Optimization of parameters of antimony modified carbidic austempered ductile iron (CADI) using Taguchi method

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Abstract: In this work, optimization of hardness, wear and impact strength of antimony modified CADI using Taguchi method was carried out. Carbidic Austempered Ductile Iron is a type of wear resistant ferrous metal having alloyed carbides inside an ausferritic matrix with an evidence of few graphite nodules in most cases. The alloy carbides which are mostly of primary coarse carbides are detrimental to its mechanical properties. The need for improvement of these mechanical properties (hardness, wear, and impact strength) in CADI has led to the usage of micro-addition of antimony to modify the carbides size which has given birth to Antimony Modified CADI. In a bid to get the optimum production factors on the mechanical properties, signal-to-noise (S/N) ratio was computed based on the design of experiments and the Straight graph of Minitab 17. The analysis of variance was computed to know the quantities of the contribution of factors on each mechanical property including its significance. From Taguchi analysis of the hardness, wear resistance and impact toughness, the signal-to-noise ratio using larger is...

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PUBLIC INTEREST STATEMENT

The Agricultural-industrial sector has discovered a material (Carbidic austempered ductile iron) that is economical and technically efficient. This material can replace Hadfield steel which is usually used for making agricultural implement like; cultivator, ploughshare and soil tiller. As a result of the difficulty in producing this hadfield steel, that is used in making this agricultural implement, and the high cost procuring this hadfield steel, the new material (carbidic austempered ductile iron) has effectively proven its potential for been used as a material for producing agricultural implement, except that it is brittle compared to hadfield steel. To achieve improvement in the properties of this material, an optimization tool like Taguchi modeling tool help in upgrading the property of this material mathematically. The essence of this optimization tool is to reduce design error, reduce time wastage, reduce the cost of producing this material and to get the maximum obtainable improvement of this new material.
better revealed that antimony content in the antimony modified CADI is the most important factor, followed by the austempering time in terms of improving the hardness and wear resistance of this material, while in the case of impact toughness, antimony content and austempering temperature are the most important factors, and that increasing these parameters would greatly improve the impact toughness of this CADI. The experimental values compared suitably with the results from Taguchi.

Subjects: Agricultural Engineering; Food Engineering; Plant Engineering; Plant Engineering & Maintenance; Manufacturing Technology; Materials Science; Metallurgical Engineering; Transport & Vehicle Engineering

Keywords: Antimony; carbidic ADI; wear resistance; impact toughness; hardness; Taguchi method

1. Introduction

Optimization is the main step to improving the performance and finding the optimal process parameters of products based on the responses involve. There are several optimization tools such as the gradient search method (GSM), the finite element method (FEM), neural network method and Taguchi method. Taguchi method is a problem-solving tool which is capable of improving the performance of the product, process design and system in a short development cycle with reduced cost. This method combines the experimental and analytical concepts to determine the most influential parameter on the result response for the significant improvement in the overall performance. To solve this task, the Taguchi method uses a special design of orthogonal array to study the entire process parameter space with a small number of experiments. Many of the researchers have attempted to analyze and optimized single and multi-performance responses of foundry process using Taguchi methodology. Among them are; multiple progressive tools by Surace (2010) and utility concept by Sun, Hu, and Chen (2008). The effect of factors on the responses were separately studied by Muhammed (2009); Jadoun, Kumar, and Mishra (2009); Dhanapal and Muhammed (2010). Carbidic Austempered Ductile Iron (CADI) which is a wear resistant austempered ductile iron with alloyed carbide in its matrix has been found to be a very useful material for the production of Agricultural implement (ploughshare). Austempered ductile iron (ADI) is known for its high tensile strength, ductility, wear resistance and toughness qualifying it as a possible replacement for forged steels in many areas of applications Seshan, (1998) and Hayrynen (1995). High toughness of austempered ductile iron is owing to ausferrite matrix which is produced by the austempering process. The high carbon austenite presents in the ausferrite matrix of ADI has a tendency to cause strain hardening effect on its surface. This gives this material high wear resistance Trudel and Gagne (1997). This material is used as agricultural implements Brezina, Filipek, and Senberger (2004), Barnabas, Oyetunji, Seidu, and Adediran (2019). Wear resistance of CADI is better compared than that of forged steel. As a result of this quality, the CADI can stand in for forged steels Zimba, Simbi, and Navara (2003). Alloying elements like copper, nickel and molybdenum improve mechanical properties of ADI Batra, Ray, and Prabhakar (2004); Eric, Rajnovic, Sidjanin, Zec, and Jovanovic (2005); and Rao and Putatunda (2003).

Carbides are the known strong wear resistance compounds which can be produced easily. The availability of carbides in the ausferrite matrix can reduce the toughness of cast iron. The available literature on CADI material shows its application, microstructure and the abrasive resistance of CADI Rimmer (2006); Hayrynen and Brandenberg (2003) and Keough and Hayrynen (2000). The literature Laino, Sikora, and Dommarco (2008) shows the unified effect of high cooling rate with copper chills and the use of carbide stabilizing elements. Carbide stabilizing agents (Mn, Mo) possess the ability to separate into the grain boundaries, which decreases the mechanical characteristics of the ADI Hayryen, Brandenberg, and Kough (2002). The analysis of variance looks at the variability, it includes the calculation of many measures of variability. The concept underlying the analysis of variance is that
the total variation of scores can be given to two sources – variance between groups (caused by the
treatment), and variance within the groups (error variance). As with t-test, a ratio is formed (the F ratio)
with group differences as the number for variance between groups and an error term as the denomi-
nator (variance within groups). If at the end of a study, the treatment variance is larger than the error
variance, a significant F ratio results, the null hypothesis is rejected. If on the other hand, the treatment
variance and error variance are essentially the same, the resulting F ratio is not significant and the null
hypothesis is not rejected. The greater the difference, the larger the F ratio. There are two main types of
ANOVA: One-way ANOVA and Two-way ANOVA.

1.1. Two-way analysis of variance
This is a step that determines the effect of two independent variables simultaneously. This helps in
reducing cost by allowing you to look at two things for the price of one. It also permits one to know
whether the two independent variables interact with respect to the effect of the dependent
variables. Table 1 shows the source of variance and degree of freedom formulae used in the
work. While Table 2 shows the formulae for calculating the analysis of variance (ANOVA). The
condition for interpreting the correlation coefficient is as presented in Table 3.

$$SS_{\text{Total}} = \sum X^2 = \frac{\sum X^2}{N}$$  \hspace{1cm} (1)

$$SS_{\text{Row}} = \sum \left( \frac{\sum X^2}{\text{Row}} - \left( \frac{\sum X}{N} \right)^2 \right)$$  \hspace{1cm} (2)

$$SS_{\text{Column}} = \sum \left( \frac{\sum (X)^2}{\text{Column}} - \left( \frac{\sum (X)}{N} \right)^2 \right)$$  \hspace{1cm} (3)

$$SS_{\text{Interaction}} = SS_{\text{Groups}} - SS_{\text{Column}} + SS_{\text{Row}}$$  \hspace{1cm} (4)

$$SS_{\text{Group}} = \sum \left( \frac{\sum (X)^2}{n\text{Group}} - \left( \frac{\sum (X)}{N\text{Total}} \right)^2 \right)$$  \hspace{1cm} (5)

$$SS_{\text{Within}} = SS_{\text{Total}} - (SS_{\text{Row}} + SS_{\text{Column}} + SS_{\text{Interaction}})$$  \hspace{1cm} (6)

$$CF = \frac{\left( \sum_{i=1}^{p} \sum_{j=1}^{v} \sum_{k=1}^{t} X_{ijk} \right)^2}{n}$$  \hspace{1cm} (7)

$$SS_{T} = \sum_{i=1}^{p} \sum_{j=1}^{v} \sum_{k=1}^{t} (X_{ijk})^2 - CF$$  \hspace{1cm} (8)

$$SS_{AT} = \sum_{i=1}^{At} \sum_{j=1}^{At} \sum_{k=1}^{nsb} (X_{ijk})^2 - CF$$  \hspace{1cm} (9)

| Source of variance | Degree of freedom (df) |
|--------------------|------------------------|
| Rows               | Number of Rows – 1     |
| Column             | Number of Columns – 1  |
| Interaction        | (Columns – 1) (Rows – 1) |
| Within             | Number of Subject – Number of Subject – 1 |
| Columns            |                         |
| Total              |                         |

$y$ is the average of observed data, $S_y^2$ is the variance of $y$, $n$ is the number of observations, and $y$ is observed data.
1.2. Signal-to-noise (S/N) ratio

Signal means the desirable value while the noise represents the undesirable value. Therefore, the S/N ratio consolidates many repetitions into one value, which reflects the amount of variation present. Signal-to-noise (S/N) ratio is used to measure the amount of deviation from the desired value. The lower-the-better (LB), the higher-the-better (HB), and the nominal-the-better (NB) are the three types used to analyze the S/N ratio.

The equations associated with signal-to-noise ratios are stated as follows:

\[ \text{Smaller—better: } S/N_s = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]

\[ \text{Larger—better: } S/N_L = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \left( y_i - \bar{y} \right)^2 \right) \]

\[ \text{Nominal—the—best: } S/N_T = 10 \log \left( \frac{y}{\bar{y}} \right) \]
2. Materials and methods
The flow chart showing the work approach is as presented in Figure 1.

2.1. Design of experiment
Two major steps were used in the production of the antimony modified carbide austempered ductile iron, one of these steps is the casting, while another step is austempering heat treatment operation. In terms of the heat treatment process; austenitization temperature, austenitization time, austempering temperature and austempering time are the controllable parameters. Three major factors which have more effects on the production of the CADI were considered: antimony content, austempering temperature and austempering time. Five levels of the antimony content, two levels of the austempering temperature and three levels of austempering time were selected (shown in Table 5) as factor levels.

2.2. Foundry considerations for the production of CADI
The composition of the antimony modified carbide ductile iron (CDI) used, was of hypereutectic composition, where the carbon and silicon contents are 3.6 and 2.4, respectively [C.E = 4.44]. Grey cast iron scraps were used as raw material been charged and melted in an indirect electric arc furnace, computed amount of heated ferro-chrome was added to the melt to increase the chromium level in the pouring ladle and also get alloyed carbides in the melt. The melt was heated up to 1400°C. The melt was then tapped into ladle, the magnesium alloy consisting of Mg-Fe-Si with 9 wt. % of Mg was introduced into the melt for nodularization, and later inoculated with FeSi (75 wt. % Si), varying amount of pulverized antimony (0.3 μm) were added. Sand mold was prepared using silica, bentonite and water. The composition of the samples was analyzed using spectrometer and the results are shown in Table 4.

2.3. The austempering process
The produced antimony modified CDI was heated to the temperature of 910°C (austenitization), followed by cooling in a salt bath (Sodium and Potassium Nitrates mix) that is already heated to austempering temperatures of 300°C, and 325°C, respectively. Salt bath has the ability to share the heat uniformly on the samples compared to the atmospheric heating (Dhanopal et al., 2009). The austempering time was varied between 1 and 3 h in a time interval of 1 h. After austempering, the specimens were cooled to room temperature in air.

Figure 1. Flow chart of the work approach.
Plate 1: Optical Micrographs of samples: (a) CADI without Sb showing blocky carbide, graphite and ausferrite; (b) CADI with 0.096 wt.% Sb showing less blocky carbide, graphite and ausferrite; (c) CADI with 0.192 wt.% Sb showing granular carbide, graphite and ausferrite; (d) CADI with 0.288 wt.% Sb showing more granular carbide, graphite and ausferrite; (e) CADI with 0.384 wt.% Sb showing granular carbide, graphite and ausferrite; and (f) CADI with 0.48 wt.% Sb showing cellulose carbide, graphite and ausferrite.

Table 4. Chemical composition of the produced alloys (wt. %)

| No | Fe   | C   | Si  | Mn  | Cr  | Ni  | Cu  | Mg  | Sb  | S   | P   | C.E |
|----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1  | 89.39| 3.62| 2.42| 0.58| 2.6 | 0.60| 0.69| 0.06| -   | 0.004| 0.040| 4.43 |
| 2  | 89.33| 3.62| 2.40| 0.57| 2.61| 0.61| 0.65| 0.07| 0.096| 0.005| 0.041| 4.43 |
| 3  | 89.24| 3.62| 2.41| 0.57| 2.62| 0.62| 0.61| 0.07| 0.192| 0.005| 0.042| 4.44 |
| 4  | 89.19| 3.63| 2.40| 0.56| 2.60| 0.60| 0.62| 0.07| 0.288| 0.005| 0.042| 4.44 |
| 5  | 89.10| 3.62| 2.41| 0.56| 2.63| 0.61| 0.62| 0.06| 0.384| 0.005| 0.040| 4.44 |
| 6  | 88.97| 3.62| 2.40| 0.58| 2.62| 0.60| 0.63| 0.06| 0.480| 0.004| 0.041| 4.43 |
2.4. Characterization of the samples

2.4.1. Microstructure examination
The chemical compositions of the alloys were determined using Spark Emission Optic Spectrometer of model Spectro-pro MAxX-LMM06 with a DV6 excitation source. The surface of the test piece was ground to ensure flatness and then, mounted on the sparking point of the spectrometer. The operation was performed for a period of 30–40 s. Then, the chemical composition of the specimen was displayed on the monitor of the machine (Ashby, Shercliffe, & Cebon, 2007).

2.4.2. Hardness
The hardness test for both as-cast and the heat-treated samples was conducted using Digital Rockwell Hardness Tester Scale C of model Indentec, following standard test method for Rockwell hardness of metallic materials (ASTM E18-19). Three points hardness was measured and the average of the three measurements was taken (Callister, 2000).

2.4.3. Wear
Wear test was carried out using Taber’s method. This was done by attaching each sample to a rotating disc of 25 cm radius and pressure of a specified load was applied according to Friedrich, Edwald, and Martin (2009). The samples used were 12 mm diameter by 40 mm long. The grit used was 220 rough with a revolution of 150 rpm. Exposing time for each sample on the wear test machine was 5 min, density of the CADI was taken to be 7.86 g/cm$^3$. After running through a fixed distance, the samples were removed, the weight loss due to wear was measured. Also, wear rate and wear resistance were recorded in line with the work of Marinov (2007).

3. Orthogonal array

3.1. Taguchi orthogonal array design
The Taguchi method provides a layout of the experimental conditions using specially designed tables called orthogonal array (OA). The choice of the orthogonal array depends upon the degrees of freedom. The factors and levels obtained for this design are $L_{30}(5^1 \times 2^1 \times 3^1)$ as shown in Table 5. This work has an array of 30 rows, each row represents an experiment, and the columns were assigned to the factor levels. The design of experiments was made of 30 tests in which the first column was assigned to antimony content (Sb), the second column was assigned to austempering temperature (AT) and the third column for the austempering time (At).

Factors and Levels = $L_{30}(5^1 \times 2^1 \times 3^1)$

3.2. Signal-to-noise ratio analysis
Table 6, shows the signal-to-noise ratio for hardness, impact toughness and wear resistance for the produced CADI. Experiment number 18, corresponds to CADI sample with 0.288 wt.% Sb that was subjected to austempering temperature of 325°C held for 3 h gave the highest signal-to-noise ratio of 33.7873 in terms of hardness values, while experiment number 4 corresponding to CADI sample of antimony content of 0.096 wt.% austempered at the temperature of 325°C and held for 3 h has signal-

| Factors | Levels |
|---------|--------|
| Antimony Content (%) | 0.096 | 0.192 | 0.288 | 0.384 | 0.480 |
| Austempering Temperature, AT (°C) | 300 | 325 |
| Austempering Time, At (hrs) | 1 | 3 | 2 |
| AT (°C) | At (h) | Sb content | Hardness (HRc) | Impact toughness (Joules) | Wear resistance (cm$^2$) | Hardness | Impact toughness (J) | Wear resistance (cm$^2$) |
|---------|--------|------------|----------------|----------------------------|-------------------------|----------|---------------------|--------------------------|
| 300     | 1      | 0.096      | 49             | 50                         | 556,000,000             | 32.2106  | 34.4044             | 179.532                  |
| 300     | 2      | 0.096      | 44             | 51                         | 529,000,000             | 31.6849  | 34.3656             | 174.912                  |
| 300     | 3      | 0.096      | 43             | 53                         | 815,000,000             | 32.5032  | 34.5222             | 176.919                  |
| 325     | 1      | 0.096      | 32             | 55                         | 1,030,000,000           | 32.6349  | 34.7112             | 181.321                  |
| 325     | 2      | 0.096      | 43             | 56                         | 970,000,000             | 31.377   | 34.6724             | 176.7                    |
| 325     | 3      | 0.096      | 40             | 57                         | 1,060,000,000           | 32.956   | 34.829              | 178.708                  |
| 300     | 1      | 0.192      | 32             | 48                         | 1,980,000,000           | 32.0636  | 33.5042             | 186.515                  |
| 300     | 2      | 0.192      | 42             | 47                         | 1,870,000,000           | 31.5379  | 33.4654             | 181.894                  |
| 300     | 3      | 0.192      | 35             | 49                         | 2,210,000,000           | 32.3562  | 33.622              | 183.901                  |
| 325     | 1      | 0.192      | 49             | 49                         | 2,810,000,000           | 32.5164  | 33.8109             | 188.303                  |
| 325     | 2      | 0.192      | 40             | 48                         | 398,000,000             | 31.9907  | 33.7721             | 183.683                  |
| 325     | 3      | 0.192      | 50             | 49                         | 3,450,000,000           | 32.809   | 33.9287             | 185.69                   |
| 300     | 1      | 0.288      | 57.6           | 47                         | 283,000,000             | 33.0419  | 33.3835             | 179.502                  |
| 300     | 2      | 0.288      | 32             | 47                         | 257,000,000             | 32.5162  | 33.3447             | 174.881                  |
| 300     | 3      | 0.288      | 51             | 47                         | 1,050,000,000           | 33.3345  | 33.5014             | 176.888                  |
| 325     | 1      | 0.288      | 51             | 48                         | 3,740,000,000           | 33.4947  | 33.6903             | 181.29                   |
| 325     | 2      | 0.288      | 35             | 48                         | 2,920,000,000           | 32.969   | 33.6515             | 176.67                   |
| 325     | 3      | 0.288      | 54             | 49                         | 298,000,000             | 33.7873  | 33.8081             | 178.677                  |
| 300     | 1      | 0.384      | 37             | 48                         | 3,290,000,000           | 31.1758  | 33.623              | 180.811                  |
| 300     | 2      | 0.384      | 30             | 48                         | 288,000,000             | 30.6501  | 33.5842             | 176.19                   |
| 300     | 3      | 0.384      | 35             | 49                         | 336,000,000             | 31.4684  | 33.7408             | 178.197                  |
| 325     | 1      | 0.384      | 35             | 50                         | 1,450,000,000           | 31.6285  | 33.9297             | 182.599                  |

(Continued)
| AT (°C) | At (h) | Sb content | Hardness (HRc) | Impact toughness (Joules) | Wear resistance (cm$^{-2}$) | Hardness | Impact toughness (J) | Wear resistance (cm$^{-2}$) |
|--------|--------|-------------|----------------|---------------------------|-----------------------------|----------|----------------------|-----------------------------|
| 325    | 2      | 0.384       | 51             | 49                        | 1,090,000,000               | 31.1028  | 33.8909              | 177.979                     |
| 325    | 3      | 0.384       | 36             | 50                        | 1,220,000,000               | 31.9211  | 34.0476              | 179.986                     |
| 300    | 1      | 0.489       | 45             | 49                        | 724,000,000                 | 31.6694  | 33.6529              | 173.948                     |
| 300    | 2      | 0.489       | 30             | 48                        | 670,000,000                 | 31.1437  | 33.6141              | 169.327                     |
| 300    | 3      | 0.489       | 43             | 49                        | 747,000,000                 | 31.962   | 33.7707              | 171.334                     |
| 325    | 1      | 0.489       | 32             | 50                        | 258,000,000                 | 32.1221  | 33.9596              | 175.736                     |
| 325    | 2      | 0.489       | 45             | 50                        | 244,000,000                 | 31.5964  | 33.9208              | 171.116                     |
| 325    | 3      | 0.489       | 42             | 49                        | 235,000,000                 | 32.4147  | 34.0774              | 173.123                     |
to-noise ratio of 34.829 in terms of impact toughness and for the wear resistance signal-to-noise ratio, experiment 10 gives the highest value of 188.303 as shown in Table 6 (Nalbant, Gokkaya, & Sur, 2007).

3.3. Data analysis
The average effects of the factors were calculated and shown in Tables 7, 8 and 9. These Tables includes the ranks based on the delta statistics, which compare the relative value of the effects. It is the difference between the highest and the lowest averages for the factor chosen. Antimony content appears as the first controlling factor for all the responses. The Taguchi analysis of hardness value versus austempering temperature, austempering time and antimony content reveals that delta statistics of the antimony content is 1.87, that of austempering temperature

| Level | Austemp. Temperature | Austempering Time | Antimony Content |
|-------|----------------------|-------------------|------------------|
| 1     | 31.95                | 32.26             | 32.36            |
| 2     | 32.41                | 31.73             | 32.21            |
| 3     | 32.55                | 32.65             | 33.19            |
| 4     |                      |                   | 31.32            |
| 5     |                      |                   | 31.82            |
| Delta | 0.45                 | 0.82              | 1.87             |
| Rank  | 3                    | 2                 | 1                |

| Level | Austemp. Temperature | Austempering Time | Antimony Content |
|-------|----------------------|-------------------|------------------|
| 1     | 33.74                | 33.87             | 34.58            |
| 2     | 34.05                | 33.83             | 33.68            |
| 3     |                      | 33.98             | 33.56            |
| 4     |                      |                   | 33.80            |
| 5     |                      |                   | 33.83            |
| Delta | 0.31                 | 0.16              | 1.02             |
| Rank  | 2                    | 3                 | 1                |

| Level | Austemp. Temperature | Austempering Time | Antimony Content |
|-------|----------------------|-------------------|------------------|
| 1     | 177.7                | 181.0             | 178.0            |
| 2     | 179.4                | 176.3             | 185.0            |
| 3     |                      | 178.3             | 178.0            |
| 4     |                      |                   | 179.3            |
| 5     |                      |                   | 172.4            |
| Delta | 1.8                  | 4.6               | 12.6             |
| Rank  | 3                    | 2                 | 1                |
is 0.45 and delta statistics of austempering time is 0.82. This shows that the most important factor for hardness property of the CADI is antimony content, followed by austempering time and the austempering temperature is the least factor (Table 10). In case of the impact toughness of the CADI, the delta statistics of the antimony content is 1.02, austempering temperature has a value of 0.31, while that of austempering time is 0.16. This means that the most important factor for the CADI is antimony, followed by austempering temperature and the least in this case is austempering time. For the wear resistance, the delta statistics of the antimony content is 12.6, that of the austempering temperature is 1.8, while that of austempering time is 4.6, this implies that the most important factor here is antimony content, followed by austempering time and the least factor here is austempering temperature, this is in conformity with Dhanapal and Muhammed (2010).

3.4. Analysis of variance (ANOVA)
F-ratio is the ratio between variance due to the effect of the factor and variance due to the error term. This ratio was used to measure the significance of factor at the desired level. F-statistics of factors – antimony content and austempering temperature are significant up to 95% confidence in all the responses. From Table 7, the percentage contribution of antimony content to the antimony modified CADI is higher in both the impact toughness, hardness and wear resistance values. A maximum value of 96%, 57% and 51% contributions of antimony content were gotten for the impact toughness, hardness and wear resistance, respectively, from the ANOVA tables (Tables 11-18). This shows that antimony content greatly influenced the impact toughness, and moderately influenced the hardness and wear resistance of the Sb-modified CADI under this experimental condition. Table 10 shows the variation in CADI production information. Also, the ANOVA data is as presented in Table 11; showing values for impact toughness of antimony modified CADI, the F critical values from the F distribution table with one, two and four degrees of freedom in the numerator and 22 degrees of freedom in the denominator are 4.30, 3.44 and 2.82, respectively; while their F-test from Table 11, are 32.92, 3.41 and 42.38, respectively. Comparing their F-critical values obtained from F-distribution table and their F-test values obtained from the ANOVA together, at a confidence interval of 0.05. The F-test values of antimony content and austempering temperature are far higher than their F-critical values, while that of austempering time are almost the same. This implies that antimony content and austempering temperature highly influenced the impact toughness of the Sb-modified CADI. Table 13 & 14 shows the factors of production of CADI for the ANOVA for wear resistance values. Table 15 shows the factors of production of CADI for the ANOVA hardness value in Table 16. The ANOVA Table 16 for hardness and

| Table 10. Factors of CADI production information |
|-----------------------------------------------|
| **Factor** | **Type** | **Levels** | **Values** |
|-----------------------------------------------|
| Austemp. temperature | Fixed     | 2          | 300, 325   |
| Austempering time   | Fixed     | 3          | 1, 2, 3    |
| Antimony content    | Fixed     | 5          | 0.096, 0.192, 0.288, 0.384, 0.489 |

| Table 11. Analysis of variance for response |
|--------------------------------------------|
| **Source** | **DF** | **Adj SS** | **Adj MS** | **F-test** | **F-Value (at p < 0.05)** |
|--------------------------------------------|
| Austemp. temperature                       | 1      | 19.653     | 19.6532    | 32.92      | 4.30                        |
| Austempering time                         | 2      | 4.075      | 2.0376     | 3.41       | 3.44                        |
| Antimony content                          | 4      | 101.195    | 25.2989    | 42.38      | 2.82                        |
| Residual                                  | 22     | 13.133     | 0.5969     |            |                            |
| Total                                     | 29     | 138.057    |            |            |                            |
### Table 12. Model summary for transformed response

| S          | R-sq  | R-sq (adj) | R-sq (pred) |
|------------|-------|------------|-------------|
| 0.772623   | 90.49%| 87.46%     | 82.31%      |

### Table 13. General linear model: wear resistance versus austempering time, antimony content. Method factor information

| Factor                  | Type  | Levels | Values                      |
|-------------------------|-------|--------|-----------------------------|
| Austempering time       | Fixed | 3      | 1, 2, 3                     |
| Antimony content        | Fixed | 5      | 0.096, 0.192, 0.288, 0.384, 0.480 |

### Table 14. Analysis of variance for response

| Source                   | DF  | Seq SS | Contribution | Adj SS | Adj MS | F-test | F-Value |
|--------------------------|-----|--------|--------------|--------|--------|--------|---------|
| Austempering time        | 2   | 0.8895 | 6.42%        | 0.8895 | 0.4447 | 0.60   | 4.46    |
| Antimony content         | 4   | 7.0720 | 51.05%       | 7.0720 | 1.7680 | 2.40   | 3.84    |
| Residual                 | 8   | 5.8923 | 42.53%       | 5.8923 | 0.7365 |        |         |
| Total                    | 14  | 13.8538| 100.00%      |        |        |        |         |

General Linear Model: Hardness Values (HRc) versus Austempering Time, Antimony Content at 325°C

### Table 15. General linear model: Hardness versus austempering time, antimony content. Factor information

| Factor                  | Type  | Levels | Values                      |
|-------------------------|-------|--------|-----------------------------|
| Austempering Time       | Fixed | 3      | 1, 2, 3                     |
| Antimony content        | Fixed | 5      | 0.096, 0.192, 0.288, 0.384, 0.489 |

### Table 16. Analysis of variance for transformed response

| Source                   | DF  | Seq SS | Adj SS | Adj MS | F-test | F-Value |
|--------------------------|-----|--------|--------|--------|--------|---------|
| Austempering Time        | 2   | 0.8895 | 6.42%  | 0.8895 | 0.4447 | 0.60    | 4.46    |
| Antimony content         | 4   | 7.0720 | 51.05% | 7.0720 | 1.7680 | 2.40    | 3.84    |
| Error                    | 8   | 5.8923 | 42.53% | 5.8923 | 0.7365 |         |         |
| Total                    | 14  | 13.8538| 100.00%|        |        |         |         |

General Linear Model: Hardness Values (HRc) versus Austempering Time, Antimony Content at 300°C
wear resistance of CADI, the F-critical values for all the factors (antimony content, and austempering time) at both austempering temperature of 300°C and 325°C are higher than their F-test values meaning no significant influence of these factors on hardness and wear resistance of the antimony modified CADI in accordance with Man, Ng, Lawrence, and Yue (2009). The factors of production of CADI for the ANOVA for impact toughness values are as presented in Table 17, while the ANOVA is shown in Table 18.

### 4. Model equation for the impact toughness of the produced CADI

The model equation for quick estimation of impact toughness value of the produced CADI is as expressed in equation (14) with the correlation value of 0.91, which can be interpreted as very highly correlated with reference to Table 3 (Oyetunji & Barnabas, 2012).

#### 4.1. Model equation

\[
\text{Impact Toughness (Joules)} = 28.80 + 0.0720AT + 0.350At - 8.40Sb
\]  

#### 4.2. Model validation of the impact toughness values of the produced CADI

Table 19 shows the validation table that compares the experimental data with the theoretical data of the produced CADI. Judging from values shown in Table 19, experimental data favorably compare with the calculated values of the impact toughness of the CADI.

### 4.3. Interaction plots for the factors

At the initial stage of the plot, it steeped down from 1 to 2 h and steeped up to 3 h. Increase of austempering time led to increase in the hardness value of the antimony modified CADI. The line of austempering temperature is not steep when compared to other factors; this shows a less effect on the hardness value of the CADI. Comparing the three factors the antimony content line steeped more; which means this affects the hardness of the antimony modified CADI most.

Among the plots in Figures 2, 3 and 4, the gradients of the antimony content plot had the highest value. The same trend is followed in all the graphs. The gradient of austempering temperature line was less when compared with the chromium content. So, the next controllable parameter is austempering temperature and the least is the austempering time.

### Table 17. General linear model: Impact toughness values (J) versus austempering time, antimony content. Factor information

| Factor                | Type   | Levels | Values                  |
|-----------------------|--------|--------|-------------------------|
| Austempering Time     | Fixed  | 3      | 1, 2, 3                 |
| Antimony Content      | Fixed  | 5      | 0.096, 0.192, 0.288, 0.384, 0.480 |

### Table 18. Analysis of variance for impact toughness value

| Source                  | DF  | Seq SS | Adj SS | Adj MS | F-test | F-Value |
|-------------------------|-----|--------|--------|--------|--------|---------|
| Contribution            |     |        | Adj SS | Adj MS | F-test | F-Value |
| Austempering Time       | 2   | 0.1166 | 0.2114 | 0.2464 | 0.2464 | 0.2464  |
| Antimony content        | 4   | 0.2114 | 0.2114 | 0.2114 | 0.2114 | 0.2114  |
| Residual                | 8   | 0.2464 | 0.2464 | 0.2464 | 0.2464 | 0.2464  |
| Total                   | 14  | 0.5743 | 0.5743 | 0.5743 | 0.5743 | 0.5743  |
**Table 19. Fits and diagnostics for all observations. Original response**

| Impact | Obs  | Toughness (Joules) | Fit   | 95% CI               |
|--------|------|--------------------|-------|----------------------|
|        | 1    | 55.00              | 55.94 | (54.79, 57.12)       |
|        | 2    | 56.00              | 55.69 | (54.54, 56.86)       |
|        | 3    | 57.00              | 56.35 | (55.19, 57.53)       |
|        | 4    | 49.00              | 48.62 | (47.62, 49.64)       |
|        | 5    | 48.00              | 48.40 | (47.40, 49.42)       |
|        | 6    | 49.00              | 48.97 | (47.97, 50.00)       |
|        | 7    | 48.00              | 48.29 | (47.29, 49.30)       |
|        | 8    | 48.00              | 48.07 | (47.08, 49.08)       |
|        | 9    | 49.00              | 48.64 | (47.64, 49.66)       |
|        | 10   | 50.00              | 49.62 | (48.60, 50.66)       |
|        | 11   | 49.00              | 49.39 | (48.38, 50.43)       |
|        | 12   | 50.00              | 49.98 | (48.95, 51.03)       |
|        | 13   | 50.00              | 49.62 | (48.60, 50.66)       |
|        | 14   | 50.00              | 49.39 | (48.38, 50.43)       |
|        | 15   | 49.00              | 49.98 | (48.95, 51.03)       |

**Figure 2. Interaction plot for hardness values (HRc) of the antimony modified CADI.**
5. Conclusions
The factor that affected the performance of the antimony modified CADI has been determined using Taguchi analysis method. Based on the fact that there is a need for optimizing the three responses (hardness values, impact toughness values and wear resistance values), larger is better (LB) signal-to-noise ratio was applied in this study. Antimony content in the CADI was the most significant factor for all the responses. In terms of hardness value, antimony content and aus-tempering time were the most important factors, while in terms of impact toughness, aus-tempering temperature and antimony content were the most important factors. Regarding the wear
resistance of the CADI, the most important factors are the antimony content, the austempering temperature and austempering time have nearly equal contribution to this property (wear resistance).

Acknowledgements
Authors acknowledge the valuable contributions of anonymous reviewers towards this work. AKA appreciates the support from Landmark University Centre for Research, Innovation and Development (LUCRID) towards this work.

Funding
The authors received no direct funding for this research.

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Citation information
Cite this article as: Optimization of parameters of antimony modified carbidic austempered ductile iron (CADI) using Taguchi method, Abel A. Barnabas, A. Oyetunji, S. O. Seidu, Adeolu A. Adediran & Emmanuel Igbagben, Cogent Engineering (2019), 6: 1629719.

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