WEAR PROPERTIES OF AUSTEMPERED ALLOYED DUCTILE CAST IRON GEARS

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ABSTRACT

Recently austempered ductile cast iron is utilized for production of gears in automotive industry in order to reduce the production costs. The problem of low hardenability ofunalloyed ductile cast iron dictated the use of alloyed ductile cast iron. The present work is devoted to investigate the wear properties of austempered alloyed ductile cast iron 2% Ni , 0.5% Mo which is chosen to replace forged gears produced from carburized and hardened steel DIN 34 17220. The programme of wear tests is based on the comparison between the performance of austempered alloyed ductile cast iron and steel DIN 34 17220. Disc type wear test specimens with diameter of 40 mm and thickness 10 mm were made from alloyed ductile cast iron and from the steel. The tests were carried out at dry sliding condition, wet sliding condition, and wet sliding plus 10% rolling. The results of wear tests showed that the wear characteristics of austempered alloyed ductile cast iron are more suitable for gear applications than the classical carburized and hardened steel DIN 34 17220.

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INTRODUCTION

Materials used in gear production applications should have certain properties in order to withstand loads acting on tooth profile and suit the conditions of operation . Table 1 shows the contact load , temperature and relative sliding at contact point for different gear applications used in automotive industry . /1/ .

Table 1 : Contact pressures, temperatures and relative sliding speed of tooth profiles at contact point in automotive gears |15|

Application	Gear	Contact Load MPa	Relative Sliding at Contact Point m/s	Contact Temp. °C
Heavy truck	First	1600	0.25	110
	Transfer box	2100	5.83	330
Wheel tractor	Final drive	800	0.42	130
Tracked tractor	Final drive	700	0.50	60

Usually , such highly stressed gears are produced from carburized and hardened steels . A typical standard material for this purpose is the low-carbon alloy steel DIN 17220 . The properties of this steel include high strength, high surface hardness and enough ductility in the core . Gears made from such steels are shaped by forging operations and needs long heat treatment cycles which raises the costs of production .

Besides the low manufacturing costs , the family of austempered ductile cast iron have also high strength and hardness combined with good ductility .

Table 2 shows a comparison between the properties of a genral class of carburized and hardened steel used in gears with the bainitic nodular iron made by early investigators /2/ .

The main outstanding problem in utilization of these materials for production of gears is their low hardenability i.e. the complete bainitic transformation allover the section . This problem has been solved by adding alloyin elements in order to increase the hardenability and to get a successful austempering heat treatment cycle for gears /3/ , /4/.

The alloyed ductile cast iron grades for gear production are still under investigations and not yet specified completely in standards . That is why alloyed samples with 2 % Ni and 0.5 % Mo were produced locally . Also the optimum heat treatment cycle to get the suitable mechanical properties for gears was obtained /5/ .

Table 2 : Comparison of properties between carburized and hardened steel 18 CRMnTi and bainitic nodular iron .

Mechanical Properties	Units	Material	
		Carb. & Hardened Steel 18 CrMnTi	Austempered Nodular Cast Iron
-Tensile strength	MPa	1000-1150	1300-1500
-Bending fatigue strength	MPa	500	310-350
-Impact toughness	J	25-30	80-100
-Surface hardness	HRC	58-60	46-49
-Static torsion strength	Nm	2800-2900	2970-3100

Tables 3,4 show the mechanical properties of the new alloy and the comparative steel 17220 used in this work .

Table 3 : Optimum mechanical properties of lower and upper bainite selected for gear production.

Austempering Temperature	Optimum Holding Time	σ_u (MPa)	δ (%)	HV10 (MN/m^2)	I.R. (kJ/m^2)
240^{o}C	120 min.	1300	5.5	545	70
370^{o}C	100 min.	1000	8.5	340	110

Wear of materials is the process of surface distruction in rubbing solids , which results in reduced dimensions of parts . The rate of wear depends on the properties of the used materials , the treatment of the surface and their quality , and also on their working conditions i.e. load , temperature , lubrication and etc. .

The new alloy has suitable mechanical properties and

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expected to have good wear performance in comparison with steel used for gears . In spite of this a test programme is important to determine the actual behaviour of this new material .

Table 4 : Mechanical properties of steel 1.7220 carburized and hardened.

Tensile strength σ_u	1000-1200	MPa
Elongation δ	11	%
Reduction in area χ	45	%
Impact value (DVM)	600	KJ/m^2

This work is aimed to insure the suitability of the wear properties of alloyed austempered ductile cast iron as a gear material .

EXPERIMENTAL WORK

Test equipment and specimens

The Amsler wear testing machine , type A 135 made in Switzerland , was used for carrying out the wear tests . The test specimens are of disc type 40 mm in diameter with a central hole 16 mm in diameter and the disc width is 10 mm . Test specimens arranged for wear tests are shown in fig.1 .

The two run discs are fixed on the machine at the end of two shafts so that they make contact with each other tangentionally . The radial force at the contact is regulated between 0-2000 N by means of adjusting the tension of a calibrated spring i.e. the load can be read at any moment on a scale . The lower test specimen is driven by an electric motor with two fixed speeds of 200 or 400 R.P.M. The upper disc has a 10 % lower speed as it is driven by a gear box .

As the two discs have the same diameter the machine can offer the following two conditions of operation :

1) The two discs run in the same sence of rotation , which represents pure sliding conditions .

2) The two discs run in an opposite sence of rotation , which represents rolling combined with 10 % sliding . This condition is mostly like the working conditions of gears .

To avoid siezing of test specimens and to get uniform wear , the upper disc is provided by a lateral reciprocating motion which is made by an eccentric. The machine ha also two indicators as follows:

1) A counter for measuring the lower disc revolutions .
2) A dynamometer to indicate the friction torque between discs .

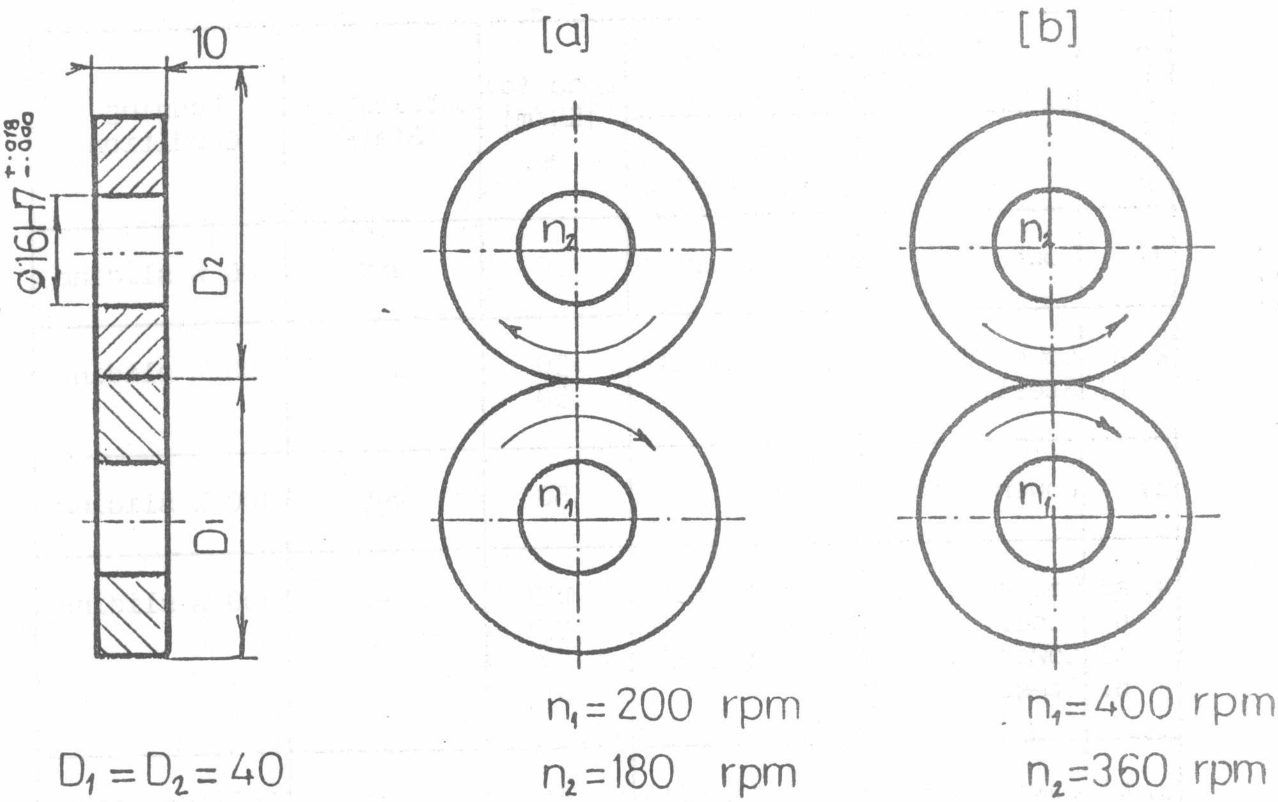

Fig. 1 : Arrangement of test specimens for wear testing

a) for pure sliding friction.
b) for rolling combined with 10 % sliding.

The amount of wear of discs was determined by weighing them before and after the test . A balance with an accuracy of 1 mg was used for weighing the test specimens .
The tests can be made with either dry or wet friction by providing oil on the test discs .

Experimental program

Table 5 shows the schedule of tests made to check the wear properties of the new alloy . The running speeds of the experiments made are shown in table 6 .
The first experiment was made to compare the wear properties of upper bainite and lower bainite ductile cast iron. The running conditions of the experiment were chosen to cause a high amount of wear in order to shorten the time of test . This was made by applying a 100 % dry sliding condition . The lower bainite structure has shown better wear resistance . That is why , the further experiments were

made using only lower bainite samples .

Table 5 : Wear experiments

Experiment No.	Rubbing Specimens Materials		Load (q) |KN/m| *	Lubrication State	Running Condition
	Upper Specimen	Lower Specimen			
1)	Lower bainite	Upper bainite	50	dry	100 % sliding
2) a) b)	Lower bainite Steel	Lower bainite Steel	50 50	dry	100 % sliding
3)	Lower bainite	Steel	50	wet	100 % sliding
4) a) b) c) d)	Lower bainite Steel Lower bainite Steel	Lower bainite Steel Lower bainite Steel	150 150 100 100	wet	100 % sliding
5) a) b)	Lower bainite Steel	Lower bainite Steel	200 200	wet	Rolling with 10 % sliding

*q : acting load per unit axial length

Table 6 : Running speeds of tested specimens.

Experiment No.	Upper Specimen		Lower Specimen		v_s m/s
	n_1 rpm	v_1 m/s	n_2 rpm	v_2 m/s	
1, 2, 3 and 4	180	0.377	200	0.419	0.796
5	360	0.754	400	0.838	0.084

Where : v_1, v_2 are prepherical velocities of upper and lower specimens respectively.

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The second , third and fourth experiments were made to check the wear properties of lower bainite and the comparative steel at dry and wet pure sliding conditions . The fifth experiment was made to simulate the running conditions of gears (rolling combind with 10 % sliding) for both steel and ductile iron samples .

Results and discussion

The first experiment showed that after 30 minuts running the amount of wear in the upper bainite specimen was three times the amount for lower bainite specimen . This experiment proved that lower bainite is more suitable structure for gears from the view point of wear . This is probably due to the high surface hardness of lower bainite.

The second experiment consisted of two tests . In the first test , two carburized and hardened steel discs were rubbed against each other under a load of 500 N in a completely dry sliding friction condition . The corresponding surface stress in the zone of contact was 340 MPa . The amount of wear was determined at equal time interval of 15 min. as shown in fig.2 .

In the second test , the same procedure was followed with a pair of lower bainite alloyed ductile cast iron discs . The test results are also shown in fig.2 . The variation in wear rate with time for both materials is represented graphically in fig. 3 .

Mainly three periods of wear were observed for both tests . These are called in standards running-in , normal operation and excessive wear periods . In the running-in period the wear rate of austempered iron and also the amount of wear were higher than that observed for steel . The wear rate of austempered iron decreases faster and reaches the steady state of wear before the steel . This means that the steel gears should have longer running-in periods than that for bainitic iron gears .
In the normal operation period in the wear curves , the bainitic iron shows a lower rate of wear than steel as indicated by the slope of the wear time curves at this period . The wear rate at this period is the most decisive in determining the service life of the rubbing components . The wear curves also show that the bainitic iron retains a longer period of operation while steel changes earlier and drastically to the excessive wear .

The behaviour of ductile iron in sliding wear can be explained as follows . In the first stage the bearing area is smaller than in steel due to the fact that cast irons cuts less clean (low surface quality after machining) . So , the bearing pressure and consequently the wear rate would be higher in this period . As the surface peaks are smoothened the bearing area increases and the bearing pressure decreases , a fast drop in the wear rate was observed . At the normal operation period the rate of wear of austempered iron is less than that of carburized and hardened steel may probably due to the following reasons :

1) The bainite constituent is hard enough to provide the

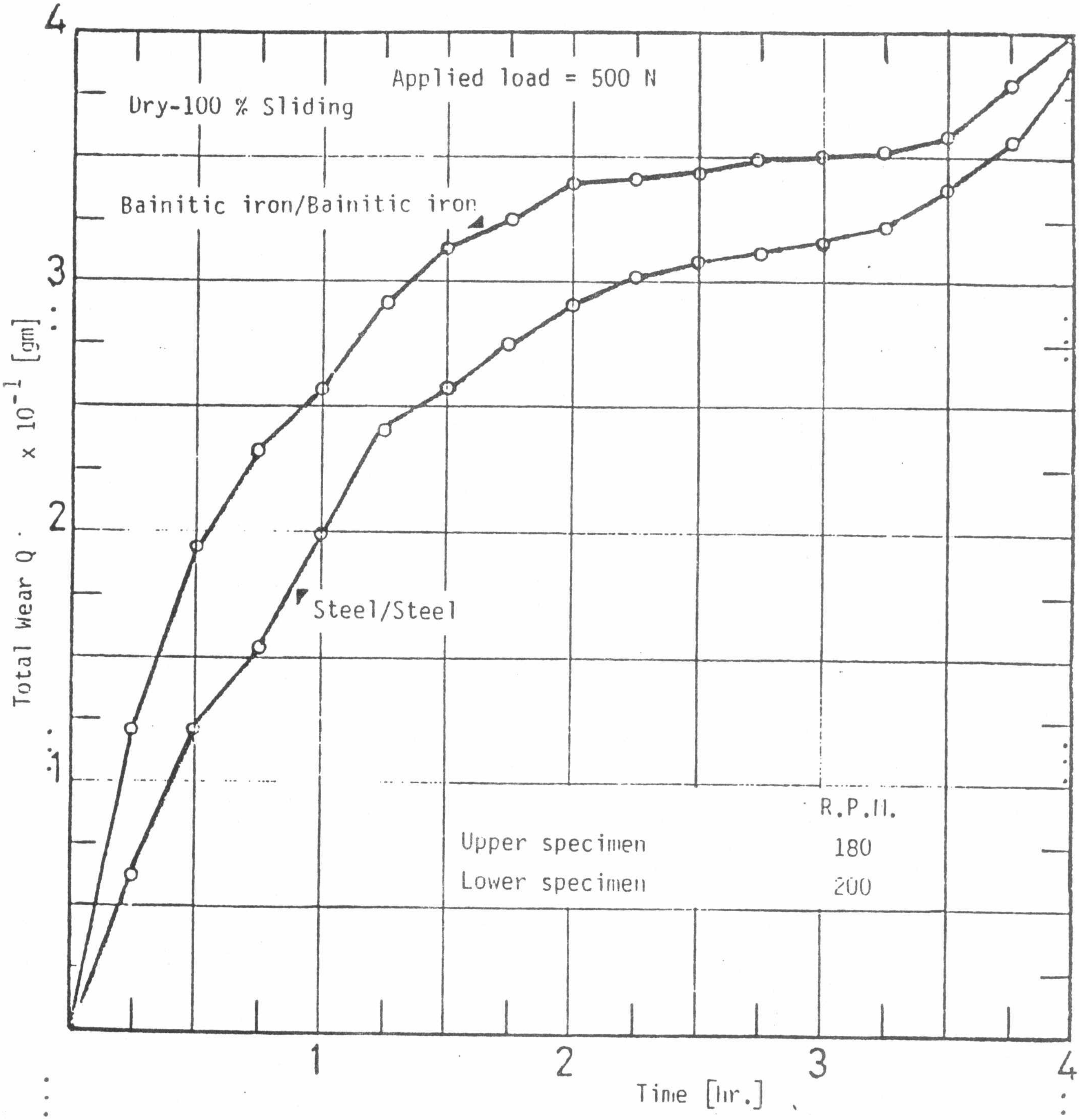

Fig. 2 : Wear-time curves for two identical discs under dry sliding conditions

a) lower bainite/lower bainite
b) carb. hard. steel/carb. hard. steel.

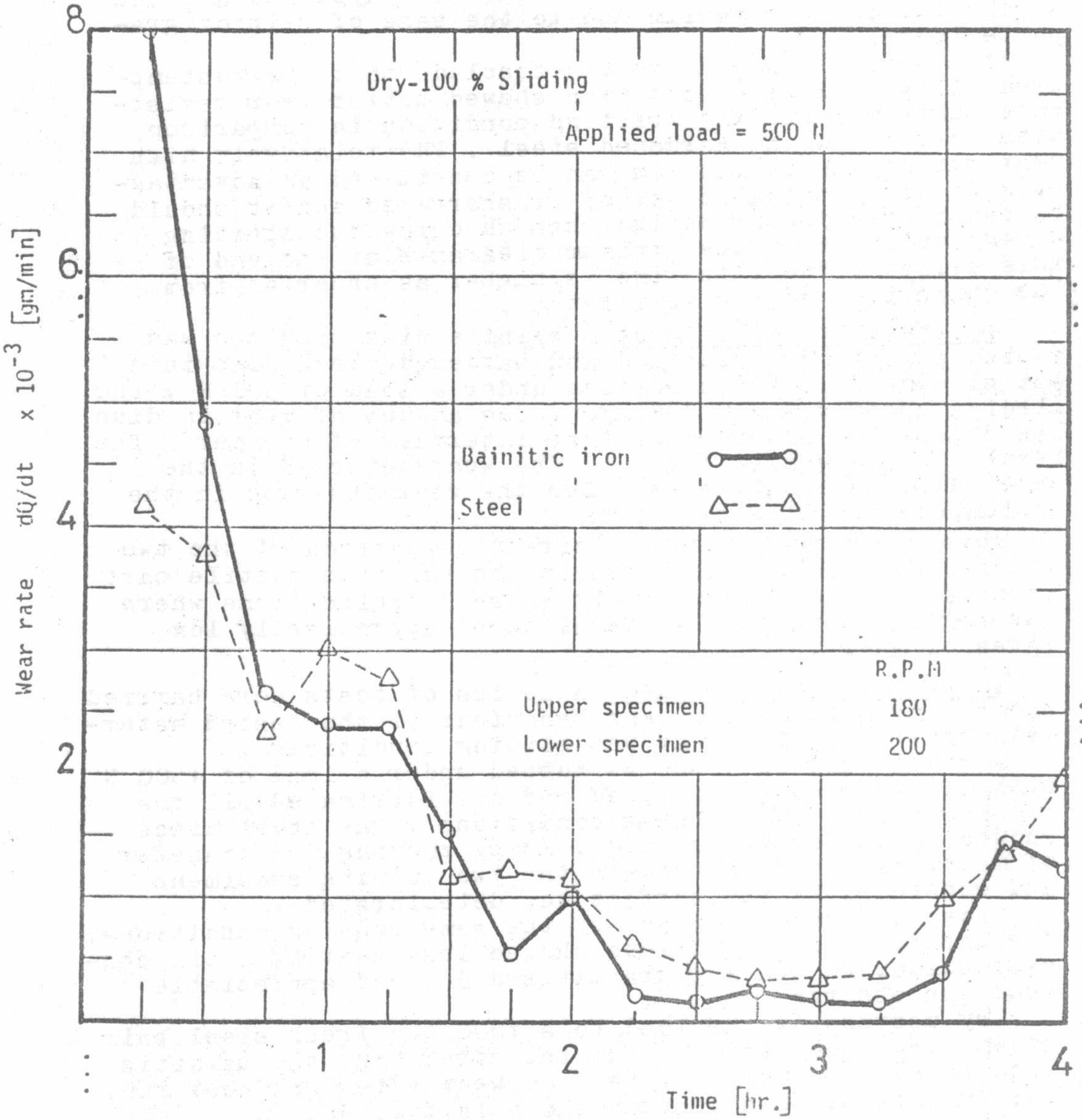

Fig. 3 : Wear rate-time curves for two identical discs under dry sliding conditions

a) lower bainite/lower bainite

b) carb. hard. steel/carb. hard. steel.

iron with sufficiently high wear resistance .
2) The graphite nodules form a surface layer and act as a self lubricating medium due to the ease of slip of graphite layers .

From this experiment we can conclude that the austempered alloyed ductile cast iron showed better wear resistance under dry sliding friction condition in comparison with carburized and hardened steel . The relatively high wear during the running-in can be considered as advantageous as the running-in period is shortened and it should be considered during design when choosing the starting dimension to reach the optimum clearance at the end of this period . The life time is higher as observed from the comparison of the wear rates .

In the third experiment a bainite disc specimen was rubbed against a carburized and hardened steel disc in a wet sliding friction condition under a load of 500 N . The sliding speed was = 0.796 m/s . The amount of wear in disc was determined after equal time intervals of an hour . The results are shown in fig. 4 . The wear detected in the steel disc is about three times the wear observed in the austempered ductile cast iron .

This experiment offers a direct comparison of the two studied materials . As a result the bainitic ductile cast iron can be used successfully in such applications where rubbing against steel is required at appreciablly low rates of wear .

In the fourth experiment a series of tests were carried out to investigate the wear behaviour of the tested materials under high loads at wet sliding conditions .

A steel pair of discs is rubbed under a load of 1500 N with 0.796 m/s sliding speed and oil lubricated all the running time . Under these conditions , the steel discs showed an excessive heating , noisy running , a transfer of material mutually between the two running specimens and consequently the surface was deteriorated .

Under the same load and by the same running conditions, the bainitic iron specimens showed less heating , oil changed colour to black (graphitized) , and appreciable wear was observed .

By decreasing the load to a 1000 N a fresh steel pair showed the same results . On the other hand the bainitic iron retained a very low rate of wear after one hour run. The results of this test are shown in fig. 5 .

Whatever the surface hardness is very high , the steels are usually faced by the danger of seizure and its alternatives (scoring, spalling , scuffing , ...) . The discontinuity of the metallic matrix due to the presence of graphite nodules at the surface , together with the self lubrication are responsible for the elimination of scoring and seizure dangers in ductile cast iron .

As a result , ductile iron is expected to bear successfully intermittent high loads even in conditions of poor lubrication as in the cases of starting , stopping and low speeds .

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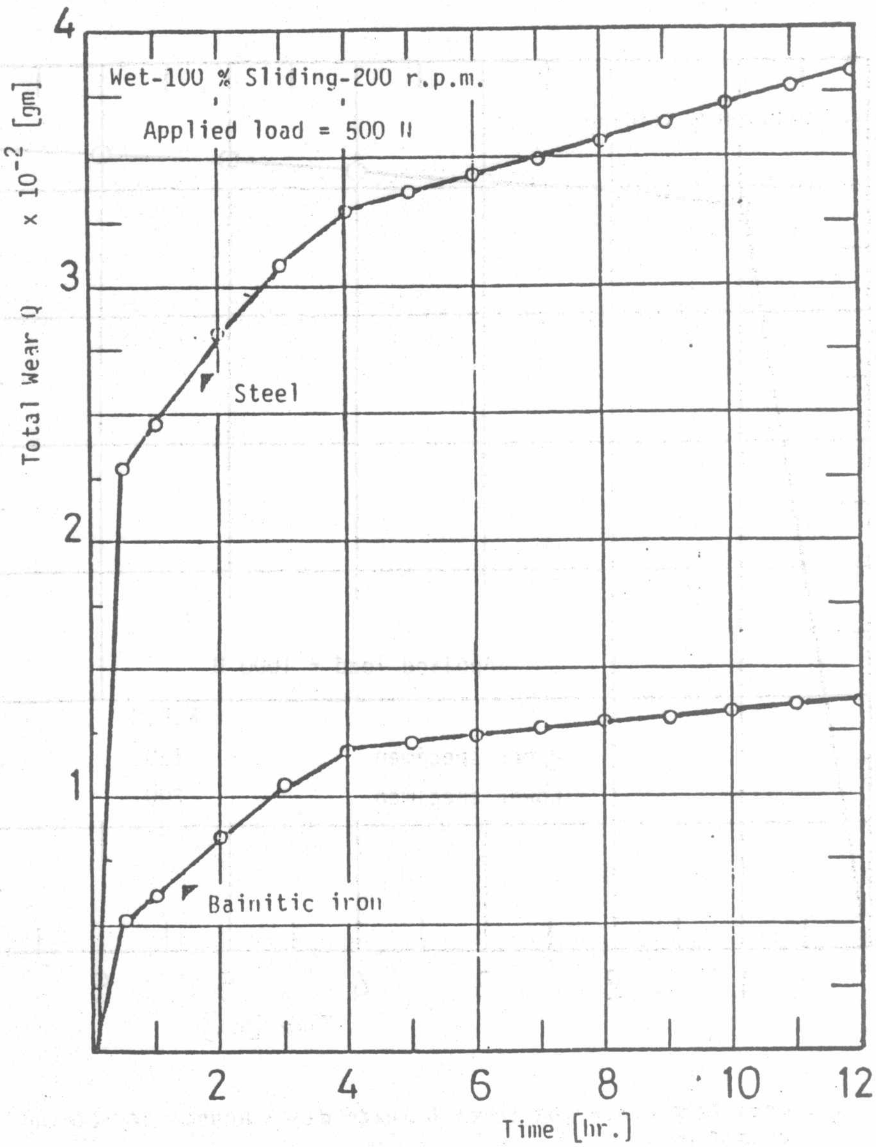

Fig. 4 : Wear-time curves for two different discs under wet sliding conditions
- lower bainite/carb. hard. steel.

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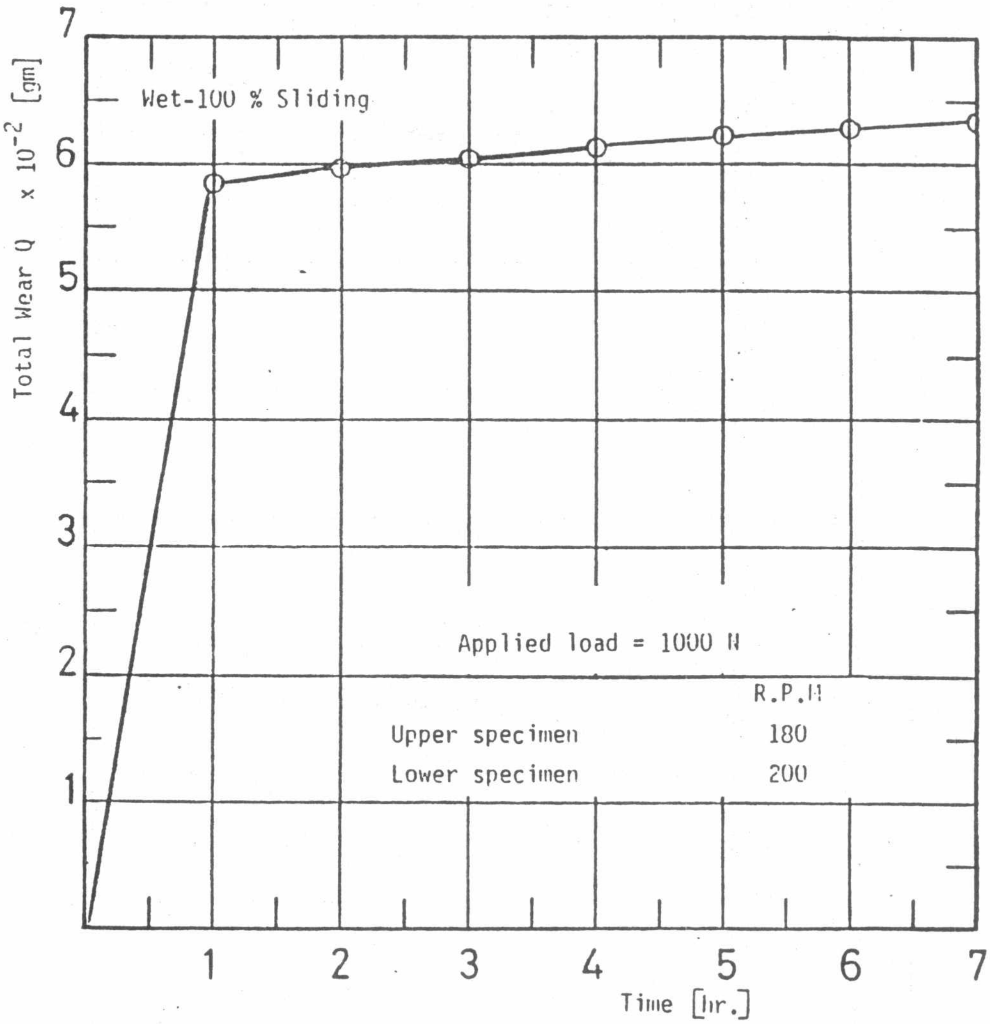

Fig. 5 : *Wear-time curve for lower bainite discs under wet sliding condition -lower bainite/lower bainite.*

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In the fifth experiment a sufficiently close simulation of the running conditions of gears was preserved . A wet rolling combined with 10 % sliding enabled the utilization of the higher load and speed offered by the test machine. The rubbed disc specimens were acted by a load of 2000 N.

As it was expected the tests under predominantly rolling condition would be long enough till a surface fatigue is detected (surface pitting) . The applied load results in a Hertzian contact pressure of about 850 MPa which is similar to the maximum surface stress of highly stressed transmission gears (Table 1) .

Both the steel pair and the bainitic ductile iron pair run satisfactorily for 50 hrs and cover about 1,200,000 cycles of loading without showing any sign for pitting initiation . During this running period the amount of wear was very small and did not affect greatly the initial surface roughness of the surface . The rate of wear of both materials during the running interval was in the range of 1 to 1.4 E -6 g/hr . Such a slow wear condition is called zero wear condition /6/ .

According to the American standards /7/ , the specified basic number of loading cycles is $N_b = 10E6$. The test specimen must sustain this number of cycles without rupture while it is acted upon by the fatigue limit (stress σ_o) .

Then $\sigma^m N = \sigma_o^m N_o$ Where m=9 /6/

so $N = 2.8 \times 10^{32}$

This fatigue formula can be found directly related to the applied load per unit axial length q

$$q = 2 \times 10^5 \ N/m$$

$$m = 3 \qquad /6/$$

$$\text{Then } q^3 N = 9.6 \times 10^{21}$$

The last form of fatigue relation is more simple , more practical in design calculations and related directly to a measured value of load (q) rather than a calculated stress (σ) . The fatigue curve is represented in fig. 6 . The surface fatigue curves of both carburized and hardened steel , and bainitic alloyed ductile cast iron were higher than this curve . This curve represents the lower bound of surface fatigue characteristics of these tested materials . Even this minimum value of surface fatigue limit ensures quite sufficient reserve to cover a wide range of gear applications in automobiles including all moderately stressed and the most of highly stressed gears .

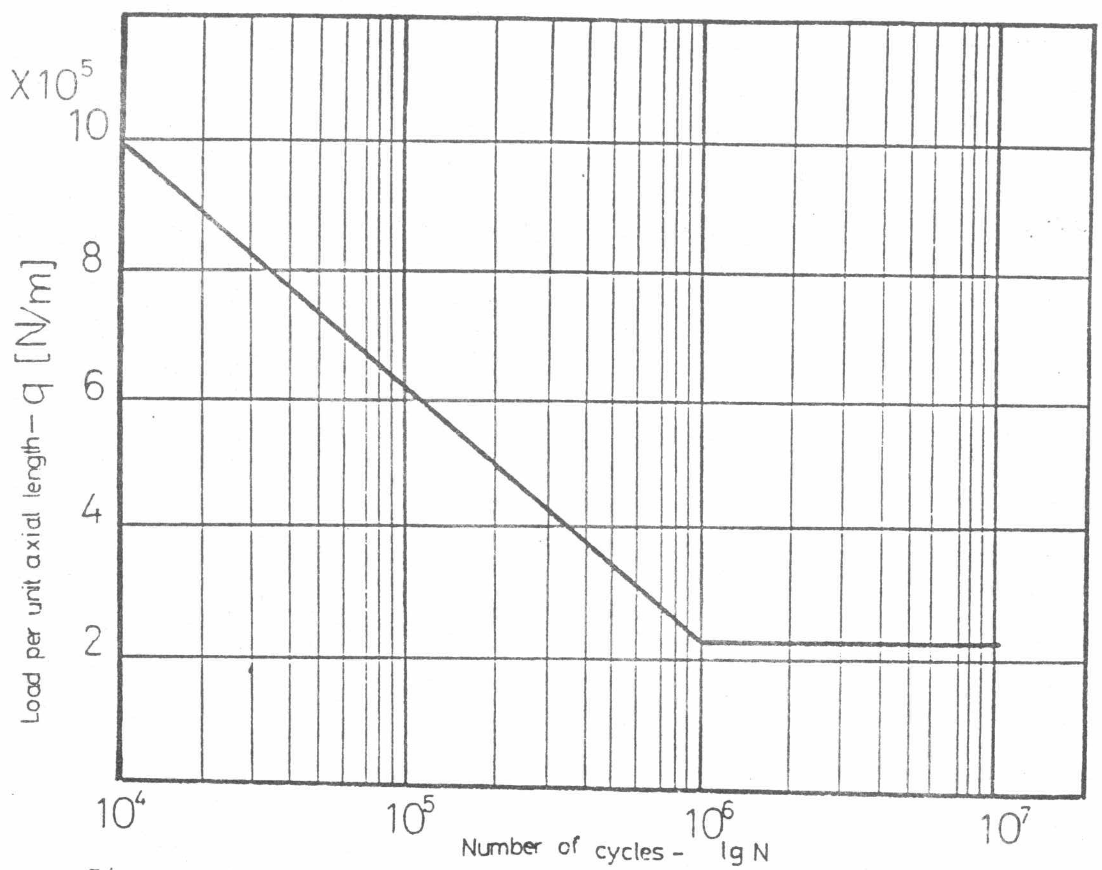

Fig. 6. : Lower bound of fatigue curves for both lower bainitic ductile cast iron and carburized hardened steel under wet rolling combined with 10% sliding.

CONCLUSIONS

The bainitic ductile cast iron is suitable for gear applications due to the following observations in comparison with steel :

1) It does not suffer from seizure and its alternatives (scoring , scuffing , ...) , and also its lubrication requirements are less .
2) The running-in period is shorter , and the operating service life is longer
3) It bears safely intermittent overloads or poor lubrication conditios with no danger of cold welding or metal transfer .
4) It offers higher mechanical efficiency as the friction losses is reduced very much .
5) It runs quitely with very low level of noise due to the high damping capacity of the material .

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