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Multi-response optimization of carbidic austempered ductile iron production parameters using Taguchi technique

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This study presents optimal production parameters in the manufacture of carbidic austempered ductile iron [CADI] through melting route using Taguchi technique. To analyze effect of production parameters on mechanical properties, signal-to-noise (S/N) ratio was calculated based on design of experiments and analysis of variance (ANOVA) used to find the amount of contribution of factors on mechanical properties and their significance. Analytical results of Taguchi method were found identical with experimental values.

Keywords: Austempering, Taguchi method, Wear

Introduction

Austempered ductile iron[1,2] [ADI] has been studied for strength properties and applications of ADI. Strength to weight ratio of ADI being more than that of aluminium, ADI can replace aluminium where strength of component is to be considered for minimum weight. Wear resistance properties of ADI and its use as ploughshares, cam shafts, and agricultural implements and respects well have been investigated[3-5]. Wear resistance of ADI is more compared to forged steels, and hence ADI can replace many of the forged steel parts[5-9]. A new ADI, containing carbides in ausferrite matrix, has been introduced in the market as carbidic ADI [CADI]. CADI material[10,11] shows microstructure and abrasive wear resistance. Laino *et al*[12] studied combined effect of high cooling rate using copper chills and addition of carbide stabilizing elements in the production of CADI.

This study presents production of CADI by melting route, its austempering heat treatment parameters and their characteristics. Effect of CADI production parameters on mechanical parameters were studied by calculating total loss function and multi signal to noise (S/N) ratio.

Experimental Section

Taguchi Method

Taguchi method combines experimental and analytical concepts to determine most influential parameter on resulting response for significant improvement in overall performance. It uses a special design of experiments called orthogonal array (OA) to study entire process parameter space with a small number of experiments. Many studies have attempted to analyze and optimize single performance responses of various processes using Taguchi method[13-18]. But final results do not deliberately state the effect of process parameter on responses. Sun *et al*[19] assigned weight factor to different S/N ratios and optimal solution was obtained for foundry process variables.

Design of Experiment

Major factors having influence in the production of CADI are chromium content, austempering temperature and austempering time. Two levels in chromium content and four levels in austempering temperature and austempering time are selected (Table.1.) as factor levels. An appropriate OA is selected using Minitab -15 software based on the number of factors and its levels. This OA gives number of experiments to be conducted with their factor levels.

Table 1—Factors and levels –L_{16} (4^2x2^1)

Code	Factors	Levels 1	2	3	4
A	Austempering time, h	1	2	3	4
B	Austempering temp., °C	250	300	350	400
C	Chromium, %	0.6	1.0		

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Table 2—Chemical composition (wt%) of samples

Melt identification	C	Si	Mn	P	S	Ni	**Cr**	Mo	Cu	Mg	Zn	Fe
CADI -0.6	3.593	2.705	0.500	0.038	0.009	0.008	**0.630**	0.013	0.406	0.046	0.015	91.92
CADI - 1.0	3.372	2.745	0.458	0.034	0.008	0.010	**0.980**	0.018	0.644	0.039	0.013	91.72

Foundry Considerations for Production of CADI

Iron scraps & turnings are melted in a medium frequency induction furnace, and composition is adjusted by adding carbon & silicon and super heated up to 1540°C. Melt is magnesium (Mg) treated in a custom designed Mg treatment ladle. Mg alloy consists of MgFeSi (Mg, 9 wt%). Melt is transferred to pouring ladle and inoculated with FeSi (75 wt% Si). Calculated amount of heated ferrochrome is added to increase chromium level in pouring ladle. Sand mold is prepared using ordinary silica sand and dried. Melt is poured into prepared sand mold within desired temperature and time. Long time interval may fad Mg. Standard Y-block castings were prepared as per ASTM standards. Casting was done in a ductile iron foundry since any foundry producing ductile iron can make this CADI without altering production line. Sample composition was analyzed using 40 element vacuum spectrometer (Table 2). Cast material is called CDI before heat treatment.

Austempering Process (AP)

AP begins with austenitization followed by rapid cooling to austempering temperature and maintaining that temperature for longer period. Austenitization was carried in a salt bath (nitride & nitrate mix) at 910°C for 2 h. Salt bath distributes heat uniformly compared to atmospheric heating. In AP, quenching salt bath was held at a temperature above martensite start temperature. Austempering temperature was varied (250-400°C) in nitrate salt mix. Austempering time was varied (1-4 h) with a time interval of 1 h. After AP, specimens were cooled to room temperature (RT) in air quenching. This cooling rate will not affect final microstructure as carbon content of austenite is high enough to lower martensite start temperature to a temperature significantly below RT.

Characterization

Strength and Hardness

Brinell hardness tests were conducted using Model B-3000 Hardness tester with maximum load capacity of 30 KN. Impressions were formed using steel ball indenter (diam 10 mm) and 30 KN load. Hardness was measured at four different places and average of 4 values was taken for consideration. Impact toughness tests were conducted as per ASTM E 23 standard at room temperature using a Charpy Impact Testing Machine with 300 Joules capacity hammer and 4.5 ms^{-1} striking velocity. Tests were conducted on unnotched test samples (size, 10 mm x 10 mm x 55 mm).

Wear

Abrasion resistance of material was measured using Pin-on-disk wear testing machine as per ASTM standard G99-05. Disc hardness of HRC – 65, Load of 98.1N was applied to specimen, with a travel velocity of 1 m/s and a distance of 10,000 m was considered for measurement of weight loss. Weight loss values were measured using 0.01 mg precision scale. Weight loss of CADI material was converted into wear resistance and is called as relative abrasion resistance (RAR).

$$\text{Relative abrasion resistance} = \frac{\text{Weight loss of ADI}}{\text{Weight loss of CADI specimens}} \quad ...(1)$$

Results and Discussion

Orthogonal Array (OA)

Taguchi method provides laying out of experimental conditions using specially designed tables called OA. L_{16} (4^2 x 2^1) OA (Table 3) consists of 16 rows, each representing an experiment; columns are assigned to factors. Two levels in chromium content and four levels of austempering temperature and austempering time are selected as factor levels. Plan of experiments is made of 16 tests, in which first column is assigned to austempering time (A), second column to austempering temperature (B) and tthird column for chromium content (C). A linear graph is employed to identify suitable treatments and interactions of factors. Linear graph (Fig. 1) indicates that parameter effects should be considered and inclusion of interaction among parameters is not required.

Signal-to-Noise (S/N) Ratio

Taguchi method uses S/N ratio of responses in optimum parameter setting analysis, where S/N ratio is calculated for responses by considering higher the better

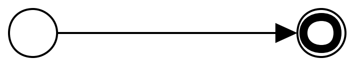

Fig.1—Linear graph for L_{16} (4^2x 2^1) OA

Table.3—L_{16} Modified orthogonal array

Trial No	Levels of input parameters A	B	C
1	1	1	1
2	1	2	1
3	1	3	2
4	1	4	2
5	2	1	1
6	2	2	1
7	2	3	2
8	2	4	2
9	3	1	2
10	3	2	2
11	3	3	1
12	3	4	1
13	4	1	2
14	4	2	2
15	4	3	1
16	4	4	1

category. S/N ratio is calculated from quality loss function (Table 4). S/N ratio consolidates several repetitions into one value, which reflects amount of variation present. Taguchi quality loss function (L_{ij}) of responses is given as

$$L_{ij} = \frac{1}{y_{ij}^2} \qquad ...(2)$$

where y_{ij} is performance respose of j^{th} trial of i^{th} performance.

Normalized quality loss function is computed because response measurements are in different units. Normalized quality loss function N_{ij} is calculated as

$$N_{ij} = \frac{L_{ij}}{\bar{L}_i} \qquad ... (3)$$

where $\bar{L}_i$ is average loss function and given as

$$\text{Average loss function } \bar{L}_i = \frac{1}{r}\sum_{j=1}^{n} L_{ij} \qquad ...(4)$$

Total quality loss function is calculated by assigning proper weighting factor to various normalized quality loss function. These weighting factors are to be decided based on priorities among responses. In this study, weighting factor (0.4) is assigned to RAR and 0.3 is assigned to impact toughness and hardness. Total loss function is given as

$$TL_j = \sum_{i=1}^{p} w_i N_{ij} \qquad ...(5)$$

where w_i is weight factor

Equation associated with higher the better S/N ratio is given as

$$\eta_j = 10\log(TL_j) \qquad ...(6)$$

Table 4—Loss functions and its S/N ratio

Expt no.	Measured responses y_{RAR}	y_{BHN}	y_{IT}	Loss functions L_{RAR}	L_{BHN}	L_{IT}	Normalized loss functions N_{RAR}	N_{BHN}	N_{IT}	Total loss function (TL_j)	Multi S/N ratio (?), dB
1	2.19	414	74	0.2085	5.83444E-06	0.0001826	0.3830	0.9024	0.0836	0.4490	3.4777
2	2.19	401	82	0.2085	6.21887E-06	0.0001487	0.3830	0.9618	0.0681	0.4622	3.3521
3	2.00	425	20	0.2500	5.53633E-06	0.0025000	0.4592	0.8563	1.1441	0.7838	1.0579
4	4.11	435	12	0.0593	5.28471E-06	0.0069444	0.1089	0.8174	3.1782	1.2422	-0.9420
5	1.78	387	38	0.3172	6.67695E-06	0.0006925	0.5826	1.0327	0.3169	0.6379	1.9524
6	0.93	380	60	1.1678	6.92521E-06	0.0002778	2.1451	1.0711	0.1271	1.2175	-0.8547
7	1.10	444	12	0.8340	5.07264E-06	0.0069444	1.5319	0.7846	3.1782	1.8016	-2.5566
8	1.53	420	14	0.4284	5.66893E-06	0.0051020	0.7868	0.8768	2.3350	1.2783	-1.0662
9	2.43	495	19	0.1689	4.08122E-06	0.0027701	0.3102	0.6312	1.2677	0.6938	1.5878
10	4.00	444	18	0.0625	5.07264E-06	0.0030864	0.1148	0.7846	1.4125	0.7050	1.5178
11	0.67	337	84	2.2250	8.80522E-06	0.0001417	4.0868	1.3619	0.0649	2.0627	-3.1444
12	0.84	311	86	1.4131	1.0339E-05	0.0001352	2.5956	1.5991	0.0619	1.5365	-1.8654
13	3.01	474	18	0.1101	4.45085E-06	0.0030864	0.2022	0.6884	1.4125	0.7112	1.4803
14	1.60	444	20	0.3894	5.07264E-06	0.0025000	0.7153	0.7846	1.1441	0.8647	0.6312
15	1.26	352	70	0.6264	8.07076E-06	0.0002041	1.1506	1.2483	0.0934	0.8628	0.6411
16	2.03	311	64	0.2417	1.0339E-05	0.0002441	0.4440	1.5991	0.1117	0.6908	1.6063

Table 5—Mean effect response table of S/N ratio

Symbol	Source of variance	Mean multi response S/N ratio, dB					Rank
		Level-1	Level-2	Level-3	Level -4	Max.-Min	
A	Austempering time	1.7364	-0.6313	-0.4760	1.0897	2.3677	2
B	Austempering temperature	2.1246	1.1616	-1.0005	-0.5668	3.1250	1
C	Chromium content	0.6456	0.2138	-	-	0.4319	3
Total mean value of S/N ratio = 0.4297 dB							

A high value of S/N ratio indicates that signal is higher than random effects of noise factors. Largest multi-response S/N ratio (Table 4) is optimum level. Experiment one among 16 experiments has the best multi performance characteristics for highest S/N ratio. Levels of best performance experiment for austempering are: time ($A_1B_1C_1$), 1 h; temp., 250°C; and chromium, 0.6%.

Data Analysis

An average effect of factors (Table 5) is the difference between the highest and the lowest S/N ratio averages for the factor chosen. Ranks (Table 5) based on delta statistics compare relative value of effects. Rank1 indicates that austempering temperature has more influence on responses compared to other parameters. Optimum level of factor gives highest average S/N ratio. $A_1B_1C_1$ is optimum level of factor in these experiments (Fig. 2). Chromium content is reciprocal with the levels; remaining two are reciprocal and proportional with levels. Slope of chromium content is less, indicating that influence of chromium content on property change is low. At lower levels, effect of austempering time and at higher levels effect of austempering time is more. Chromium, the carbide stabilizer, increases carbides in material, which is harmful to mechanical properties of ductile iron. Higher and longer austempering generates upper bainite matrix, which has low combination of strength compared to the lower bainite.

Sample Calculations

$L_i = \frac{1}{r}\sum_{j=1}^{n} L_{ij}$=1/16(0.2085+0.2085+0.2500+0.0593 +0.3172+1.1678+0.8340+0.4284+0.1689+0.0625+ 2.22 = 50+1.4131+0.1101+0.3894+0.6264+0.2417) =0.5444.

$N_{ij} = \frac{L_{ij}}{L_i}$ = 0.2085/0.5444 = 0.3830.

$TL_j = \sum_{i=1}^{p} w_i N_{ij}$= 0.4*0.3830+0.3*0.9024 +0.3*0.0836 = 0.4490

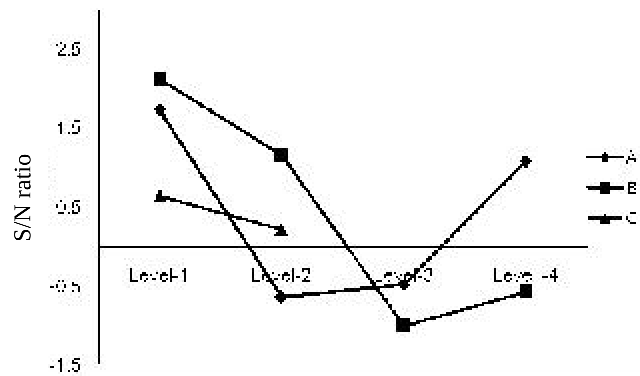

Fig.2—Effect of levels on multi response S/N ratio

$\eta_j = 10\log(TL_j)$ = 10*log (0.4490) = 3.477.

Multiple Regression Analysis (MRA)

MRA is used to form relationship among factors and responses. Most frequently used method is linear regression equation as

$$Y= a+b_1X_1+b_2X_2+b_3X_3+\ldots\ldots\ldots +b_kX_k \quad \ldots(7)$$

where Y is dependent variable; X_1, X_2, X_3 ..... X_k are predictors; and a, b_1, b_2, b_3 ...... b_k are coefficients. Values of coefficients are calculated using SPSS software.

Mathematical model for hardness, relative wear resistance and impact toughness are given as

Hardness = 408 + 5.86 *A - 0.525 *B +194* C …(8)

Wear resistance = 1.37 - 0.127 *A -3.20 X10^{-3} *B+2.47*C …(9)

Impact toughness = 133 + 0.87*A+ 0.0435*B-133*C …(10)

Hardness, wear resistance and impact toughness of materials can be predicted for any given values of process parameters using Eqs (8)-(10).

Analysis of Variance (ANOVA)

ANOVA establishes significance of factors in terms of contribution (%) to response and is also needed for

Table 6—ANOVA

Symbol	Source of variance	DOF	Sum of squares	Mean square	F-Statistics	F,95%	P (%)
A	Austempering time	3	16.3566	5.4522	8.2531	3.01	28.02
B	Austempering temperature	3	25.7868	8.5956	13.0114	3.01	44.18
C	Chromium content	1	0.3730	0.3730	0.5646	4.26	0.64
	Error	24	15.8549	0.6606			27.16
	Total	31	58.3713				100

estimating variance of error for the effects and confidence interval of prediction error. F-statistics of factors shows that austempering time and austempering temperature are significant at 95% confidence level. Austempering temperature contributes maximum, and next is austempering time (Table 6). austempering temperature decides mobility of carbon atoms and formation of austenite in CADI matrix. So this affects mechanical properties of material. On the other hand, influence of chromium content is negligible. Error term also contributes more due to interaction of parameters.

Conclusions

CDI castings were made by adding chromium in the melt. This is austempered to form CADI. Austempering temperature is the most significant and maximum contributing parameter. Chromium content is the least significant factor. $A_1B_1C_1$ is optimum level of factor in this experiment. Optimal parameter calculated by Taguchi method coincides with experimental results.

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References

1 Gundlach R B & Janowak J F, Development of a ductile iron for commercial austempering, *AFS Trans*, **94** (1983) 377-388.

2 Hayrynen K L, ADI: Another avenue for ductile iron foundries, *Mod Cast*, **8** (1995) 35-38.

3 Trudel A & Gagne M, Effect of composition and heat treatment parameters on the characteristics of austempered ductile irons, *Canad Metallurg Quart*, **36** (1997) 289-298.

4 Brezina R, Filipek J & Senberger J, Application of ductile iron in the manufacturing of ploughshares, *Res Agric Engg*, **50** (2004) 75-80.

5 Zimba J, Simbi D J & Navara E, Austempered ductile iron: an alternative material for earth moving components, *Cement & Concrete Composites*, **25** (2003) 643-649.

6 Batra U, Ray S & Prabhakar S R, The influence of nickel and copper on the austempering of ductile iron, *J Mater Eng Performance*, **13** (2004) 64-68.

7 Eri O, Rajnivic D, Sidjanin L, Zec S & Jovanovic M T, An austempering study of ductile iron alloyed with copper, *J Serb Chem Soc*, **70** (2005) 1015-1022.

8 Rao P P & Putatunda S K, Investigations on the fracture toughness of austempered ductile irons austenitized at different temperatures, *J Mater Sci Engg*, **A 349** (2003) 136-149.

9 Dhanapal P, Premkumar R & Nazirudeen S S M, A study on the influence of heat treatment on the wear resistance of alloyed Austempered Ductile Iron, *Indian Foundry J*, **55** (2009) 32-38.

10 Hayrynen K L & Brandenberg K R, Carbidic Ductile iron (CADI) – The New wear material, *AFS Trans*, **5** (2003) 3-8.

11 John R K & Kathy L H, Carbidic Ausempered Ductile iron (CADI), Presented at DIS Meeting, 14 November 2000.

12 Laino S, Sikora J A & Dommarco R C, Development of wear resistant carbidic austempered ductile iron (CADI), *Wear*, **265** (2008) 1-7.

13 Seong J K, Kwang S K & Ho J, Optimization of manufacturing parameters for a break lining using Taguchi method, *J Mater Process Technol*, **136** (2003) 202-208.

14 Kumanan S, Edwin R D J & Gowthaman K, Determination of submerged arc welding process parameters using Taguchi method and regression analysis, *Indian J Eng Mater Sci*, **14** (2007) 177-183.

15 Rossella S, Luigi A, Antonio D & Giancarlo, Application of Taguchi method for the multi-objective optimization of aluminium foam manufacturing parameters, *Int J Mater Form*, **3** (2010) 1-5.

16 Osama M, Haitham R S & Hussam L A, Using of Taguchi method to optimize the casting of Al-Si / Al_2O_3 composites, *Engg &Tech J*, **27** (2009) 1143-1150.

17 Jadoun R S, Kumar P & Mishra B K, Taguchi's optimization of process parameters for production accuracy in ultrasonic drilling of engineering ceramics, *Prod Engg Res Dev*, **3** (2009) 243-253.

18 Parashar V, Rehman A, Bhagoria J L & Puri Y M, Investigation and optimization of surface roughness for wire cut electro discharge machining of SS304L using Taguchi dynamic experiments, *Int J Engg Stud*, **1** (2009) 257-267.

19 Zhizhong S U N, Henry H U, Xiang, Q & Wenying Y, Gating system design for a magnesium alloy casting, *J Mater Sci Technol*, **24** (2008) 93-95.