)$$

The effective Young's Modulus of matrix is then derived as

$$E_{eff} = 9 K_{eff} / 1+(3 K_{eff} / \mu_{eff}) \qquad (2)$$

Replacing E_m by E_{eff} in equation (1) gives,

$$E_c = E_{eff}(1 - V_r) + X E_r V'_r \qquad (3)$$

In order to verify the validity of the above said equation, the results obtained are compared with Halpin-Tsai [18] equations, modified equation of Hermans [19] and Hill's [20] work. The modified equation of Hermans and Hill's to suit particulate composites is as given below,

$$P / P_m = 1 + \xi\eta V_p / 1 - \eta V_p \qquad (4)$$

Where P and Pm represent moduli of composite and matrix respectively, η and ξ are empirical factors and η is given by

$$\eta = [(P / P_m) - 1] / [(P / P_m) + 1]$$

For predicting the bulk modulus K, substitute ξ as

$$\xi = 2\,(1 - 2V_m) / (1 + V_m)$$

For predicting the shear modulus μ, substitute ξ as

$$\xi = (7 - 5\,V_m) / (8 - 10\,V_m)$$

From the values of K and μ the young's modulus can be calculated using equation (2)

3. Experimental Procedure

3.1 Material

The hot rolled 2124 aluminum alloy (Al-4.4 Cu-1.5 Mg-0.6) matrix composite plates containing 10 wt % (7.8 vol %) of silicon carbide particles (SiC_p) with an average size of 23 μm were selected for this experimental trial. The sizes of the specimen, shown in Fig. 1, were 175 X 125 X 6-8mm. Eight such pieces were selected and identified asA1, A2, B1, B2, C1, C2, D1 and D2. These specimens were subjected to ultrasonic and x-ray evaluation.

Fig. 1: Hot rolled composite plate

3.2 Processing

The synthesis of MMC was carried out using conventional stir casting technique. The cleaned metal ingots were melted in a pit furnace. The reinforcing particulate silicon carbide was preoxidised and then introduced into the liquid matrix alloy at a constant rate. After that the melt was heated and cast into a metal mold to obtain composite ingots of (250 x 225 x 40) mm. After homogenizing the ingots were forged in two steps using 0.5 and 1.0 ton forging hammer to reduce the thickness to 15- 17 mm. Later, the forged blanks were cut into two halves and rolled in a high strip rolling mill to obtain sheets of thickness 6-8 mm. After secondary processing, the plates were solutionised, quenched and aged.

3.3 Porosity Measurement

Average volume percentage of porosity of each specimen is calculated by Archimedean principle.

3.4 Ultrasonic Velocity Measurement

The test pieces were divided into 35 zones and subjected to ultrasonic testing wherein the ultrasonic velocity in each zone is measured using a delay probe and a Krautkramer make thickness gauge. The measured velocities of the pieces are represented in Figs. (2,3,4,5).

3.5 X-Ray Radiography

The test specimens of the experimental trials are subjected to X-Ray radiography using single wall single image techniques.

The exposure parameters are selected in such away as to obtain a density of 2.5 approximately in the region of interest. Among the pieces tested, D1 and D2 were found to be defective.

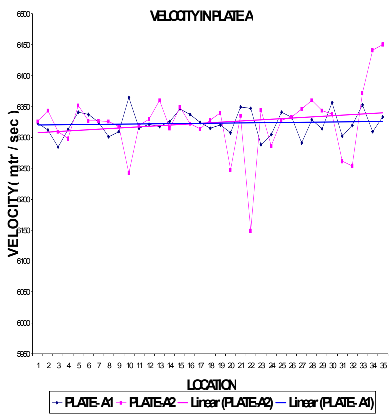

Figure 2

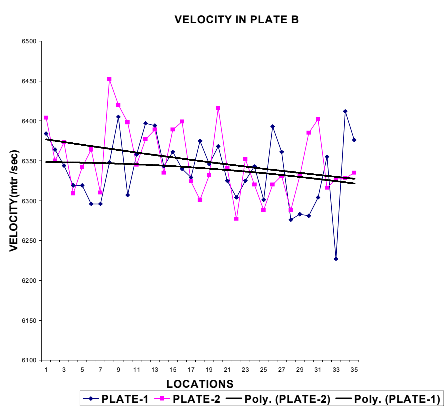

Figure 3

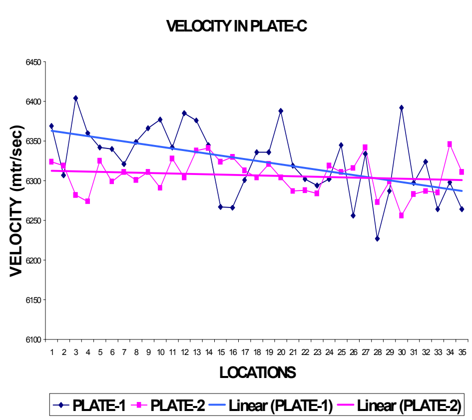

Figure 4

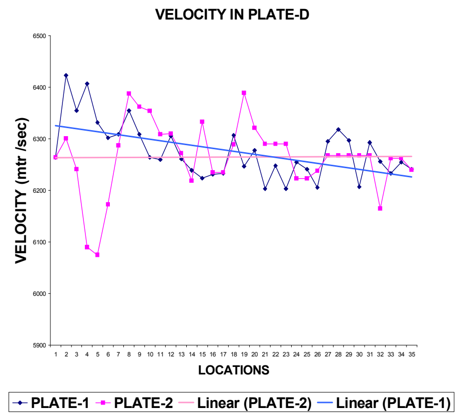

Figure 5

Table 2: Average values of porosity content in specimens after rolling

Specimen Identification	Avg. vol % of porosity
A1, A2	1.75
B1, B2	2.41
C1,C2	1.99
D1,D2	2.37

4. Results and Discussion

The average value of porosity content in the rolled specimen is given in Table 2. The possible porosity content in the specimen may be due to the air entrapment through vortex at the time of processing and since the melt becomes less fluid due to further addition of SiC, it will be difficult for already entrapped air bubbles to escape from the melt during solidification.

From figures 2 to 4, it is seen that the deviation in velocity from mean shows a uniformity throughout the plate. It indicates uniform distribution of particles and absence of objectionable defects. In Fig. 5 the low values of velocity observed in specimen is due to the effect of voids. Like wise particle agglomeration is found to be the reason for high velocity observed in some locations as waves can travel at a high velocity in SiC particles. Further the Young's moduli of the specimens are calculated using the mean longitudinal velocity (V_L) value obtained.

$$E_c = \frac{\rho_c (1+\sigma_c)(1-2\sigma_c) V_L^2}{(1-\sigma_c)}$$

where υ_c and ρ_c are the Poisson's ratio and density of the composite respectively. The effective Poisson's ratio and density of the composite material containing a porous matrix of volume fraction of porosity, v_p and reinforcement particle of volume fraction v_r is given by the rule of mixtures law as

$$\sigma_c = \sigma_r v_r + v_m (1-v_p)(1-v_r)$$

and

$$\rho_c = \rho_r v_r + \rho_m (1-v_p)(1-v_r).$$

Table 3: Comparison of Elastic Modulus

Method	Value Obtained (in GPa)
Using Present Equation	78.99
By Halpin and Tsai Equation	77.43
By Experiment	79.43

Table 3 shows a comparison of experimental data with predicted values of elastic modulus of 2124 – 10 % SiCp composite.

It is clear that prediction according to the present equation is well in agreement with the experimental value and the standard Halpin and Tsai Equation. Also an ultrasonic velocity measurement on composite products can be used as a non-destructive method for quality evaluation of the product. The equation (3) can be used for the prediction of elastic modulus. However its effectiveness with respect to higher percentage of dispersoids are to be studied further. Also deviated a velocity value obtained in specimens (D1 and D2) clearly indicates the presence of defects in it and it is visualised by X-ray inspection.

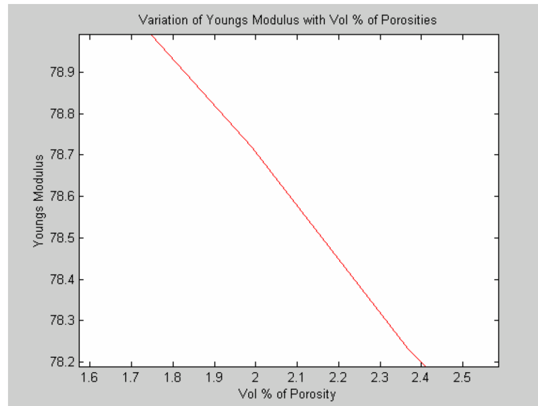

Figure 6

Table 4: Variation of Elastic Modulus with Vol% of Porosities

Specimen Identification	**Avg. vol % of porosity**	**Young's Modulus in GPa**
A1, A2	1.75	78.99
B1, B2	2.41	78.19
C1,C2	1.99	78.72
D1,D2	2.37	78.23

Table 4 and Fig. 6 indicates the effect of porosity on the elastic properties of particulate metal matrix composites. The porosities and the debond are the main causes for the weakening of metal matrix composites. In this paper it is assumed that the debond will result in porosities and so the estimation of volume % of porosities includes debonding also.

5. Conclusion

A theoretical model has been proposed for predicting the Young's modulus of 10 % SiC reinforced Al matrix composite products. An ultrasonic velocity method for defect detection and evaluating the elastic property of composites is also proposed. The derived data from the proposed model and experimental are well in agreement with those derived from established models.

More experiments are planned to study the effectiveness of the proposed model for higher percentage of dispersoids.

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