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Abrasive wear study of bainitic nodular cast iron

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The abrasive wear properties of the bainitic nodular cast iron under different austenitizing and isothermal transformation temperature and time were studied in the present paper. Using Optimol schwingung reibung verschleiß wear tester, the point contact is adopted to compare the effect of those various heat-treatment conditions on wear properties. The weight loss, wear-scar diameter and friction coefficient were measured to evaluate the wear properties. Using scanning electron microscopy, the wear mechanisms can be understood by observing the worn surface. From the results of weight loss, wear-scar diameter and friction coefficient, it can be concluded that the wear resistance increased with increasing austenitizing temperature and the most suitable austempering temperature of the material used in the present study is from 270–300 °C for 4 h.

1. Introduction

Austempering is a relatively new treatment in the field of ductile iron castings. This heat treatment was found to improve the ductility of ductile irons at high levels of strength, rendering ductile iron castings superior to steel forgings. Recently, there has been a number of well-documented accounts [1–3] of the application of austempered ductile irons in components such as crankshafts, camshafts, railway wagon wheels, and particularly gears of various types. The mechanical properties of austempered ductile iron, including tensile properties [4, 5], impact toughness [6, 7], fracture toughness [8] and fatigue properties [9, 10] have been evaluated and the microstructural characteristics of a number of the irons have been characterized and correlated to chemical composition and heat treatment.

The influence of the microstructure on the properties of the material has also been studied in many publications [11–14]. Franetovic *et al.* [15] investigated the influence of austempering temperature, austenitizing time and silicon content on the impact properties using transmission electron microscopy. They indicated that austempering at 370 °C for 1 h results in the optimum combination of strength and impact toughness. Krasowsky *et al.* [16] studied the fracture toughness of nodular cast irons with differing percentages of pearlite structures. From the fractographic observations, graphite inclusions play an important role in the process of fracture. A series of studies by Doong [17–21] and colleagues covered the heat-treatment effect for various matrix microstructures on the fracture toughness and fatigue crack-growth properties.

At present, very limited information on the abrasive wear properties of austempered ductile iron is available. Wear is one of the major ways by which materials cease to be useful. Process plant and subsidiary processes contend with a much bigger wear problem than in the case of machine parts, although their life is often much shorter. Therefore, it is important to enhance the wear resistance of cast irons. From the studies mentioned above, it is possible to produce a ductile casting with good impact strength, fracture toughness and fatigue properties, which can be processed to provide a wear-resistant surface. The Tan *et al.* [22] investigated the wear resistance of the bainitic nodular cast iron by laser surface hardening for various heat-treatment conditions. However, the study was focused on the influence of the laser-processed conditions. The effects of different bainitic iron transformation temperatures and different isothermal transformation times on the wear resistance are not yet understood. The purpose of the present study was to fill in gaps in the previous study [22] and to produce wear properties useful in industry. Scanning microscopy was performed in order to understand the more detailed wear mechanisms of worn surfaces.

2. Experimental procedure

The material of test specimens was a nodular cast iron that was melted in a 50 kg high-frequency induction furnace, and then magnesium treated in a ladle and cast into sand moulds. The chemical composition of cast iron is given in Table I. A typical specimen was 22 mm × 12 mm × 2.5 mm thick and ground to a surface roughness value, R_a, of 0.6 ± 0.07 μm. In order to study the effects of austempering temperature on wear behaviour, specimens were austenitized at 900 °C for 1 h, then quenched between 270 and 450 °C for $1\frac{1}{2}$ h. The influence of austenitizing temperature on wear resistance was also investigated, and thus specimens were austenitized at 850, 900 and 950 °C, respectively,

TABLE I Chemical composition (wt %) of nodular cast iron and steel balls

	C	Si	Mn	P	S	Cr	Mg	Ni	Mo	Cu
Nodular cast iron	3.306	2.330	0.042	0.035	0.012	0.037	0.023	0.481	0.031	0.051
Steel ball	1.04	0.23	0.30	0.02	0.02	1.45	–	–	–	–

TABLE II Specimen number and austempering treatment conditions

Specimen number	Austenitizing temperature (°C), time (h)	Austempering temperature (°C), time (h)
A1	900, 1	270, 1.5
A2	900, 1	300, 1.5
A3	900, 1	350, 1.5
A4	900, 1	400, 1.5
A5	900, 1	450, 1.5
B1	850, 1	350, 1.5
B2	900, 1	350, 1.5
B3	950, 1	350, 1.5
C1	900, 1	350, 0.15
C2	900, 1	350, 0.5
C3	900, 1	350, 1.5
C4	900, 1	350, 4.0
C5	900, 1	350, 9.0

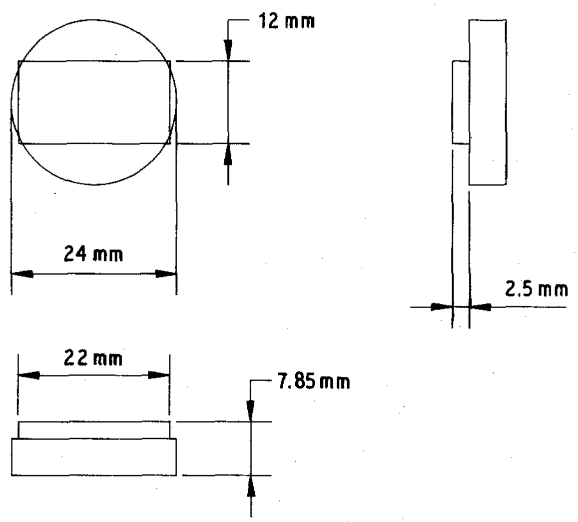


Figure 1 Dimensions of the wear-test specimen.

for 1 h, then quenched at 350 °C for $1\frac{1}{2}$ h. In addition, specimens with an austempering temperature at 900 °C for 1 h, then quenched at 350 °C for various isothermal transformation times, were prepared for wear tests. All the heat-treatment conditions are shown in Table II.

A low-carbon steel disc, 24 mm diameter and 5.35 mm thick, was used as the base plate. The specimens with different heat-treatment conditions were fixed to the base plates with mixed adhesive. The dimensions of the wear test specimen are shown in Fig. 1. The Optimol schwingung reibung verschleiß (SRV) wear tests were performed with ball-on-plane contact under two different loads (30 and 60 N) at room temperature for 1 h (equivalent sliding distance of 360 m). The stroke and frequency were 1 mm and 50 Hz, respectively. The upper specimen was 10 mm diameter chromium steel balls (nominal compositions are shown in Table I) with average hardness HR_c 62 ± 2. The friction coefficient was recorded for each 1 h test. Before and after testing, specimens were cleaned ultrasonically in acetone, dried and weighted to an accuracy of $\pm$ 0.1 mg. The average wear-scar diameter was measured in directions parallel and perpendicular to the sliding motion, using a microscope. The wear mechanisms at work on the worn surfaces were identified from scanning electron micrographs.

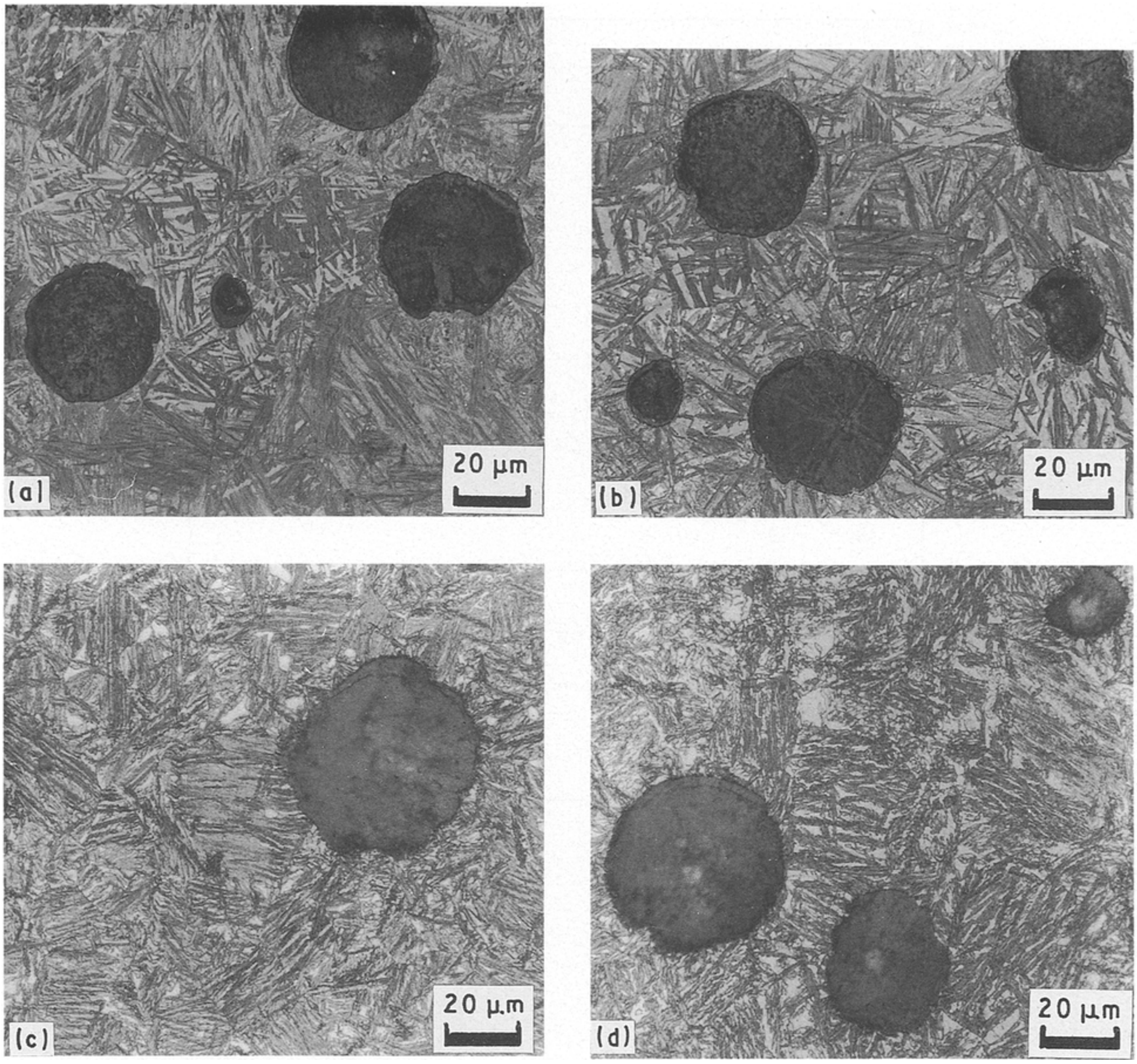
3. Results and discussion

In previous studies [20, 21], the microstructures of various austempering treatment conditions were discussed in detail and some of those results are mentioned here. According to Dorazil *et al.* [23], the isothermal transformation of austenite in the bainitic region can be divided into three stages. (1) A considerable amount of martensite is formed. (2) Trans-

TABLE III Mechanical properties and retained austenite

Specimen number	Ultimate strength ($kgf\,mm^{-2}$)	Yield strength[a] ($kgf\,mm^{-2}$)	e[b] (%)	Brinell hardness (HB)	Retained austenite (%)
A1	145.0	125.4	0.89	372	2.45
A2	138.0	115.7	1.61	327	5.55
A3	102.0	84.2	6.20	270	18.12
A4	105.0	75.0	12.80	248	20.28
A5	100.3	71.0	5.20	239	18.00
B1	104.0	85.0	4.42	290	13.21
B2	102.0	84.2	6.20	270	18.12
B3	100.0	75.0	8.12	257	30.00
C1	99.3	76.1	2.90	300	5.64
C2	101.7	80.1	4.82	283	7.85
C3	102.0	84.2	6.20	270	18.12
C4	104.0	84.5	3.88	280	14.25
C5	104.5	95.0	3.80	282	14.00

[a] 0.2 offset.
[b] 25 mm gauge length.



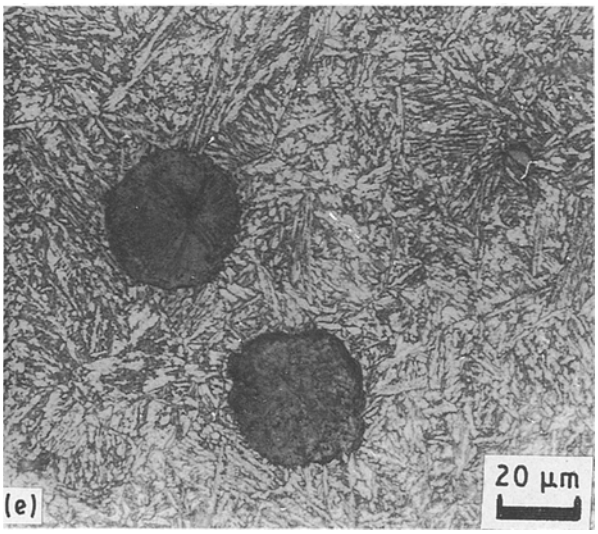


Figure 2 Microstructures with different austempering temperatures. (a) 270 °C (b) 300 °C (c) 350 °C (d) 400 °C (e) 450 °C.

formation continues mainly by the lateral growth of bainitic ferrite plates. The best combination of tensile strength and ductility are reached at this stage. (3) The austenite decomposes to form additional ferrite and plate-like carbide precipitates. Fig. 2 shows the microstructures with different austempering temperatures. The finer lower bainitic structures obtained at austempering temperatures of 270 and 300 °C are shown in Fig. 2a and b. For higher austempering temperatures of 400 and 450 °C, the upper bainitic structures can be observed in Fig. 2d and e.

Table III shows the effects of austempering temperature, austempering time and austenitizing temperature on mechanical properties and retained austenite. From Table III, the high tensile strength and high hardness obtained at low temperature (270 °C) is based on the quality of the lower bainite. Owing to the small amount of retained austenite, the elongation remains very small and hardness remains at a large value. At higher austempering temperatures, more stable retained austenite is created and then the tensile strength and hardness decrease, whereas the elongation increases considerably. When the austempering temperature exceeds 400 °C, the retained austenite and elongation substantially decrease. The influence of

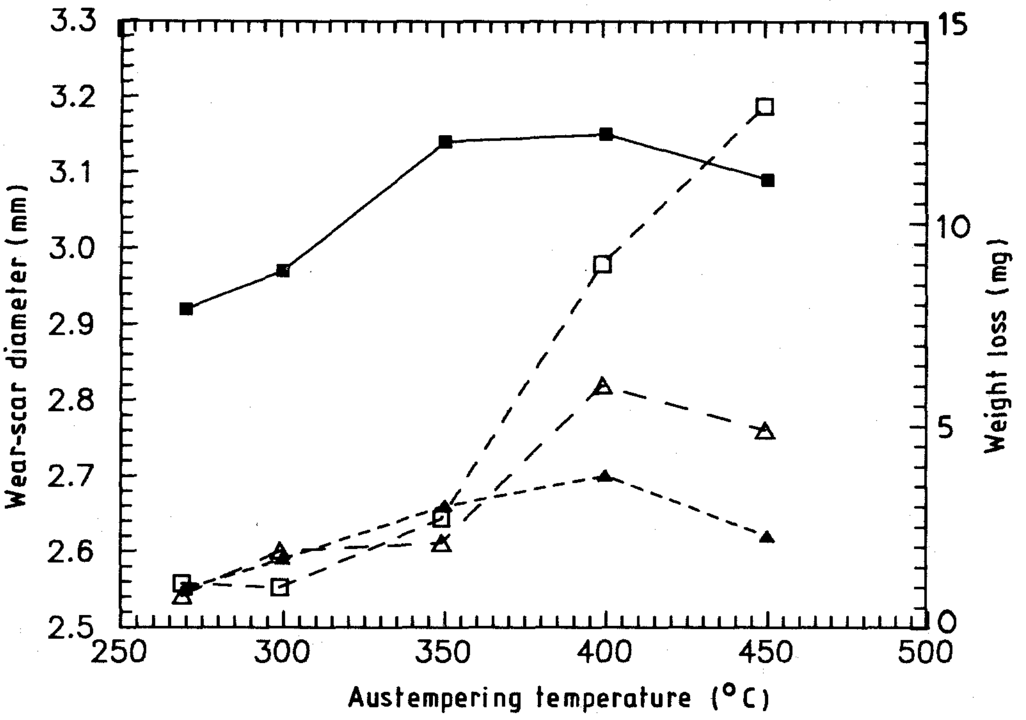


Figure 3 (▲,■) Wear-scar diameter and (△, □) weight loss of specimens with different austempering temperatures at (▲, △) 30 N load, (■, □) 60 N load.

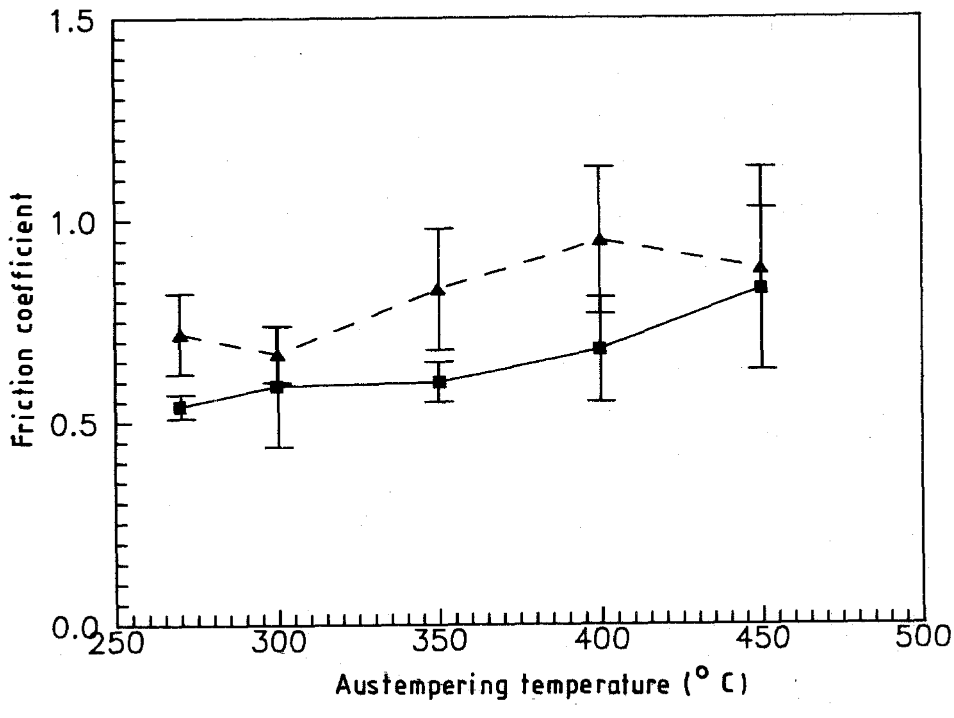


Figure 4 Friction coefficient of specimens with different austempering temperatures at (▲) 30 N load, (■) 60 N load.

austempering temperature on the abrasive wear is shown in Fig. 3. It can be seen that the weight loss and wear-scar diameter increase with increasing austempering temperature. According to Fig. 4, the friction coefficient of the higher austempering temperature specimen is higher than that of the lower austempering temperature. This characteristic coincides with the decrease in hardness and increase of retained austenite. It can be concluded that wear resistance absolutely depends on the amount of retained austenite and the hardness of the matrix structures.

Fig. 5 shows the effects on weight loss and wear-scar diameter of austenitizing temperature in the range 850–950 °C. At higher austenitizing temperature, the weight loss and wear-scar diameter of bainitic ductile cast iron decrease. From comparison with the hardness and retained austenite data, it can be found that approximately the same hardness values are shown at

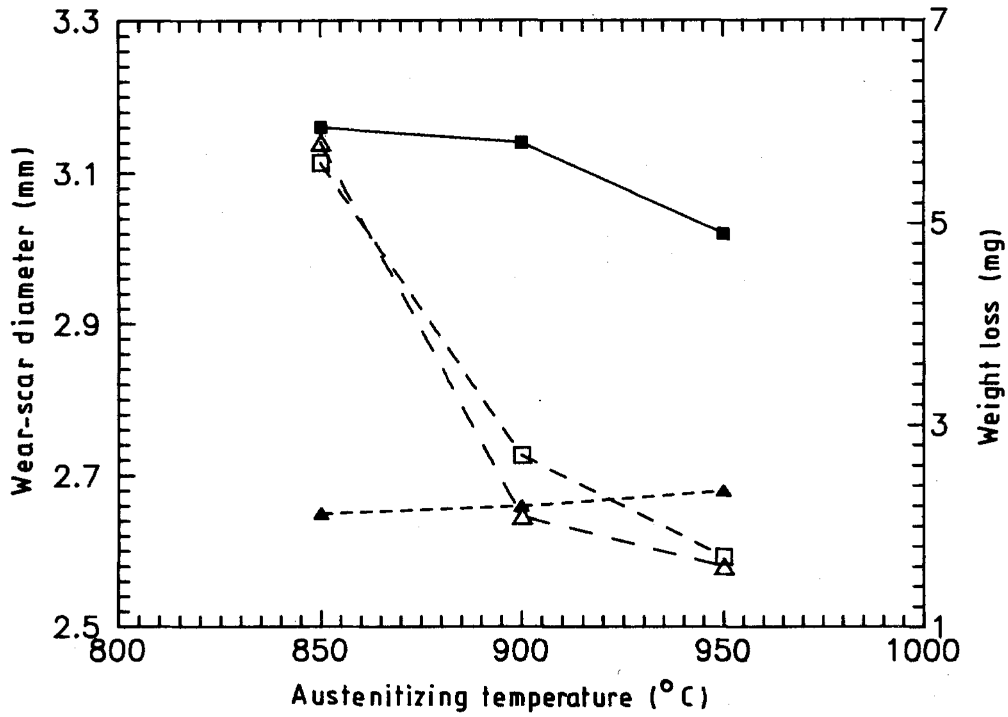


Figure 5 (▲, ■) Wear scar diameter and (△, □) weight loss of specimens with different austenitizing temperatures at (▲, △) 30 N load, (■, □) 60 N load.

TABLE IV Wear-scar diameter, weight loss and friction coefficient of wear tests

Specimen number	Load = 30 N			Load = 60 N		
	Wear diameter (mm)	Weight loss (mg)	Friction coefficient	Wear diameter (mm)	Weight loss (mg)	Friction coefficient
A1	2.55	0.8	0.72 ± 0.10	2.92	1.1	0.54 ± 0.03
A2	2.59	1.9	0.67 ± 0.07	2.97	1.0	0.59 ± 0.15
A3	2.66	2.1	0.83 ± 0.15	3.14	2.7	0.60 ± 0.05
A4	2.70	6.0	0.95 ± 0.18	3.15	9.0	0.68 ± 0.13
A5	2.62	4.9	0.88 ± 0.25	3.09	12.9	0.83 ± 0.20
B1	2.65	5.8	0.87 ± 0.17	3.16	5.6	0.75 ± 0.20
B2	2.66	2.1	0.83 ± 0.15	3.14	2.7	0.60 ± 0.05
B3	2.68	1.6	0.88 ± 0.15	3.02	1.7	0.60 ± 0.08
C1	2.57	2.1	0.82 ± 0.10	3.01	4.0	0.63 ± 0.10
C2	2.58	2.0	0.82 ± 0.10	3.16	3.1	0.63 ± 0.08
C3	2.66	2.1	0.83 ± 0.15	3.14	2.7	0.60 ± 0.05
C4	2.64	2.3	0.95 ± 0.15	3.07	1.4	0.59 ± 0.08
C5	2.57	2.0	0.92 ± 0.13	3.07	2.7	0.72 ± 0.18

the three different austenitizing temperatures and that significant variations in retained austenite among them are observed. Nevertheless, the friction coefficient of different austenitizing temperature specimens is about the same. The large amount of retained austenite results in lower weight loss.

The influence of various isothermal holding times on weight loss of 350 °C austempering temperature is shown in Fig. 6, which shows that the weight loss generally decreased with increasing austempering time and the minimum value of weight loss is reached at 4 h for higher load. As for lower load, the effect of holding time to weight loss is not significant. It is believed that an isothermal holding time of 9 h is too long for about 350 °C austempering temperature, and the bainite transformation is in the third stage and results in higher weight loss.

After point contact wear testing, it is not difficult to examine a worn surface to classify the nature of the damage in terms of ploughing, scuffing, abrasion and adhesion, etc. Fig. 7 shows scanning electron micrographs of worn surfaces on Specimen A3 under 60 N load. Some significant scratches are shown in the upper area of the worn surface (Fig. 7a), and surface polishing is dominate in the central area (Fig. 7b), while on the right-hand side (Fig. 7c) ridges of metal can be observed. From Fig. 8 it is very clear that ploughing grooves due to abrasive wear dominant on the worn surface of Specimen A1. As for Specimen A3 (Fig. 9), the fatigue spalling due to microcracking is

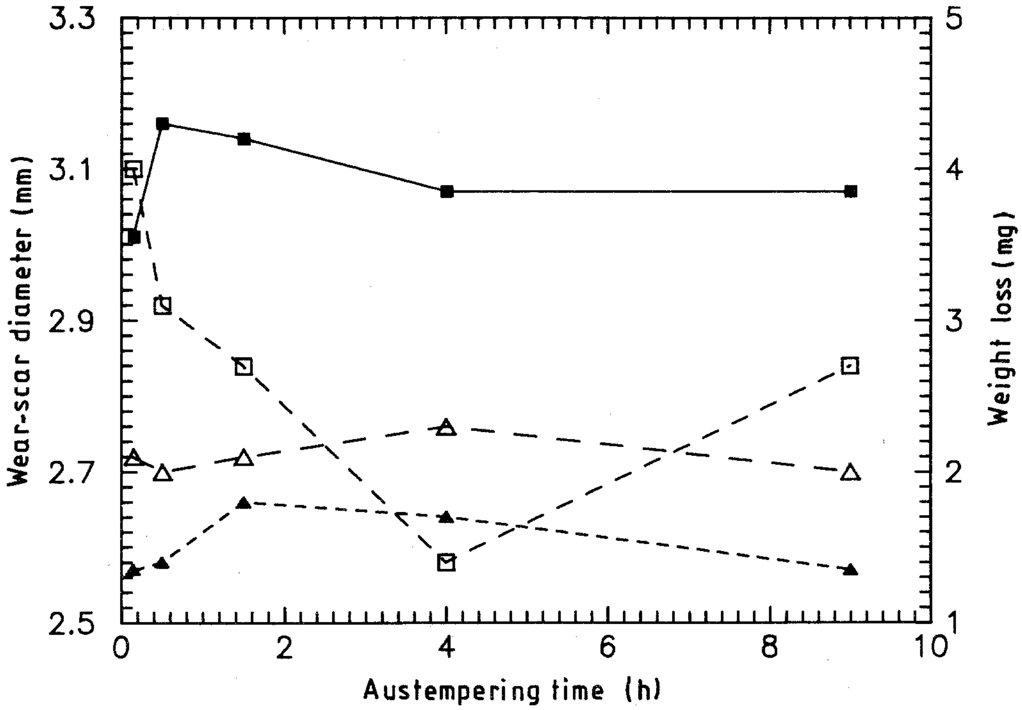


Figure 6 (▲, ■) Wear scar diameter and (△, □) weight loss of specimens with different isothermal holding time at (▲, △) 30 N load, (■, □) 60 N load.

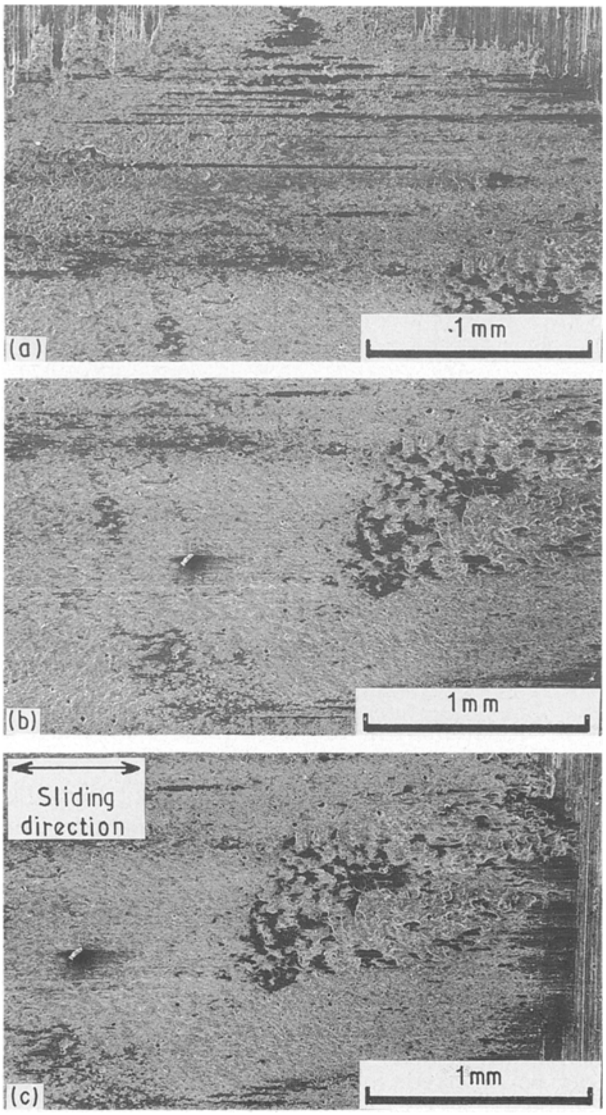


Figure 7 Microstructure of worn surface on Specimen A3 under 60 N load.

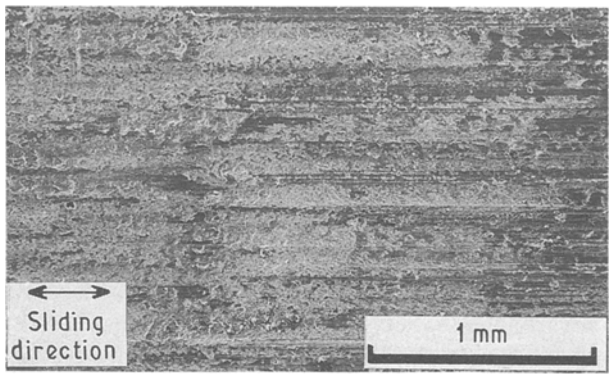


Figure 8 Microstructure of worn surface on Specimen A1 under 30 N load.

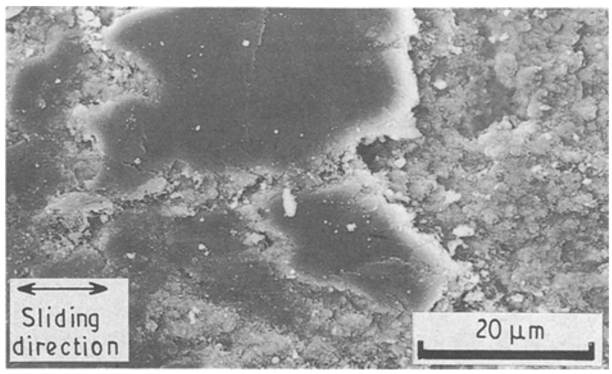


Figure 9 Microstructure of worn surface on Specimen A3 under 30 N load.

significant. The adhesive wear is shown on the worn surface of Specimen A5 in Fig. 10. The wear debris was adhered to the worn surface.

4. Conclusions

1. Wear resistance of bainitic nodular cast iron is very relevant to the volume fraction of retained austenite.

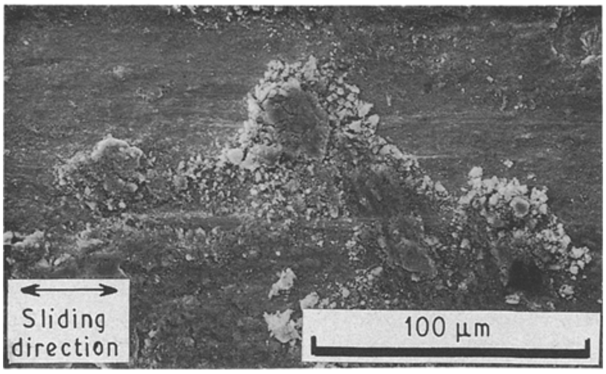


Figure 10 Microstructure of worn surface on Specimen A5 under 30 N load.

2. From the point of view of wear resistance ability, the most suitable austempering temperature of the material used in the present study is from 270–300 °C.
3. For the same austempering temperature, weight loss initially decreased with increasing austempering time and a minimum value is reached after 4 h for higher load.
4. The wear resistance increases with austenitized temperature for both test loads.
5. Three wear mechanisms (abrasive wear, adhesive wear and fatigue spalling) can be found from observing the worn surface.

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