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Abrasive wear property of bainitic nodular cast iron in laser processing

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The effects of the different austenitizing and isothermal transformation temperature and time on the wear resistance in bainitic ductile iron has been investigated and compared with surface hardening by laser processing, to find the best wear resistance for the bainitic ductile iron. It was found that the wear resistance of the lower bainitic ductile iron was better than upper bainitic ductile iron, and that the factor affecting hardness and wear properties the most was the isothermal transformation temperature. After surface hardening by laser processing, the hardening reached RC 55 or more, no evidence of any difference between the lower and the upper bainitic ductile iron being found.

1. Introduction

Austempered ductile irons offer high tensile strengths combined with good ductility. Recently, they have been used in components such as crankshafts, camshafts, railway wagons and particularly gears of various types. A number of investigators have studied the mechanical properties of austempered ductile iron, including tensile properties [1], impact toughness [2], fracture toughness [3] and fatigue properties [4]. 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.

It is possible to produce a ductile casting with good impact strength and fracture toughness being processed to provide a wear-resistant surface, and this may point to future applications of laser hardening in a laser heat treatment as a viable means of producing a shallow hardened case on nodular bainitic-type cast iron.

There has been widespread interest in the use of lasers for material processing applications; altering a specific area of a component to withstand the harsh environment to which it is subjected, optimizes the component performances by saving money and strategic material. In a recent investigation, Bergmann *et al.* [5] reported the wear properties of laser-melted spheroidal graphite (SG) iron. Sliding wear processes of various cast irons samples surface melted by laser were studied by Leech [6]. Cavitation wear of grey cast iron by laser-surface melting was studied by Tomlinson *et al.* [7], who confirmed that erosion resistance of a laser-processed coating in distilled water was higher than untreated material, owing to the increase in hardness and new structures.

The hardness, microstructure and chemical composition of bainitic nodular cast iron have a marked effect on its wear resistance. The purpose of this study was to investigate the effects of different bainitic iron transformation temperatures and different isothermal transformation times on the wear resistance. In addition, the wear resistance of the bainitic nodular cast iron processed by laser surface hardening is compared with unprocessed samples.

2. Experimental procedure

The material selected for the study 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 the cast iron is given in Table I and the microstructure of as-cast sample is shown in Fig. 1a.

A typical specimen was rectangular in shape 25 mm × 76 mm × 4 mm thick, and was subsequently machined from the castings and ground to a roughness R_a of $0.6 \pm 0.07\,\mu$m for laser treatment. In order to compare the influence of austempering temperature on the wear resistance, specimens were austenitized at 900° C, then quenched between 250 and 450° C, and held at this temperature for 4 h. The amount of bainite produced can be controlled by varying the holding time at the isothermal treatment temperature. Holding times varied from 2 min to 10 h at isothermal transformation temperatures of 300 and 400° C in order to compare the influence of bainite transformation extent on the wear resistance. All the heat treatment conditions are given in Table II.

Specimens surface processed by laser surface hardening were produced by a continuously focused beam continuous-wave CO_2 laser, 10.6 μm wavelength with an overlap of individual traces by 50% used to create full area coverage. Because metals are good reflectors for 10.6 μm wavelength produced by the CO_2 lasers, the samples surface were sprayed with a

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TABLE I Chemical composition (wt %)

C	Si	Mn	P	S	Mg	Cu	Mo	Ni
3.03	2.4	0.08	0.008	0.009	0.03	0.54	0.18	0.04

thin graphite layer to enhance heat absorption. Argon shielding gas was used to minimize oxidation. The laser processing conditions of power density $1.43 \times 10^4\,\mathrm{W\,cm^{-2}}$, beam diameter 4 mm and interaction time 0.1 sec, resulted in a uniformly hardened layer 0.4 to 0.6 mm deep.

Laboratory wear testing was carried out using a conducting dry sand/rubber wheel abrasion test to evaluate the wear resistance of as-cast iron, nodular bainitic cast iron and nodular bainitic cast iron processed by laser surface hardening. The experimental procedure meets the ASTM G65-85 standard. AFS 60 mesh silicon carbide was used as abrasive particles, and the sand flow was about $275\,\mathrm{g\,min^{-1}}$. Before testing, the specimens were ultrasonically cleaned, dried and weighed to an accuracy of 0.1 mg. Cross-sections of the hardened zone were polished metallographically and examined by optical microscopy; the hardness of microstructure was measured by Vickers and Rockwell hardness, and the worn surfaces were studied by scanning electron microscopy as a means of identification of the wear processes.

3. Results and discussion

3.1. Microstructural analysis

The metallograph of the as-cast iron is shown in Fig. 1a and the microstructures of different austempering temperatures are shown in Figs 1b to f. The austempering temperature below 350° C will have large temperature gradient, because it was difficult for the carbon in the growing ferrite to diffuse, and thus the earlier forming ferrite will saturate with carbon. The ferrite will not grow until precipitation of Fe_3C occurs. There were many fine nuclei of Fe_3C which transformed to needle-type lower bainite. In the same bainitic structure, the lower the transformation

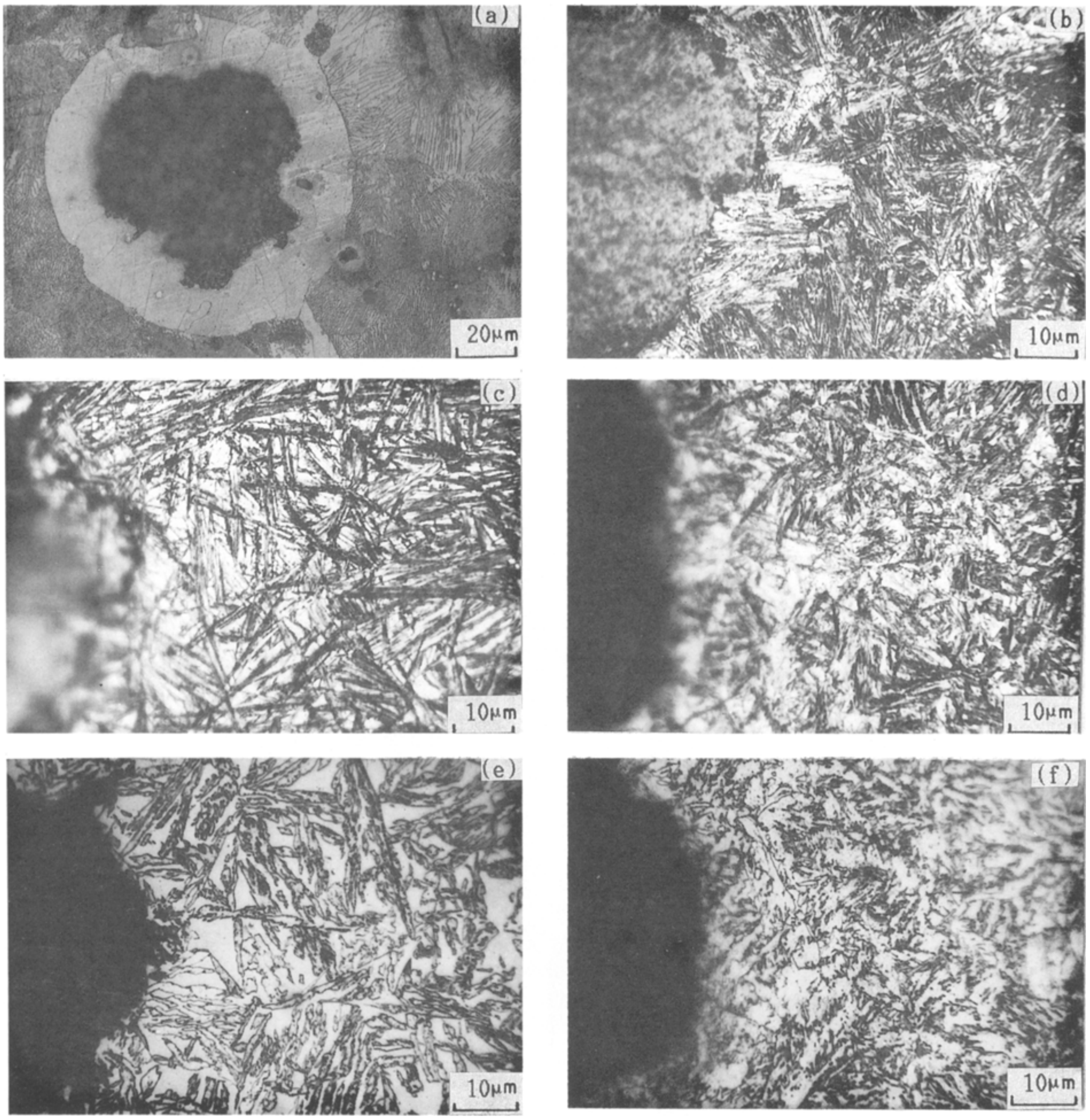

Figure 1 (a) Bullseye pearlite structure. (b) 250° C, finer lower bainitic structure. (c) 300° C, lower bainitic structure. (d) 350° C, lower bainitic structure. (e) 400° C, upper bainitic structure. (f) 450° C, upper bainitic structure.

TABLE II Heat treatment conditions and wear data (L: laser treated)

Heat-treatment condition	Specimen no.	Hardness (Rc)	Wt loss (g) 200 r.p.m.	Heat-treatment condition with laser hardening	Specimen no.	Hardness (Rc)	Hardness after laser	Wt loss		
								200 r.p.m.	500 r.p.m.	800 r.p.m.
As-cast	1	19.4	0.6007	As-cast + L	1a	18.4	40.1	0.2934	0.5068	0.9852
900° C (1 h) → 250° C (1.5 h)	2	48.4	0.3123	900° C (1 h) → 250° C (1.5 h) + L	2a	48.2	58.4	0.2356	0.6079	0.9265
900° C (1 h) → 300° C (1.5 h)	3	45.6	0.3746	900° C (1 h) → 300° C (1.5 h) + L	3a	45.2	57.8	0.2317	–	–
900° C (1 h) → 350° C (1.5 h)	4	37.1	0.4145	900° C (1 h) → 350° C (1.5 h) + L	4a	37.3	57.4	0.2142	0.5565	0.9273
900° C (1 h) → 400° C (1.5 h)	5	31.7	0.4173	900° C (1 h) → 400° C (1.5 h) + L	5a	31.6	56.7	0.2334	–	–
900° C (1 h) → 450° C (1.5 h)	6	28.5	0.5739	900° C (1 h) → 450° C (1.5 h) + L	6a	27.3	55.1	0.2208	0.5603	0.9497
900° C (1 h) → 300° C (2 min)	7	55.1	0.2197	900° C (1 h) → 300° C (2 min) + L	7a	55.7	58.7	0.2293	0.5607	0.8715
900° C (1 h) → 300° C (9 min)	8	47.1	0.3215	900° C (1 h) → 300° C (9 min) + L	8a	46.7	57.5	0.2452	–	–
900° C (1 h) → 300° C (30 min)	9	46.0	0.3767	900° C (1 h) → 300° C (30 min) + L	9a	46.0	58.1	0.2232	0.5693	0.9141
900° C (1 h) → 300° C (1.5 h)	10	46.6	0.3746	900° C (1 h) → 300° C (1.5 h) + L	10a	46.2	58.4	0.2317	–	–
900° C (1 h) → 300° C (4.0 h)	11	45.9	0.3727	900° C (1 h) → 300° C (4.0 h) + L	11a	46.3	58.0	0.2261	0.5621	0.9223
900° C (1 h) → 400° C (2 min)	12	44.0	0.3407	900° C (1 h) → 400° C (2 min) + L	12a	43.6	57.6	0.2387	–	–
900° C (1 h) → 400° C (9 min)	13	30.6	0.4165	900° C (1 h) → 400° C (9 min)	13a	29.7	56.8	0.2267	–	–
900° C (1 h) → 400° C (30 min)	14	29.4	0.3982	900° C (1 h) → 400° C (30 min) + L	14a	29.8	55.2	0.2232	–	–
900° C (1 h) → 400° C (1.5 h)	15	30.7	0.4173	900° C (1 h) → 400° C (1.5 h) + L	15a	30.6	56.7	0.2508	–	–
900° C (1 h) → 400° C (10 h)	16	32.6	0.4737	900° C (1 h) → 400° C (10 h) + L	16a	31.1	55.1	0.2356		
850° C (1 h) → 300° C (1.5 h)	17	46.0	0.3669	850° C (1 h) → 300° C (1.5 h)	17a	46.0	57.7	0.2342	–	–
900° C (1 h) → 300° C (1.5 h)	18	46.6	0.3746	900° C (1 h) → 300° C (1.5 h) + L	18a	46.2	57.8	0.2317	–	–
950° C (1 h) → 300° C (1.5 h)	19	45.8	0.3465	950° C (1 h) → 300° C (1.5 h) + L	19a	45.7	57.7	0.2297	–	–
850° C (1 h) → 370° C (1.5 h)	20	34.3	0.4191	850° C (1 h) → 370° C (1.5 h) + L	20a	35.5	56.3	0.2201	–	–
900° C (1 h) → 370° C (1.5 h)	21	35.3	0.3831	900° C (1 h) → 370° C (1.5 h) + L	21a	35.7	56.4	0.2304	–	–
950° C (1 h) → 370° C (1.5 h)	22	36.4	0.3753	950° C (1 h) → 370° C (1.5 h) + L	22a	35.1	56.5	0.2298	–	–

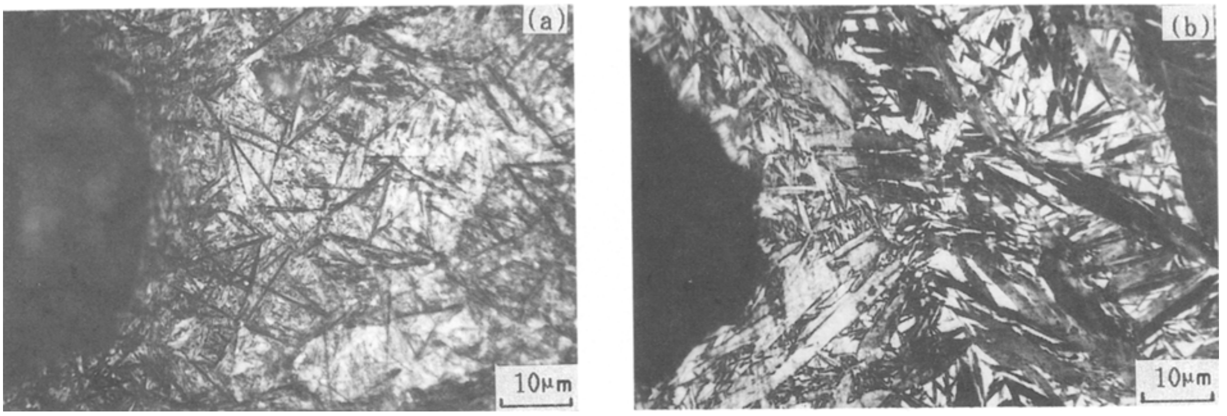

Figure 2 (a) Lower bainitic structure produced with insufficient isothermal transformation time. (b) Upper bainitic structure produced with insufficient isothermal transformation time.

temperature, the thicker the carbon content and the finer the ferrite plate became and the more Fe_3C grains were observed (see Figs 1b to d). The high hardness obtained at 250° C austempering is based on the quality of the lower bainite (Fig 1b), Figs 1c to d are lower bainite. As the austempering temperature is higher than 400° C, because of the lower temperature gradient, carbon can diffuse freely into austenite which surrounds the growing ferrite. As the growth of ferrite proceeds, the carbon content in austenite will increase and surround the ferrite plate. When the carbon in the austenite is enriched to some degree, it will precipitate plate-type or bar-type Fe_3C which will form upper bainite. In the same upper bainite, the lower the transforming temperature the finer the ferrite plate and the Fe_3C plate become. Figs 1e and f show upper bainite. From the basic of the studies of Dorazil *et al.* [8], the course of isothermal transformation of austenite in the bainite region can be divided into three stages.

1. During the beginning of the first stage of the austempering transformation, the considerable amount of martensite formed from the austenite by quenching, markedly affects the properties. With increasing holding time of isothermal transformation, both the amounts of bainite and that of carbon-enriched untransformed austenite, increase and the amount of martensite is reduced in the final structure.

2. In the second stage, the transformation continues mainly by lateral growth of bainitic ferrite plates. The additional carbon diffuses into the austenite as additional ferrite forms. This carbon enrichment of the austenite is sufficient to stabilize fully the austenite even when cooling rapidly to room temperature. The untransformed austenite kept at room temperature is called the retained austenite. The tensile strength reaches its maximum value at this stage.

3. The final stage of the transformation is characterized by the decomposition of austenite to form additional ferrite and plate-like carbide precipitates. A mixture of ferrite and carbide is found in areas where bainitic ferrite plates have grown into each other. This suggests that at this stage austenite transformation is in the form of the eutectoid-type reaction, $\gamma \rightarrow \alpha + C$ (C is carbide). In Figs 2a and b, the austenite isothermal transformation can be divided into three stages: in the first stage, the austenite transformation speed is very fast, as the forming of bainitic ferrite less carbon are dissolved most of the carbon concentrated on austenite, if the transformation time is insufficient, the farther austenite have not enough carbon to concentrate. If quenched from the isothermal transformation temperatures the retained austenite will transform to martensite, so the microstructure will consist of martensitic and bainitic. At the beginning of bainite transformation, the hardness of the structure is quite high, but the tensile strength and fracture toughness are lower [9] and the fatigue crack growth rate is higher [10]. As the isothermal transformation time increases, the bainitic structure will increase, and non-transformed carbon-concentrated austenite will become less, but it has a higher strength and lower hardness. Fig. 3 shows the martensite structure in the hardened layer of the as-cast sample which was heated by laser processing to above the austenitizing temperature, and then self-quenched. As seen in Figs 4a and b, whatever the lower or upper bainitic structure, martensitic structure can also be obtained in the hardened layer by laser processing. Otherwise, a mixed structure of martensite and lower bainitic (or upper bainitic) will be produced in the heat-affected zone by laser processing (see Figs 5a and b).

3.2. The influence of austempering temperature

The austempering heat treatment at different temperatures (250 to 450° C) can produce different microstructure and hardness. The hardness and microstructure of cast iron have marked effects on its wear resistance;

Figure 3 Optical micrograph of as-cast sample after laser treatment. Martensite structure (surface hardening zone).

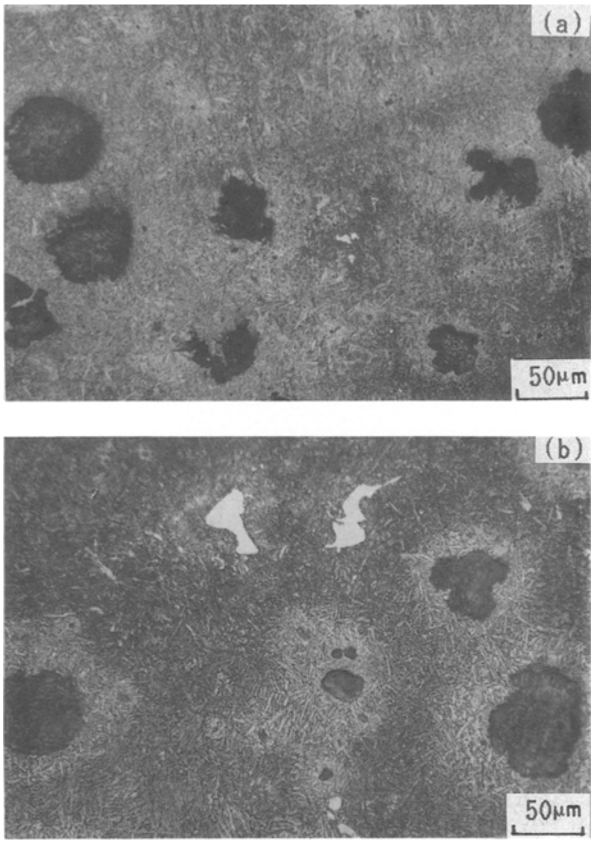

Figure 4 (a) Martensite structure of the hardened surface of lower bainitic structure. (b) Martensite structure of the hardened surface of upper bainitic structure.

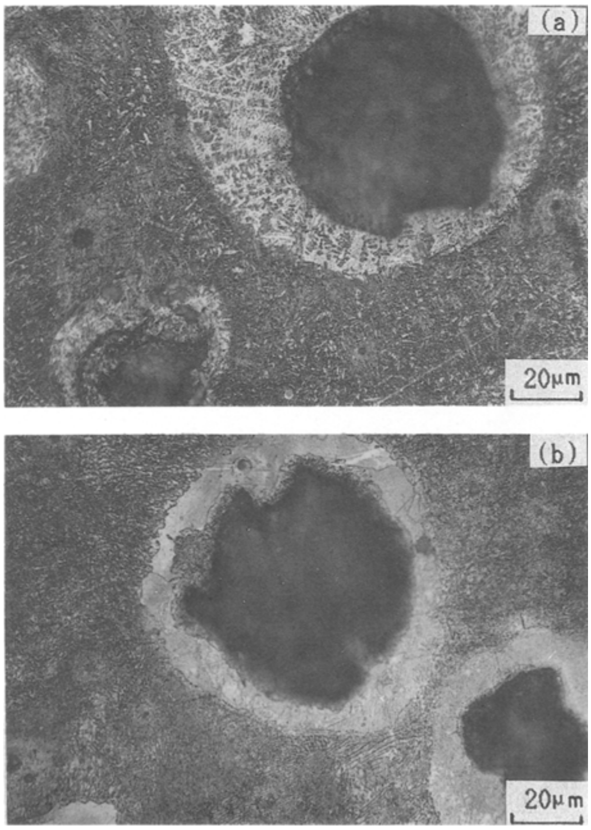

Figure 5 (a) Martensite and lower bainitic structure of the heat-affected zone. (b) Martensite and upper bainitic structure of the heat-affected zone.

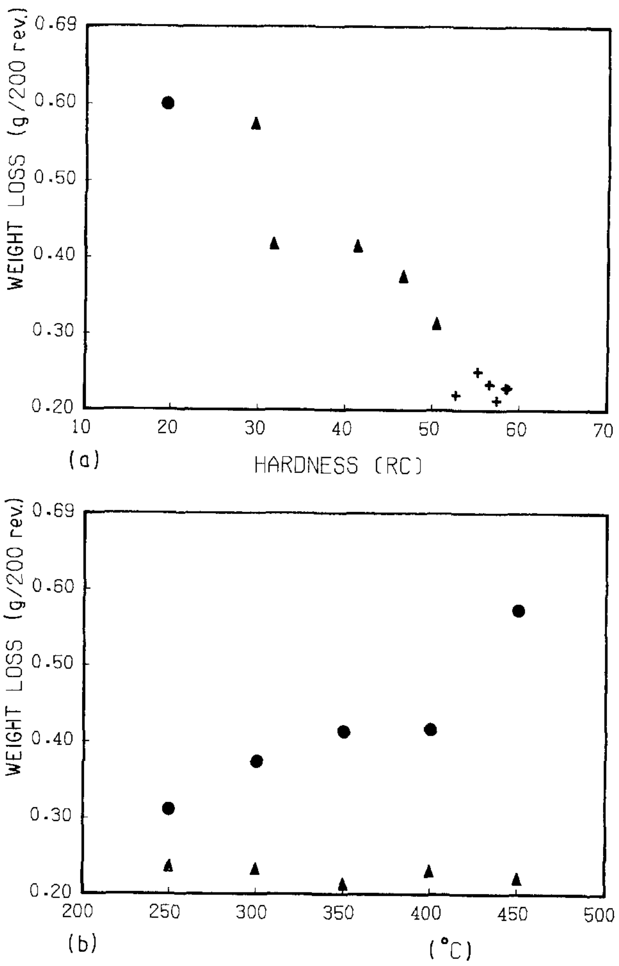

Figure 6 Variation of (a) hardness and (b) temperature with weight loss, for (●) the untreated sample, and (a) (▲) the austempered and (+) laser treated and (b) (▲) the laser treated samples.

Fig. 6a show that the differences between upper and lower bainite are that the Fe_3C in the former will precipitate outside the ferrite plate, but in the latter will precipitate inside the ferrite plate. Because of the over-saturated carbon content in the ferrite plate and the fineness and close packing of Fe_3C, the lower bainite has a higher strength and hardness. It is found that the as-cast iron has lower hardness and worse wear resistance; upper bainite is slightly worse, but the best of the three is the lower bainite. On the other hand, the bainitic structures obtained at different austempering temperatures were treated by laser surface hardening in which the specimen's surface was heated to a temperature below its melting point, and the microstructure of the near surface layer can be given a surface hardness as high as RC55. Fig. 6a shows that the weight loss of bainitic nodular cast iron during laser processing was less than in the bainitic nodular cast iron and as-cast iron. Also, it is believed that abrasive wear is affected by a combination of surface hardness and microstructure. Bainitic nodular cast irons have different microstructure and hardness, but the microstructure of the near surface layer and the surface hardness produced by laser surface hardening are similar; the wear resistance of the surface layer structure of bainitic nodular cast is also similar.

The effects of austempering temperature on wear resistance are shown in Fig. 6b. The high tensile strength and high hardness at low austempering temperature (250° C) are based on the quality of the lower

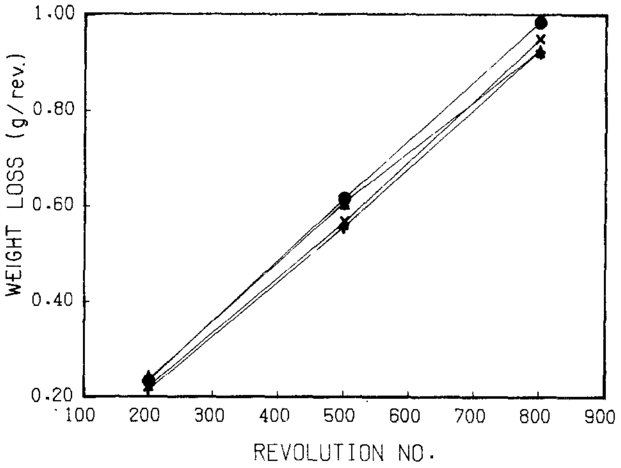

Figure 7 Variation of weight loss with number of revolutions under different conditions.(○) As-cast + L, (△) 250° C temper + L, (+) 35° C temper + L, (x) 450° C temper + L.

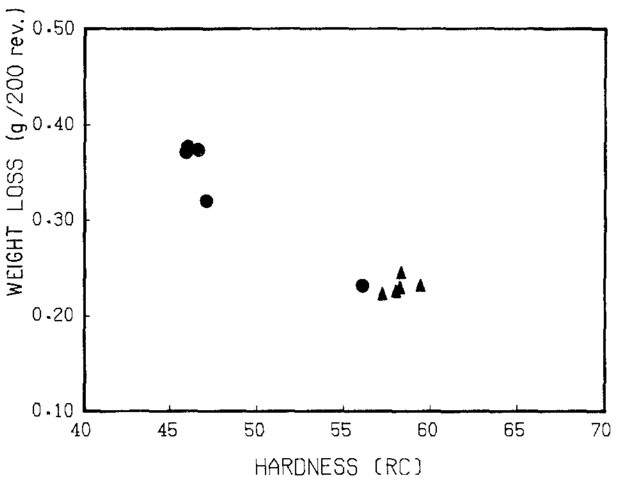

Figure 8 Variation of weight loss with hardness for different isothermal holding time compared with laser treated sample. (○) As-cast, (△) laser treated.

bainite, thus it exhibited a higher wear resistance than the other microstructure. From a previous study [10] it was found that the lower bainitic structure produced at 350° C austempering temperature has the slowest fatigue crack growth rate, good toughness and medium strength, but the wear resistance is not good for the lower bainitic structure of 350° C austempering.

In order to obtain low fatigue crack growth rate and high wear resistance, we must obtain high surface hardness using laser surface hardening. Fig. 6 shows that the abrasive wear characters of bainitic nodular cast iron can be improved by surface hardening with a CO_2 laser. On the other hand, in order to investigate the different depths of the hardened layer we carried

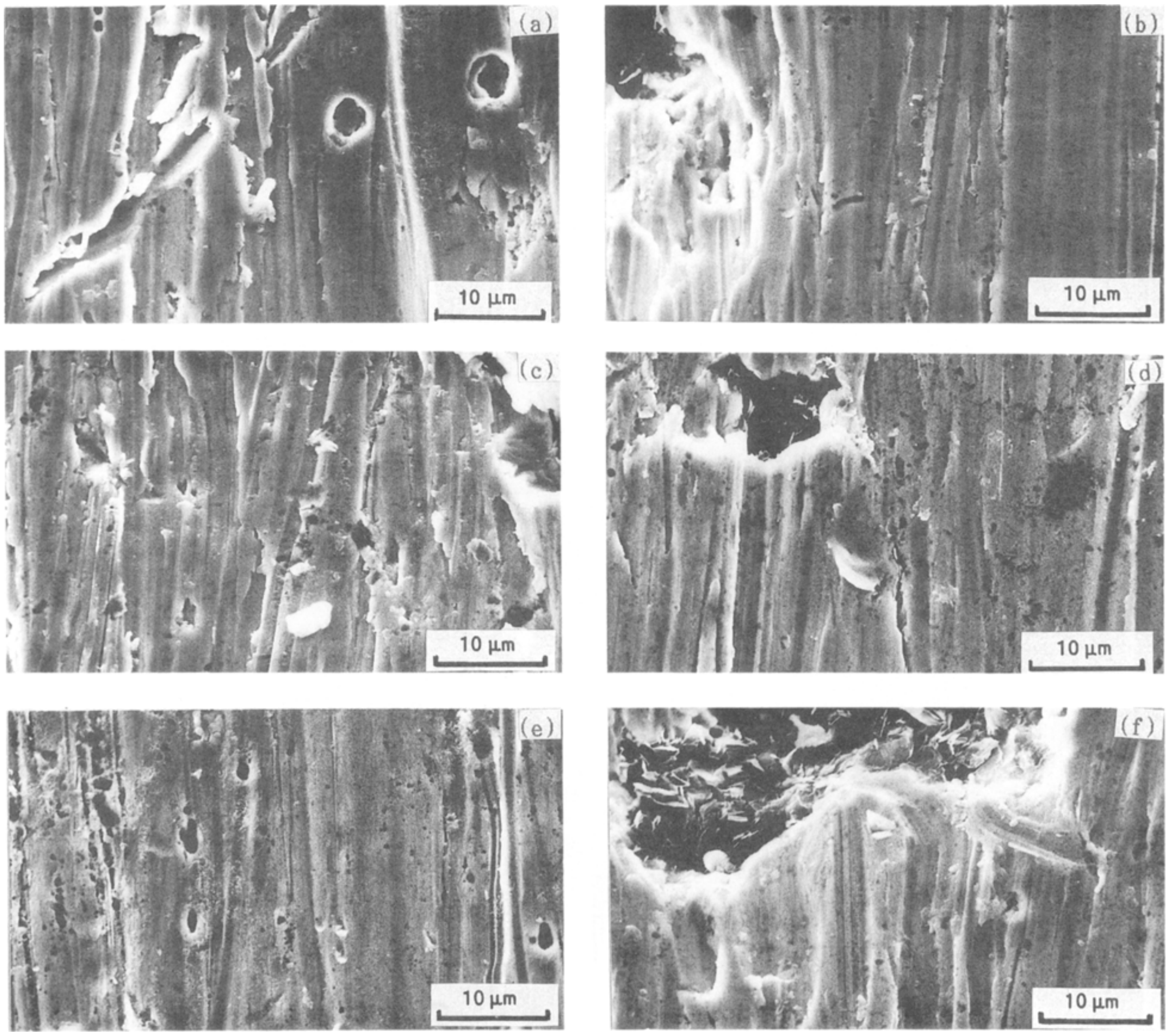

Figure 9 Scanning electron micrographs of the worn surfaces (L: laser treated). (a) As-cast, (b) lower bainitic structure, (c) upper bainitic structure, (d) martensite structure (as-cast + L), (e) martensite structure ((b) + L), (f) martensite structure ((c) + L).

out abrasive wear testing using three steps until the total number wear revolutions reached 800. These results are shown in Fig. 7, and it can be observed that as-cast iron and different austempering temperature samples have the same wear resistance as that obtained by laser processing.

3.3. The influence of isothermal holding time

Fig. 8 shows the influence of lower bainitic ductile irons with various isothermal holding times on the wear resistance of irons. With increasing austempering time, the tensile strength, elongation, impact toughness and fracture toughness increase while hardness is reduced. The weight loss generally increased with increasing austempering time. Although a 2 min austempering time exhibits a high hardness and lower weight loss, the martensite will cause the crack growth rate to increase quickly. Therefore, these lower bainitic ductile cast irons with a more than 30 min austempering time can be obtained with a high surface hardness of above RC55 by laser processing, in order to enhance the wear resistance and maintain its fatigue and toughness properties. In Fig. 8, the specimens produced by laser processing have a reduced weight loss, thus we must select the laser surface hardening to modify the surface layer of bainitic nodular cast iron, and this will cause the weight loss to be reduced.

After abrasive wear testing, it is not difficult to examine a worn surface to classify the nature of damage in such terms as ploughing, scuffing, abrasion, freeting, etc. Figs 9a to f show that scratches where material has been removed can be seen on the surface of the specimens abraded with silicon carbide. The sliding direction is along the vertical axis and all scratches were in the sliding direction, as expected. This is a typical abrasive wear characteristic. From Figs 9a to c, it can be observed that the low bainitic structure produced with a 250° C austempering temperature, exhibits a high hardness, so the smaller width and shallow depth of the scratches produced in the wear test give an indication of wear resistance. Similarly the relatively soft matrix in the as-cast sample has deeper and wider wear scratches, as shown in Fig. 9a. On the other hand, on comparing the laser processed and unprocessed samples surface, (Figs 9d to f), the wear resistance of laser processed samples is seen to be significantly enhanced by their martensite structure and improved hardness in the hardened layer.

4. Conclusions

1. After 1.5 h austempering time, the lower bainitic structure exhibits a good wear resistance, the upper bainitic a medium resistance, and the as-cast sample the worst resistance. The wear resistance decreases with increasing austempering temperature.
2. At 300° C austempering temperature, the wear resistance decreases with increasing of austempering time.
3. The austempering temperatures have a marked effect on the hardness and wear resistance.
4. The nodular bainitic cast iron can be obtained with a high hardness surface layer by laser surface hardening, and the wear resistance can be improved by laser material processing.

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