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

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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.

Carbidic 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 applicating 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 (Carbidic Austempered Ductile Iron)?

Carbidic 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: Element composition

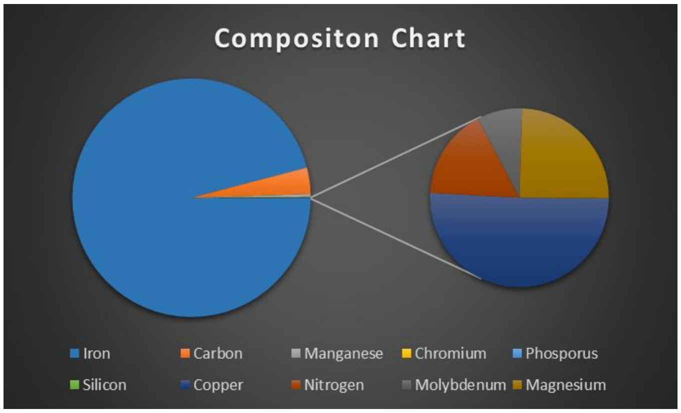

Fig: Composition Chart

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. Increases 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.

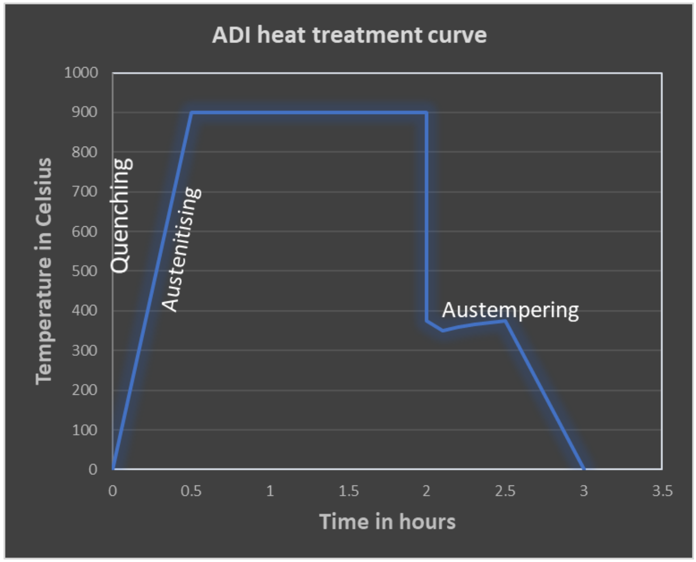

Fig: ADI heat treatment diagram

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

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

Table: 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– 915ºC, below which phase transformation is pretty much useless. So, we preferred 900ºC 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 objective of the study is to –

- 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.

Fig: Pin on disk wear testing machine

Design of experiment for wear testing-

In this work, Taguchi's L09 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.

SI 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: L09 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.

A. For temperature T1- 300ºC for 30 mins

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (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

Table: Wear results for temperature T1

Using above data, wear rate and S/N ratio (Signal to Noise ratio) is calculated with following formulas -

Wear rate = Wt loss / (Rpm*time*3.14*D)

Where D – Diameter of rotating disk =0.15M

S/N ratio = -10*LOG (Wear rate ^2)

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

Table: Wear rate calculated for temperature T1

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

LOAD	RPM	TIME
L1= 92.92805	S1= 95.58097903	T1= 86.46113
L2= 96.86848	S2= 95.24822269	T2= 94.72035
L3= 92.08031	S3= 91.04763126	T3= 100.6954

Table: Response table for temperature T1

Fig: SN ratio v/s factor level

In above graph, SN ratio v/s factor level are plotted. L1 L2 L3 represents loading condition 1.5,2,2.5kg load respectively. Similarly, S1, S2, S3 represents speed 100, 200, 300 RPM. Whereas T1, T2, T3 indicates time 3, 6, 9mins.Through the plot, we could observe that optimum wear rate occurs at L2 (2kg) of loading, Speed S1(100RPM) and Time T3 (9Mins).

To find optimum wear rate below formula can be used,

Optimum wear rate = average wear rate of (L2) +average wear rate of (S1) +average wear rate of (T3) - 2*(average (wear rate)

Optimum wear rate = 1.17892E-06 MG/M

Using this data, we can construct Anova table. Which will help us to understand contribution of individual factors on wear rate.

	DOF	SOS	VAR	TRUE VAR	F	% CONT.
Load	2	85.18	42.59	778.98	-2.24	23.0%
Rpm	2	1067.11	533.55	1760.90	-5.07	51.9%
Time	2	156.90	78.45	850.69	-2.45	25.1%
Error	2	-693.79	-346.89	0	0	0.0%
Total	8	615.42	307.71	3390.58	-9.77	100%

Table: Anova table for temperature T1

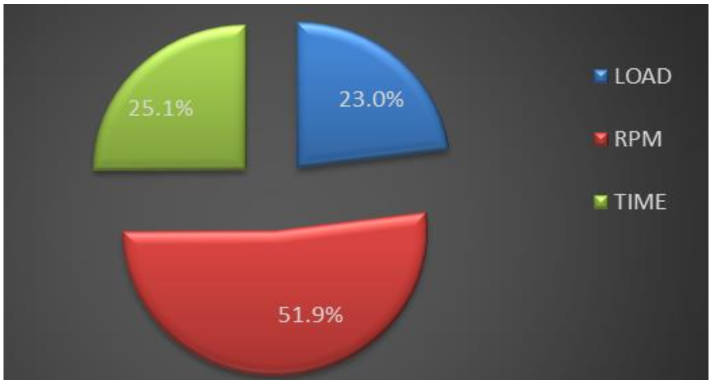

Fig: Contribution of factors to wear rate

Through above pie chart, we can observe amount of effect of individual factors on wear of material. We can observe in this case contribution of RPM i.e., speed is majorly affecting wear compared to Load and Time. Both have almost equal effect on wear of specimen. So, we can say, as we reduce speed by x times, load or time can be doubled keeping wear constant.

B. For temperature T2- 325⁰C for 60 mins

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (g)	Wt. loss (g)
1	1.5	100	3	6.001	6	0.001
2	1.5	200	6	6	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

Table: Wear results for temperature T2

Using above data, wear rate and S/N ratio (Signal to Noise ratio) is calculated with following formulas -

Wear rate = Wt loss / (Rpm*time*3.14*D)

Where D – Diameter of rotating disk =0.15M

S/N ratio = -10*LOG (Wear rate ^2)

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

Table: Wear rate calculated for temperature T2

By using the data, response table is constructed. Which can be done by taking average of S/N ratios individual factors.

LOAD	RPM	TIME
L1= 102.2976	S1= 87.86165733	T1= 93.32528
L2= 83.94835	S2= 94.62874897	T2= 92.53795
L3= 85.93635	S3= 89.6918623	T3= 86.31903

Table: Response table for temperature T2

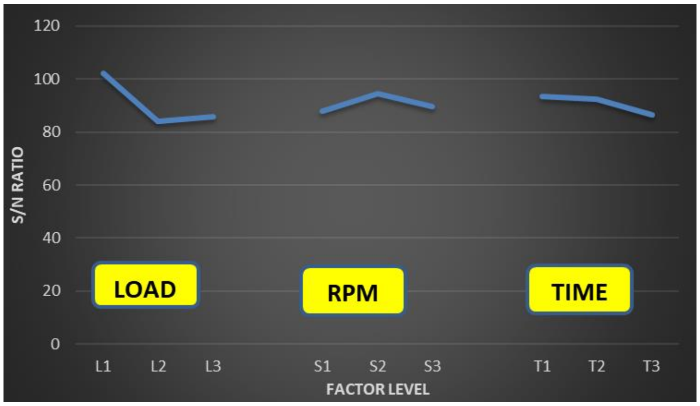

Fig: SN ratio v/s factor level

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2(200RPM) and Time T1 (3Mins).

To find optimum wear rate below formula can be used,

Optimum wear rate = average wear rate of (L1) +average wear rate of (S2) +average wear rate of (T1) - 2*(average (wear rate)

Optimum wear rate = 1.68106E-05MG/M

	DOF	SOS	VAR	TRUE VAR	F	% CONT.
Load	2	1032.83	516.41	3348.45	-2.89	32.3
Rpm	2	1876.34	938.17	4191.96	-3.62	40.4
Time	2	520.99	260.49	2836.62	-2.44	27.3
Error	2	- 2315.62	- 1157.81	0	0	0
Total	8	1114.54	557.27	10377.05	-8.96	100

Table: Anova table for temperature T2

Fig: Contribution of factors to wear rate

Through above pie chart, we can observe amount of effect of individual factors on wear of material. We can observe in this case contribution of RPM i.e., 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.

C. For temperature T3- 350⁰C for 90 mins

EXP. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (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

Table: Wear results for temperature T3

EXPT. No.	Wear rate MG/M	S/N RATIO
1	1.41471E-05	96.987
2	4.24412E-05	87.444
3	1.41471E-05	96.987
4	7.07354E-05	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

Table: Wear rate calculated for temperature T3

LOAD	RPM	TIME
93.80586	89.31155029	93.80586
90.84788	89.14605973	87.39112
89.0356	95.23172523	92.49236

Table: Response table for temperature T3

Fig: SN ratio v/s factor level

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S3(300RPM) and Time T1 (3Mins).

To find optimum wear rate below formula can be used,

Optimum wear rate = average wear rate of (L1) +average wear rate of (S3) +average wear rate of (T1) - 2*(average (wear rate)

Optimum wear rate = 1.30991E-06 MG/M

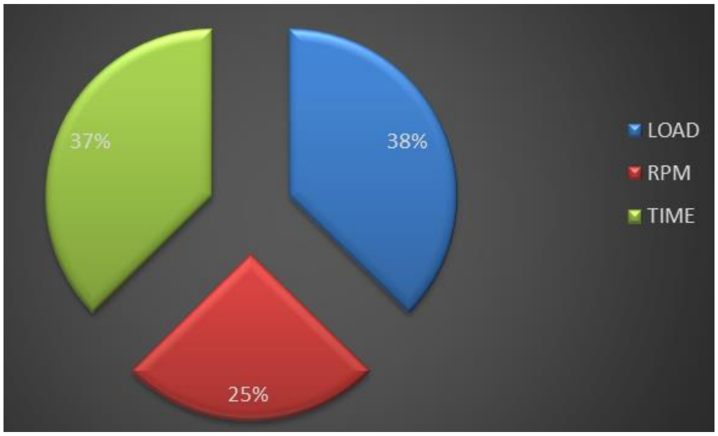

Fig: Contribution of factors to wear rate

Through above pie chart, we can observe amount of effect of individual factors on wear of material. 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.

D. For temperature T4- 375⁰C for 30 mins

EXP. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (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

Table: Wear results for temperature 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

Table: Wear rate calculated for temperature T4

LOAD	RPM	TIME
94.33373	84.4862597	82.63638
89.579	96.06465014	94.86161
89.39798	92.75980681	95.81273

Table: Response table for temperature T4

Fig: SN ratio v/s factor level

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2(200RPM) and Time T3 (9Mins).
To find optimum wear rate below formula can be used,
Optimum wear rate = average wear rate of (L1) +average wear rate of (S2) +average wear rate of (T3) - 2*(average (wear rate)

Optimum wear rate = 7.99048E-06 MG/M

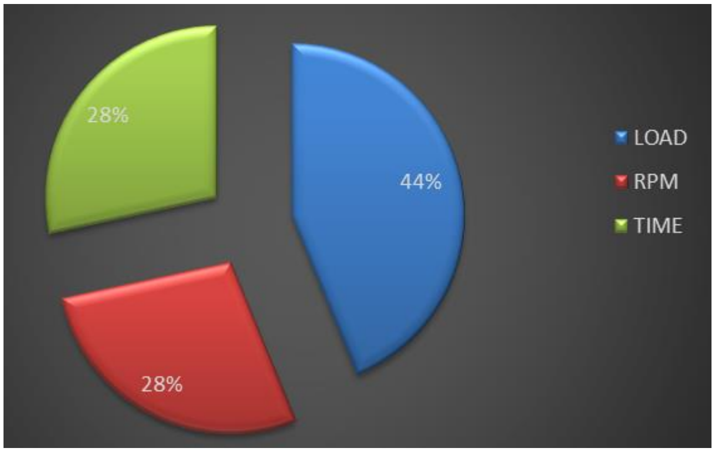

Fig: Contribution of factors to wear rate

Through above pie chart, we can observe amount of effect of individual factors on wear of material. 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.

E. For temperature T5- 400⁰C for 60 mins

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (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

Table: Wear results for temperature 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	3.0652E-05	90.271
7	1.88628E-05	94.488

8	3.18309E-05	89.943
9	1.65049E-05	95.648

Table: Wear rate calculated for temperature T5

LOAD	RPM	TIME
97.81959	93.80585976	91.22623
95.58098	96.30463449	95.0254
93.35955	96.64962564	100.5085

Table: Response table for temperature T5

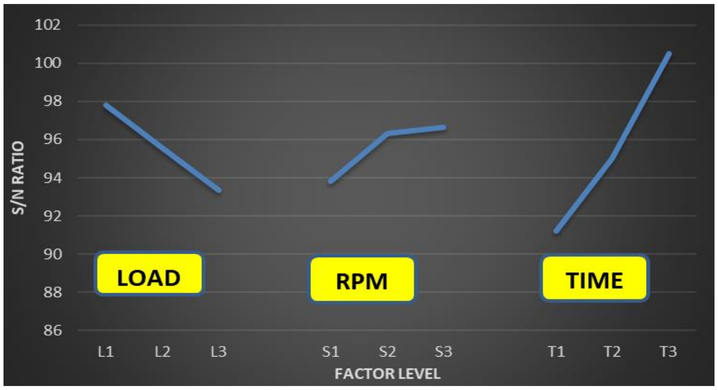

Fig: SN ratio v/s factor level

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S3(300RPM) and Time T3 (9Mins).

To find optimum wear rate below formula can be used,

Optimum wear rate = average wear rate of (L1) +average wear rate of (S3) +average wear rate of (T3) - 2*(average (wear rate)

Optimum wear rate = 5.34882E-06 MG/M

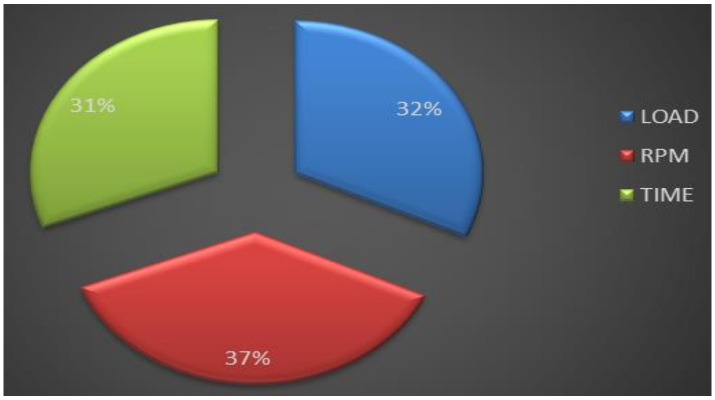

Fig: Contribution of factors to wear rate

Through above pie chart, 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.

F. For temperature T6- 425⁰C for 90 mins

EXPT. No.	LOAD (Kg)	RPM	TIME (min)	I Wt. (g)	FWt. (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

Table: Wear results for temperature T6

EXPT. No.	Wear rate MG/M	S/N RATIO
1	1.41471E-05	96.987
2	5.30515E-06	105.506
3	3.92974E-06	108.113
4	2.47574E-05	92.126
5	4.71569E-06	106.529
6	6.36618E-05	83.922
7	4.71569E-06	106.529
8	2.47574E-05	92.126
9	1.17892E-05	98.570

Table: Wear rate calculated for temperature T6

LOAD	RPM	TIME
103.5351	98.54722283	91.01166
94.19247	101.3870144	98.73408
99.0751	96.86847635	107.057

Table: Response table for temperature T6

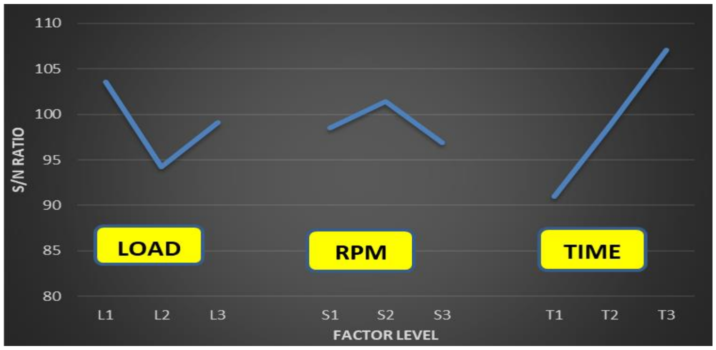

Fig: SN ratio v/s factor level

Through the plot, we could observe that optimum wear rate occurs at L1 (1.5kg) of loading, Speed S2(200RPM) and Time T3 (9Mins).

To find optimum wear rate below formula can be used,

Optimum wear rate = average wear rate of (L2) +average wear rate of (S2) +average wear rate of (T3) - 2*(average (wear rate)

Optimum wear rate = 1.12216E-05MG/M

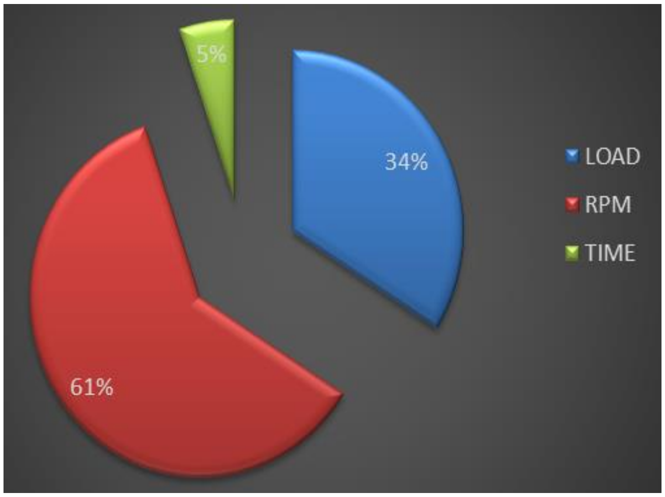

Fig: Contribution of factors to wear rate

Through above pie chart, we can observe in this case contribution of RPM i.e., speed is majorly affecting wear compared to Load and Time. Whereas 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 factor vary with Austempering temperature and time. To analyse the overall effect Austempering temperature is plotted against percentage contribution to wear.

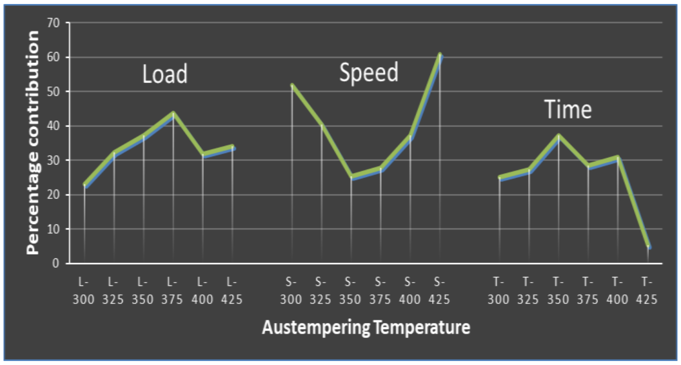

Fig: Austempering temperature v/s Percentage contribution

In above graph we can observe three factors contribution varying as Austempering temperature is increased. In first plot of load, we can observe that contribution of load increase with Austempering temperature until 375ºC. After that load contribution drops. This implies for application like bulldozer shovel grabber this specific case can be helpful, where load is major concerned. In second plot of speed, we could observe contribution of speed decrease during initial increase in temperature and increase as we go beyond 350ºC. In third plot of time, we can observe contribution of time increases initially and start to fall as Austempering temperature increases. At higher Austempering temperature time contribution is negligible. This implies application like drill bit chuck. Where, as far as speed and load is controlled, we can operate it for longer duration without compromising on wear.

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