

Abrasive wear resistance of austempered ductile iron at room temperature

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Abstract

The use of austempered ductile iron obtained by heat treating spheroidal-graphite cast iron is very important in the gear industry. However the nature of the bainitic structure, which is used to improve wear resistance, has never been fully identified.

The aims of this study were:

- to optimize the upper bainitic structures in S.G. cast irons (usually called austempered ductile iron or A.D.I.) to have the best abrasive wear resistance at room temperature.
- to study the influence of the solidification cell characteristics upon these optimized structures.
- to determine the evolution of the microstructures during the abrasion test.

Results clearly indicate the primordial influence of the retained austenitic phase. A high percentage of retained austenite promotes a high abrasive wear resistance. The analysis of the results shows that this austenitic phase is heterogeneous. The best abrasive wear resistance is associated with the lowest hardness value. During abrasion, austenite at or near the surface is gradually and partly transformed to martensite.

Riassunto

Resistenza all'usura abrasiva della ghisa sferoidale, sottoposta ad austempering, a temperatura ambiente

L'uso di ghisa con grafite sferoidale austemprata sta diventando molto importante nell'industria degli ingranaggi. Ciò nonostante il trattamento termico bainitico, che è necessario per migliorare la resistenza all'usura, non è mai stato ben identificato.

Il presente studio si proponeva di:

- ottimizzare le strutture bainitiche superiori nelle ghise sferoidali (spesso chiamate "austempered ductile iron" o "A.D.I.") misurandone la resistenza all'usura abrasiva, a temperatura ambiente, in una macchina che simula l'abrasione.
- studiare l'influenza delle caratteristiche delle celle di solidificazione su tali strutture ottimizzate.
- determinare l'evoluzione delle microstrutture durante la prova di abrasione.

I risultati indicano chiaramente l'influenza fondamentale della fase austenite residua la quale, se in alta percentuale, favorisce una più alta resistenza all'usura abrasiva. L'analisi dei risultati mostra che tale fase è eterogenea. La resistenza più elevata all'usura abrasiva è associata ai valori di durezza più bassi. Durante l'abrasione, l'austenite in superficie o presso la superficie si trasforma gradualmente e parzialmente in martensite.

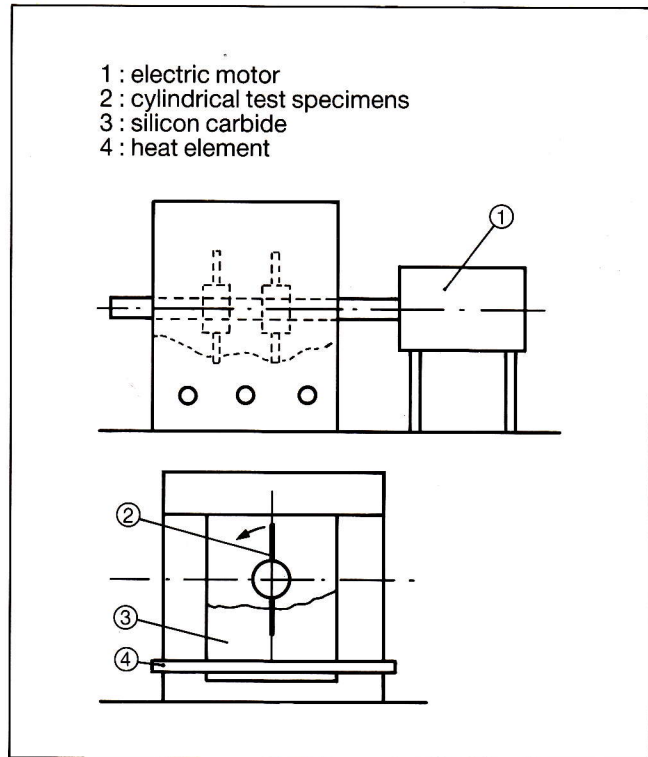
Introduction

Austempered ductile irons (A.D.I.) obtained by isothermal heat treatment of spheroidal graphite cast irons (S.G. cast irons) are known to produce beneficial mechanical properties. However, these properties

depend strongly on the composition, and heat treatment conditions (austenitisation and isothermal reactions) (1-7).

Some authors have shown that A.D.I. structures have a lower wear rate than does a quenched and tempered steel of similar hardness (8-9). To our knowledge, the influence of different A.D.I. microstructures on wear resistance has never been studied before, and the aim of this work is to determine this correlation.

Fig. 1 - Diagram of the abrasive wear test machine.



Experimental procedures

In this study an unalloyed ductile iron was used, the chemical composition of which was 3.40% C; 2.46% Si; 0.08% Mn; 0.008% S; 0.05% Mg. This alloy had a count of 200 nodules/mm². Cylindrical test specimens (L = 80 mm, R = 6 mm) were austempered for various times to produce a variety of microstructures. The following heat treatment cycles were used:

- austenitise at 930°C for 1 h.
- austemper in a wood's alloy bath at 380°C for various times ranging from 5 min to 1200 min.
- water quench.

A.D.I. specimens were tested in an abrasion test device described in previous publications (10). The machine, sketched in Fig. 1, stirs the specimens through abrasive material (silicon carbide — 2 mm "granulometry"). The characteristics of this machine are:

- rotation speed 200 rpm (linear speed: 2.5 m/sec⁻¹ at the end of the specimen).
- test temperature: room temperature.

Hardness measurements, made at room temperature, were HV 30 type; magnetic measurements were made using a Magne-Gage apparatus.

Microstructure observations

Various microstructures were observed by conventional optical microscopy after nital etching and the abraded surfaces were examined by scanning electron microscopy (SEM). Phase percentages were determined using a Texture Analyser System (T.A.S.) marketed by E. Leitz A.G. and the apparent degree of advancement of the reaction was analysed by dilatometry.

The loss of matter, ΔP , was measured every 0.5 million revolutions and compared with the initial weight of the specimen. Wear rate was defined as the ratio $\Delta P/P$.

Fig. 2 - Variation of the first stage bainitic transformation as a function of austempered time at 380°C

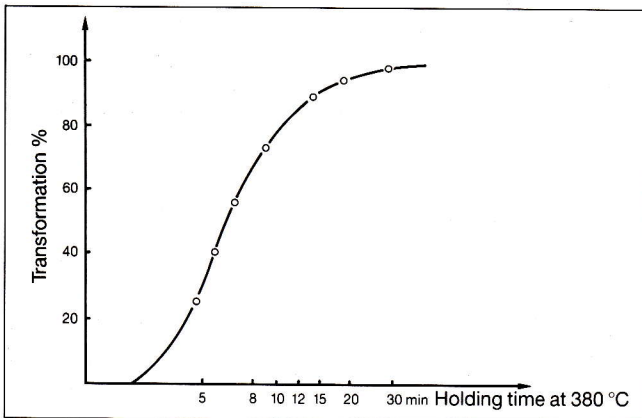
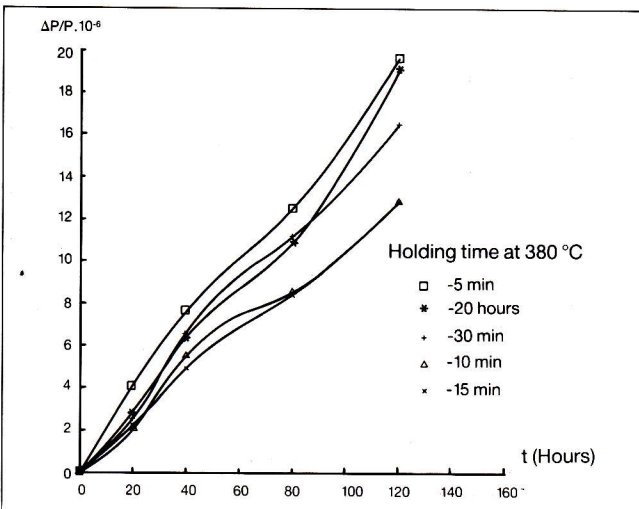


Fig. 3 - Variations of wear rates as a function of austempering time at 380°C



Results and discussion

The first tests were made to determine how to obtain different microstructures. Specimens were cooled from 930°C to 380°C and held for various times. The percentage austenite transformed to bainite is given in Fig. 2. It can be seen that the transformation is 90% complete in 20 min. In order to obtain a well finished bainitic product, one specimen was heat treated for 1200 min (20 h) at 380°C. Wear tests were run at room temperature on these heat-treated specimens.

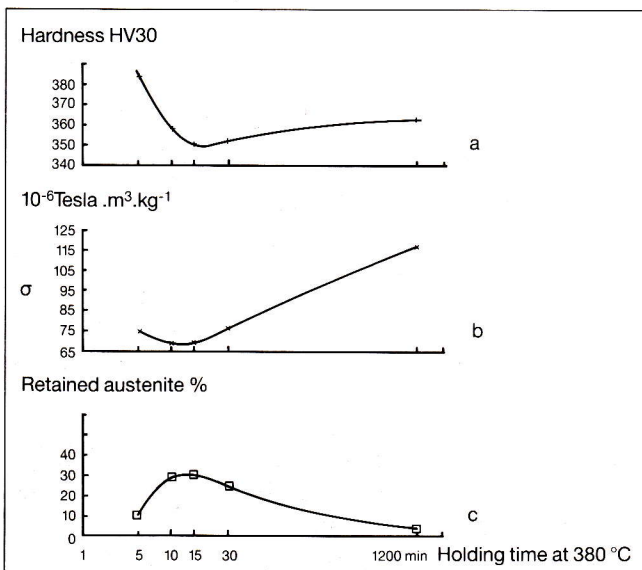
Fig. 3 illustrates the variation in wear rate as a function of austempering time. A comparison between Fig. 2 and Fig. 3 shows that the best resistance to wear does not correspond to the end of the bainitic reaction. In fact, the highest wear resistance is associated with a microstructure obtained after 10 or 15 min bainitic holding time at 380°C (about 80% bainite).

Fig. 4 is most instructive, because it shows that these times correspond to the maximum of retained austenite and to the lower values of both the HV 30 hardness and the magnetic characteristic σ . Other very important results, such as the following, can be noticed from Fig. 4:

- Even after 20 h at 380°C, the microstructure contains austenite, which means that the bainitic reaction is not finished, and this in turn explains the apparent end of the reaction noticed in Fig. 2.
- Again, the best abrasion resistance is not associated with the highest hardness value.

Fig. 4 - Evolutions of characteristics such as:

- * hardness - a -
- * magnetic property - b -
- * retained austenite percentage - c -



These important remarks illustrate the importance of the upper bainitic reaction. The fact that ductile irons are cast alloys increases the complexity of the problem. It must be remembered that the upper bainitic reaction, occurring in Fe-C-Si alloys, such as homogeneous steels, can be divided into two stages (11, 12):

$\gamma \rightarrow (\alpha) + (\gamma)$: 1st stage

$(\alpha) + (\gamma) \rightarrow \alpha + \text{carbides}$: 2nd stage

where γ : initial austenite

(α) : carbon supersaturated ferrite

(γ) : carbon enriched austenite, "post-bainitic austenite"

α : ferrite

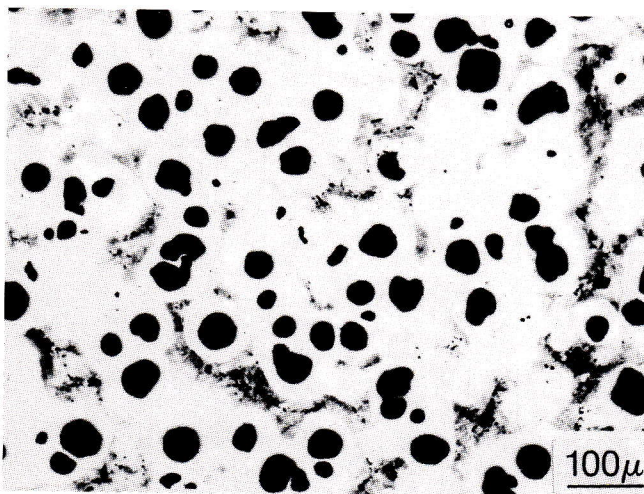
Carbides produced during the 2nd stage are induced by the desaturation of (α) and initiated by the decomposition of (γ) . The enriched austenite (γ) has a new M_s temperature and therefore is generally stable from room temperature to -130°C even though the M_s temperature of the initial austenite is above 20°C .

These two stages are well separated.

The evolution of the retained austenite percentage witnesses to the existence of several kinds of austenite. This evolution is the result of both reactions $\gamma \rightarrow (\alpha) + (\gamma)$ and $\gamma \rightarrow \alpha' + \gamma$, the second reaction occurring during the quenching operation from 380°C to 20°C . The retained austenitic phase contains both γ and (γ) which are the initial and the enriched phases. Under these conditions it is clear that the amount of austenite reaches a maximum value but this peak is not associated with the maximum enriched austenite percentage.

In ductile irons, which are Fe-C-Si cast alloys, the problem is more complex because the initial structure consists of solidification cells, and each of them contains a graphite nodule (Fig. 5).

Fig. 5 - Microstructure of the S.G. cast iron in its as-cast state: the solidification cell boundary (Zone III) contains pearlite



The chemical composition of this cell is most heterogeneous. Usually the matrix inside a single cell can be divided into three zones (Fig. 6) (13):

Zone I: near the graphite, has the highest silicon concentration and the lowest manganese concentration.

Zone III: at the solidification cell boundary, has the highest manganese concentration and the lowest silicon concentration.

Zone II: represents the rest of the matrix and has intermediate silicon and manganese concentrations. Since the first stage incubation and reaction times are functions of the composition of the initial austenite phase at high temperature, it is clear that the end of the first stage reaction is not the same in Zones I, II and III. Fig. 7 illustrates, for example, the case of the apparently finished first stage reaction followed by a water quench operation. In this case, it is clear that Zone III will be embrittled by martensite. Fig. 8 represents the different microstructures observed after 5, 10, 15 and 30 min and 20 h at 380°C .

Under these conditions it is very difficult to determine what types of austenite compose the austenite phase percentage (Fig. 4c). In particular, this austenite phase contains various austenites presenting different M_s temperatures above and below 20°C .

Fig. 6 - Repartition of various alloying elements inside the solidification cell (Zones I, II, III)

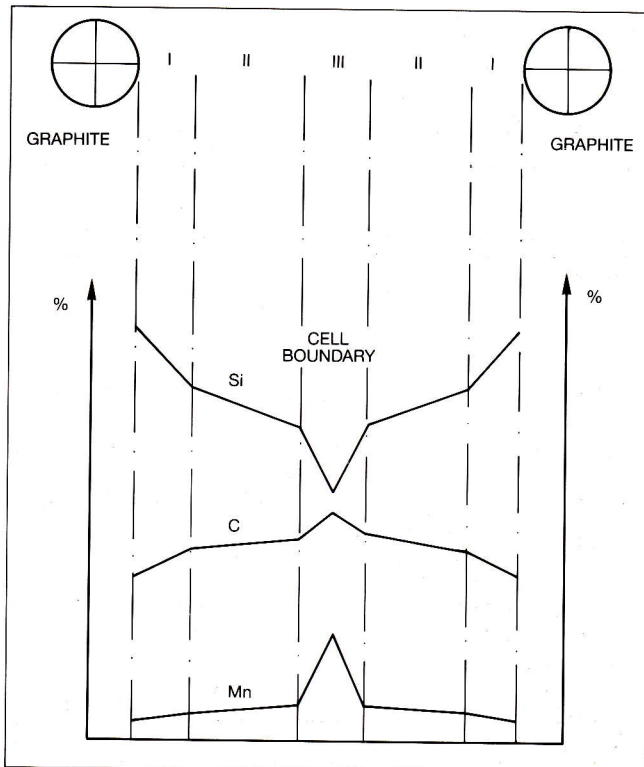
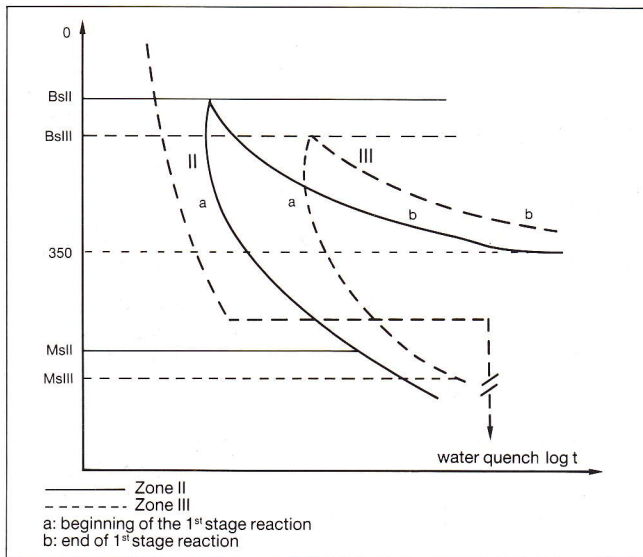


Fig. 7 - Relation between the variation of composition in Zone II and Zone III and the formation of martensite in Zone III after an apparently finished first stage

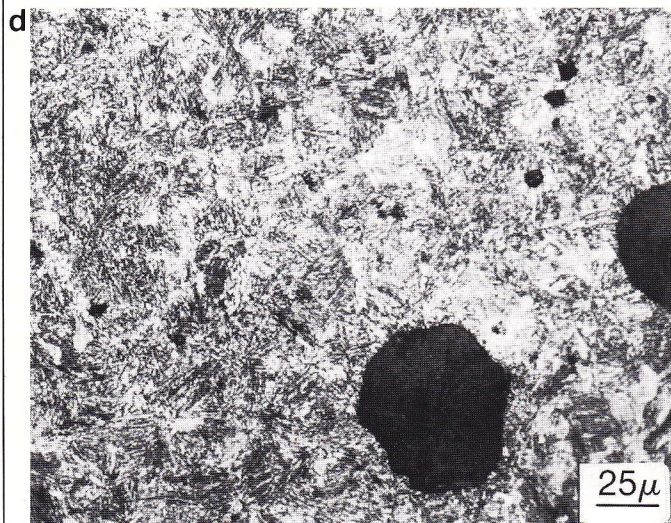
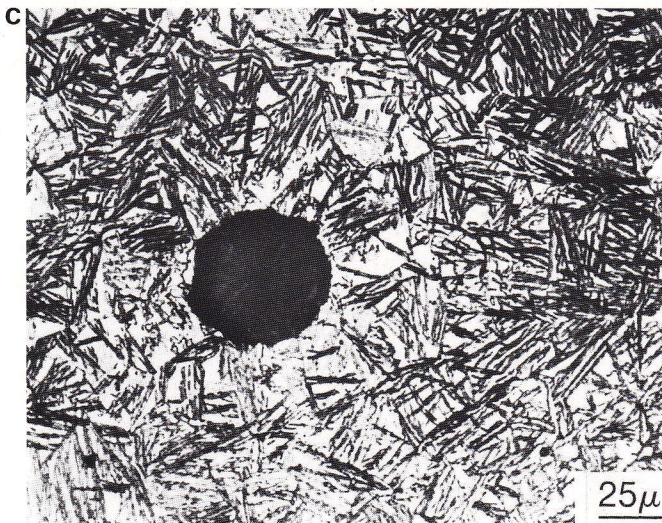
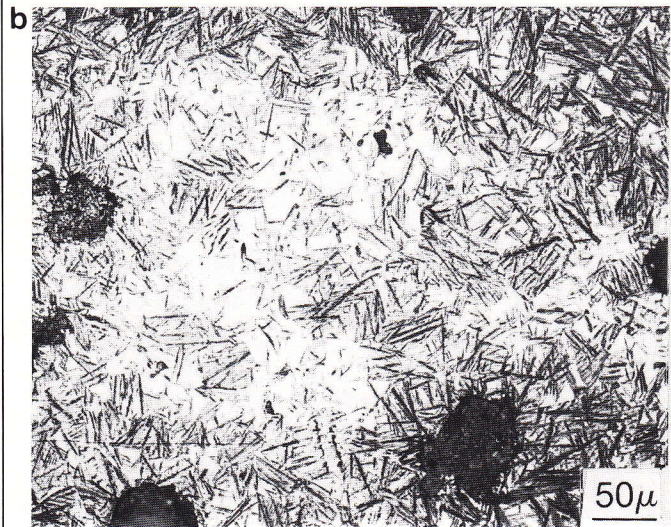
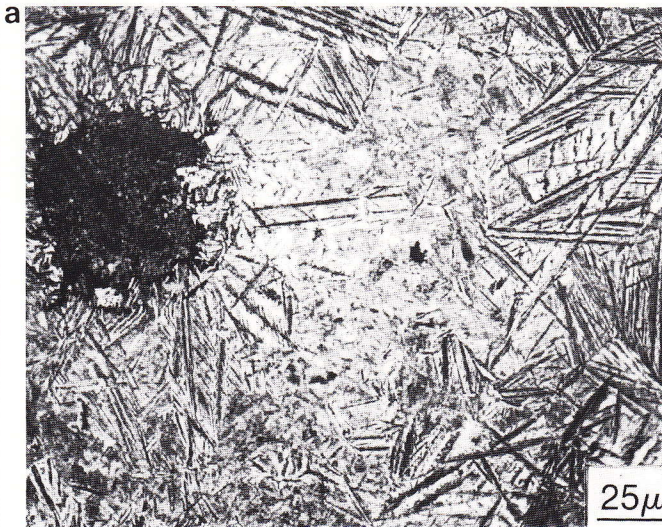


It will be seen from Fig. 8 that the distribution of the various phases is very heterogeneous. For example, in Fig. 8a, the first stage bainitic reaction has started into Zones I and II, but some areas situated in Zone III are free of any bainitic products.

A comparison of microstructures obtained after different bainitic reaction times shows very clearly the evolution of this microstructural heterogeneity. Although the

Fig. 8 - Evolution of the microstructure as a function of the austempering time at 380°C:

- a - $t = 5$ min
- b - $t = 15$ min
- c - $t = 30$ min
- d - $t = 20$ h



fundamental mechanisms involved during the second stage reactions differ from those occurring during the first stage reaction, the microstructural heterogeneity persists (14).

For these reasons, in ductile irons (S.G. cast irons), it is very difficult to obtain a matrix representing only a first-stage-reaction microstructure.

Under these conditions, it is clear that hardness measurements (Fig. 4a) do not represent a unique structure, and only the evolution can be analysed.

If the best abrasive wear resistance is obtained in a specimen which exhibits the lowest hardness value, and the highest retained austenite percentage, this means that the phases composing the microstructure must be:

- martensite α'
- supersaturated ferrite (α)
- initial austenite γ
- enriched austenite (γ)
- austenite " γ ", partially enriched.

It is not possible to associate a better wear resistance with the presence of martensite which is a very hard phase. This applies also to ferrite and silicon carbides obtained after 20 h at 380°C.

Fig. 9 shows the average gradient of each curve described in Fig. 3, as a function of the bainitic holding time at 380°C compared with the retained austenite percentage. There is no doubt about the choice of the preliminary bainitic heat treatment. The problem remains, however, as described above. The austenitic phase responsible for this improved wear resistance is a mixture of austenites. So, it was interesting to study the stability of these austenites during an abrasion test. This study was done by observing the magnetic properties, measured after every 500,000 cycles. The results are plotted in Fig. 10. During the abrasion test, the austenite percentage varies and gradually

Fig. 9 - Relation between the retained austenite percentage and the average gradient of different wear rate curves as a function of the austempering time

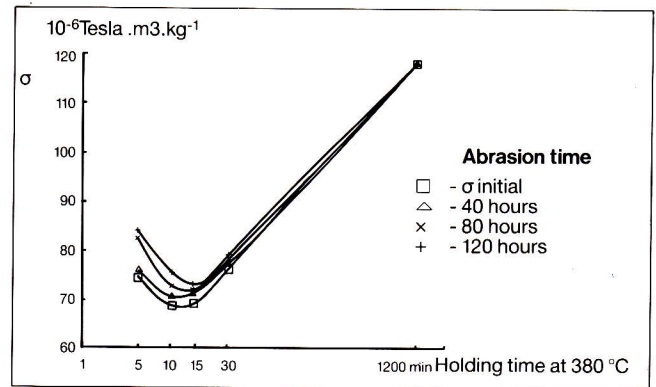
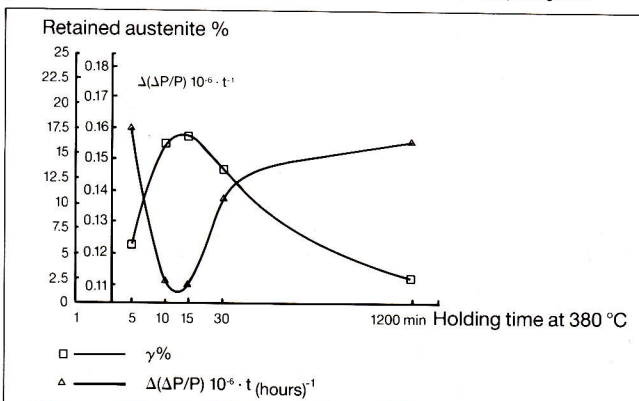


Fig. 10 - Variation of " σ " as a function of abrasion time.

decreases, but the most spectacular result is that this evolution is strongly related to the initial bainitic reaction holding time.

The retained austenite change during wear testing is extremely important. In fact, it can be seen that this change becomes more important if the bainitic holding time is shorter (about 3%). This can be explained by the association of two mechanisms:

- relaxation of internal stresses in the austenitic phase;
- application of external stresses to the relaxed austenitic phase.

After a martensitic transformation occurring in a homogeneous matrix quenched in a medium at a temperature situated in the M_S - M_F scale, the structure contains martensite and austenite. It is known that relaxation of stresses within the austenite can promote a new formation of martensite. This can be done either by tempering at 100°C and cooling at room temperature (15) or thinning the austenitic matrix with an M_S temperature situated below room temperature and containing stresses (11).

Similarly, it is also well known that an applied stress promotes the progression of martensite reactions within an apparently stable martensite - austenitic structure. In this study it is evident that the retained austenite, containing several types of austenite will not have the same response to this new martensitic formation.

The above conditions are present only at the start of the bainitic first stage reaction in Zones I, II and III. The major portion is encountered after rather short bainitic holding times, and the phenomenon is very noticeable ($t < 15$ min). With a longer bainitic reaction time the variation becomes less and less important.

Stress relaxation is obtained by raising the temperature at the surface of the test specimen (60-80°C) and the application of stress is achieved by abrasive particles impinging on the abraded surface. At this temperature

it is evident that only a martensitic transformation can be observed.

Under these conditions, the production of new martensitic particles certainly accelerates the process of loss of matter, but after a certain time, equilibrium is achieved within the surface layer. In all cases the enriched austenite remains untransformed.

Fig. 11 shows the appearance of the surface after abrasive wear on a specimen austempered for 5 min. It will be clearly seen that the surface does not respond uniformly to the abrasive process. Near the hole (representing the site of a graphite nodule) the matrix is composed of supersaturated ferrite (α) and enriched austenite (γ). The rest of the matrix consists, for the most part, of martensite α' and austenite γ containing particles of (α) and some areas of (γ).

The damage caused by abrasive particles is more serious in Zones II and III (grey matrix) than in Zone I (white matrix) near the graphite area. In all cases, it is the "centred" phase (tetragonal or cubic) which is extracted from the austenitic matrix and the role of this phase seems to be most important (16-17). In particular, Fig. 12 indicates this loss of martensitic or ferritic particles making it possible to recognize the classical "feathery" upper bainitic structure.

Fig. 11 - (SEM) analysis of an austempered specimen austempering time $t = 5$ min

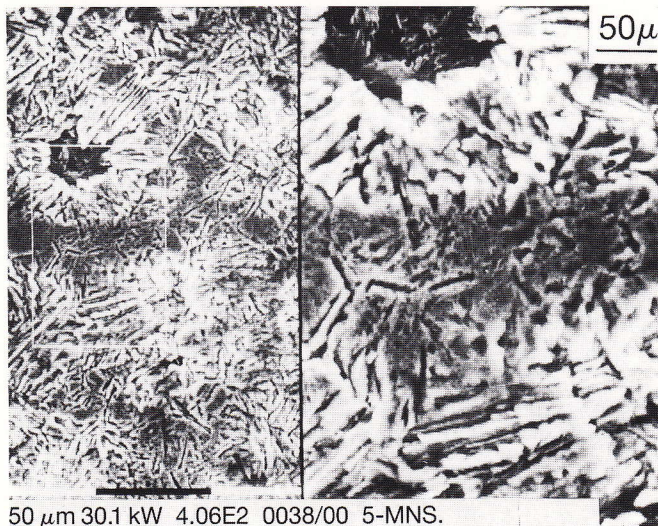


Fig. 12 - (SEM) analysis of the matrix after extraction of ferrite and martensite particles.

Conclusions

- This study has demonstrated the importance of the upper bainitic structure during abrasion test at room temperature.
- The lowest wear rate is associated with the highest volume percentage of retained austenite.
- This critical volume percentage of retained austenite is not related to the apparent or the real end of the first stage bainitic reaction.
- The low hardness associated with this high retained austenite percentage corresponds to a high wear abrasion resistance.
- Formation of martensite is observed during the test at and near the abraded surfaces.
- The wear is not uniform in the matrix. It is a function of the solidification cell structure which is heterogeneous in composition.

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