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## Effect of Addition of Inoculants on Mechanical Properties & Wear Behaviour of Grey Cast Iron

Y.E. Mangulkar<sup>1</sup> and S.C.Borse<sup>2</sup>

P.G. Student, Department of Mechanical Engineering, DIEMS, Aurangabad, India<sup>1</sup>

Assistant Professor, Department of Mechanical Engineering, DIEMS, Aurangabad, India<sup>2</sup>

**ABSTRACT:** Effect of inoculation on the microstructure, Hardness, Tensile strength and Wear behavior of grey cast iron has been investigated in this work. Grey iron is treated with 0.4% Compound inoculants. The cast samples were machined in various sizes for different analysis. The microstructure shows that the mechanical properties are dependent on matrix, graphite forms. The addition of inoculants (Fe-Si 75+RE Alloy) resulted in increase of carbon equivalent and the tensile and hardness properties found to be decreased. Also the wear behavior before and after addition of inoculants is studied by using Pin-on-disc wear tester and found that wear volume loss has increased on addition of inoculants.

**KEYWORDS:** ANOVA, Cast iron, Inoculation, Inoculants, Pin on disc.

### I. INTRODUCTION

Gray iron is used for variety of parts with broad spectrum of machines and structures. Automotive applications include pistons, cylinders, cylinder blocks and heads for gasoline and diesel engines, brake drums and discs, and hardened iron for camshafts. Gray irons usually contain Carbon(C) 2.5 to 4%, Silicon (Si) 1 to 3% Si, and additions of manganese, depending on the desired microstructure [1]. The microstructure and properties of cast iron can be modified to suit a specific application by addition of certain alloying additions which will probably minimize the defects, influence graphitization, fluidity of the molten metal, strength and hardenability of the grey cast iron where as elements like Mo, Cu, Ti, and rare earth elements influence the flake morphology and prevent chilling tendency of the cast iron [2].

Inoculation is defined as the late addition of certain silicon alloys to molten iron to produce changes in graphite distribution, to obtain more uniform microstructure, improvements in mechanical properties, and a reduction of the chilling tendency [1]. Grey Irons are inoculated for various reasons and various researchers have dedicated themselves for determining the mechanism behind inoculation although many theories exist; no conclusions have been reached regarding possible mechanisms. Mostly ferrosilicon alloys are used to treat gray iron since it act as carriers for the inoculating (reactive) elements, like aluminum, barium, calcium, cerium or other rare earths (RE), magnesium, strontium, titanium, and zirconium [2].

Casting inoculated with 40% FeSi75 + 60% RE had highest maturity level, suitable hardness and ideal quality coefficient [3]. Wear rate is influenced by the amount of graphite which is released into the interface during sliding to provide lubrication and reduce wear. Inoculation with rare earth misch metal has a positive influence over graphite morphology in gray iron [4]. A Zr, Ca, Al-FeSi alloy appears to be an effective inoculants in low S, low Al, gray cast irons,

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especially for a late inoculation technique, with beneficial effects [5]. Tensile and yield strength decrease with increasing RE content to 0.02% and increase slightly with increasing RE content to 0.04% [6].

Carbon equivalent value of a gray cast iron increases on addition of varying percentage of inoculants and leads to a decrease its mechanical properties like tensile strength and hardness [7]. The scope of this present work is specifically to study the process of inoculation of grey cast iron and its effect on the mechanical properties such as Tensile strength, Hardness, Chemical composition, Microstructure of resulting alloy and Carbon equivalent Value (CEV) of resulting specimens. The inoculants used during process of inoculation are INOK 75 and Rare Earth. Also the effect of wear parameters on abrasive wear behaviour of inoculated and un-inoculated specimens under dry lubrication has been investigated.

## II. EXPERIMENT DETAILS

The grey cast iron of the following composition has been used in this study: C 3.2%–3.6%, Si 1.8%–2.0%, Mn 0.8%–1.0%, P  $\leq$ 0.08%, S <0.1%, Cr 0.2%–0.3%. The samples were sand cast in a foundry Krishna Metal Works, Aurangabad, Maharashtra. The iron was melted using a 40 kg capacity crucible furnace which is heated up 1550°C. Two cylindrical shaped wooden patterns of dimension Dia. 35 .0 x 350 mm were used to make a pair of cope and drag moulds. The moulds were prepared one day before of the actual casting from a mixture of dried fresh silica sand, water and some additives. This was done to dry the mold completely which results in reduction in casting defects. The two moulds were labelled as sample 1 and 2 respectively. 10 Kg known quantity of pig iron and some cast iron foundry returns were melted in a 40 kg capacity crucible furnace which is heated up to 1550° C and poured at 1450°C into improvised moulds. No inoculants were added in first batch and the melt was poured into the mould labelled sample 1. Thereafter, a known quantity of (0.4 % wt) combination of Ferrosilicon granules (60 % of wt) and RE alloy (40 % wt) was added to the molten bath. The inoculants addition began into the stream of melt when the ladle was  $\frac{1}{4}$ <sup>th</sup> full and finished when it was about  $\frac{3}{4}$ <sup>th</sup> full, and stirred manually with a dry wooden stick to facilitate a homogeneous bath and poured into the second mould labelled sample 2. This is to ensure thorough mixing of inoculants granules with the melt, and it was thereafter poured in the sand mould. The inoculants ferrosilicon (FeSi75) contains 73.47% Si, 0.76% Sr, 0.68% Ca and 0.23% Al whereas RE alloy contains 63.83% Ce and 34.52% La.

The sample representatives from each bar were cut and brought a NABL accredited laboratory for Hardness Test, Micro Constituents test and Image analyzer test respectively. The bars were machined to Dia. 30.0 x 300 mm and tensile strength was measured using Universal Testing Machine (model- UTE 100, max.capacity-1000 KN, Make-Fuel Instruments & Engineer’s Pvt. Ltd., Maharashtra) as per ASTM standard. The hardness of the samples was determined using Brinell hardness tester (Make-Saroj Udyog Pvt. Ltd., Maharashtra, India) carried out under a load of 187.5 N and a dwell time of 5. German made optical emission spectrometer (OES) machine is used for chemical analysis of specimens. Table 1 shows the composition of un-inoculated specimen and inoculated specimen under study. Structure reveal machine (Make ZEISS Axiovert 40 MAT, Japan) was used to take micro structural images of the specimens at 100 X magnification before etching and after etching with 3% nital.

**Table 1. Composition of Un-Inoculated and Inoculated samples**

| Specimen/Elements | C    | Si   | Mn   | P     | S     | Cr   | CEV   |
|-------------------|------|------|------|-------|-------|------|-------|
| Un-Inoculated     | 3.56 | 2.12 | 0.68 | 0.1   | 0.083 | 0.08 | 4.3   |
| Inoculated        | 3.50 | 2.6  | 0.59 | 0.201 | 0.053 | 0.07 | 4.467 |

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To investigate the dry sliding wear characteristic of grey cast iron the part of each sample is machined to form a cylindrical pin of diameter 10 mm and height 30 mm. The readings for wear loss of samples are taken on Pin on Disc Wear Testing Machine (Make Magnum, India) available at Materials and Metallurgy Laboratory, MIT, Aurangabad (ASTM G99-05).

The wear test was carried out on a disc of dia.180 mm on which emery paper of size 150 micron was mounted. Each sample was placed at distance of 37.5 mm from the centre of disc in contact with emery paper during the test. The weight of the samples was measured before and after each test with a measuring electronic scale (Make Essae Vibra) with 0.001 mg accuracy available at Materials and Metallurgy Laboratory, MIT, Aurangabad. Prior to weighing, the worn out samples were cleaned with cotton cloth and the emery paper intermittently replaced. The wear volume loss was calculated from the weight loss due to wear. The experiments were designed and conducted by full factorial design [8] standards with a view to investigate effect of process parameters such as speed, load and time on wear loss. Two levels of each of the three factors were used for the statistical analysis. The treatment combinations for the two levels and three factors as per the requirement of design of experiments are tabulated in Table 2.

**Table 2. Design Layout and Combination of parameters**

| Sr. No.   | Run Order | SPEED | TIME | LOAD | Sr. No.   | Run Order | SPEED | TIME | LOAD |
|-----------|-----------|-------|------|------|-----------|-----------|-------|------|------|
| <b>1</b>  | 1         | 125   | 2    | 15   | <b>13</b> | 15        | 125   | 1    | 15   |
| <b>2</b>  | 2         | 125   | 2    | 15   | <b>14</b> | 16        | 250   | 1    | 15   |
| <b>3</b>  | 3         | 250   | 1    | 10   | <b>15</b> | 17        | 250   | 2    | 10   |
| <b>4</b>  | 4         | 250   | 1    | 10   | <b>16</b> | 18        | 125   | 2    | 10   |
| <b>5</b>  | 5         | 250   | 1    | 15   | <b>17</b> | 20        | 250   | 2    | 10   |
| <b>6</b>  | 6         | 250   | 2    | 15   | <b>18</b> | 21        | 250   | 1    | 15   |
| <b>7</b>  | 7         | 250   | 2    | 15   | <b>19</b> | 22        | 125   | 1    | 10   |
| <b>8</b>  | 8         | 125   | 1    | 15   | <b>20</b> | 23        | 250   | 2    | 15   |
| <b>9</b>  | 9         | 250   | 1    | 10   | <b>21</b> | 24        | 125   | 2    | 10   |
| <b>10</b> | 11        | 125   | 1    | 10   | <b>22</b> | 25        | 125   | 2    | 10   |
| <b>11</b> | 12        | 125   | 2    | 15   | <b>23</b> | 26        | 125   | 1    | 15   |
| <b>12</b> | 13        | 125   | 1    | 10   | <b>24</b> | 27        | 250   | 2    | 10   |

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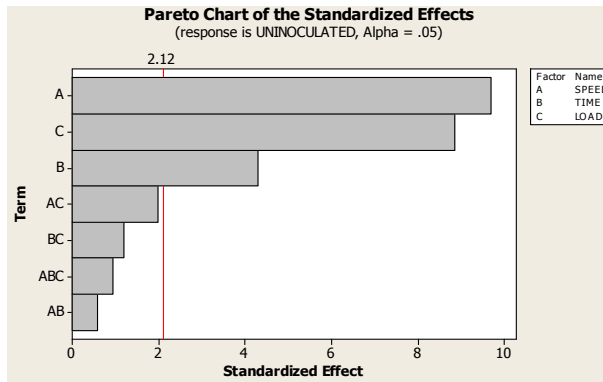


Chart 1 Pareto Chart (Un-Inoculated)

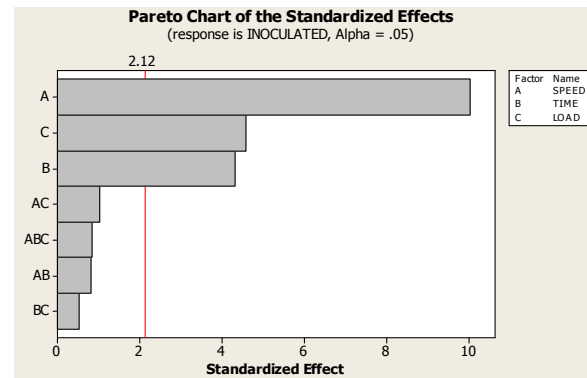
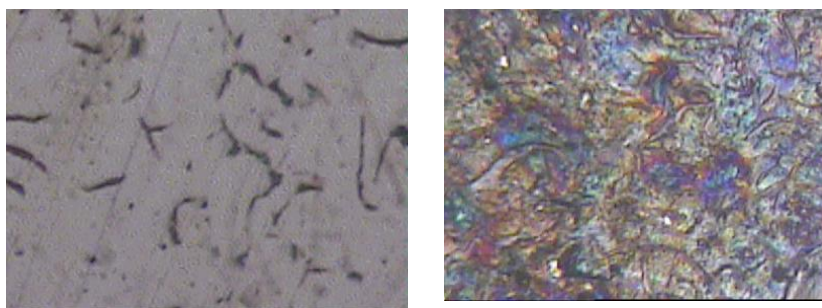


Chart 2 Pareto Chart (Inoculated)

Chart 1 & 2 shows the result of standardized effect versus factors and their combinations selected for wear testing. It is thus observed that three factors considered Speed of rotation of disc; sliding Time and Load applied on pin have significantly affected wear volume loss. Also, it can be concluded that speed is the most influencing factor affecting wear volume loss.

### III. RESULTS AND DISCUSSION

The results of wear volume loss of the samples obtained on wear testing machine are analyzed. The direct influence of individual process parameters and their effects on wear volume loss were investigated using direct effects plots. The analysis of variance (ANOVA) was used to check the adequacy of the linear regression model. The micrographs show the effect of inoculants addition on the resulting alloy produced. The un-inoculated iron is characterized with high percentage of cementite and little or no graphite flakes. Fig.1 shows micrographs of un-inoculated sample before etching and after etching with 3% nital solution.



A) Sample without etching

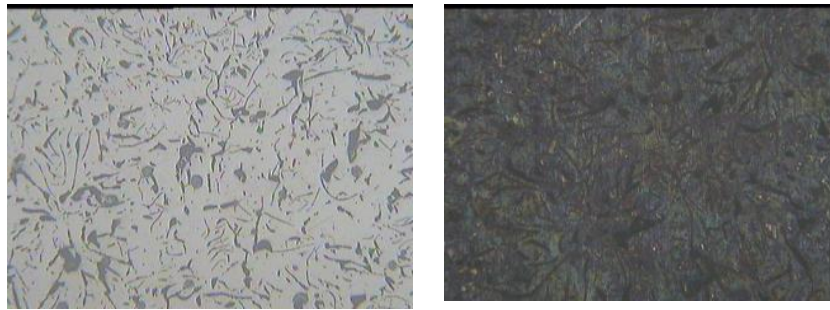
B) Sample after etching

Fig. 1 Micrographs of Un-inoculated sample before and after etching.

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A) Inoculated sample without etching    B) Inoculated sample after etching

**Fig. 2 Micrographs of Inoculated sample before and after etching.**

Addition of inoculants gives distinct graphite flakes with varying sizes uniformly distributed and randomly oriented as shown in Fig. 2. This type of graphite is typical of type A graphite which is usually preferred for most engineering applications. Fig. 2 shows micrographs of un-inoculated sample before etching and after etching with 3% nital solution.

The elemental composition and summary of the mechanical properties and carbon equivalent value of un-inoculated and inoculated specimens were shown in Table 3. It is observed that the silicon content increases with increasing inoculants and gives clear indication that the inoculation was effective. Also this is attributed to an increased degree of graphitization. The reduction in sulphur content reduces the degree of graphitization that led to reduced tensile strength and hardness in gray cast iron. The carbon equivalent value (CEV) is calculated [2] and found to be increasing with increase in addition of inoculants. However, an inverse relationship is observed to exist between the mechanical properties and carbon equivalent value. Cr is present in negligible amount.

**Table 3. Elemental composition and summary of the Mechanical Properties**

| Elements             | C    | Si   | Mn   | P     | S     | Cr   | CEV   | BHN | UTS (N/mm <sup>2</sup> ) |
|----------------------|------|------|------|-------|-------|------|-------|-----|--------------------------|
| <b>Un-Inoculated</b> | 3.56 | 2.12 | 0.68 | 0.1   | 0.083 | 0.08 | 4.244 | 229 | 227                      |
| <b>Inoculated</b>    | 3.5  | 2.51 | 0.59 | 0.201 | 0.053 | 0.07 | 4.325 | 187 | 202.68                   |

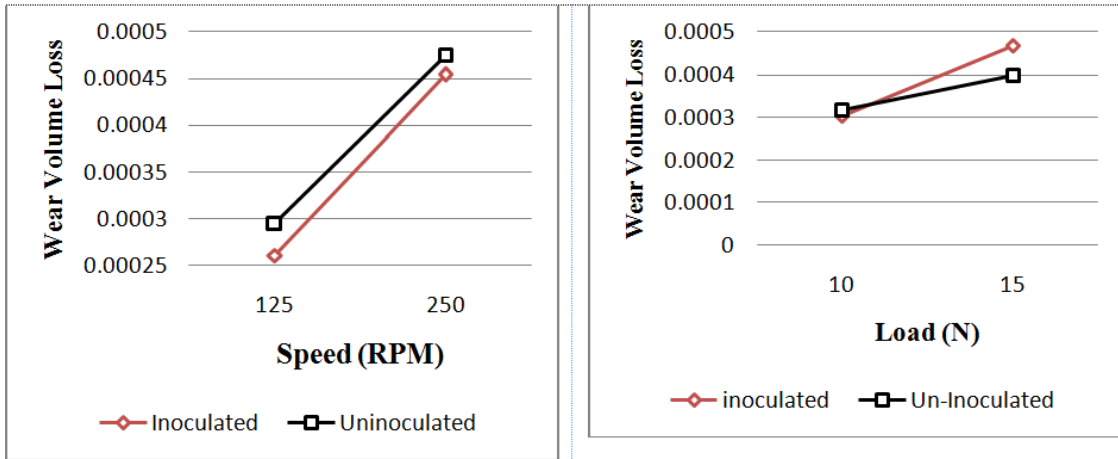
The CEV of gray iron is an indicator of the structure in relation to the potential for carbon precipitation as graphite in the eutectic iron formed. In this respect, the higher the CEV, the greater the graphite precipitation during the eutectic reaction and the percentage eutectic iron formed [7].

The effect of process parameters on wear volume loss (mm<sup>3</sup>) is plotted against parameters and shown in Graph 1, 2, and 3. The performance of un-inoculated specimen in terms wear volume loss when compared with inoculated specimen is better as expected.

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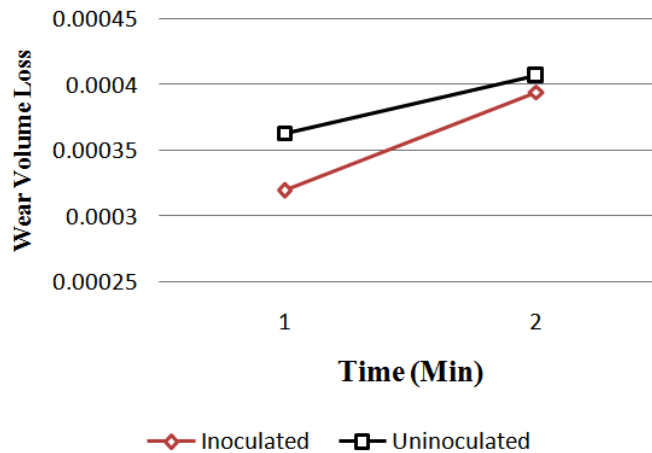
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Graph 1. Speed Vs. Wear volume loss

Graph 2. Load Vs. Wear volume loss

It can be observed from the Graph 1, 2 & 3 that the slope of line plotted for inoculated specimen is more as compared to that line plotted for un-inoculated specimen, which indicates increase in rate of wear for inoculated specimen even though same levels of parameters mentioned above are kept.



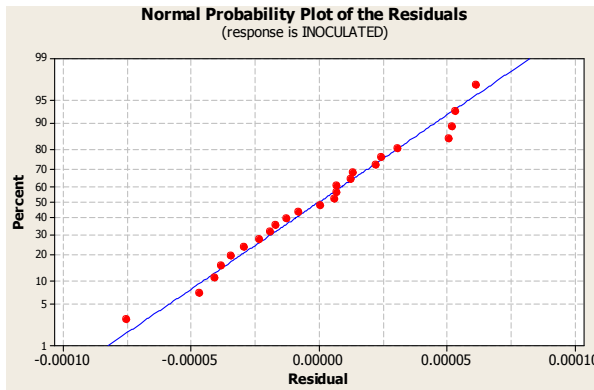
Graph 3. Time Vs. Wear volume loss

In the normal probability plot of the residuals shown in Graphs 4 and 5, the data were plotted against a theoretical normal distribution which was used to check the normality distribution of the residuals. The data points lies along an approximate straight line indicates that data is normally distributed [9]. Hence it is reasonable that the assumptions of normality were satisfied for the data.

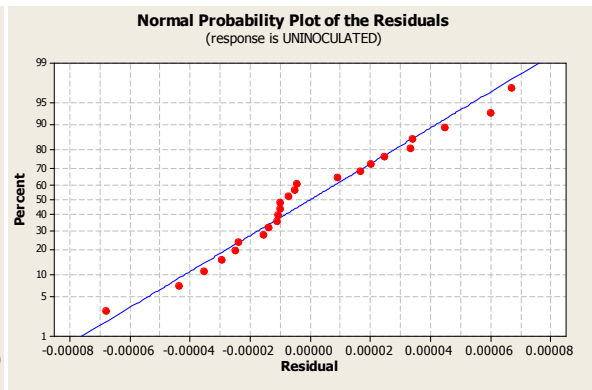
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**Graph 4.** Normal Probability Plot of Residuals (Un-Inoculated)



**Graph 5.** Normal Probability Plot of Residuals (Inoculated)

Analysis of variance (ANOVA) has been performed to check the adequacy of the models as well as significance of the individual model coefficients. ANOVA is similar to regression in that it is used to investigate and model the relationship between a response variable and one or more predictor variables. ANOVA table for individual model coefficients is presented here in Tables 4 and 5.

It can be seen that the P-value for the main effects is 0.000 and that of two way and three way interaction effects of parameters for wear volume loss is very close to 0.05 and is significant at 95 % confidence level. Thus it may be concluded that all the selected parameters and there ranges are significant [10].

After analysis the values of Estimated Effects and Coefficients for Un-inoculated specimen (coded units) are:

$$S = 0.0000391728 \quad R\text{-Sq} = 92.50\% \quad R\text{-Sq(adj)} = 89.21\%$$

**Table 4.** ANOVA table for Un-inoculated (Coded Units)

| Source             | DF | Seq SS      | Adj SS     | F     | P     |
|--------------------|----|-------------|------------|-------|-------|
| Main Effects       | 3  | 0.00000029  | 0.00000029 | 63.56 | 0.000 |
| 2 Way Interactions | 3  | 0.00000001  | 0.00000001 | 1.89  | 0.172 |
| 3 Way Interactions | 1  | 0.00000000  | 0.00000000 | 0.87  | 0.365 |
| Residual Error     | 16 | 0.00000002  | 0.00000002 |       |       |
| Total              | 23 | 0.000000033 | 0.00000002 |       |       |

After analysis the values of Estimated Effects and Coefficients for Inoculated specimen (coded units) are:

$$S = 0.0000425026 \quad R\text{-Sq} = 89.91\% \quad R\text{-Sq(adj)} = 85.49\%$$

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**Table 5. ANOVA table for Inoculated (Coded Units)**

| Source             | DF | Seq SS     | Adj SS     | F     | P     |
|--------------------|----|------------|------------|-------|-------|
| Main Effects       | 3  | 0.00000025 | 0.00000025 | 46.61 | 0.000 |
| 2 Way Interactions | 3  | 0.00000000 | 0.00000000 | 0.66  | 0.589 |
| 3 Way Interactions | 1  | 0.00000000 | 0.00000000 | 0.71  | 0.411 |
| Residual Error     | 16 | 0.00000003 | 0.00000003 |       |       |
| Total              | 23 | 0.00000033 | 0.00000002 |       |       |

The linear regression equations for the wear loss of the Un-inoculated and Inoculated samples are expressed as follows:

$$\begin{aligned}
 & \text{(Wear volume loss)}_{\text{Un-Inoculated}} \\
 & = (-0.68640 \text{ E} - 04 + 1.158592\text{E} - 06 * \text{SPEED} + 3.048\text{E} - 05 * \text{TIME} + 2.3294\text{E} - 05 * \text{LOAD} - 1.04256\text{E} - 06 \\
 & \quad * \text{SPEED} * \text{TIME} - 2.43968\text{E} - 05 * \text{SPEED} * \text{LOAD} - 1.01920\text{E} - 05 * \text{TIME} * \text{LOAD} + 9.536\text{E} \\
 & \quad - 08 * \text{SPEED} * \text{TIME} * \text{LOAD})
 \end{aligned}$$

$$\begin{aligned}
 & \text{(Wear volume loss)}_{\text{Inoculated}} \\
 & = (-2.7864020\text{E} - 04 + 2.10048\text{E} - 06 * \text{SPEED} + 0.000206640 * \text{TIME} + 2.60640\text{E} - 05 * \text{LOAD} - 9.4656\text{E} - \\
 & \quad 07 * \text{SPEED} * \text{TIME} - 8.37120\text{E} - 08 * \text{SPEED} * \text{LOAD} - 1.392\text{E} - 05 * \text{TIME} * \text{LOAD} + 9.36960\text{E} - 08 * \text{SPEED} * \text{TIME} * \text{LOAD})
 \end{aligned}$$

### IV. CONCLUSIONS

In this work the effect of inoculation on mechanical properties of gray cast iron was studied. Also the response for wear test of both inoculated and un-inoculated samples have been investigated. It was observed that due to inoculants addition the CEV of a gray cast iron has been increased and it leads to decrease in Tensile strength and Hardness as expected. Increase in the Silicon and decrease in sulphur content, resulted into increase in the degree of graphitization and reduction into tensile strength and hardness of samples. The wear volume loss of inoculated sample found to be more than the un-inoculated sample. Full Factorial method can be successfully employed and the developed linear equation models which can be used for predicting wear loss of the samples within the set experimental conditions.

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