

Optimizing Wear Resistance in Carbide Austempered Ductile Iron through Austempering Parameter Variation

Srinivasu.N¹, Dr Mk Murulidhara², Dr Mahendra .Kv³

¹Research scholar VTU Mechanical Department, RR Institute of Technology, Bangalore – 90/Asst professor

Dr Ambedkar Institute of Technology, Bangalore - 56

²Mechanical Department, RR Institute of Technology, Bangalore – 90

³Mechanical Department, RR Institute of Technology, Bangalore – 90

Abstract — Austempered ductile iron (ADI), as implied by its name, is a variant of ductile iron known for its enhanced strength and toughness compared to cast iron. Distinguishing itself from cast iron, ductile iron exhibits higher strength and toughness, particularly in tensile tests. The nomenclature "Austempered" in ADI stems from its unique heat treatment process called Austempering. While numerous research journals delve into the wear resistance of Compacted Graphite Iron (CGI) materials, there is a notable gap in understanding the correlation between Austempering temperature and abrasion properties. Material wear is influenced by various factors within the application environment, broadly categorized as time, load, and speed. This journal provides a comprehensive exploration of how these variables collectively impact the wear characteristics of Austempered ductile iron.

Index Terms — Austempered ductile iron, Taguchi analysis, Wear test, pin on disk wear testing machine, Anova analysis.

I. Introduction

The markets for austempered ductile iron had quickly and steadily started to increase in early 1970's. Still the industry is finding difficulties in applying this material for their products. Reason behind this is lack of reliable data for production.

Since the use of appropriate temperature for Austempering and bringing desirable effects were restricted to research community, an effort is made to understand relationship between wear and heat treatment temperature. It is fair to say, this production technique is low-cost manufacturing comparing to number of mechanical advantages it imparts to the material. Austempering heat treatment brings about a microstructure called ausferrite. Adequate amount of carbon enriched austenite will impart optimal properties of ADI material.

Carbide austempered ductile iron (CADI) is a class of ADI having higher carbon composition comparatively. CADI initially developed in United States in 2011, then after it always been a area of research and development. Most of the industries are trying to adopt CADI for their applications as it said to be indicating excellent wear resistance/ Abrasion resistance, reason behind which is proved to be the free carbides present in its molecular structure. In this journal efforts are made to understand this adage.

Ii. History And Production Of Adi

It all started in 1971, when ADI is manufactured at Czechoslovakia and used for applications such as tractor shovel and diesel engines. In 1977, a multination automotive manufacturing corporation called General Motors made effort of applying ADI in replacement to their steel material product for automobile parts. In 1983, American multinational corporation Cummins Engineering co-operation used ADI in their automobile engines. As the global warming and other environmental effects are pushing the manufacturers to switch to high mechanical strength compared to weight materials.

A. What is CADI (Carbide Austempered Ductile Iron)?

Carbide Austempered Ductile iron as name indicates, it's a form of ductile iron which has high amount of carbides. CADI can be produced by Austempering ductile cast iron.

B. What is Austempering?

Austempering in simple words is a heat treatment process for cast iron and its family of materials. During this heat treatment process microstructure of material changes due to which it imparts superior performance to weight ratio.

iii. Chemical Composition

Usually, ductile cast iron is composed of 95% of iron, 3.2 to 3.6% of carbon and other element in decimal percentages. For our experiment we casted our material with following composition.

Element	% Composition
Iron	95.90%
Carbon	3.58%
Manganese	0.31%
Chromium	0.10%
Phosphorus	0.01%
Silicon	0.02%
Copper	0.06%
Nitrogen	0.02%
Molybdenum	0.01%
Magnesium	0.03%

Table 1: Element composition

Ductile iron is alloyed with Manganese which combines with sulphur to prevent brittleness. Also, Manganese allows quenching of steel in Oil rather than water, which avoids distortion and cracks. Manganese and Molybdenum increase the hardenability of steel. Chromium increases toughness and wear resistance. Whereas silicon increases ferrite strength.

iv. Research Elaboration

The material procured as per mentioned composition is then proceeded for heat treatment phase. To obtain austempered ductile iron, we have to follow three major steps in heat treatment. They are Austenitising, Quenching and Austempering.

Our materials are divided into six sections. All six sections had same Austenitising temperature of 900°C with Austenitising time of 120 mins. But each section had different Austempering temperature and time as tabulated below.

Temperature No	Temperature (Celsius)	Time (minutes)
T1	300°C	30
T2	325°C	60
T3	350°C	90
T4	375°C	30
T5	400°C	60
T6	425°C	90

Table 2: Austempering temperature and time

For any transformation to take place, the microstructure of the metal must be austenite structure. To reach austenite microstructure temperature generally recommended is in-between 790-915°C, below which phase transformation is pretty much useless. So, we preferred 900°C as austenitising temperature and by differing Austempering temperature and time, we could produce variety of microstructural scales. This research will help us understand, how mechanical performance changes with this microstructure.

A. Use of Potassium nitrate (KNO₃) and Sodium nitrate (NaNO₃) salt for quenching

Quenching is nothing but rapid cooling of high temperature metal by immersing it in water or oil. Through this we control mechanical properties associated with a crystalline structure or phase distribution that would be lost upon slow cooling. This process decides the crystalline structure and through Heat treatment quenching salts chosen based on their working temperature range and melting point.

After heat treatment process, specimens are ready to undergo wear test. The objectives of the study are:

- To obtain optimum parameter for wear.
- To determine the maximum contributing factor for specimen wear.

B. Why Pin on disk wear testing machine?

Wear or abrasion is conducted to investigate wear mechanism that occurs in material, which help us to understand its application. A correct use of instrument will enable us to control critical inputs precisely. Pin on disk wear testing machine is used the most, when understanding abrasion as it provides us reliable results.

Design of experiment for wear testing:

In this work, Taguchi's L9 Orthogonal array is used to study wear performance of ADI material. Variables used for construction are Load, Speed and Time. As these three factors are majorly affecting wear of material, we concentrate to measure how much. During the experiment other factors like radial distance on instrument and environmental effects are considered constant.

Sl No	Load (Kg)	Speed (RPM)	Time (Min)
01	1.5	100	3
02	1.5	200	6

03	1.5	300	9
04	2	100	6
05	2	200	9
06	2	300	3
07	2.5	100	9
08	2.5	200	3
09	2.5	300	6

Table 3: L9 Taguchi array designed for wear analysis

As shown above, L9 array consists of three different load, speed and time values. These values are decided discussing other works and capability of machine. Results for each Austempering temperature are discussed below.

V. Results And Discussion

Experiment was conducted for an hour and environmental effects are ignored. Stable power supply is maintained and constant human monitoring was ensured till the completion.

Using the experimental data, wear rate and S/N ratio (Signal to Noise ratio) are calculated using the following formulas:

$$\text{Wear Rate} = \frac{\text{Wt loss}}{\text{Diameter of rotating disk}} \times \frac{3.14 \times D}{0.15 \times M} \times \text{time}$$

$$\text{S/N Ratio} = -10 * \text{LOG} (\text{Wear rate}^2)$$

S/N ratio represents how much signal strength is more than noise level. Higher the S/N ratio, better the signal quality. Using the data, the response table is constructed by taking the average of S/N ratios of factors.

For temperature T1 — 300°C for 30 mins

Wear results for temperature T1:

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	6.216	6.203	0.013
2	1.5	200	6	6.203	6.198	0.005
3	1.5	300	9	6.198	6.18	0.018
4	2	100	6	6.18	6.177	0.003
5	2	200	9	6.177	6.167	0.01

6	2	300	3	6.167	6.157	0.01
7	2.5	100	9	6.157	6.155	0.002
8	2.5	200	3	6.155	6.141	0.014
9	2.5	300	6	6.141	6.085	0.056

Calculated Wear Rate and S/N Ratio for T1:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	9.2E-05	80.7284
2	8.84E-06	101.0691
3	1.41E-05	96.98667
4	1.06E-05	99.48544
5	1.18E-05	98.57029
6	2.36E-05	92.54969
7	4.72E-06	106.5291
8	4.95E-05	86.10531
9	6.6E-05	83.60653

Response Table for T1:

LOAD	RPM	TIME
L1 = 92.92805	S1 = 95.58098	T1 = 86.46113
L2 = 96.86848	S2 = 95.24822	T2 = 94.72035
L3 = 92.08031	S3 = 91.04763	T3 = 100.6954

Through the plot, we could observe that optimum wear rate occurs at L2 (2kg) of loading, Speed S1 (100RPM) and Time T3 (9Mins). Optimum wear rate = 1.17892×10^{-6} MG/M. Through Anova analysis, we can observe the amount of effect of individual factors on wear of material. In this case, the contribution of RPM (speed) is 51.9%, majorly affecting wear compared to Load (23.0%) and Time (25.1%). So, we can say, as we reduce speed by x times, load or time can be doubled keeping wear constant.

For temperature T2 — 325°C for 60 mins**Wear results for temperature T2:**

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	6.001	6.0	0.001
2	1.5	200	6	6.0	5.999	0.001
3	1.5	300	9	5.999	5.953	0.046
4	2	100	6	5.953	5.902	0.051
5	2	200	9	5.902	5.851	0.051
6	2	300	3	5.851	5.841	0.01
7	2.5	100	9	5.841	5.819	0.022
8	2.5	200	3	5.819	5.802	0.017
9	2.5	300	6	5.802	5.767	0.035

Calculated Wear Rate and S/N Ratio for T2:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	7.07354E-06	103.007
2	1.76838E-06	115.048
3	3.61536E-05	88.837
4	0.000180375	74.876
5	6.01251E-05	84.419
6	2.35785E-05	92.550
7	5.18726E-05	85.701
8	6.01251E-05	84.419
9	4.12623E-05	87.689

Response Table for T2:

LOAD	RPM	TIME
------	-----	------

L1 = 102.2976	S1 = 87.86166	T1 = 93.32528
L2 = 83.94835	S2 = 94.62875	T2 = 92.53795
L3 = 85.93635	S3 = 89.69186	T3 = 86.31903

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2 (200RPM) and Time T1 (3Mins). Optimum wear rate = 1.68106×10^{-5} MG/M. Contribution percentage: RPM (40.4%), Load (32.3%), and Time (27.3%). Speed is majorly affecting wear compared to Load and Time. We can say even though contribution percentage is different, almost all three factors have comparatively similar effect on wear as it has minimal difference in percentage. But by lowering speed by x times usage time can be increased by 1.5x times.

For temperature T3 — 350°C for 90 mins

Wear results for temperature T3:

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	5.744	5.742	0.002
2	1.5	200	6	5.742	5.718	0.024
3	1.5	300	9	5.718	5.7	0.018
4	2	100	6	5.7	5.68	0.02
5	2	200	9	5.68	5.66	0.02
6	2	300	3	5.66	5.654	0.006
7	2.5	100	9	5.654	5.637	0.017
8	2.5	200	3	5.637	5.625	0.012
9	2.5	300	6	5.625	5.603	0.022

Calculated Wear Rate and S/N Ratio for T3:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	1.41471×10^{-5}	96.987
2	4.24412×10^{-5}	87.444
3	1.41471×10^{-5}	96.987
4	7.07354×10^{-5}	83.007

5	2.35785E-05	92.550
6	1.41471E-05	96.987
7	4.00834E-05	87.941
8	4.24412E-05	87.444
9	2.59363E-05	91.722

Response Table for T3:

LOAD	RPM	TIME
93.80586	89.31155	93.80586
90.84788	89.14606	87.39112
89.03560	95.23173	92.49236

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S3 (300RPM) and Time T1 (3Mins). Optimum wear rate = 1.30991E-06 MG/M. Contribution percentage: Load (38%), Time (37%), Speed (25%). We can observe in this case contribution of Load and Time is almost equal and major compared to speed. So, we can say, as we control time and load to fair extent we can operate the material for higher speed.

For temperature T4 — 375°C for 30 mins**Wear results for temperature T4:**

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	5.482	5.462	0.02
2	1.5	200	6	5.45	5.446	0.004
3	1.5	300	9	5.446	5.437	0.009
4	2	100	6	5.437	5.427	0.01
5	2	200	9	5.462	5.45	0.012
6	2	300	3	5.427	5.396	0.031
7	2.5	100	9	5.396	5.378	0.018
8	2.5	200	3	5.378	5.367	0.011

9	2.5	300	6	5.367	5.347	0.02
---	-----	-----	---	-------	-------	------

Calculated Wear Rate and S/N Ratio for T4:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	0.000141471	76.987
2	7.07354E-06	103.007
3	7.07354E-06	103.007
4	3.53677E-05	89.028
5	1.41471E-05	96.987
6	7.30932E-05	82.722
7	4.24412E-05	87.444
8	3.89045E-05	88.200
9	2.35785E-05	92.550

Response Table for T4:

LOAD	RPM	TIME
94.33373	84.48626	82.63638
89.57900	96.06465	94.86161
89.39798	92.75981	95.81273

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2 (200RPM) and Time T3 (9Mins). Optimum wear rate = 7.99048E-06 MG/M. Contribution percentage: Load (44%), Speed (28%), Time (28%). We can observe in this case contribution of load is major compared to time and speed. Time and Speed share almost same amount of effect on wear. So, as we reduce load by x times, we can increase speed and time to almost 2x times, keeping wear constant.

For temperature T5 — 400°C for 60 mins**Wear results for temperature T5:**

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	6.164	6.161	0.003

2	1.5	200	6	6.161	6.152	0.009
3	1.5	300	9	6.152	6.144	0.008
4	2	100	6	6.144	6.138	0.006
5	2	200	9	6.138	6.132	0.006
6	2	300	3	6.132	6.119	0.013
7	2.5	100	9	6.119	6.111	0.008
8	2.5	200	3	6.111	6.102	0.009
9	2.5	300	6	6.102	6.088	0.014

Calculated Wear Rate and S/N Ratio for T5:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	2.12206E-05	93.465
2	1.59155E-05	95.964
3	6.28759E-06	104.030
4	2.12206E-05	93.465
5	7.07354E-06	103.007
6	3.06520E-05	90.271
7	1.88628E-05	94.488
8	3.18309E-05	89.943
9	1.65049E-05	95.648

Response Table for T5:

LOAD	RPM	TIME
97.81959	93.80586	91.22623
95.58098	96.30463	95.02540

93.35955

96.64963

100.5085

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S3 (300RPM) and Time T3 (9Mins). Optimum wear rate = 5.34882×10^{-6} MG/M. Contribution percentage: Load (32%), RPM (37%), Time (31%). We can observe in this case contribution of all three factors are almost equal, meaning that decreasing or increasing any factor will have same effect on wear of material.

For temperature T6 — 425°C for 90 mins

Wear results for temperature T6:

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	F Wt. (g)	Wt. Loss (g)
1	1.5	100	3	6.121	6.119	0.002
2	1.5	200	6	6.119	6.116	0.003
3	1.5	300	9	6.116	6.111	0.005
4	2	100	6	6.111	6.104	0.007
5	2	200	9	6.104	6.1	0.004
6	2	300	3	6.1	6.073	0.027
7	2.5	100	9	6.073	6.071	0.002
8	2.5	200	3	6.071	6.064	0.007
9	2.5	300	6	6.064	6.054	0.01

Calculated Wear Rate and S/N Ratio for T6:

EXPT. No.	Wear Rate (MG/M)	S/N RATIO
1	1.41471×10^{-5}	96.987
2	5.30515×10^{-6}	105.506
3	3.92974×10^{-6}	108.113
4	2.47574×10^{-5}	92.126
5	4.71569×10^{-6}	106.529
6	6.36618×10^{-5}	83.922

7	4.71569E-06	106.529
8	2.47574E-05	92.126
9	1.17892E-05	98.570

Response Table for T6:

LOAD	RPM	TIME
103.5351	98.54722	91.01166
94.19247	101.38701	98.73408
99.07510	96.86848	107.0570

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2 (200RPM) and Time T3 (9Mins). Optimum wear rate = 1.12216E-05 MG/M. Contribution percentage: RPM (61%), Load (34%), Time (5%). Through the results, we can observe that contribution of RPM (speed) is majorly affecting wear compared to Load and Time, whereas the effect of time is almost negligible implying that as we have lower RPM and load, we can operate the material for longer duration without compromising on wear.

Vi. Conclusion

Through the results, we can observe that contribution of three factors vary with Austempering temperature and time. To analyse the overall effect, Austempering temperature is plotted against percentage contribution to wear.

In the analysis of Load, we can observe that contribution of load increases with Austempering temperature until 375°C. After that, load contribution drops. This implies for applications like a bulldozer shovel grabber this specific case can be helpful, where load is the major concern.

In the analysis of Speed, we could observe contribution of speed decreases during initial increase in temperature and increases as we go beyond 350°C.

In the analysis of Time, we can observe contribution of time increases initially and starts to fall as Austempering temperature increases. At higher Austempering temperature, time contribution is negligible. This implies applications like a drill bit chuck where, as far as speed and load are controlled, we can operate it for longer duration without compromising on wear.

References

- [1] Srinivasu.N, Dr MK Murulidhara, "The influence of Austempering conditions on machining of austempered ductile iron using wire EDM method for varying heat parameters."
- [2] N. Srinivasu, Dr MK Muralidhara, "The influence of Austempering conditions on tensile test of Carbide Austempered Ductile Iron for varying heat parameters," Mechanical Department, Dr Ambedkar Institute of Technology Bangalore-56, Mechanical Department, Dr RR Institute of Technology Bangalore-90.
- [3] Andrzej Gazda, Malgorzata Warmuze, "Optimization Of Mechanical Properties Of Complex, Two-Stage Heat Treatment Of Cu-Ni (Mn, Mo) Austempered Ductile Iron," Foundry Research Institute In Cracow.
- [4] Adam Bitka, "Lukasiewicz Research Network - Krakow."
- [5] Beny Bandanadjaja, "The Effect Of Two-Step Austempering Heat Treatment Holding Time To The Mechanical Properties Of Austempered Ductile Iron (ADI)," Polytechnics Manufaktur Bandung.

- [6] Christopher Bixler, Kathy Hayrynen, and John Keough, "Locally Austempered Ductile Iron (LADI)," Applied Process, Inc.
- [7] George Pfaffmann, "Ajax Tocco Magnethermic Corporation," Scott Gledhill, "ThyssenKrupp Waupaca, Inc."
- [8] Jagmohan Datt and Uma Batra, "Influence of Composition and Austempering Temperature on Machinability of ADI."
- [9] Gajen P. Dubal, "The Basics of Molten Salt Quenchants," Heatbath/Park Metallurgical Corp. Detroit, Mich.