# Martensite Formation in Austempered Ductile Iron with Unidirectional and Cyclic Loading

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## Introduction

The purpose of austempered ductile iron (ADI) is to produce an acicular matrix which consists of high carbon austenite and ferrite as shown in fig. 1. With this matrix structure nodular cast iron displays remarkable strength and ductility. Because of the appearance of the matrix structure it is often called bainite.

Fig. 1: Microstructure of bainitic spheroidal graphite cast iron

By classical definition, bainite is a mixture of carbide and ferrite. But ADI shows an intermediate structure formed during the austenite decomposition to bainite. The presence of retained austenite (RA) affects the mechanical properties of the casting. The stability of the unreacted austenite depends on the content of carbon, silicon and gamma-phase-extending alloying elements, such as nickel. The amount of RA is proved to be about 40 vol.-% depending on the austempering time.

Under the influence of externally applied loads a transformation of retained austenite into martensite may be obtained. We distinguish between stress assisted and strain induced martensite nucleation. Stress assisted nucleation includes the spontaneous transformation on cooling but assisted by the thermodynamic effect of applied stress below the yield point, while strain induced nucleation involves the production of new nucleation sites by plastic deformation (1). In lack of quantitative data the present study is concerning with determination of the loading conditions influencing the transformation of retained austenite into martensite in the upper bainitic state of ADI.

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The transmission electron microscopy (TEM) enables the merites of high resolving power to characterize possible nucleation sites. The preparation of the specimens for TEM investigation was carried out by ion beam thinning because of the multi-phased nature of the specimens. Various different heat treatment conditions, with and without subsequent deformation by uniaxial tensile loading, surface deformation or by alternating bending, were investigated to assess any microstructural changes which might have occured (2,3).

## Experimental

Unalloyed ferritic nodular cast iron (GGG-40) and an alloyed spheroidal cast (mass-%: 2 Ni, 0.9 Cu, 0.33 Mo) have been austempered in the upper bainitic region. The influence of the austempering time on the matrix structure and the mechanical properties have been studied.

The austempering reaction of the unalloyed cast at 365°C leads to an increase in tensile strength up to 1150 MPa accompanied with an elongation ($A_5$) between 12 to 15 % when holding time exceeds 80 minutes (fig. 2).

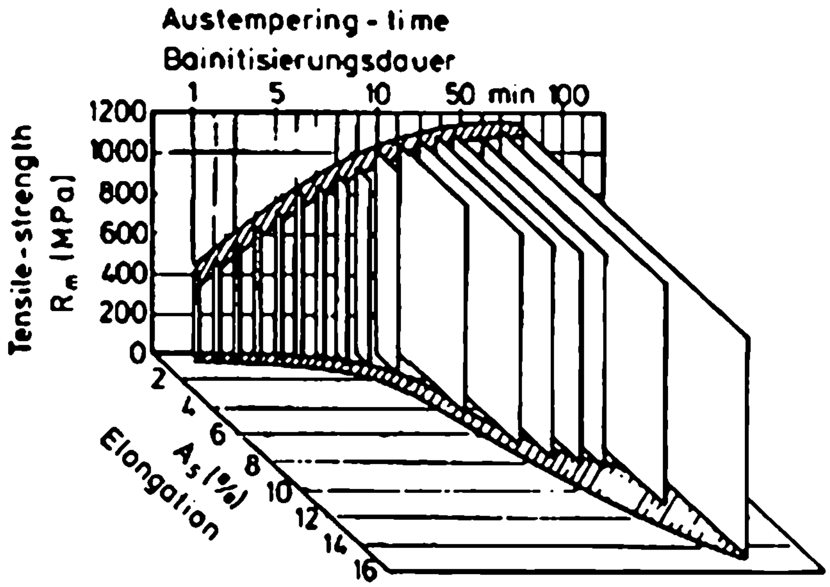


Fig. 2: Influence of the austempering time on tensile strength and elongation; 930°C 90 min / 365°C 1 to 80 min / water

The microstructural investigations carried out in the TEM is characterized by ferrite needles adjacent to seams of retained austenite (fig. 3). The retained austenite could be distinguished from the ferrite by electron diffraction. From qualitative observations, the dislocation density must be considered to be very high. These lattice defects are due to internal stresses from the heat treatment process, because of the misfit between ferrite and austenite lattice. The applied stress associated with the spontaneous transformation on cooling generates small lenses of plate martensite (fig. 4), which often have a midrib. The martensite twins have a width of about 5 nm.


Fig. 3: Seams of retained austenite showing twin formation surrounding a ferrite plate; TEM-micrograph


Fig. 4: Twinned plate-martensite after the bainitic transformation

The alloyed cast shows a continuous increase of the ductility exhibited by the increment of elongation with increasing austempering time (fig. 5). The addition of nickel and molybdenum originate a delay in starting of the bainitic reaction and therefore the maximum amount in RA, causing the maximum in ductility, is obtained after longer austempering times.

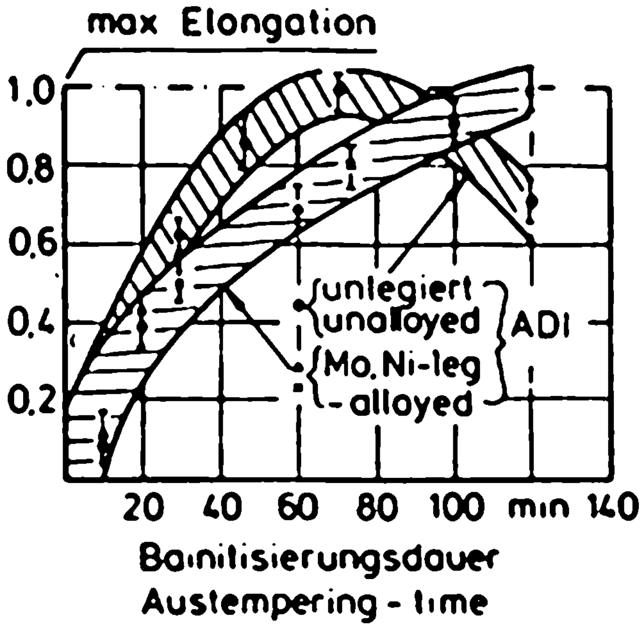


Fig. 5: Influence of alloying elements on the austempering time effecting optimal ductility

Austempering of the unalloyed cast at longer holding times generates carbide formation and therefore a reduction in ductility. Nickel and copper are shifting further carbide formation to much longer austempering times. Therefore no reduction in ductility has been detected in this case.

The transformation of RA into martensite under tensile loading has been detected in situ by means of magnetic measurements under various temperatures (4). By this the martensite formation as a function of applied stress and the associated temperature dependence have been detected for both, unalloyed and alloyed nodular cast iron (fig. 6). Regarding the critical stress for

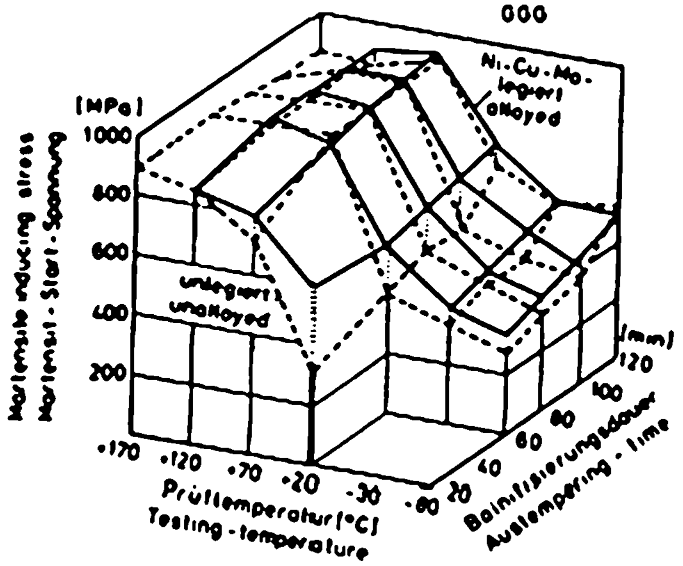


Fig. 6: Martensite inducing tensile stress versus testing temperature and austempering time

martensite formation due to austempering time, the unalloyed cast shows a gradual increase in stability. This is caused by the carbon enrichment and the formation of carbides during austempering more than 120 minutes. The alloyed casting shows a full stabilization of the retained austenite, when the austempering time exceeds 60 minutes. With increasing austempering time the influence of the testing temperature decreases and the martensite inducing stress converges to the yield stress. Environmental temperature ranges above room temperature (RT) lead to values of about 900 MPa. Below RT the critical load is between 550 and 600 MPa. The strong temperature dependence of the critical load due to austempering times of less than 60 minutes indicates a predominant stress assisted martensite nucleation (5). This was proved by TEM analysis of a tensile test specimen after austempering at a holding time of 20 minutes (fig. 7). The stress induced martensite can be characterized by an acicular arrangement of ferritic and twinned martensite regions.

Strain induced martensite is generated in highly saturated RA at deformation rates near the yield strength (6). This can be verified by defined surface strengthening, such as strengthening rolling or shot peening. It is well established that shear-band intersections can be very effective nucleation sites for the formation of strain induced martensite (fig. 8). The bright field TEM micrograph shows strongly diffracting martensite embryos at micro-shear-band intersections (fig. 8a).


Fig. 7: Transformation of retained austenite to martensite as a result of tensile testing

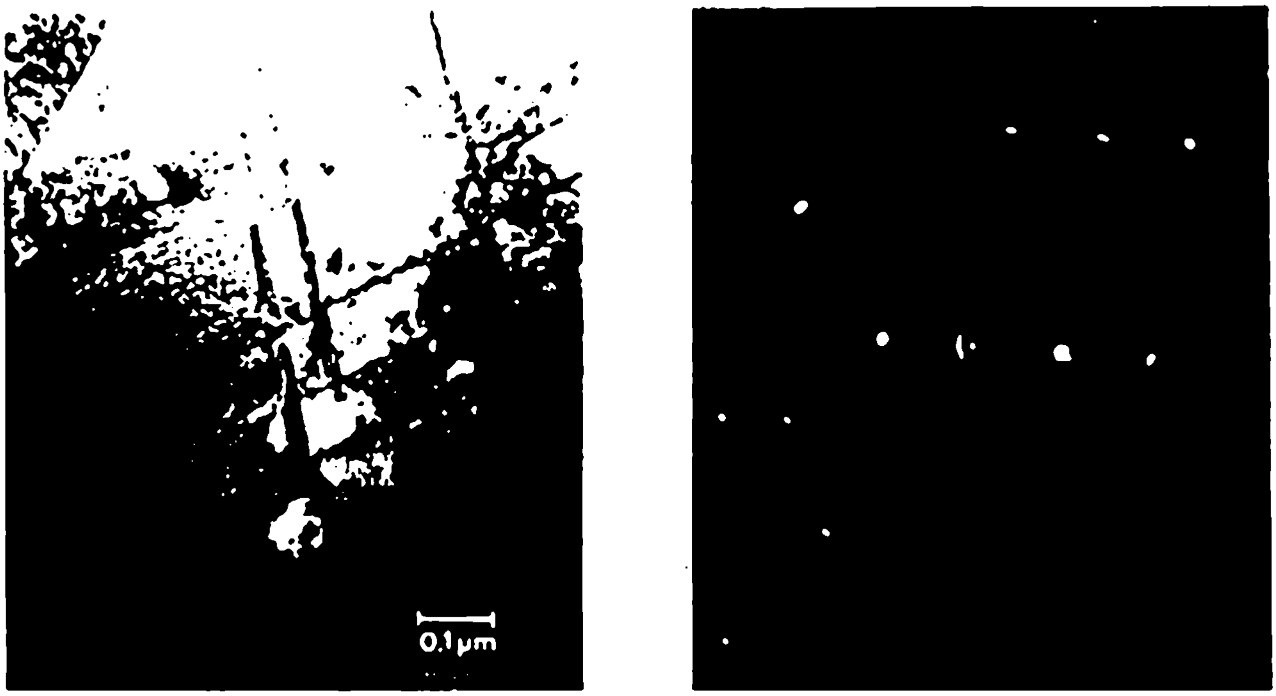


Fig. 8:
a) TEM-micrograph showing nucleation at shearband intersections after shot peening; unalloyed cast

b) electron diffraction pattern corresponding to a) showing spots of <100>-, <110>- and <211>-zones of martensite

Bending fatigue tests with a loading ratio of R = -1 showed an endurance limit between 270 and 380 MPa for the unalloyed material respctively between 240 and 350 MPa for the alloyed material (fig. 9). The acutal endurance limit obtained cannot be correlated with

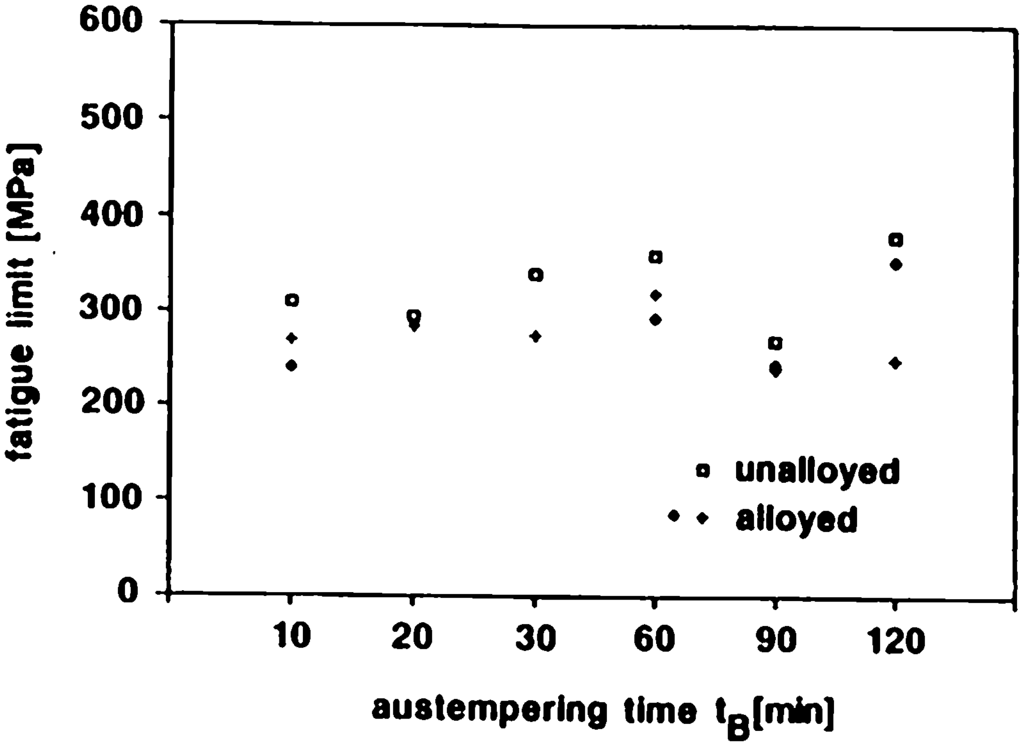


Fig. 9: Alternating bending fatigue limit as a function of austempering time

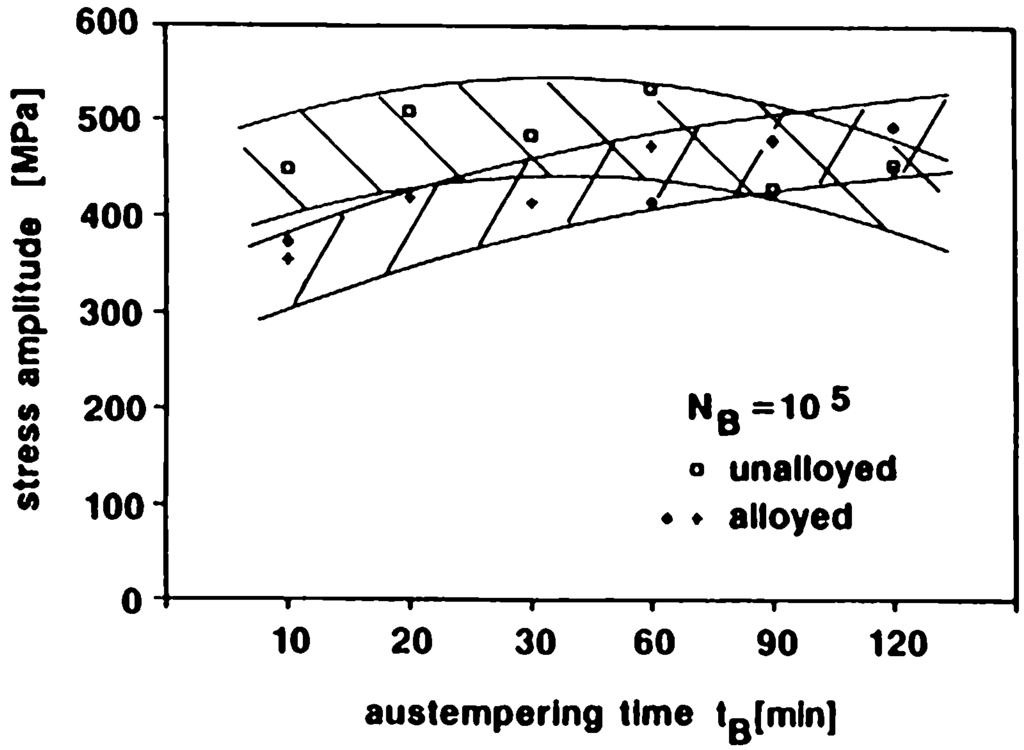


Fig. 10: Stress amplitude leading to $10^5$ cycles to fracture as a function of austempering time

the austempering time. The comparison of alloyed and unalloyed casts indicates that the alloyed ADI cannot compete with the unalloyed type studied in this research. At $10^8$ cycles to fracture an influence ot the austempering time on the corresponding stress amplitude can be detected (fig. 10). While the curves obtained for unalloyed cast show a maximum at a holding time of 60 minutes the alloyed type exhibits an increase of the stress amplitude up to longer austempering times.

TEM investigations on specimens treated with cyclic loading showed following: Distinct dislocation structures are not present. Twin formation in RA occurs on the 111 -plane. Strain induced martensite as a result of cyclic loading was not detected. One reason for this may be the fact that the applied strains were below the values for martensite induction. Within the RA deformation twins have been formed (fig. 11). By means of dark field illumination it can be proved that the twins in one austenitic crystal show identical orientation (fig. 12).

Fig. 11: Twinned austenite after alternating bending at 350 MPa; unalloyed cast

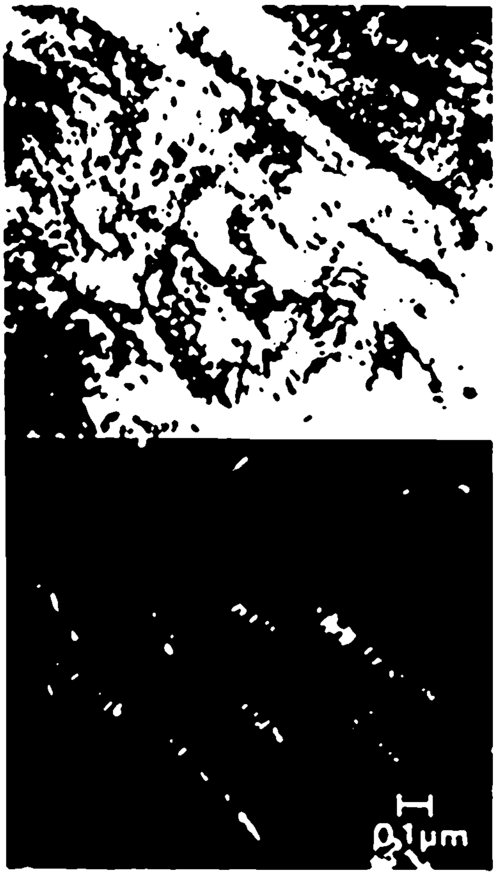


Fig. 12: Bright and dark field micrograph (spot: (111)-austenite) showing identical orientation of austenite twins; unalloyed cast

## Conclusions

From these observations and experimental data following conclusions are drawn:

1. The external stress necessary to induce martensite formation depends strongly on
   - the content of elements which cause austenite stabilization in alloyed casts,
   - the carbon diffusion during the austempering which causes the grade of austenite stabilization in unalloyed castings,
   - the environmental temperature.

2. Stress assisted nucleation of martensite occurs at short austempering times below 60 minutes and includes mainly the spontaneous transformation at temperatures below RT.

3. Strain induced nucleation of martensite can be obtained in high stabilized austenite under stresses near the yield strength.

4. TEM observations proved the different types of martensite. The stress induced martensite shows plate formation with a midrib. Strain induced martensite has been detected within heavily deformed cells of high stable retained austenite. The volume element of martensite nucleated in the interectional area of micro-shear-bands was determined by means of TEM.

5. Cyclic loading does not induce a greater amount of martensite formation than under comparable uniaxial loading conditions.

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