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Influence of Slab Reheating Practice on the Microstructural Evolution and Toughness Behavior of Quenched and Tempered Plates of Medium Carbon Microalloyed Steel

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In the current study, granular bainite was found to be the major component in the microstructure of air cooled 80 mm thick plates of medium carbon microalloyed steel. The second constituent in this granular bainite was identified as cementite. It was further observed that (1) ferrite lath size and (2) amount of cementite in granular bainite varied with slab reheating time before plate rolling. Smaller ferrite laths and a lesser amount of cementite were found in the plate processed with the longer slab reheating time of 26 h. Contrary to this, very large sized ferrite laths and a larger population of cementite were formed in the plate processed with the shorter slab reheating time of 4 h. Subsequent quenching and tempering of these plates favored the formation of lower bainite and tempered martensite in the plate with 26 h slab reheating time. On the other hand, upper bainite and coarser cementite were formed after the quenching and tempering of the plate with 4 h of slab reheating time. The influence of different microstructures, formed due to varied slab reheating time, on the toughness property of tempered plates was evaluated under different test conditions. In tensile test and fracture toughness testing of thinner specimens, a ductile mode of fracture was observed, irrespective of varied microstructures in the tempered plates. However, in the three-point bend test of full thickness specimens, the mode of fracture was ductile in the tempered plate with 26 h slab reheating time, while the tempered plate from the slab with 4 h reheating time gave rise to a predominantly brittle mode of fracture. These observations showed that the toughness property of these tempered plates was sensitive to the microstructure only under the specific condition, which prevailed during the three-point bend test of full thickness specimens. Under this condition, coarse cementite and upper bainite became prone to cracking resulting in a lower toughness of the tempered plate associated with lower slab reheating time.

Keywords cementite, ferrite laths, granular bainite, load displacement curve, lower bainite, plain strain fracture toughness test, three-point bend test, upper bainite

1. Introduction

Slab reheating time is one of the major factors that decide the nature of a microstructure evolved in a hot-rolled plate. The influence of slab reheating time on the microstructure is due to its control on austenite grain coarsening and dissolution of carbides at a given slab reheating temperature. Therefore, longer reheating time is expected to produce a microstructure in the hot rolled plate that will be different from the microstructure evolved in the same plate, if processed with shorter slab reheating time, but otherwise under identical rolling conditions. Further, since the initial microstructure of hot-rolled plates strongly influences the microstructures evolved after quenching and tempering of plates, the variation in slab reheating time is expected to result in the formation of different types of microstructures in quenched and thereafter in tempered plates. In line with these facts, the present study was undertaken to understand the influence of slab reheating time on the nature of the microstructure evolved after hot rolling, quenching, and tempering of a medium carbon microalloyed steel plate. Also, the influence of microstructure on the toughness property of tempered plates was examined for the plates processed with varied slab reheating time.

It should be pointed out here that slab reheating time is a crucial factor from the productivity point of view, and therefore an assessment regarding the influence of slab reheating time on toughness property of the tempered plate is desirable for designing an optimum slab reheating practice to achieve superior toughness in the quenched and tempered plates.

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2. Experimentation

Two commercially produced slabs (thickness: 240 mm) of medium carbon microalloyed steel were selected for this study. The typical chemistry of these slabs was as follows: 0.30% C, 0.20% Si, 0.010% S, 0.015% P, 0.45% Mn, 1.56% Ni, 1.38% Cr, 0.40% Mo, 0.10% V, 0.030% Al.

One of these slabs was heated and soaked in a walking beam furnace at 1280 °C for a total time of 4 h. The other slab was slowly heated to 1280 °C for 22 h in the walking beam furnace and soaked at that temperature for 4 h, which summed up to a total reheating time of 26 h. Both slabs were then rolled into 80 mm thick plates in a four-high single stand plate mill, and hot rolled plates were cooled in the air to room temperature. During plate rolling, a similar reduction schedule and finish rolling temperature (~1020 °C) were maintained. Subsequently, both plates were subjected to a stress-relieving treatment at 700 °C. The stress-relieved plates were austenitized at 920 °C for 160 min and quenched in an oil bath. These quenched plates were subjected to tempering at 640 °C for 4 h. Samples were collected from the mid-section of both the plates after every stage of processing, namely, hot rolling, stress relieving, quenching, and tempering. Extensive metallographic studies were carried out on these specimens using optical and transmission electron microscopy to understand the effect of slab reheating time on the nature of the microstructure evolved in hot rolled plates and the influence of the initial microstructure on the nature of microstructures evolved in the plates during subsequent stress-relieving, quenching, and tempering stages.

Toughness of both the tempered plates was evaluated under varied conditions by using different techniques, i.e., tensile test, fracture toughness test, and three-point bend test.

For the tensile test, through thickness specimens of 6 mm diameter were prepared and broken in a tensile machine. The mode of fracture at broken surface of the tensile specimens was identified with the help of scanning electron microscopy (SEM).

The fracture toughness test was conducted in accordance with ASTM 399 specification.[1] Compact tension type specimens (thickness: 12.5 mm) were prepared with notch orientation being normal to the rolling plane and in the through thickness direction (equivalent to L-S configuration). The precracked specimens were loaded to fracture at a specified loading rate in a tensile testing machine, and load-crack opening displacement (COD) plots were recorded for the determination of K_{IC} value. During testing, it was found that determination of K_{IC} was not possible due to the limitation of our tensile testing machine in providing the necessary condition (P_{max}/P_Q >1.1) for determining K_{IC}. Therefore, the fracture toughness property of the plates was evaluated in terms of K_Q values.

For the three-point bend test, specimens of size 300mm × 100mm × full thickness were cut in the transverse direction of tempered plates, and a U-notch perpendicular to the surface was made on the specimens. The notched specimens were broken by applying adequate load, and the fractured surfaces of broken specimens were examined through SEM to identify the nature of fracture that occurred in both plates.

3. Results and Discussions

In this section, the plate processed with slab reheating time of 26 h is referred to as Plate A, while the other plate with 4 h of slab reheating time is referred to as Plate B.

3.1 Microstructures of Hot-Rolled Plates

Optical microscopy revealed that granular bainite was the main component in the microstructures of both the hot-rolled plates. In general, granular bainite has been defined as a composite structure of ferrite laths and a second constituent consisting mainly of austenite and martensite (M-A constituent). Formation of granular bainite takes place when a suitable alloyed steel, after austenitization, is continuously cooled at a cooling rate slower than what is required for the formation of upper bainite.[2] At this cooling rate, ferrite laths are initially formed that reject super saturated carbon atoms in the remaining austenite. Since the cooling rate required for the formation of granular bainite is relatively slower, the rejected carbon atoms diffuse deep in the austenite matrix. Such diffusion of carbon atoms prevents the development of cementite at interlath boundaries and thus arrests the formation of upper bainite. On the other hand, it leads to stabilization of remaining austenite, which partly transformed into martensite as the temperature of steel drops below M_S temperature. The amount of martensite formed in the granular bainite depends on the alloy chemistry and cooling rate. Many times, the M-A constituent may transform into other products like pearlite or cementite, depending upon the cooling history.

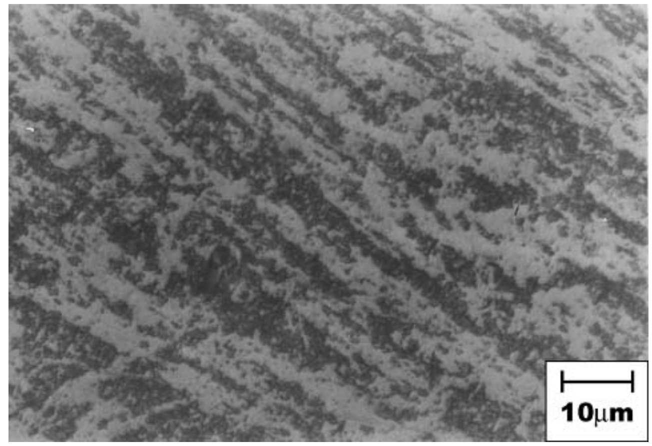

Fig. 1 Microstructure of hot-rolled plate processed from 4 h of slab reheating cycle showing granular bainite with larger size ferrite laths (×1000)

In the current study, formation of granular bainite in both hot-rolled plates was attributed to the presence of alloying elements like Cr, Mo, and V, which resulted in enhancement of the hardenability property of the plates. The superior hardenability, in turn, facilitated the formation of granular bainite during air cooling of the plates. Also, it was found from transmission electron microscopy (TEM) that the second constituent of granular bainite was essentially cementite. Formation of cementite as a constituent of granular bainite was, perhaps, due to the autotempering of M-A constituent at a lower temperature during air cooling of the plates.

Though granular bainite was the common microstructural feature in both the plates, it was, however, observed that the ferrite laths were larger in Plate B in comparison to that in Plate A as shown in Fig. 1 and 2, respectively. Similarly, the relative proportion of cementite decreased with the increase in slab reheating time. TEM also confirmed the larger proportion of cementite particles in Plate B (Fig. 3), while fewer cementite particles were observed in Plate A (Fig. 4).

The observed differences in ferrite lath size and proportion

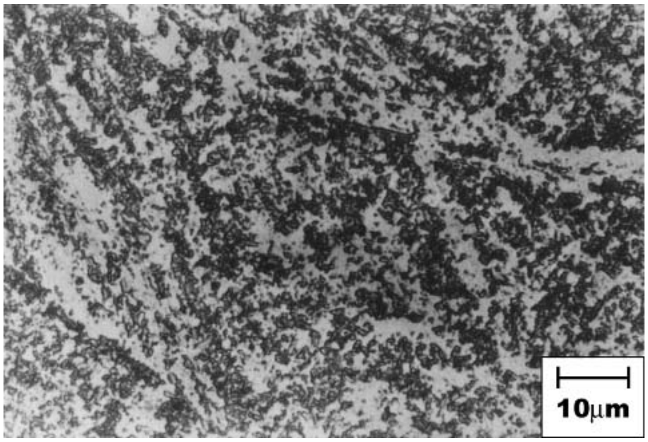

Fig. 2 Microstructure of hot-rolled plate processed from 26 h of slab reheating cycle showing granular bainite with smaller ferrite laths (×1000)

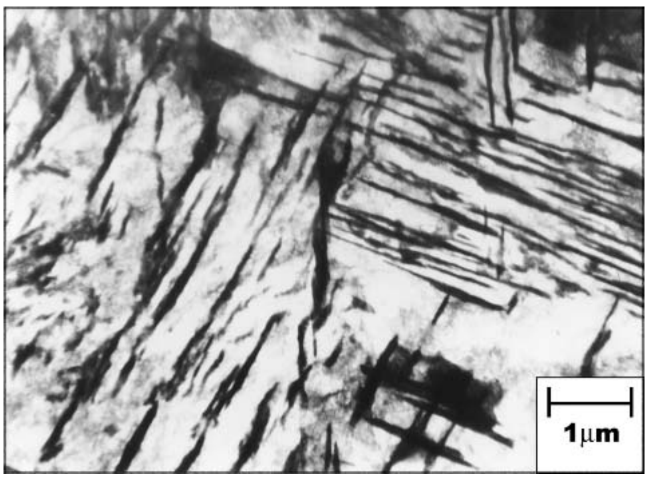

Fig. 3 TEM photograph of hot-rolled plates processed from 4 h of slab reheating cycle showing large clusters of cementites (×10 000)

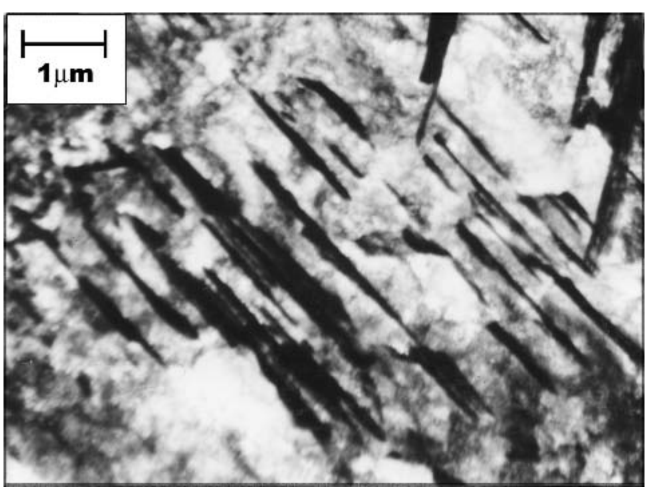

Fig. 4 TEM photograph of hot rolled plates processed from 26 h of slab reheating cycle showing cementites (×10 000)

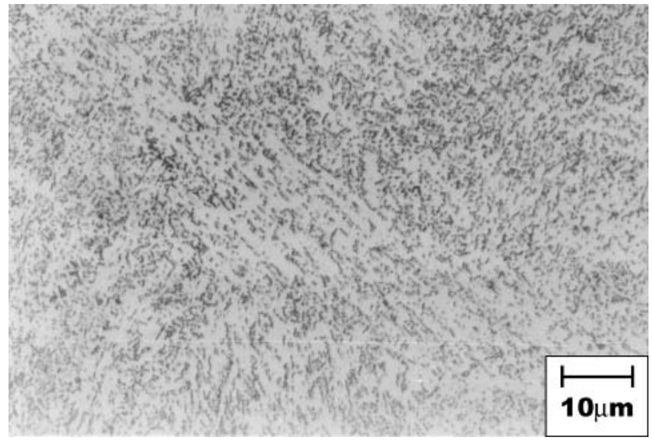

Fig. 5 Uniformly distributed finer carbides in the stress relieved plate processed from 26 h of slab reheating cycle (×1000)

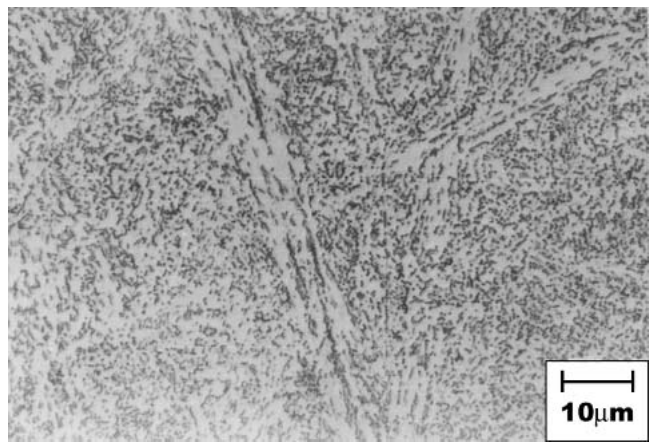

Fig. 6 Coarser carbides and ferrite laths in the stress relieved plate processed from 4 h of slab reheating cycle (×1000)

of cementite in the two plates can be explained in terms of variation in grain size of austenite and the extent of dissolution of carbides in these plates. In this respect, 26 h must have favored the coarsening of austenite grains as well as the dissolution of carbides of Cr, V, and Mo present in the steel. This in turn, must have resulted in substantial improvement in the hardenability property of Plate A, which facilitated the formation of smaller ferrite laths along with fewer cementite. On the other hand, 4 h of slab reheating time must have resulted in marginal austenite grain coarsening and limited dissolution of carbides. Therefore, hardenability of Plate B could not improve substantially, and this caused formation of larger ferrite laths with a greater proportion of cementite.

3.2 Microstructures of Plates After Stress Relieving

During the stress-relieving treatment of Plate A, a relatively larger amount of granular bainite transformed into evenly distributed finer cementite (Fig. 5). Since finer cementite particles are easily dissolved during austenitizing treatment, their pres-

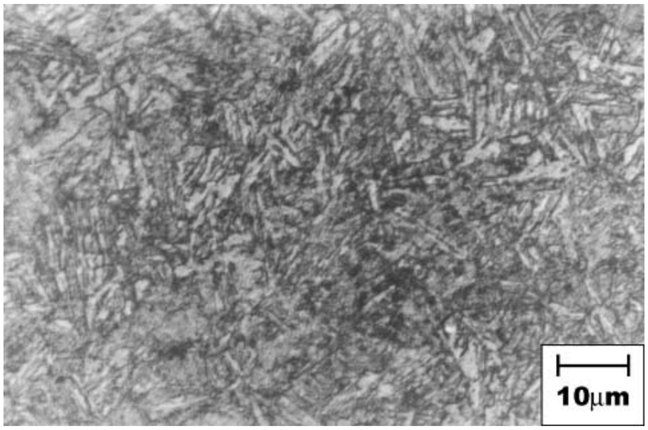

Fig. 7 Martensite laths in the quenched plate processed from 26 h of slab reheating cycle (×1000)

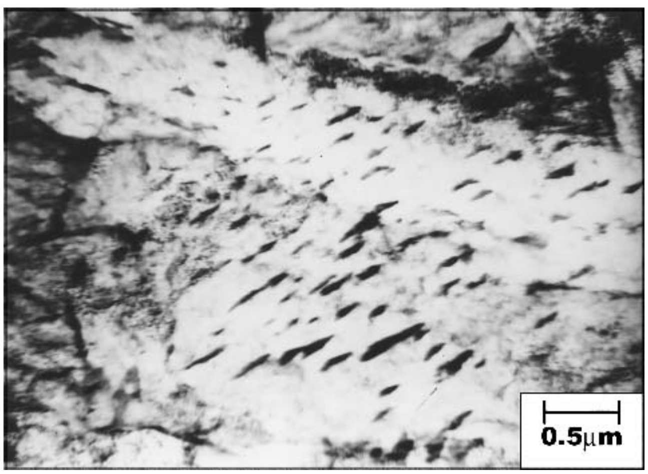

Fig. 8 TEM photograph of quenched plate processed from 26 h of slab reheating cycle showing lower bainite (×20 000)

ence is desirable for achieving better hardenability in the austenitized steel. On the other hand, Plate B showed some evidence of lath structure with comparatively much coarser cementite (Fig. 6) after stress relieving. It is worth mentioning that the presence of coarse carbides is undesirable due to their sluggish dissolution during austenitization. This, in turn, reduces the hardenability property of plates and adversely affects transformation behavior during oil quenching.

3.3 Microstructures of Quenched Plates

The quenched microstructure of Plate A was essentially a combination of lower bainite and martensite (Fig. 7 and 8). On the other hand, the quenched microstructure in Plate B was composed of granular bainite with small amounts of upper bainite (Fig. 9 and 10). This variation in the microstructures of the two plates was due to the size difference of cementite after stress relieving of the plates, as explained in the previous section.

Fig. 9 Granular bainite and upper bainite in the quenched plate processed from 26 h of slab reheating cycle (×1000)

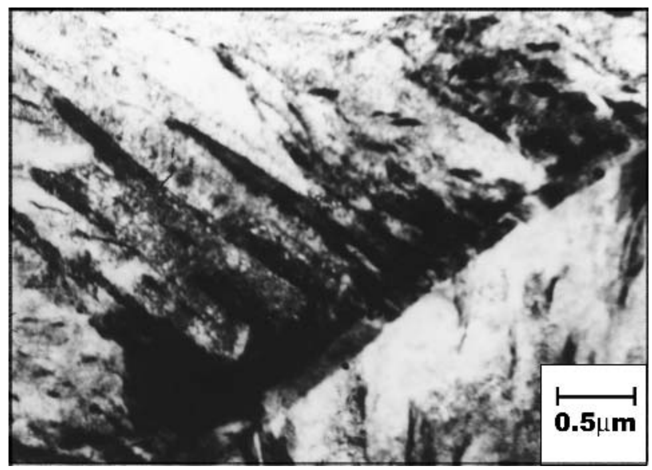

Fig. 10 TEM photograph of quenched plate processed from 4 h of slab reheating cycle showing upper bainite (×20 000)

3.4 Microstructures of Plates After Tempering

Primarily, tempering of quenched steel results in transformation of martensite into ferrite and spheroidized carbides, while lath type bainite undergoes the following sequential microstructural changes[3]:

- recovery of bainitic dislocation sub-structure
- coarsening of bainitic ferrite lath
- complex changes in the composition and morphology of the carbides

In the current study, tempering of Plate A transformed the quenched microstructure into a microstructure of lower bainite and tempered martensite (Fig. 11). This indicates that lower bainite remained unaffected during tempering, while martensite transformed into ferrite and cementite. In comparison to the above results, the microstructure of tempered Plate B showed the presence of coarse cementite with upper bainite

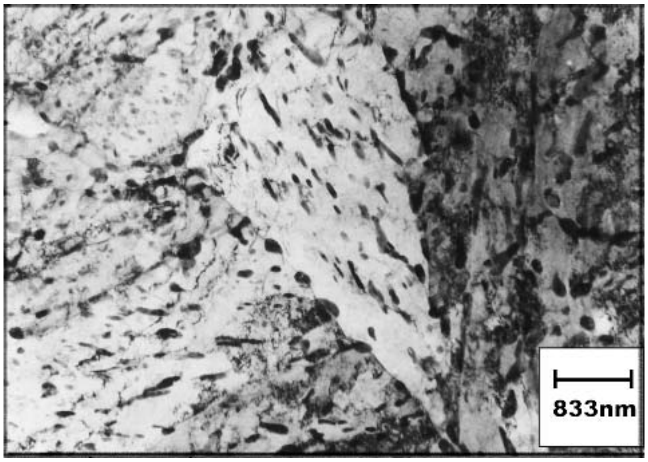

Fig. 11 Lower bainite and tempered martensite in the tempered plate processed from 26 h of slab reheating cycle (×12 000)

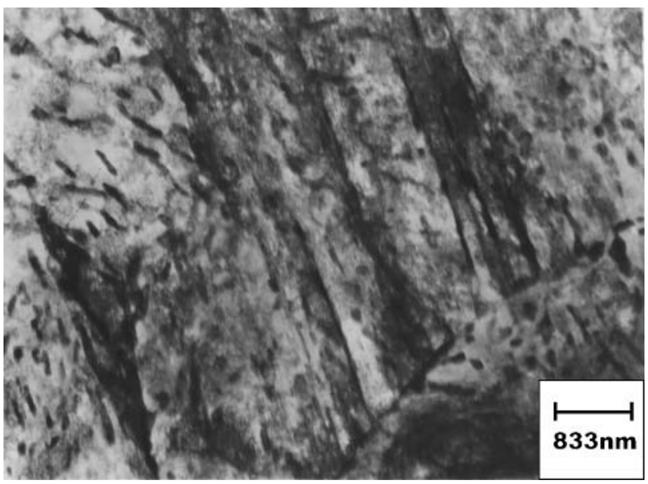

Fig. 12 Upper bainite and coarse carbides in the tempered plate processed from 4 h of slab reheating cycle (×12 000)

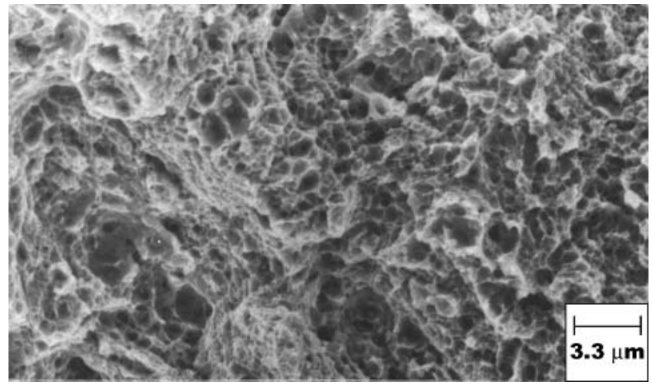

Fig. 13 Fractograph of broken tensile specimen showing ductile nature of fracture in tempered plate processed from 26 h of slab reheating cycle (×3000)

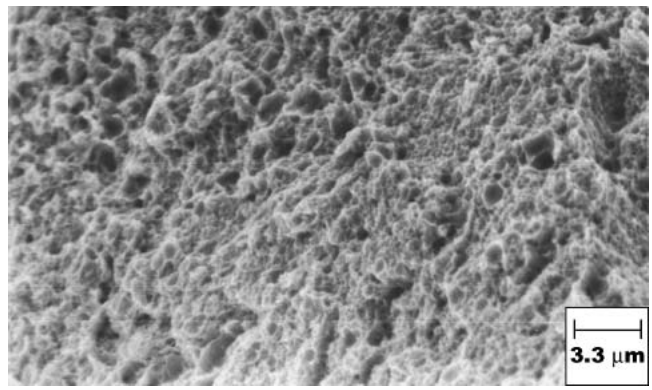

Fig. 14 Fractograph of broken tensile specimen showing ductile nature of fracture in tempered plate processed from 4 h of slab reheating cycle (×3000)

(Fig. 12). This was presumably due to the presence of a greater volume fraction of granular bainite in the quenched microstructure, which ultimately caused formation of coarser cementite in Plate B, while upper bainite remained unchanged under the given tempering conditions.

3.5 Toughness Behavior of Tempered Plates

The variation in the microstructures as discussed above was expected to result in a varied toughness property in the tempered plates. In fact, an inferior toughness property was anticipated in Plate B on account of the presence of coarser cementite and upper bainite in its microstructure. In general, cementite has low effective surface energy and is brittle in nature.[4] This makes the presence of cementite highly detrimental for toughness in the steels. However, it has been found that, in the case of bainitic steels, the role of cementite is marginal in influencing the toughness, provided the carbon is less than 0.1%.[5,6] In such steels, bainite packet size is the main microstructural feature that affects the toughness. On the other hand, toughness is sensitive to cementite particle size in steels with higher carbon content.[7,8] In such cases, coarse cementite readily cracks under stress to form defects of super critical size,[9] which subsequently leads to brittle fracture as in the case of upper bainite. In contrast, fine cementite associated with lower bainite does not crack easily. Further, even if the crack initiation takes place in finer cementite, the size of the crack is lower than the critical size required for the propagation of cracks. Also, propagation of these cracks is obstructed by other finer cementite present in the lower bainite.[10] This resistance of fine cementite towards crack initiation and propagation enhances the toughness property of lower bainite in comparison to that of upper bainite.

In the current study, it was found from the fractography of broken specimens that the mode of fracture was essentially ductile in both the tempered plates during their tensile test (Fig. 13 and 14). Similarly, the load displacement plots, recorded during plain strain fracture toughness test for both plates, were typical of ductile fracture (Fig. 15). Further, the K_Q values for both the plates were also similar as shown in Table 1. These similarities in toughness property show that crack initiation and propagation behavior were insensitive to the differences in the microstructures during tensile and plain strain fracture toughness tests. Interestingly, even the presence of coarse cementite and upper bainite did not adversely affect the toughness prop-

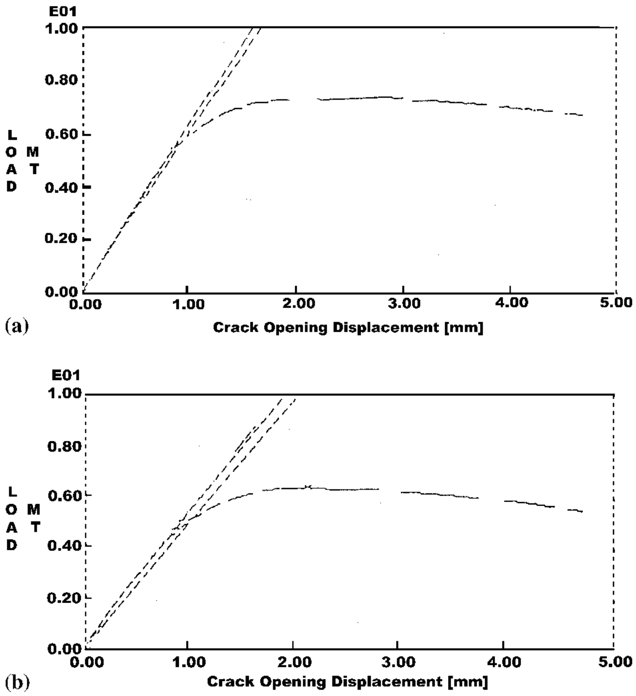

Fig. 15 Load displacement plots (i) tempered plate processed from 24 h of slab reheating cycle and (ii) tempered plate processed from 4 h of slab reheating cycle

Table 1 K_Q **Values of Plates Determined From Fracture Toughness Test**

Plate Category	K_Q Value (MPa $\sqrt{m}$)
Plate with 26 h of slab reheating time	156
Plate with 4 h of slab reheating time	149

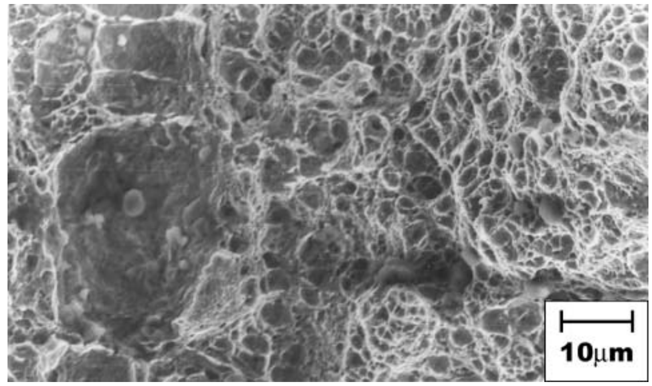

Fig. 16 Fractograph of fractured specimen showing ductile nature of fracture in three-point bend test of tempered plate processed from 26 h of slab reheating cycle (×1000)

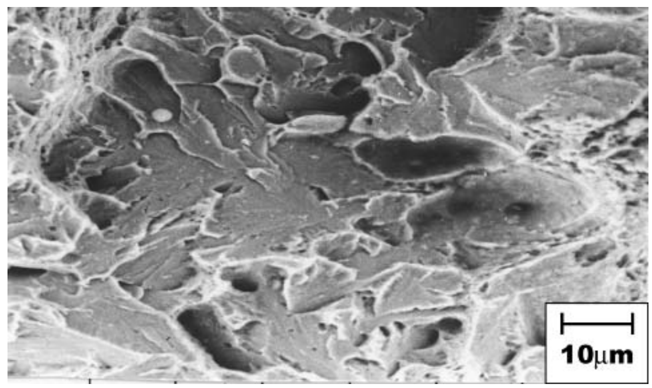

Fig. 17 Fractograph of fractured specimen showing mixed type of fracture in three-point bend test of tempered plate processed from 4 h of slab reheating cycle (×1000)

erty of Plate B. This was perhaps due to the fact that during these tests in which the specimens' thicknesses were comparatively less, the intensity of stresses generated in the specimens was not strong enough to crack even coarse cementite associated with microstructure of Plate B.

In the three-point bend test of full thickness specimens, the nature of the fracture in the almost complete cross-sectional fractured area of Plate A (Fig. 16) was ductile, while the fracture in a large area of broken surface of the fractured specimen of Plate B was brittle/quasi-brittle in nature (Fig. 17). This difference in toughness property of two plates was perhaps due to high intensity of stresses, which must have developed during this test due to restricted plastic flow of material ahead of the notch tip in 80 mm thick specimens. It seems that the smaller cementite of Plate A did not crack even under such stresses. On the other hand, the coarse cementite could not withstand the stresses and cracked, which resulted in the manifestation of brittle fracture in Plate B.

4. Conclusions

Granular bainite was formed in 80 mm thick medium carbon microalloyed steel plates when rolled after slab reheating at 1280 °C for a period of 4-24 h. The Martensite-Austenite constituents of granular bainite transformed into cementites during air cooling.

Longer slab reheating time of 26 h prior to hot rolling of the plates led to the evolution of smaller ferrite laths and a smaller proportion of cementite particles. This microstructure facilitated dissolution of cementite at the subsequent austenization stage prior to oil quenching. The ensuing improvement in hardenability led to formation of lower bainite and martensite after oil quenching. Lower bainite was retained even after tempering at 640 °C, while martensite decomposed into ferrite and fine cementite.

Larger ferrite laths and greater amounts of cementite were formed in the plate, which was rolled with 4 h of slab reheating time. This microstructure resulted in formation of upper bainite and granular bainite in quenched plates. Subsequent tempering of this plate transformed the granular bainite in coarser cementite, while retaining upper bainite.

Toughness of both the tempered plates did not vary significantly under conditions that prevailed during tensile and plain strain fracture toughness tests. This showed that toughness of the tempered plates was insensitive to the size of cementite when the thickness of the test specimens was comparatively smaller. On the other hand, toughness in the three-point bend fracture test of plates was found more sensitive to microstructure. Under this test condition, microstructure composed of coarser cementite and upper bainite produced brittle fracture, while another type of microstructure consisting of lower bainite and tempered martensite favored ductile fracture. This was due to the fact that coarser cementite could not withstand the higher intensity of stresses generated during the loading of thick specimens in the three-point bend test and therefore cracked, giving rise to brittle fracture.

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