Austempering Heat Treatment of AISI 4340 Steel and Comparative Analysis of Various Physical Properties at Different Parameters

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Abstract— **In this study a special heat treatment process named austempering on AISI 4340 steel is carried out. Heat treatment on steel is carried out to enhance mechanical properties. In this regard, it is considered essential to undertake a study to evaluate different changes occurred in AISI 4340 steel in terms of hardness, tensile strength and impact strength at different austempering temperatures and cooling times and achieving the best combination of these improved mechanical properties for better and optimum utilization of this grade of steel. By using software Design Expert DOE is formulated with Taguchi orthogonal arrays comprising of L18 (3*3) with 03 factors and 03 responses to be calculated. Results of experiments are analyzed via Taguchi method. Signal to noise ratio of responses are carried out to determine the significant factors among the 03 factors chosen for experimental runs. Overall analysis showed that impact factor along with hardness is improved to great extent by austempering process.**

***Keywords*— Austempering Temperature, AISI 4340 Steel, Bainite and TAGUCHI**

I. INTRODUCTION

AISI 4340 is a medium carbon steel with a carbon content ranging from 0.38 to 0.43 % Carbon and usually referred as nickel - chromium – molybdenum high tensile steel. AISI 4340 are used widely in aircraft, particularly in critical applications such as landing gears, as a structural steel for aircrafts and also in automobiles (military as well as commercial), aerospace equipments, shafts, crank shafts, connecting rods, heavy duty axels etc [1]. Steels can be heat treated to high hardness and strength levels by using variety of methods [2]. Structural components of aircrafts, automobiles etc subjected to high operating stress need the high strength and need resist wear and deformation. Austempering of steel has a wide range of industrial application and can be well substituted by conventional quench and temper process due to following major advantages [3]-[4].

- To enhance mechanical properties of hardness.
- To enhance and improve impact strength and ductility of materials.
- Improve resistance against subsequent embrittlement.
- To improve wear resistance of materials.
- To reduce the surface cracking and distortion during heat treatment

Austempered steels have many industrial applications due to improved mechanical properties. Austempering is a nontraditional heat treatment technique in which bainite is obtained in microstructure of steel. In austempering process to avoid the formation of pearlite or martensite, the steel is quenched in a bath of molten metal's or salts. This quickly cools the steel and let it pass away that point where pearlite can be formed resulting into achieving the bainite-forming range. The steel is then held at the bainite-forming temperature in the molten salt bath till bainite structure fully forms. The steel is then taken out of salt bath and allowed to cool in air. Austempering process can produce either upper or lower bainite depending on temperature rate [5]. For T ~ 300-540°C upper bainite will be formed. For T ~ 200-300°C, lower bainite will be formed. The austempering cycle will comprise of following steps [6]-[7]:

- Heating the steel to a temperature within the austenitizing range, usually 790 to 915 °C for one hour.
- Quenching in a molten salt bath of $NaNO_3$ maintained at a constant temperature, usually in the range of 260 to 400 °C.
- Allowing the steel to transform isothermally to bainite in this bath for certain time duration.
- Cooling it to room temperature, usually in still air.

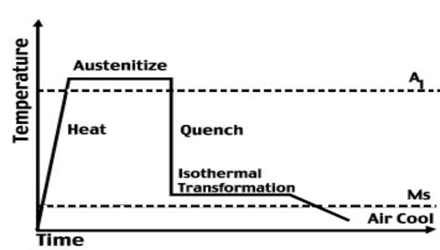


Fig. 1: Schematic diagram for austempering process

II. EXPERIMENTAL PROCEDURES

The material used for study is AISI 4340 steel. Three types of mechanical testing are required to be carried upon samples of AISI 4340 which are austempered. For each test a specific shape and size of specimen is to be prepared. The tests include impact testing, tensile testing and hardness testing. Samples of AISI 4340 purchased from local market are in raw form of metallic bars and rods. The bars and rods are converted to specified samples as per required dimensions according to *ASTM* A370 by undergoing it through machining process of lathe and finishing them in end. The spectro graphic analysis of AISI 4340 steel was conducted in the start of study to analyze the chemical composition of steel being used the result showed following composition:

Chemical composition (Wt %)							
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
0.42	0.2	0.6	0.035	0.04	0.75	0.25	1.8

A) Ms (Martensite Start Temperature) for AISI 4340

Determination of Ms or Martensite start temperature for a certain grade of steel prior undergoing heat treatment process on that is very important. A number of techniques and empirical formulae are available in literature to calculate martensite start temperature [8]:

We can calculate Ms using formulae. We have used 03 different empirical formulae for calculations and the result is then averaged to get an average Ms Temperature range for our samples.

Choosing formula of Grange and Stewart:

$Ms = 538 – (361×\%C) – (39 ×\%Mn) – (19 ×\%Ni) – (39 ×\%Cr)$ (in °C)

$Ms = 538 – (361×0.42) – (39 × 0.72) – (19 × 1.74) – (39 × 0.78)$ (in °C)

$Ms= 538 - 151.62 - 28.08 - 33.06 - 30.42$

$Ms= 294.82$

Choosing formula of Nehrenberg:

$Ms = 500 – (300 ×\%C) – (33×\%Mn) – (22×\%Cr) – (17×\%Ni) – (11×\%Si) – (11×\%Mo)$ (in °C)

$Ms = 500 – (300× 0.42) – (33×0.72) – (22×0.78) – (17×1.74) – (11×0.28) – (11×0.22)$ (in °C)

$Ms= 500 – 126 - 23.76 - 17.16 - 29.58 - 3.08 - 2.42$

$Ms=298$

Choosing formula of Steven and Hans:

$Ms = 561.1 – (473.9*\%C) – (21.1*\%Mn) – (16.7*\%Ni) – (16.7*\%Cr)$ (in °C)

$Ms = 561.1 – (473.9 ×0.42) – (21.1×0.72) – (16.7×1.74) – (16.7×0.78)$ (in °C)

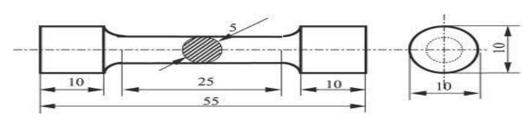
$Ms= 561.1 - 199.04 - 15.192 - 29.058$

$Ms=304.78$

An average value of 300 °C for Ms (Martensite start temperature) of AISI 4340 samples is obtained. After determination of Ms, the temperature range for austempering temperature can be determined and chosen for salt bath (quenching medium) temperature in which the samples will be quenched. 03 temperature ranges above the Ms Temperature i.e., 320, 350, 380 °C are considered.

B) Samples Preparation

Samples of AISI 4340 purchased from local market are in raw form of metallic bars and rods. The bars and rods are converted to specified samples as per required dimensions according to *ASTM* A370 by undergoing it through machining process of lathe and finishing them in end. The exact dimension and configuration of samples are mentioned below for impact testing and tensile testing.



Tensile test specimen

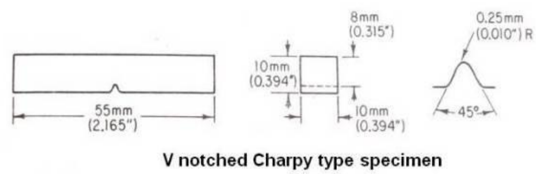


Fig. 2: Samples for tensile test and Impact strength test

C) Design of Experiments

Taguchi method is a problem solving tool which can improve 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. Preliminary tests without undergoing austempering process on samples using portable hardness tester EQUOTIP 3, Charpy test and tensile test via Houns-Field Tensometer gave following results:

Hardness: 298 BHN
Impact Toughness: 66 Joules
Tensile Strength: 980 MPa

D) Orthogonal Array

The Taguchi method provides laying out the experimental conditions using specially designed tables called Orthogonal Array (OA) [10]. An appropriate choice of orthogonal array depends upon the degrees of freedom. In our study 03 factors austenizing temperature, austempering temperature and soaking time is considered and 03 responses hardness, impact strength and tensile strength are measured. The three factors each consists of three levels i.e., Austenizing temperature (830,850,870), austempering temperature (320,350,380) and soaking time (30,60,90) are considered. The Taguchi orthogonal array of L18(3×3) i.e., 03 factors with 03 levels is chosen for experimental runs.

E) Austempering of AISI 4340

Two furnaces are used for austempering process. The samples are first heated to austenizing temperature in heat treatment furnace at temperatures of 830,850 and 870 ^{o}C in order to get austenite in microstructure of steel .the samples remain at these temperatures for one hour. The austenized AISI 4340 at mentioned temperatures are then quickly transferred to salt bath furnace with salt bath of nitrate-nitrate salt. In this research sodium nitrate + potassium nitrate in a mixture of 50% + 50% by weight is used. The samples are heated in salt bath furnace at austempering temperature range of 320^{o}C, 350^{o}C and 380 ^{o}C. The time of soaking is also other factor considered for our experimental; runs so these samples are dipped in salt bath at austempering temperatures for 30 min, 60 min and 90 minutes. The samples are finally taken out from salt bath furnace after its designed soaking time in salt bath and allowed to cool in open air. The austempered samples are then tested for mechanical properties.

III. RESULT AND ANALYSIS

The experimental runs comprising of eighteen set of experiments were conducted as per devised DOE by Taguchi method. The results obtained via each experiment were tabulated in the following format:

Table 1: Experimental Runs Data

Experiment RUNS	Austenizing Temperature °C	Austempering Temperature °C	Soaking Time Minutes	Hardness HRC	Impact strength Joules	Tensile strength MPa
1.	830	320	30	373	79	1185
2.	830	320	60	377	82	1190
3.	850	350	60	392	80	1258
4.	850	320	90	376	88	1225
5.	870	320	90	382	86	1226
6.	850	350	90	384	86	1235
7.	870	350	60	392	78	1260
8.	870	350	90	382	84	1230
9.	870	320	60	382	81	1227
10.	850	320	60	379	83	1194
11.	870	380	30	378	79	1216
12.	870	380	60	390	79	1252
13.	830	380	60	390	82	1250
14.	830	350	60	388	82	1245
15.	850	380	60	391	78	1255
16.	850	380	30	382	81	1228
17.	830	350	90	383	87	1232
18.	830	380	90	380	87	1212

Graphical Representation:

The graphical representation of all three factors vs. the responses are discussed in detail along with the trend it is following:

Graphical Representation for Hardness:

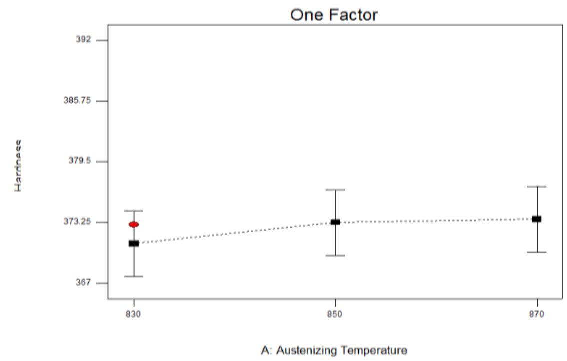


Fig. 3: Hardness Vs Austenizing temperature

The graph shown above represents the overall effect on hardness of samples due to austenizing temperature during all experimental runs. With the increase in austenizing temperature hardness tends to improve. The graph shows that the change brought by austenizing temperature is not so significant as the range of change is very small.

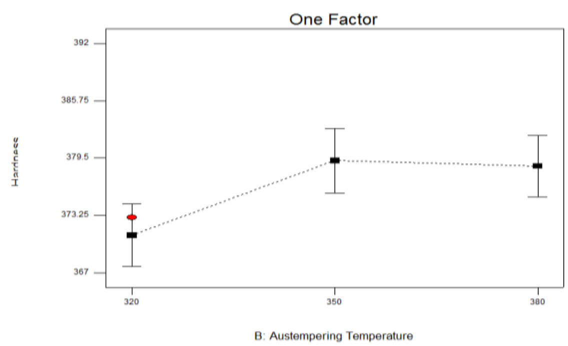


Fig. 4: Hardness Vs Austempering temperature

The graphical representation shows that improvement in hardness is observed till austempering temperature of 350 ^{o}C but with further increase in temperature the trend shows a decline in hardness. The formation of lower bainite occurs from 300 to 350 ^{o}C. During this time period martensite microstructures are also present along with austenite which imposes more hardness and overall lower bainite are much harder than upper bainite. As austempering temperature increases from 350 ^{o}C, upper bainite start forming which is lower in hardness properties than the lower bainitic structures.

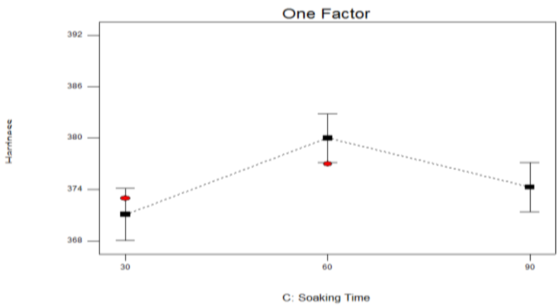


Fig. 5: Hardness Vs Soaking Time

The graphical representation shows here that soaking time has great influence upon the hardness of AISI 4340 samples. As time increses till one hour there is a direct relation regarding increase in hardness but as time is further extended to 90 minutes there is inverse relation observed with decrease in hardness properties. The soaking time of samples in salt bath gave necessary transformation of austenite into lower bainite and further upper bainite microstructures. The increase in hardness is due to presence of lower bainite and as formation of upper bainite takes place the hardness tends to decrese with time.

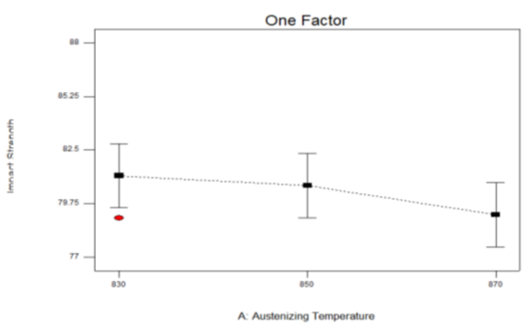


Fig. 6: Impact Strength Vs Austenizing temperature

Austenizing temperature and impact strength has indirect relation with each other. The impact strength tends to slightly decrease with increase in austenizing temperature. The decrease in the impact strength is due to microstructure changes within samples of AISI 4340. However this decrease due to austenizing temperature is not so prominent as the range of change is very small.

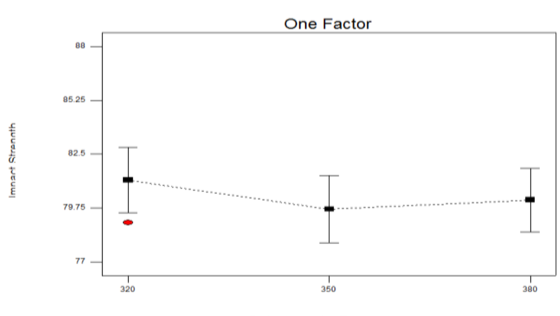


Fig. 7: Impact Strength Vs Austempering temperature

Austempering temperature has slightly significant effect upon strength as it shows slightly decrease than increase with increasing austempering temperature. As discussed previously upto temperature range of 350 ^{o}C due to austempering process lower bainite are formed in microstructure which are better in hardness but lower in impact strength. As temperature exceeds 350 ^{o}C upper bainite structures are obtained which are greater in impact toughness. Hence the impact strength decreases till 350 ^{o}C and an increase in impact toughness observed till 380 ^{o}C from 350 ^{o}C.

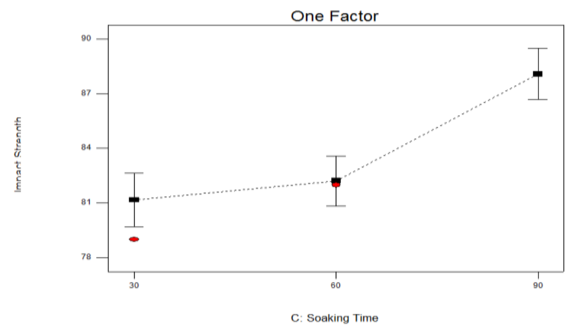


Fig. 8: Impact Strength Vs Soaking time

The graphical representation shows that soaking time has great effect upon impact strength. With increase in time of soaking in salt bath impact strength observed improved. Marked improvement in impact strength observed due to increase in soaking time. This is due to sufficient time provided to transform lower bainite to upper bainite completely as time period is enhanced.

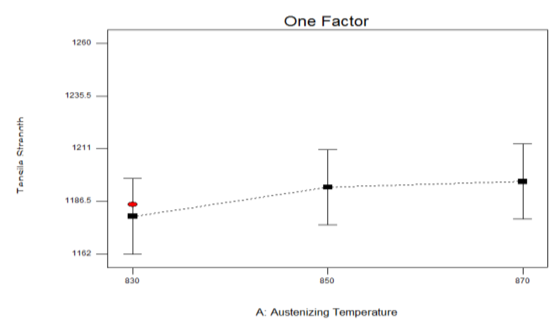


Fig. 9: Tensile Strength Vs Austenizing temperature

The tensile strength is increased with austenizing temperature. A direct relationship is observed between tensile strength and austenizing temperature. The amount of increase is not so significant.

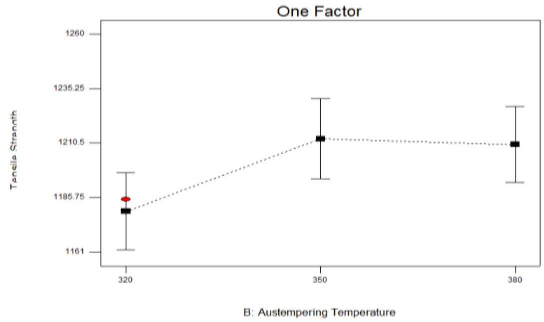


Fig. 10: Tensile Strength Vs Austempering temperature

Tensile strength graph shows an increase in strength with austempering temperature till 350 ^{o}C. But after that it shows little decrease with increase in austempering temperature. Tensile strength is sometimes referred as directly proportional to hardness. Same reason lies here for this case as was for hardness. The formation of lower bainite till 350 ^{o}C cause increase in hardness and subsequently tensile strength and as the temperature increased further the formation of lower bainite cause decrease in tensile strength.

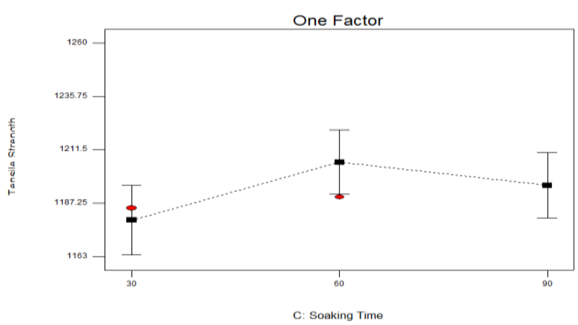


Fig. 11: Tensile Strength Vs Soaking time

The tensile strength increase with soaking time but with extended immersion in salt bath results in decrease in strength due to formation of upper bainite in its microstructure which posses good impact strength but lower hardness and tensile properties.

IV. CALCULATIONS

Signal-to-Noise (S/N) Ratio:

Signal-to-noise ratio where signal represents the desirable value and the noise represents the undesirable value [10]. Therefore, the S/N ratio consolidates several repetitions into one value, which reflects the amount of variation present. There are three S/N ratios available, higher is the better (HB) is used for all three responses found out i.e., hardness, Impact toughness, and tensile strength.

S/N_{HB} = -10 Log_{10} [mean of sum squares of reciprocal of measured data]

Table 2: Signal to Noise Ratio

Experimental Runs	S/N Ratio Hardness	S/N ratio Impact strength	S/N ratio Tensile strength
1.	51.434	37.952	61.474
2.	51.526	38.276	61.1511
3.	51.865	38.062	61.199
4.	51.503	38.889	61.176
5.	51.6413	38.689	61.177
6.	51.686	38.689	61.833
7.	51.865	37.842	62.007
8.	51.6412	38.485	61.798
9.	51.6413	38.169	61.776
10.	51.5727	38.382	61.54
11.	51.549	37.953	61.698
12.	51.8212	37.953	61.952
13.	51.8212	38.276	61.938
14.	51.776	38.276	61.90338
15.	51.8435	37.842	61.9728
16.	51.6413	38.169	61.784
17.	51.664	38.7903	61.8122
18.	51.595	38.7903	61.67005

RESPONSE TABLES

Response Table for Hardness:

Table 3: Hardness response Table

Factors		Signal to noise ratio averages			Max-Min	Rank
Parameters	Levels	Level 1	Level 2	Level 3		
Austenizing Temp	830,850, 900	51.636	51.685	51.693	0.057	3
Austempering Temp	320,350, 380	51.5531	51.7495	51.71186	0.1964	2
Soaking Time	30,60,90	51.5414	51.7479	51.6217	0.2056	1

Response Table for Impact Strength:

Table 4: Impact strength Response Table

Factors		Signal to noise ratio averages			Max-Min	Rank
Parameters	Levels	Level 1	Level 2	Level 3		
Austenizing Temp	830,850 ,900	38.3934	38.3388	38.1818	0.2116	3
Austempering Temp	320,350 ,380	38.3928	38.3574	38.16388	0.229	2
Soaking Time	30,60,90	38.02466	38.11977	38.7221	0.697	1

Response Table for Tensile Strength

Table 5: Tensile Strength Response Table

Factors		Signal to noise ratio averages			Max-Min	Rank
Parameters	Levels	Level 1	Level 2	Level 3		
Austenizing Temp	830,850,900	61.658	61.60	61.74	0.140	3
Austempering Temp	320,350,380	61.3824	61.7588	61.834	0.4516	1
Soaking Time	30,60,90	61.6522	61.72	61.577	0.143	2

V. FINDINGS

The overall analysis of results shows following important developments:

- The highest reading for hardness was observed in experiment run No.7 in which hardness value of 392 BHN was obtained.
- The highest value for impact strength was observed in experiment No.4 in which impact strength of 88 Joules was obtained.
- The highest value for tensile strength was observed in experiment No. 7 in which tensile strength of 1260 MPa was obtained.
- The overall best values observed in experiment run No.17 with Hardness of 383 BHN, impact strength of 87 Joules and tensile strength of 1232 MPa.

Following percentage improvement in terms of Hardness, impact strength and tensile strength of AISI 4340 steel samples was observed keeping in view the initial values prior undergoing austempering heat treatment process and final values after they were austempered:

Table 6: Percent Improvement in Mechanical Properties

Response	**Initial Values**	**Final Values**	**% Improvement**
Hardness	298 BHN	383 BHN	28.5 %
Impact strength	66 Joules	87 Joules	**31.81%**
Tensile strength	980 MPa	1232 MPa	25.7%

The impact strength was improved up to 31.81 % which is indeed a great improvement for this grade of steel to be applied in aerospace industry where high impact strength is needed. Moreover along with impact strength, hardness and tensile strength properties are also improved to 28.5 % and 25.7 % which are also a good improvement.

VI. CONCLUSION AND SUMMARY

Austempering process carried upon samples of AISI 4340 improved a lot overall mechanical properties of samples. Especially great improvement in impact strength was observed. Analysis of results showed that hardness was affected greatly by austempering temperature and soaking time, impact strength greatly affected by soaking time and tensile properties affected greatly by austempering temperature. Overall the major variation in mechanical Austempering process carried upon samples of AISI 4340 improved mechanical properties of samples to a great extent. Especially great improvement in impact strength was observed. Analysis of results showed that hardness was affected greatly by austempering temperature and soaking time, impact strength greatly affected by soaking time and tensile properties affected greatly by austempering temperature.

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REFERENCES

[1]. Hebsur M, Recent attempts of improving the mechanical properties of AISI 4340 steel by control of microstructure - A brief review, *Journal of Materials for Energy Systems*. Vol. 4, No. 1, pp 2837, 1982.
[2]. Http://en.wikipedia.org/wiki/Austempering.
[3]. Steel Heat Treatment Hand Book Second Edition. George E Totten.
[4]. Steels: Heat Treatment And Processing Principles. G.Krauss.
[5]. Bainite in steels, 2nd edition bhadeshia, h. K. D. H, (2001)
[6]. Putatunda, s. K. (2003). Influence of austempering temperature on microstructure and fracture toughness of a high-carbon, high-silicon and high-manganese cast steel. Material and design , p. 435–443.
[7]. Heat treatment : principles and techniques by t. V. Rajan, sharma c. P., ashok sharma
[8]. Iron Making and Steel Making 1996, Vol. 23, No. 5 page. 433
[9]. P. Dhanapal Parameter Optimization Of Carbidic Austempered Ductile Iron Using Taguchi Method, International Journal of Engineering Science and Technol0gy Vol. 2(8), 2010, 3473- 3474.
[10]. Design of Experiments Using the Taguchi Approach By Ranjit K. Roy.