International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 5, November 2014)

Study of Factors Influencing Hardness Behaviour of Austempered Gray Iron (AGI) Using Taguchi Method

T Sarkar[1], G. Sutradhar[2]

[1]*Research scholar, School of Automotive Engineering, Jadavpur University, Kolkata, India*
[2]*Professor, Mechanical Engineering Department, Jadavpur University, Kolkata, India*

***Abstract*—Heat treatment of gray cast iron produces austempered gray iron (AGI). Austempered gray iron (AGI) is a new class of engineering material with better properties than regular as-cast conventional gray iron. The properties of AGI can be varied over a wide range by varying the heat treatment process parameters. In the present work, hardness behaviour of austempered gray iron (AGI) had been studied with the help of Taguchi's (L_{27}) orthogonal array (OA) design. The (L_{27}) orthogonal array design is constructed using three process parameters like- Austenitizing, austempering temperature and quenching time. The results are then analyzed using hardness (BHN) as system response to obtain the optimal combination of process parameters. To verify the experimental results confirmation tests were carried out. Analysis of variance (ANOVA) is performed to observe the significance of factors influencing each of the process parameters and their interactions. Finally as-cast and austempered microstructure are observed and an attempt has been made to correlate the obtained hardness values with the microstructure.**

***Keywords*—Austempered gray iron (AGI), Hardness, Microstructure, Taguchi method, Analysis of variance (ANOVA).**

I. INTRODUCTION

The term "cast iron" designates an entire family of metals with a wide variety of properties. Cast iron contains more than 2% carbon present as a distinct graphite phases as individual flakes [1]. Cast iron is an important metallic material, which is extensively used in many applications, due to good cast-ability, machinability, wear resistance and relatively at low cost than the other cast metals [2]. Austempered gray iron (AGI) is considered to be an important engineering material because of its attractive properties such as better ductility at high strengths, good wear resistance property, fatigue strength and fracture toughness etc. Therefore, it is used extensively in many structural applications, automotive industry and earth moving machineries etc [3, 4].

Austempering is a well-established process for enhancing the mechanical properties of ductile irons with high strength, hardness toughness, wear properties etc [5].

The tensile strength and hardness of gray iron can be increased with additions of chromium, copper, molybdenum, and nickel and dimensional stability at elevated temperatures of gray iron improves with additions of molybdenum, copper, chromium, and manganese [6]. Another way to obtain increases properties of gray iron is to subject the material to an austempering heat treatment, in which the ferritic matrix of normal cast iron is replaced by an austenitic matrix [3, 7]. The fine-scale dispersion of ferrite in the austenite is responsible for the properties-higher strengths and hardness in both austempered ductile iron (ADI) and in austempered gray iron (AGI) [8, 7].

Austempered gray iron (AGI) is subjected to an isothermal transformation or heat treatment process known as ''austempering''. During austempering transformation, formed the acicular or bainitic ferrite microstructure [9]. In conventional austempering process, the cast iron is austenitizing at a temperature range of 871–982°C (1600–1800°F) for sufficient time to get a full austenite (γ) matrix, and then quenched to an intermediate temperature range of 260–400°C (500–750°F) and then holding before air cooling to ambient temperature. During austempering reaction, austenite (γ) decomposes into ferrite (α) and high carbon or transformed austenite (Y_{HC}) [10-12].

$$\gamma \rightarrow \alpha + \gamma_{HC} \qquad (1)$$

In the present work, hardness behaviour of austempered gray cast iron (AGI) has been studied. Taguchi's L_{27} orthogonal array design is employed to obtain optimal combination of austempered process parameters for hardness. Furthermore, a statistical analysis of variance (ANOVA) is performed to determine the statistical significance (factors influence) of austempering parameters. A confirmation test is carried out to verify the optimal process parameters obtaining from the parameters design. Finally, the as-cast and austempered microstructures were studied and an attempt has been made to verify the validation of the investigation with respect to that analysis with the help of optical microscope and SEM.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 5, November 2014)

II. Taguchi Method

Dr. Genechi Taguchi's standardized version of Design of Experiment (DOE) is known as Taguchi Method [13, 14] which is a powerful tool for design of high quality systems. This optimization technique is carried out in a three stage approach such as system design, parameter design and tolerance design. System design reveals the usage of scientific and engineering information required for producing a part. Parameter design is used to obtain the optimum levels of process parameters for developing the quality characteristics and to determine the product parameter values depending on optimum process parameter values. Tolerance design is used to determine and analyze tolerance about the optimum combinations suggested by parameter design. In the present study, parameter design is used to optimize the hardness (BHN) behaviour of austempered gray iron (AGI) components.

Using L_{27} Taguchi method [15] and based on orthogonal arrays the number of experiments required for the purpose is reduced. Thus the time required and cost of experimentation is decreased. Taguchi method uses S/N (Signal/Noise) ratio to identify the quality characteristics. The three categories of quality characteristics are (i) Smaller-the-better, (ii) Higher-the-better and (iii) Nominal-the-best. For the present investigations hardness is maximized, therefore the higher-the-better criterion is used. Furthermore, a statistical analysis of variance (ANOVA) is performed. With the use of both S/N ratio and ANOVA analysis, the optimal combination of austempered process parameters is predicted.

III. Experimental Details

A. Melting of as-cast gray iron

The material used in this investigation was a copper alloyed gray cast iron. The chemical composition of the material is reported in Table I. The gray cast iron is melted in a cupola furnace with an addition of 0.25% inoculants (70% ferrosilicon) and is poured into a plate casting (5mm thick) sand moulds (5x25.4x200 mm). The use of inoculants is promotes graphitization, or provides nucleation sites for graphite to precipitate and form graphite flakes during solidification [16, 17]. Copper is added to increase tensile strength, hardenability and subsequently to help austempering heat treatment [18].

Table I
Chemical Compositions Of Gray Cast Iron (Wt. %)

Materials	C	Si	Mn	P	S	Cu	Fe
Gray Cast Iron	3.46	2.27	0.53	0.19	0.1	0.50	Balance

B. Austempered Heat Treatment

In this study, Taguchi's L_{27} orthogonal array (OA) design has been referred for experimental design to optimize the process parameters (Table III) of austempering process. In this experiment, the specimens was austenitized for 1hr to get uniform austenite structure and rapidly transferred to a salt bath (KNO_3-55% and $NaNO_3$-45%) for isothermal cooling and holding different time, before air cooling to ambient temperature.

C. Characterization Study on Samples

The as-cast and austempered (5mm section thickness) samples were taken for evaluation of hardness (BHN) by BHN hardness testing machine with 5mm ball and applying 750 Kg load. For microstructural analysis, the austempered samples were prepared with emery paper (600 grit size) and mirror finished with 5µm diamond paste and etched with 2% nital solution. Microstructures of the polished AGI samples were examined in optical microscope and SEM.

D. Design of Experiments (DOE)

The number of experiments were planned [15] by are performed by varying the design factors or the control factors which affect the hardness behaviour of austempered gray iron (AGI). For this experimental study, the austenitizing temperature (A), austempering temperature (B) and quenching time (T) are chosen as the design factors or the control factors of austempered process. Table II represents the design factors and their three levels. Since the hardness behaviour of AGI is studied, hardness values are taken as response variable. R.A. Fisher [19] introduced design of experiment which is a powerful statistical technique. Design of experiment mainly refers to the process of planning, designing and analysing the experiment so that valid and objective conclusions can be drawn. To reduce the number of experiments for the study orthogonal array is chosen based on Taguchi method. This step is carried out to optimize hardness behaviour of austempered gray iron. The orthogonal array is chosen on the basis of total number of degrees of freedom. For this experimental purpose L_{27} orthogonal array is chosen since total degree of freedom is 26. The degree of freedom for each design factors is 2 and for each two way interaction is 4. Table III shows the L_{27} orthogonal array with its design factors and interaction along with experimental hardness (BHN) behaviours. The L_{27} orthogonal array is designed by austenitizing temperature (A) to column 1, austempered temperature (B) to column 2 and quenching time (T) to column 3.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 5, November 2014)

Table II
Design Factors And Its Levels

Design Factors	Unit	Levels Values		
		1	2	3
A	°C	875	905[i]	935
B	°C	270	300[i]	330
T	Minutes	30	60[i]	90

**i= initial condition,*A-Austenitizing temperature, B-Austempering temperature and T- Quenching time*

Table III
L_{27}, Orthogonal Array With Design Factors (Heat Treat Cycle) And Results

Column				Results	
Trial No.	1	2	3	4	5
SL NO.	A (°C)	B (°C)	T (Min)	BHN	S/N Ratio
1	875	270	30	370	51.3640
2	875	270	60	382	51.6413
3	875	270	90	376	51.5038
4	875	300	30	307	49.7428
5	875	300	60	324	50.2109
6	875	300	90	315	49.9662
7	875	330	30	275	48.7867
8	875	330	60	285	49.0969
9	875	330	90	290	49.2480
10	905	270	30	365	51.2459
11	905	270	60	388	51.7766
12	905	270	90	375	51.4806
13	905	300	30	320	50.1030
14	905	300	60	330	50.3703
15	905	300	90	328	50.3175
16	905	330	30	270	48.6273
17	905	330	60	288	49.1878
18	905	330	90	282	49.0050
19	935	270	30	360	51.1261
20	935	270	60	376	51.5038
21	935	270	90	366	51.2696
22	935	300	30	308	49.7710
23	935	300	60	325	50.2377
24	935	300	90	318	50.0485
25	935	330	30	248	47.8890
26	935	330	60	265	48.4649
27	935	330	90	262	48.3660

IV. Results And Discussion

A. Hardness

Experimental hardness (BHN) values of austempered gray irons (AGI) samples are shown in Table III. The hardness of as-cast gray iron and austempered gray iron varies between 209-388 BHN. The hardness of austempered gray iron is influenced by microstructure and austempered conditions like- austenitizing and austempering temperature and time. Experimental results show that, the hardness of the austempered gray iron (AGI) steadily decreases with increase in the austempering temperatures.

B. Analysis of signal-to-noise ratio

Taguchi method stresses the importance of studying the response variation using signal-to-noise (S/N) ratio, resulting in minimization of experiments variation due to uncontrollable parameter. The hardness was considered as the better characteristic with the concept of "the larger-the-better". The S/N ratio used for this type response is given by [20].

The S/N ratio for the larger-the-better is: S/N=-10*log (mean square deviation)

$$S/N = -\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \qquad (2)$$

Where n is the number of measurements in a trial/row, in this case, n=1 and y is the measured value in a run/row. The S/N ratio values are calculated by taking into consideration Eqn. 2. The hardness of austempered gray iron (AGI) is to be "maximized higher" the better criterion is chosen in this purpose. Table III represents the experimental plan and S/N ratio for each experiment obtained from the L_{27} Taguchi method analysis. In table IV the response table for mean S/N ratio is summarized. The influence of each control factor like- austenitizing temperature (A), austempering temperature (B) and quenching time (T) on the hardness behaviour is obtained from the response table of mean S/N ratio. The main effects plot of S/N ratio is shown in Figure 1, where it is observed that the S/N ratio is higher at 270°C for austempered temperature parameter, at 60 minutes for quenching time parameter and 905°C for austenitizing temperature parameter.

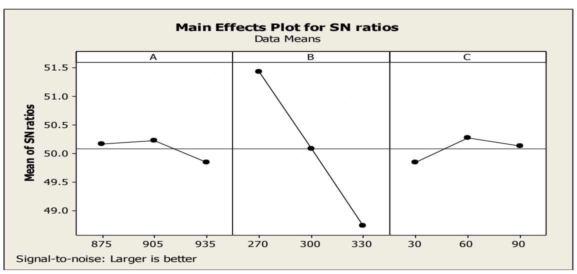
International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 5, November 2014)

Thus, from the mean S/N ratio table IV and main effect plot the optimal combination of austempered process parameter is found to be 905ºC austenitized temperature (A2), 270ºC austempered temperature (B1) and 60 min quenched time (T2) A2B1T2 (Figure 1). Figure 2 shows the two way interaction plots of the process parameters. From the interaction plots we can see that parameters austenitizing temperature (A) and austmpered temperature (B) are better interactions whereas interaction between austenitizing temperature (A) and quenching time (T) and austmpered temperature (B) and Time (T) are nominal.

Table IV
Response Table For Signal To Noise Ratios

Level	A	B	T
1	50.17	51.43	49.85
2	50.23	50.09	50.28
3	49.85	48.74	50.13
Delta	0.38	2.69	0.43
Rank	3	1	2

*Total Mean S/N Ratio = 50.08dB, *Larger is better



**A2-905ºC austenitized temperature,*
B1-270ºC austempered temperature & T2- 60 min quenched time.

Figure 1 Main Effects Plot (A2B1T2)

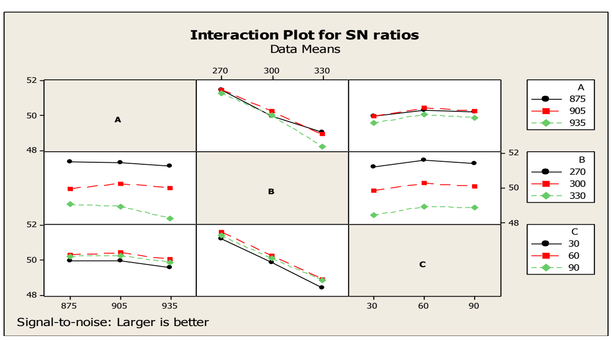


Figure 2 Interaction Plot (i) Austenitized temp Vs Austempered temp (ii) Austenitized temp Vs Quenched time and (iii) Austempered temp Vs Quenched time

C. Analysis of Variance (ANOVA)

To find out the significance of each process parameters and its interactions and also their effect on the response variable "analysis of variance" is performed. This is accomplished by separating the total variability of the S/N ratio, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. The percentage contributions of variance can be calculated by using the following equations. The total sum of square deviations SS_T from the total mean of the S/N ratio (η_n) can be evaluated as [21].

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_n)^2 \quad \text{................(3)}$$

Where, n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the ith experiments. The percentage of contributions r can be calculated as follows:

$$P = \frac{SS_d}{SS_T} \quad \text{................................(4)}$$

Where, SS_d is the sum of the square deviations. In the statistical analysis, F - tests [22] are carried out to see which design parameters have a significant effect on the response characteristics. To conduct the F–test, the mean of the square deviations SS_m due to each design parameter need to be calculated.

$$SS_m = -\frac{\text{Sum of squared diviations } (SS_d)}{\text{Number of degrees of freedom of each parameters}} \quad \text{..(5)}$$

F-value can be found out with following equation:

$$V - \text{ value } \frac{\text{Mean squared deviation } (SS_m)}{\text{Mean squared error } (SS_e)} \quad \text{.......................(6)}$$

Experimental results are analysis through Minitab software version-16 and apply ANOVA for confirmation of experiment. Table V represents the analysis of variance (ANOVA), observe the factor influencing significant of each of the factor process parameters and their interactions. From this table, it is observed that austempered temperature (B) is the most influencing parameter with 93.28 % contribution while the quenching time (T) and austenitizing temperature (A) are 2.42% and 2.17% contribution respectively.

The interaction between A*B (contribution of 1.77%), A*T (contribution of 0.04%), B*T (contribution of 0.18%) also influence the hardness behaviour of the austempered gray iron (AGI) specimens.

Table V
Anova For Snra1, Using Adjusted Ss For Tests

Source	DF	Seq SS	Adj MS	F	Contribution (%)
A	2	0.7570	0.3785	55.32	2.17
B	2	32.6433	16.321	2385.7	93.28
T	2	0.8465	0.4232	61.86	2.42
A*B	4	0.6180	0.1545	22.58	1.77
A*T	4	0.0153	0.0038	0.56	0.04
B*T	4	0.0597	0.0149	2.18	0.18
Error	8	0.0547	0.0068		0.16
Total	26	34.9945			100

D. Confirmation Test

To validate and check the accuracy of the results obtained from analysis of experimental results of hardness confirmation test is performed. The estimated S/N ratio $\hat{\eta}$, using the optimal level of the testing parameters is calculated as [22].

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o}(\overline{\eta}_i - \eta_m)........................(7)$$

Where, η_m is the total mean S/N ratio, $\overline{\eta}_i$ is the mean S/N ratio at the optimal testing parameter level and o is the number of main design process parameters that significantly affect the hardness performance of austempered gray iron (AGI). Table VI shows the comparison of the estimated hardness with the actual hardness (BHN) using the optimal condition. Good agreement seems to take place between the estimated and actual hardness. The improvement of S/N ratio from initial to optimal condition is 1.4063 dB.

Table VI
Confirmation Results Table

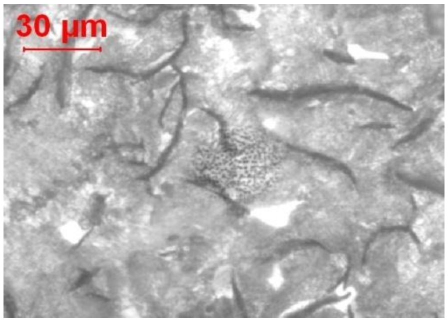
	Initial parameter	Optimal parameter	
		Predicted	Experimental
Level	A2B2T2	A2B1T2	A2B1T2
Hardness	330		388
S/N ratio (dB)	50.3703	51.63	51.7766

**Improvement of S/N ratio=1.4063 Db*

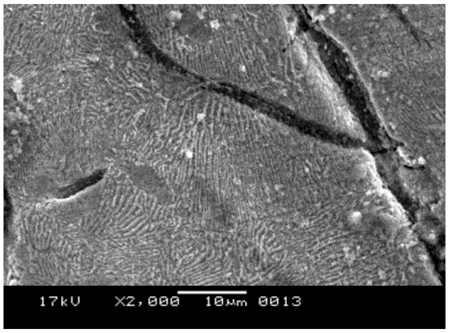
E. Microstructure

Microstructure of austempered gray cast iron (AGI) play a dominant role in determining the physical, mechanical and wears properties [3]. All the cast irons in this study showed pearlitic microstructure in the matrix in as-cast solidified condition (Figure 3). The pearlite lamellae in certain regions are coarse with wider distribution of ferritic phase (white phase). This may be the results of cast structure, where dendrite core has lead to coarser pearlite.

Figure 4, represents the specific types including-optimum, initial and other conditions of austempered microstructures (Table III, Sl No. 11, 14 & 17), which has austenitized at 905°C for 1hr and austempered at 270°C, 300°C and 330°C for 60 minutes quenched respectively. Due to austempering process, shows the ausferritic (γ) microstructure with sheaves of acicular ferrite needles in carbon stabilized austenite matrix in AGIs. It is observed that, improving the austempered ausferritic (γ) microstructure as well as hardness behaviour of AGI was also improved. It is also investigated that, hardness behaviour of AGI was noticeably improved due to the presence of austempered ausferritic (γ) austenite microstructure.



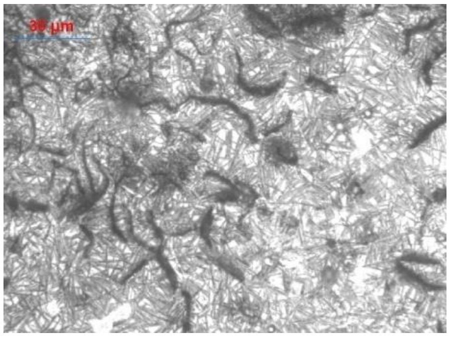
(a)



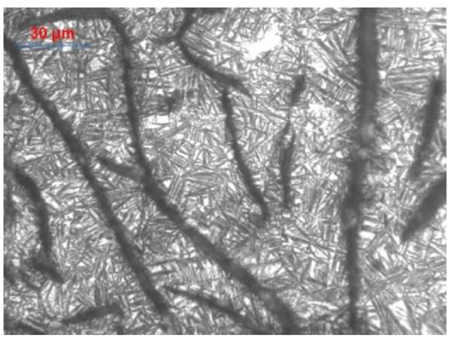
(b)

Figure 3 (a, b) Microstructure of an as-cast specimen: (a) Optical micrograph; (b) SEM micrograph

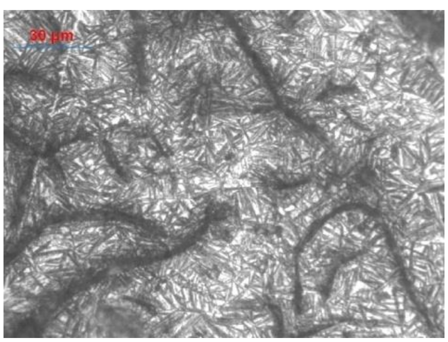
International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 5, November 2014)



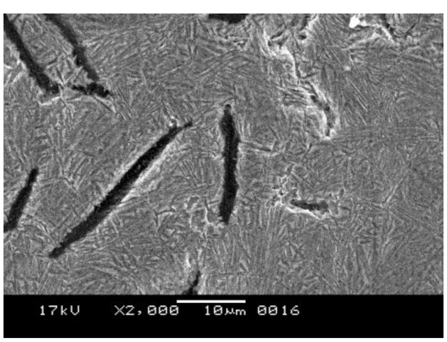
(a) Tγ = 905°C, T_A = 270° C



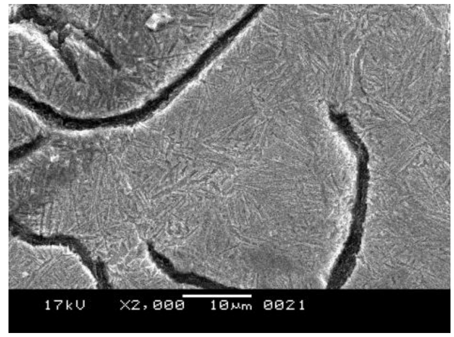
(b) Tγ = 905°C, T_A = 300° C



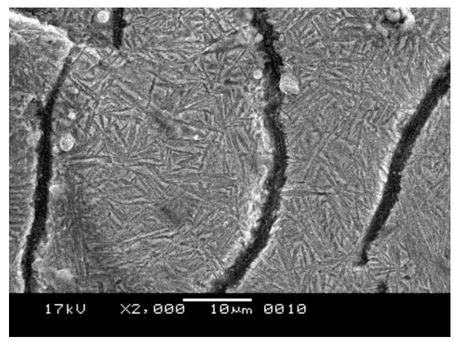
(c) Tγ = 905°C, T_A = 330° C



(d) Tγ = 905°C, T_A = 270° C



(e) Tγ = 905°C, T_A = 300° C



(e) Tγ = 905°C, T_A = 330° C

Figure 2 (a-c) and (d-f) are AGI's optical (500X) and SEM micrographs respectively

V. CONCLUSION

It is observed that, the hardness of as-cast and austempered gray iron's varied between 209-388 BHN and also observed that, the hardness of austempered gray iron (AGI) is decreases with increases the austempering temperatures.

From the experimental investigate, it can be concluded that due to austempering process both the microstructure as well as hardness behaviour of austempered gray irons (AGI) has improved.

Applying L_{27} Taguchi's method, the optimum result (388BHN) was obtained using the optimal combination's cycle of austempered process parameters of 905°C as austenitizing temperature, then 270°C as austempering and at 60 min isothermal quenching (A2B1T2).

From ANOVA, the austempering temperature (B) was found most influencing parameter with a contribution of 93.28% on BHN values while the quenching time (T) and austenitizing temperature (A) are 2.42% and 2.17% contribution respectively.

From the confirmation test it was found that the improvement of S/N ratio from initial to optimal testing condition for optimization of hardness (BHN) is 1.4063 dB.

Acknowledgments

This research work has been funded by UGC under RGNF scheme in 2011/12. The author is also thankful to Jadavpur University for providing infrastructure and administrative facility. The raw material has been provided by M/S Binay Udyog Pvt. Ltd, Howrah, The author is thankful to the entire person who directly and indirectly associated with this work.

REFERENCES

[1] ASM Metals Handbook. 1990. Properties and Selection Irons, Steel, and High-Performance Alloys (Cast Iron). 1. 38-41.

[2] Walton, C. F. and Opar, T. J. 1981. Iron Castings Hand book. Iron Castings Society, New York.

[3] Kovacs, B. V. and Keough, J. R. 1993. Physical Properties and Application of Austempered Gray Iron. AFS Transactions. 93, 283-291.

[4] Bedwell, T. J. and Miller, J.F. 2004. Austempered Gray Iron Cylinder Liner and Method of Manufacture. US Patent No. 6, 732, 698 B1.

[5] ASM Metals Handbook. 1991. Heat Treating. 4. 1485-1509.

[6] Goodrich, G.M. 2003. Iron Castings Engineering Handbook. American Foundry Society.

[7] VanMaldegiam, M. D. 1987. MS Thesis. Michigan Technological University.

[8] Rundman, K. B., Moore, D. J., Hayrynen, K. L., Dubensky, W. J. and Rouns, T. N.1988. On the Structure and Properties of Austempered Ductile Cast Irons. Journal of Heat Treating. 5, 79-85.

[9] ASM Metals Handbook. 1991. Heat treatment. 4, 1472-1473

[10] Yang, J. and Putatunda, S. K. 2004. Improvement in Strength and Toughness of Austempered Ductile Cast Iron by a Novel Two-Step Austempering Process. Materials and Design. 25, 219–230.

[11] Yang, J. and Putatunda, S. K. 2004. Influence of a Novel Two-Step Austempering Process on the Strain-Hardening Behavior Of Austempered Ductile Cast Iron (ADI), Materials Science and Engineering A. 382, 265-279.

[12] Gowri, S. 2013. Understanding Austempered Ductile Iron Process, Production, Properties and Applications - Part II. Indian Foundry Journal. 59, 54-57.

[13] Taguchi, G. 1990. Introduction to Quality Engineering. Asian Productivity Organization.

[14] Roy, R. K. 1990. A primer on Taguchi method. Society of Manufacturing Engineers. Michigan.

[15] Ghosh, S. and Sahoo, P. 2012. Friction Behavior of Medium Leaded Brass UNS C34000 Against Steel Using Taguchi Method. Academic Research Journals (India). 1, 77-87.

[16] Harvey, J. N. and Noble, G. A. 2007. Inoculation of Cast Irons- an Overview. 55th Indian Foundry Congress.

[17] Jezierski, J. Bartocha, D. 2007. Properties of Cast Iron Modifying With use of New Inoculants. Journal of Achievements in Materials and Manufacturing Engineering. 22, 25-28.

[18] Apelien, D., Paliwal, M. and Herrschaft, D. C. 1981. Casting with Zinc Alloys. Journal of Metals. 12-18.

[19] Fisher, R. A. 1951. Design of Experiments. Edinburgh: Oliver & Boyd.

[20] Taguchi, G. and Hocheng. 1987. Taguchi Methods Orthogonal Arrays and Linear Graphs, Tools for Quality Engineering. Dearborn, MI: American Supplier Institute. 35-38.

[21] Lindman, H. 1992. Analysis of Variance in Experimental Design. Springer-Verlag. New York.

[22] Ross, P. J. 1996. Taguchi Techniques for Quality Engineering, McGraw-Hill International Editions, Singapore.