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OPTIMIZING THE MECHANICAL CHARACTERISTICS OF BABBITT-ILMENITE COMPOSITE THROUGH TAGUCHI METHODOLOGY: A COMPREHENSIVE INVESTIGATION FOR INDUSTRIAL ENGINEERING APPLICATIONS

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Abstract
Babbitt Ilmenite composite is prepared via vortex stir casting technique with percentage weight of Ilmenite, stirring speed and aging time as the test parameters. The morphological tests of the composite were conducted to ascertain the uniform distribution of the reinforcement in metal matrix. The mechanical properties of the composite viz. hardness, impact strength and tensile strength of the composite were investigated using Taguchi technique. The percentage contribution of the significant test parameters for optimizing the mechanical properties of the composite is determined using ANOVA statistical analysis and the regression models developed for the mechanical attributes of the fabricated composite are reported in the study. There is an improvement in the mechanical properties of the composite at optimized conditions as compared to the Tin-Babbitt alloy. The fabricated composite can be used as bearing material for the axles and crankshafts in the automobile industry.
Keywords: **-** Babbitt, Ilmenite, Vortex casting, Morphological, Aging, Taguchi, DOE, Significant parameters

I. Introduction
There has been a lot of demand for low cost materials which exhibit good overall properties. Various researchers are continuously working towards development of low cost materials to replace high cost materials with low cost ones having good mechanical properties [1]. Babbitt metal matrix composites also gained importance since they have improved mechanical properties as compared to conventional Babbitt alloy for application in manufacturing of bearings of light machinery and for automotive parts like crankshaft and connecting rod [2-5].The metal matrix composites are developed economically via vortex stir casting technique [6-9].The controllable test parameters for stir casted composites include percentage weight of reinforcement, stirring speed, aging time, particle size and mould temperature [10-13].Taguchi is an effective DOE tool that is utilised to improve the performance characteristics of the stir casted composites with less number of trials thereby reducing experimentation cost [14-17].

II. Methodology
2.1 Fabrication of sample
The matrix material ingots (ASTM B-23 Grade 2 Babbitt) are cut into small pieces so that they can be arranged into the crucible. According to the selected orthogonal array of experimentation, the matrix material and reinforcement material (Ilmenite) are weighed. Then, the matrix material is put into the muffle furnace using crucible and the temperature is maintained at 400^{o}C (considering heat loss also) to melt the material. After melting the matrix material, the reinforcement is added into the matrix material and stirred for 5 minutes at the chosen rpm of stirrer according to orthogonal array. The material is heated up to the temperature of 440^{o}C and is stirred again for 5 seconds only. Then, at a pouring temperature of 440^{o}C, the material is poured into the moulds. After some time, the material gets solidified and the castings thus obtained can be machined to obtain the desired size and shape for mechanical tests. This method of stir casting is repeated to complete the experimentation process according to the selected orthogonal array. Then, the samples were aged at 150^{o} C and allowed to cool at room temperature to improve the material properties.

2.2 Testing

2.2.1 Morphological tests

Scanning electron micrographs (SEM) and Energy dispersive spectrum (EDS) of Tin- Babbitt, Ilmenite and Babbitt-Ilmenite composite was conducted at Sophisticated Analytical Instrumentation Facility (SAIF) laboratory of Panjab University, Chandigarh. Figure 1 and Figure 2 shows SEM and EDS of Tin-Babbitt and Ilmenite respectively.

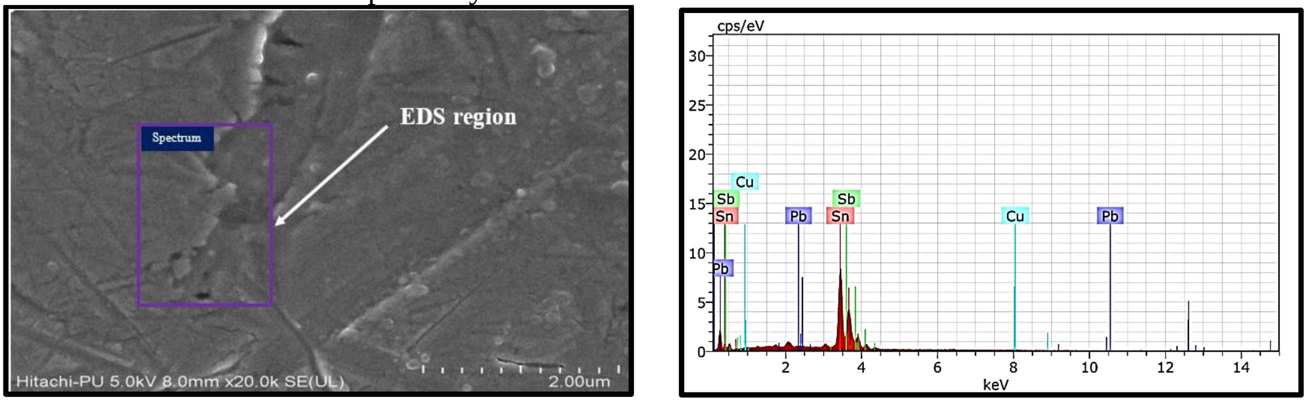


Figure 1: a) SEM of Babbitt alloy (20000X magnification) b) EDS of Babbitt alloy

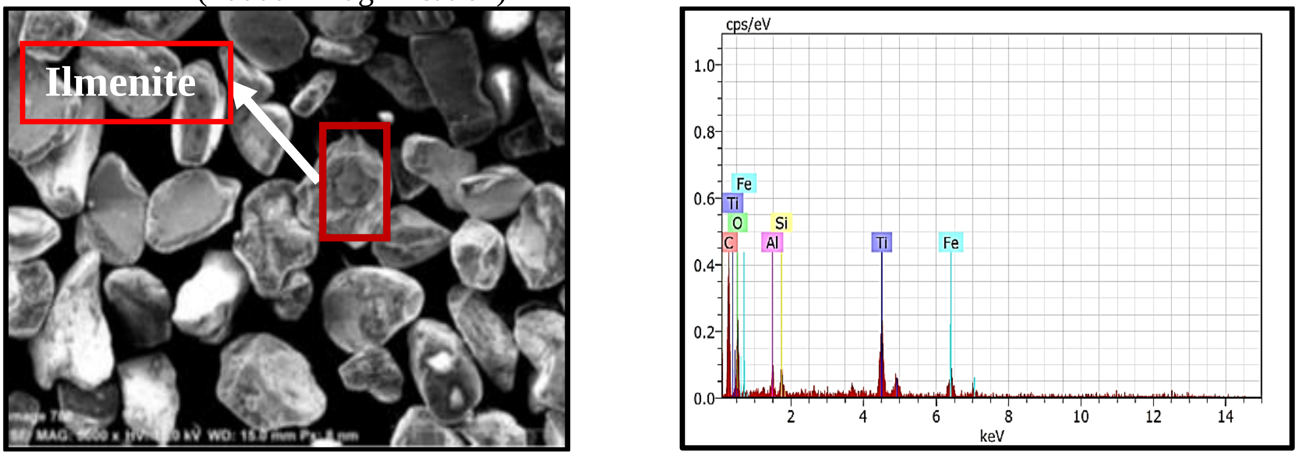
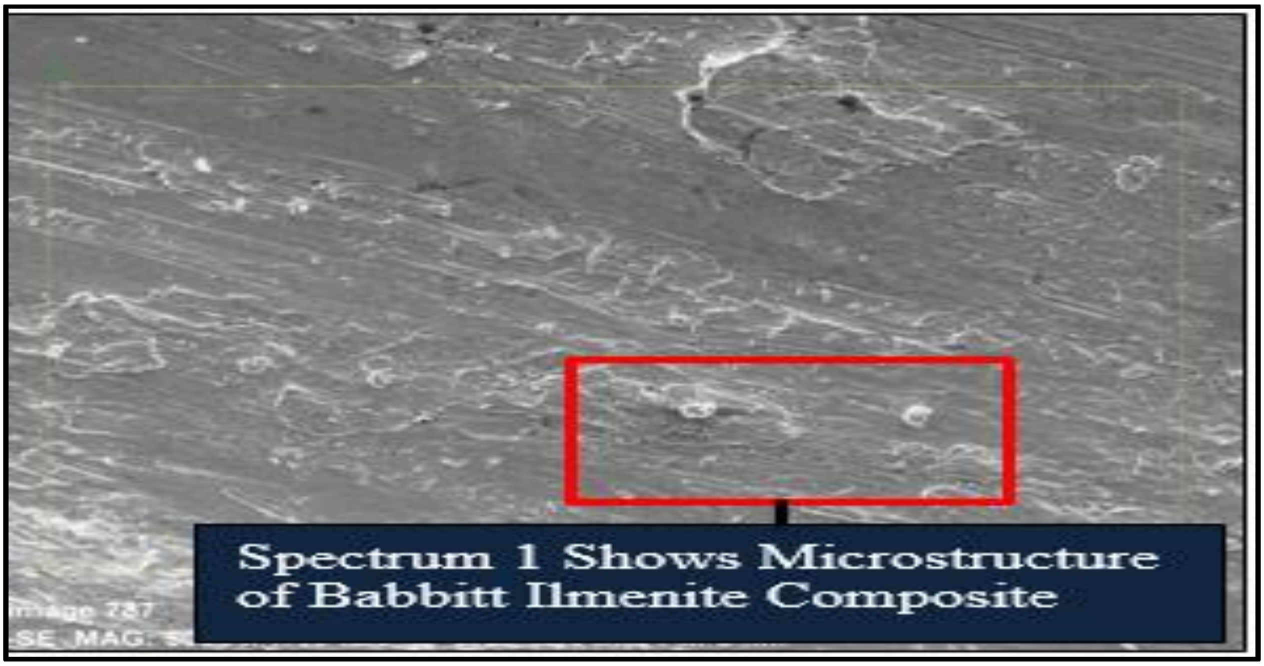
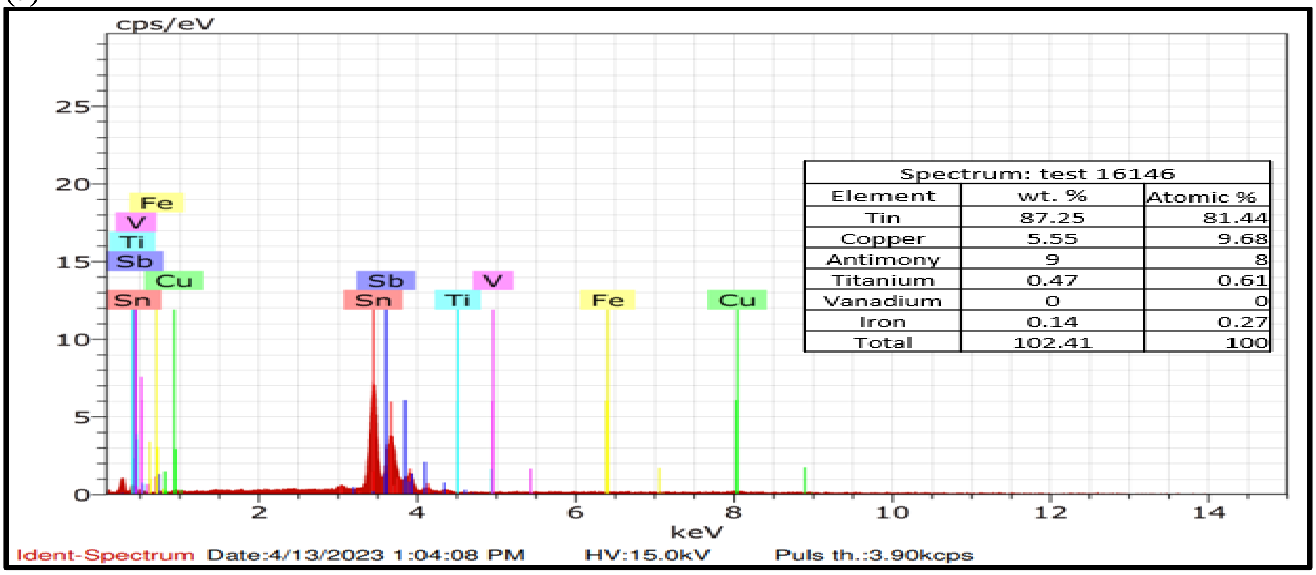


Figure 2: a) SEM of Ilmenite b) EDS of Ilmenite

The SEM and EDS of the fabricated composite corresponding to process parameters: 6% wt. of ilmenite, 250 rpm stirring speed and 12 hours of aging time is shown in Figure 3.



(a)



(b)

Figure3**:** a) SEM of the composite b) EDS of the composite

(6% wt. of ilmenite, 250 rpm stirring speed and 12 hours aging time)

The scanning electron micrographs and energy dispersive spectrum of the Babbitt Ilmenite composite depicts uniform dispersal of Ilmenite in the Babbitt metal matrix.

2.2.2 Mechanical tests

I) Hardness Test

For Rockwell hardness measurement, a metal ball indenter with a diameter of 1.58 mm is used. A minor load of 10 kg is applied to the specimen before a main load of 50 kg is applied to the composite specimen to determine the Rockwell Hardness at F scale (HRF). The Rockwell Hardness tester is shown in Figure 4.

II) Impact test

Izod testing method is used for determining the impact strength of the composite samples. It involves striking a notched sample with a pendulum to determine the energy required to break the specimen. For the test, a standard test piece with an overall length of 75 mm and a square cross-section of 10 mm side with a standard 45°, 2 mm deep notch is used. The Impact test set up and specimen details are shown in Figure 5.

III) Tensile test

Samples of the Babbitt Ilmenite composite are clamped into the UTM grips that are aligned with the direction of the applied load. The tensile test is then carried out by gradually increasing the load applied to the sample until it reaches its breaking point. During the test, the UTM records the applied force as well as the sample's deformation. The tensile test and the specimen details are shown in Figure 6.

Figure 4: Rockwell Hardness Tester

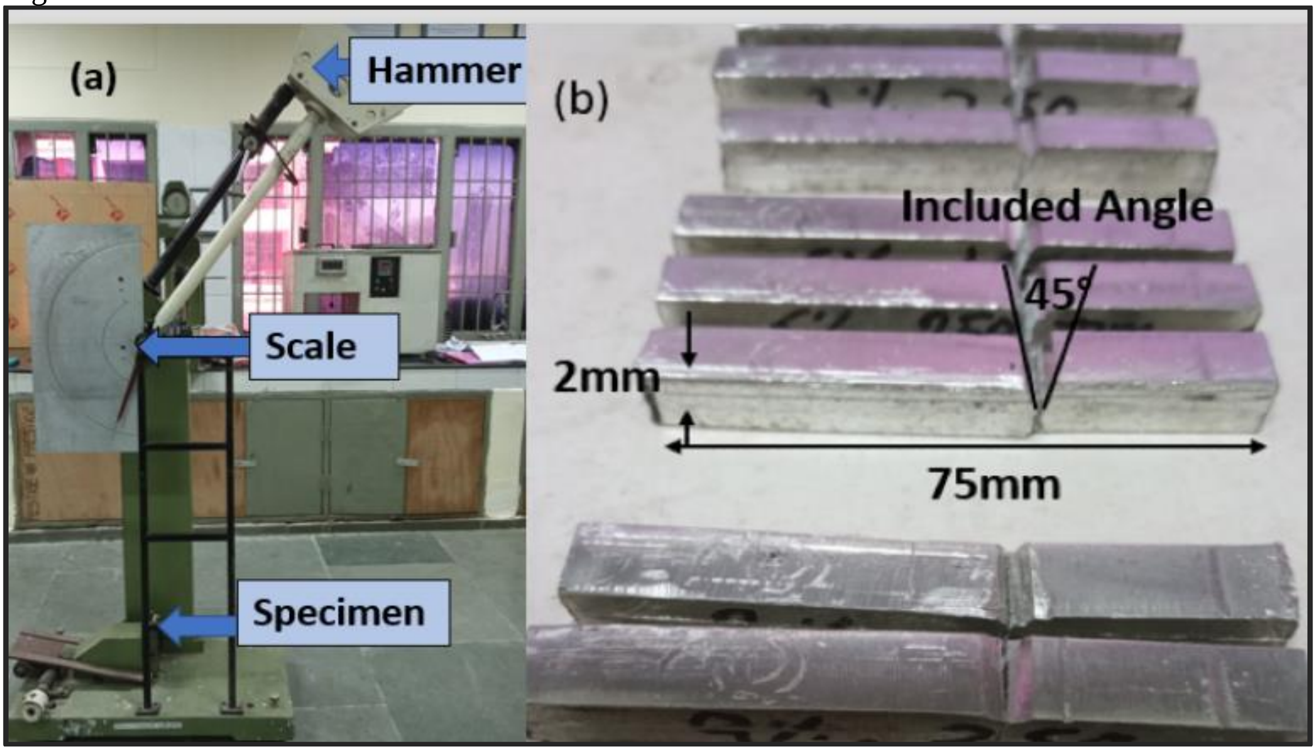


Figure 5: (a) Setup of Izod Impact Test (b) Samples for Izod Testing

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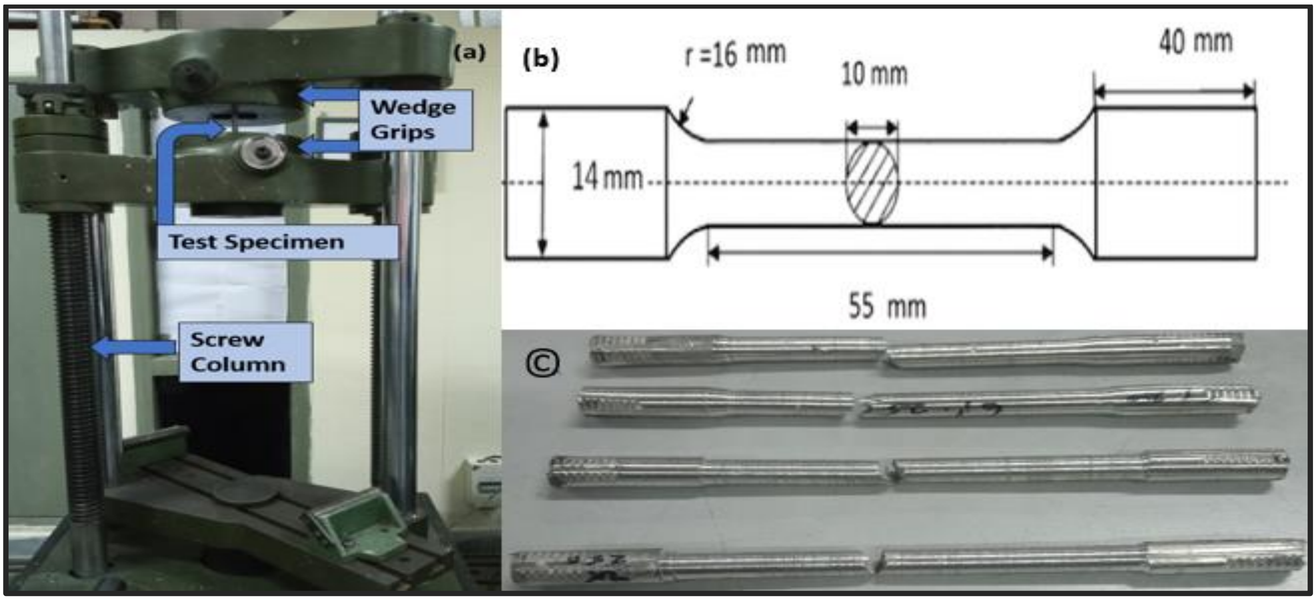

Figure 6: (a) Setup of UTM (b) Standard dimension used in tensile testing (c) Samples after testing

111. Results and Discussion

The test parameters and their levels are decided based on the literature survey and L9 array is used for Taguchi analysis. The main effect plots of means for the mechanical attributes of the composite are obtained using MINITAB-17 software. Delta analysis is conducted to determine the rank of the test parameter for each mechanical attribute and ANOVA statistical technique is used to determine the significant controllable parameters (having p value less than 0.05) and their percentage contribution for optimization of each mechanical attribute viz. Hardness, Impact strength and Tensile strength. The results of the mechanical tests performed on Babbitt-Ilmenite composite samples prepared according to L9 Taguchi array are discussed in this section.

3.1 Rockwell Hardness

The results of L9 Taguchi array for Rockwell Hardness is tabulated in Table 1 Delta and ANOVA analysis of the results are presented in Table 2 and Table 3 respectively.

Table 1. Rockwell Hardness test results

% wt. of Ilmenite	**Stirring Speed (RPM)**	**Aging Time (Hrs)**	**Hardness (HRF)**
3	150	4	13
3	250	8	11
3	350	12	12
6	150	8	11
6	250	12	10
6	350	4	12
9	150	12	10
9	250	4	9
9	350	8	8

Table 2. Delta analysis of the Rockwell Hardness

Level	**% wt. of Ilmenite**	**Stirring Speed**	**Aging time**
1	12.000	11.333	11.333
2	11.000	10.000	10.000
3	9.000	10.667	10.667
Delta	3.000	1.333	1.333
Rank	1	2.5	2.5

Table 3. ANOVA analysis of Rockwell Hardness

Source	**DF**	**Adj. SS**	**Adj. MS**	**F-value**	**p-value**
Regression	3	14.833	4.944	4.78	0.062
% wt. of Ilmenite	1	13.50	13.50	13.06	0.015
Stirring speed	1	0.6667	0.6667	0.65	0.458
Aging time	1	0.6667	0.6667	0.65	0.458
Error	5	5.1667	1.0333		
Total	8	20.000			

The main effect for means of response (Rockwell Hardness) is shown in Figure.7.The maximum hardness is obtained at parameter setting: 3 weight percentage Ilmenite, 150 rpm stirring speed and aging time of 4 hours which corresponds to first experiment of an orthogonal array so no confirmation test is required.

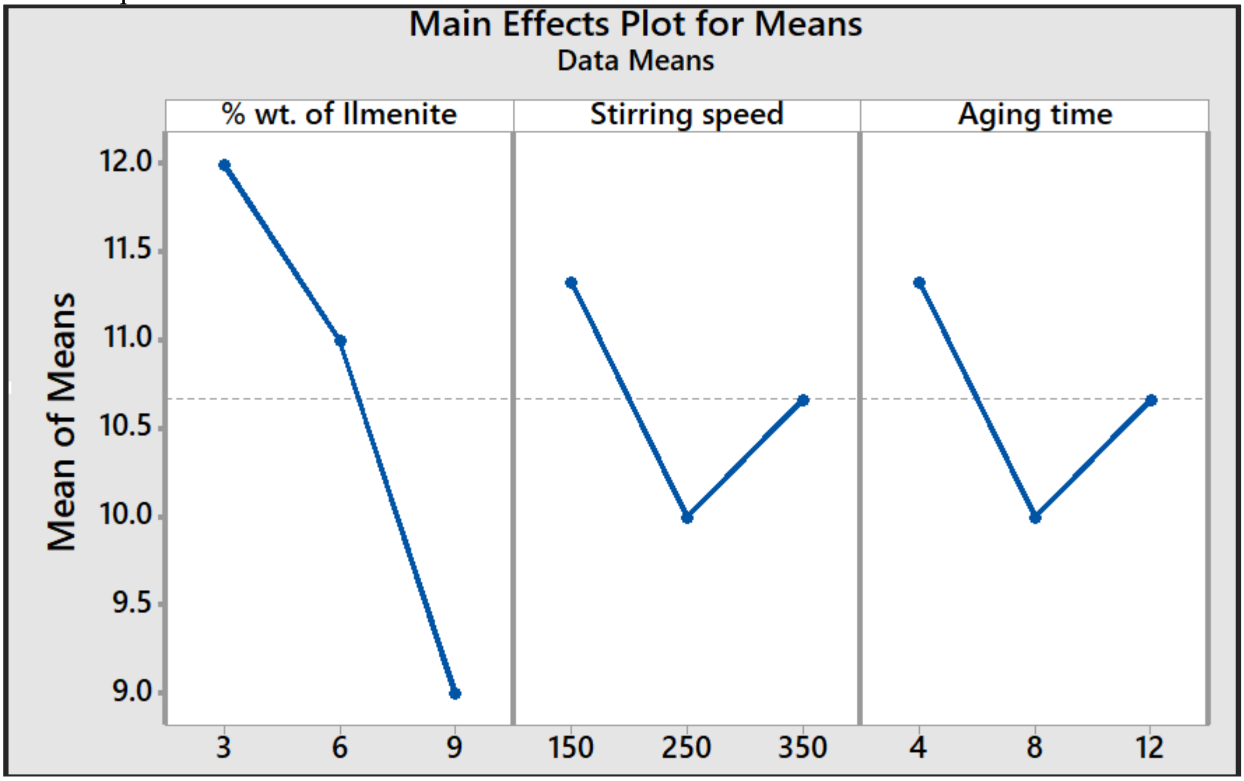

Figure 7: Main effect plot for Rockwell hardness

The linear regression equation to model hardness in terms of test parameters at 95% confidence level using MINITAB - 17 software is given as:

Hardness =15.17 - 0.500 % wt. of Ilmenite - 0.00333 Stirring Speed - 0.083 Aging time (1)

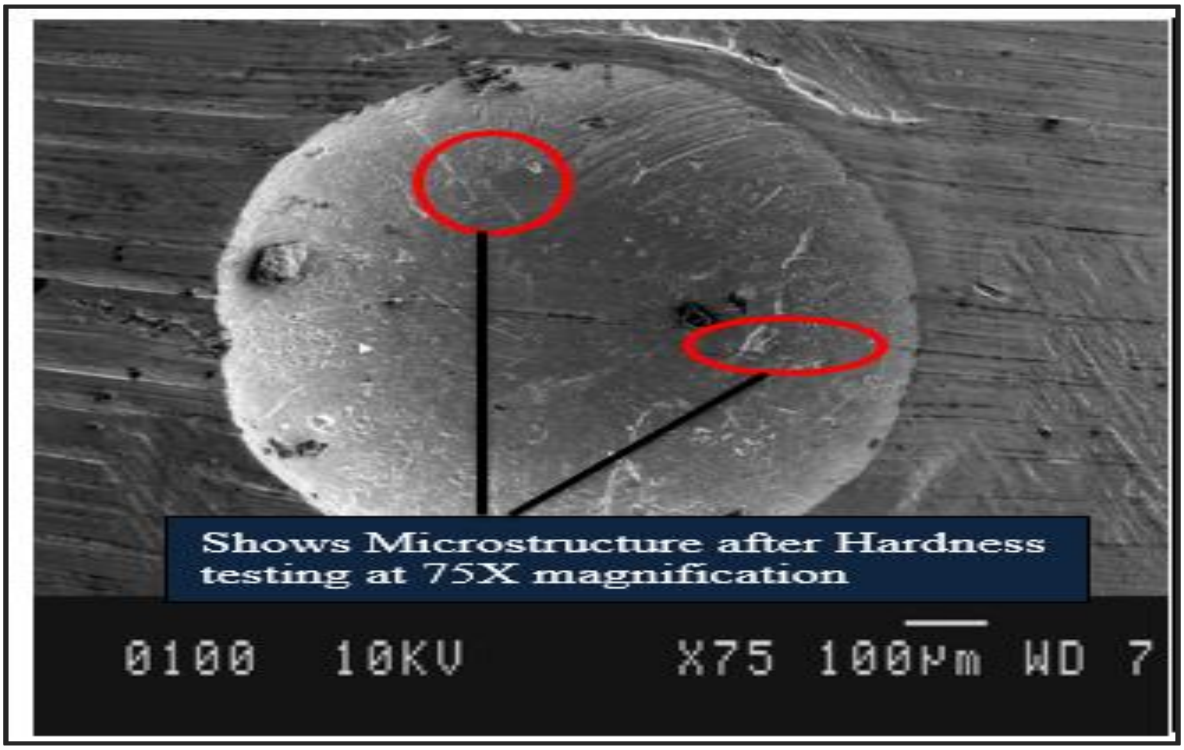

Figure 8 :SEM images of Babbitt-Ilmenite composite(3% wt. ilmenite , 150 rpm stirring speed and 4 hours aging)

Figure 8 shows the SEM image of the microstructure of Babbitt Ilmenite metal matrix composite (3 wt. % of ilmenite, stirring speed of 150 rpm and aging time of 4 hours at magnification of 75X) The image reveals the shape of impression made by the ball indenter and presence of ilmenite indicated in red. The surface morphological analysis shows that ilmenite reinforcement is uniformly dispersed within the matrix material and is not forced out of the matrix.

3.2 Impact Strength

The results of L9 Taguchi array for Impact strength is tabulated in Table 4 .Delta and ANOVA analysis of the results are presented in Table 5 and Table 6 respectively.

Table 4. Impact strength test results

%Wt. of Ilmenite	**Stirring Speed (RPM)**	**Aging Time (Hrs)**	**Impact strength (Joule)**
3	150	4	3
3	250	8	5
3	350	12	6
6	150	8	4
6	250	12	5
6	350	4	4
9	150	12	6
9	250	4	4
9	350	8	5

Table 5. Delta analysis of the Impact strength

Level	**% wt. of Ilmenite**	**Stirring Speed**	**Aging time**
1	4.667	4.333	3.667
2	4.333	4.667	4.667
3	5.000	5.000	5.667
Delta	0.667	0.667	2
Rank	2.5	2.5	1

Table 6. ANOVA analysis of Impact strength

Source	**DF**	**Adj. SS**	**Adj. MS**	**F-value**	**p-value**
Regression	3	6.8333	2.2778	9.76	0.016
% wt. of Ilmenite	1	0.1667	0.1667	0.71	0.437
Stirring speed	1	0.6667	0.6667	2.86	0.152
Aging time	1	6.0000	6.0000	25.71	0.004
Error	5	1.667	0.2333		
Total	8	8.000			

The main effect for means of response (Impact strength) is shown in Figure.9.The maximum impact strength is obtained at parameter setting: 9 weight percentage Ilmenite, 350 rpm stirring speed and aging time of 12 hours. The parameter setting corresponding to optimum impact strength does not lie in L9 orthogonal array so confirmation test has to be conducted. The optimum impact strength can be predicted from the equation [18]:

$$\mu_{RH} = A_3 + B_3 + C_3 - 2T_{RH} \quad (2)$$

where A_3 is the average impact strength at third level of reinforcement, B_3 is the average impact strength at third level of stirring speed , C_3 is the average impact strength at third level of aging time and T_{RH} is the average of all values of impact strength in an orthogonal array. The only significant parameter for impact strength is the aging time, Eq. (2) can be written as:

$\mu_{RH} = C_3 = 5.66$

Table 7.Confirmation Test for Impact strength

Response	**Optimum Level of Parameter**	**Predicted result**	**Experimental Result**
Impact strength	$A_3B_3C_3$	5.666	6

Figure 9: Main effect plot for Impact strength

The confirmation test validated the predicted result and indicated that Taguchi methodology can be adopted to evaluate the impact strength of the composite with deviations of 5.56%.The linear regression equation to model impact strength in terms of test parameters at 95% confidence level using MINITAB -17 software is given as:

Impact strength = 1.50 - 0.0556 % wt. of Ilmenite + 0.00333 Stirring Speed + 0.2500 Aging time (3)

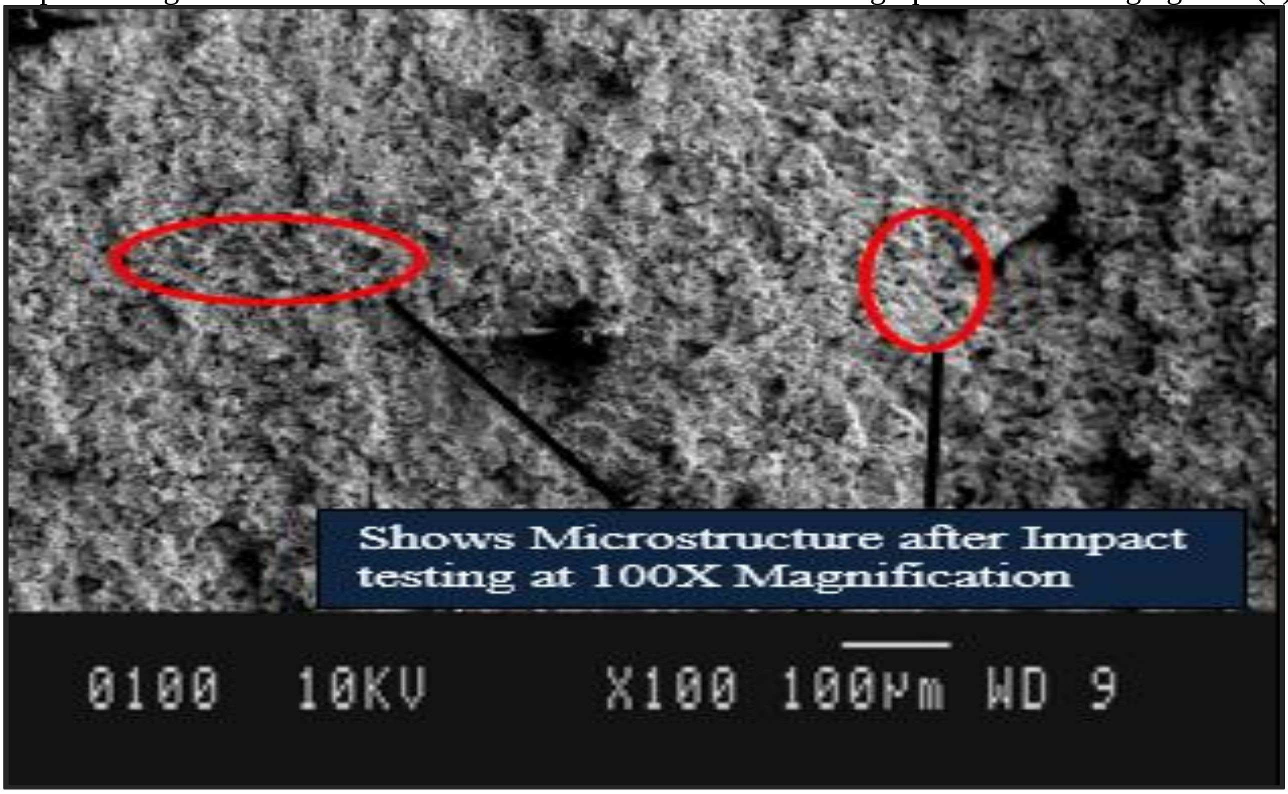

Figure 10: SEM images of Babbitt-ilmenite composite(9% wt. ilmenite , 350 rpm stirring speed and 12 hours aging)

Figure 10 shows the scanning electron micrograph of the optimized sample of Babbitt ilmenite composite at magnification of 100 X . The sample was properly polished and cleaned for morphological testing .SEM image reveal that the reinforcement was uniformly distributed and bonded with the matrix material marked as red. The texture created by the hit of pendulum is clearly shown in the micrograph.

3.3 Tensile Strength

The results of L9 Taguchi array for Tensile strength is tabulated in Table 8 .Delta and ANOVA analysis of the results are presented in Table 9 and Table 10 respectively

Table 8. Tensile strength test results

%wt. of Ilmenite	**Stirring Speed (RPM)**	**Aging Time (Hrs)**	**Tensile strength (MPa)**
3	150	4	104.46
3	250	8	128.28
3	350	12	120.76
6	150	8	118.44
6	250	12	128.41
6	350	4	108.66
9	150	12	123.31
9	250	4	112.48
9	350	8	110.11

Table 9. Delta analysis of the Tensile strength

Level	**% wt. of Ilmenite**	**Stirring Speed**	**Aging time**
1	117.8	115.4	108.5
2	118.5	123.1	118.9
3	115.3	113.2	124.2
Delta	3.2	9.9	15.6
Rank	3	2	1

Table 10. ANOVA analysis of the Tensile strength

Source	**DF**	**Adj. SS**	**Adj. MS**	**F-value**	**p-value**
Regression	3	383.353	127.784	2.85	0.145
% wt. of Ilmenite	1	7.437	7.437	0.17	0.701
Stirring speed	1	9.627	9.627	0.21	0.663
Aging time	1	366.289	366.289	8.16	0.036
Error	5	224.405	44.881		
Total	8	607.758			

The main effect for means of response (Tensile strength) is shown in Figure 11.The maximum tensile strength is obtained at parameter setting: 6 weight percentage Ilmenite, 250 rpm stirring speed and aging time of 12 hours which corresponds to fifth experiment of the orthogonal array so no confirmation test is required.

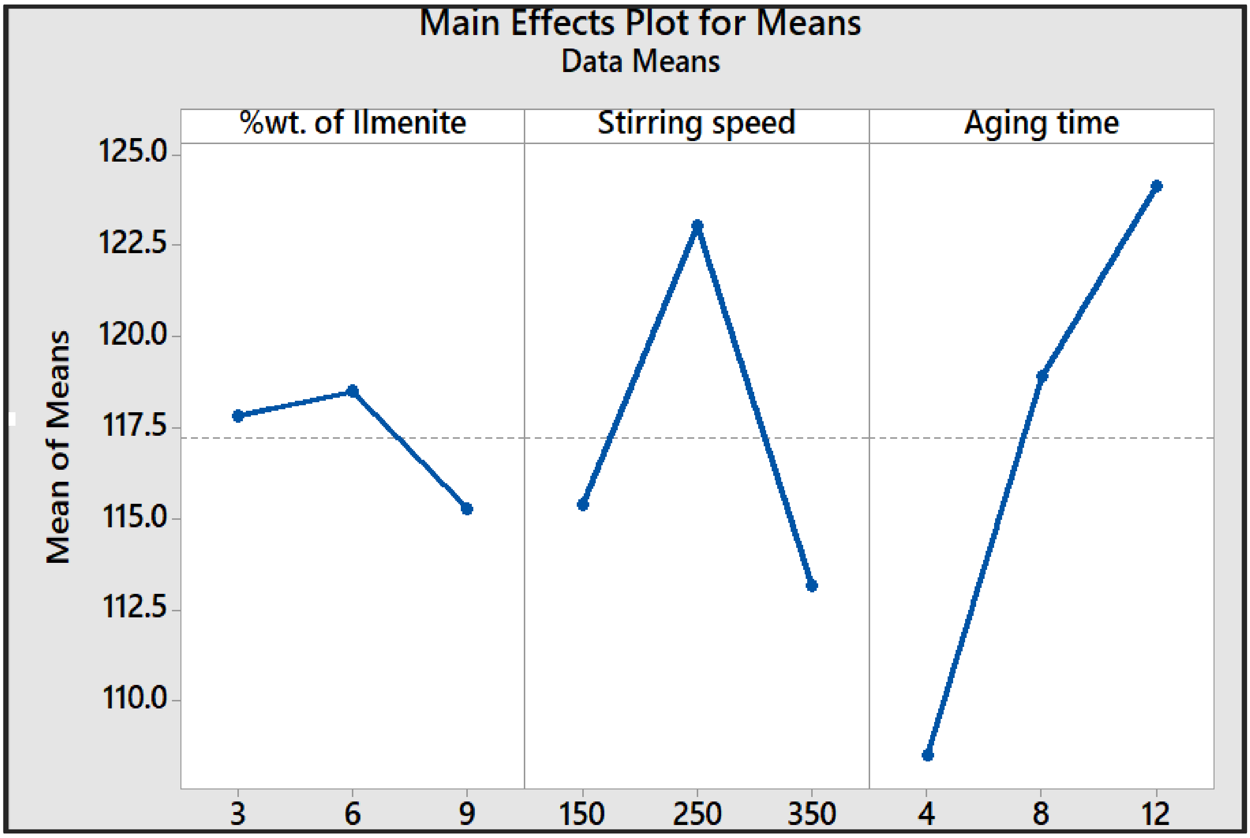

Figure 11: Main effect plot for Tensile strength

The linear regression equation to model tensile strength (σ) in terms of test parameters at 95% confidence level using MINITAB - 17 software is given as:

$$\sigma = 106.9 - 0.422 \text{ \% wt. of Ilmenite} - 0.0111 \text{ Stirring Speed} + 1.953 \text{ Aging time} \quad (4)$$

The morphological test of the composite sample at optimal parameter setting: 6 weight percentage Ilmenite, 250 rpm stirring speed and aging time of 12 hours subjected to tensile test is shown in Figure 12.The microstructure of the composite shows small holes and voids which will lead to necking of the specimen suggesting ductile fracture of the composite subjected to tensile load.

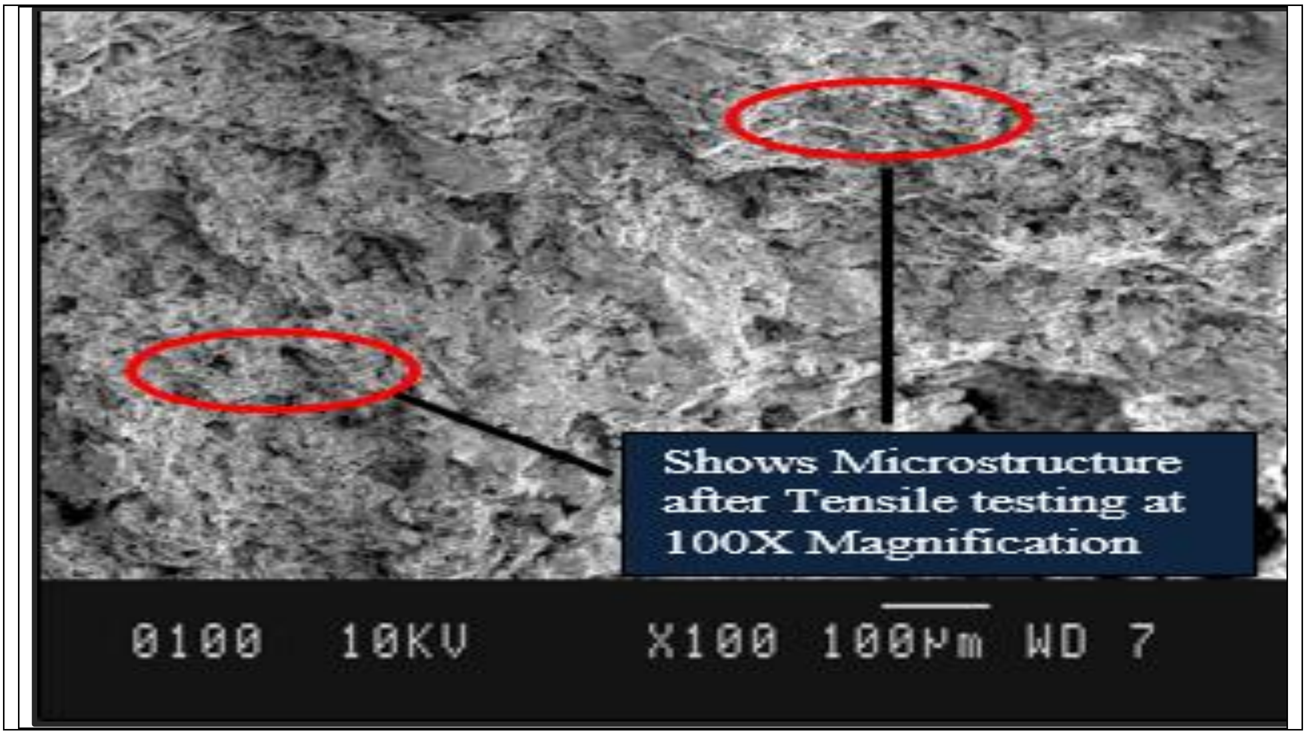

Figure 12: SEM image of the composite sample at 100X magnification

IV. Comparison of the mechanical properties of the Babbitt/Ilmenite composite at optimized conditions with Tin-Babbitt alloy

The Hardness, Impact strength and Tensile strength of the composite at optimized conditions is compared with Tin-Babbitt and improvement in the mechanical attributes of the composite is reported in Table 11.

Table 11. Comparison of the mechanical attributes

Mechanical attribute	**Babbitt/Ilmenite composite at optimized conditions**	**Tin-Babbitt**	**% Increase**
Hardness (HRF)	13	9	44.44
Impact strength (Joule)	6	4	50
Tensile strength (MPa)	128.41	77	66.76

V. Conclusions

1)Babbitt Ilmenite composite is developed successfully via vortex stir casting and morphological analysis conducted suggests uniform dispersal of the Ilmenite in the Tin-Babbitt matrix

2 i)The maximum hardness is obtained at parameter setting: 3 weight percentage Ilmenite, 150 rpm stirring speed and aging time of 4 hours.

ii)The maximum impact strength is obtained at parameter setting: 9 weight percentage Ilmenite, 350 rpm stirring speed and aging time of 12 hours.

iii)The maximum tensile strength is obtained at parameter setting: 6 weight percentage Ilmenite, 250 rpm stirring speed and aging time of 12 hours.

3)The percentage weight of Ilmenite is the significant parameter for Rockwell Hardness of the composite while aging time is the significant parameter for Impact strength and the Tensile strength of the composite.

4)The percentage contribution of the significant test parameters for optimization of the response is determined by the ratio of Adj. SS of each parameter and the total Adj. SS from the ANOVA table of each response. The percentage contribution of the % weight of Ilmenite for optimization of Hardness of the composite is found to be 67.5% and percentage contribution of aging time for optimization of Impact strength and Tensile strength is found to be 75% and 60.27% respectively.
5)There is an improvement in Rockwell Hardness, Impact strength and Tensile strength of the composite at optimized conditions by 44.44%,50% and 66.76% respectively when compared with the Tin Babbitt alloy.

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