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Evolution of non-uniform grain structure during hot deformation of a Nb-Ti microalloyed steel

T. Katajarinne*, M. Somani**, P. Karjalainen** and D. Porter***

Abstract Recrystallisation and the evolution of the abnormally grown austenite grains were investigated for a continuously cast slab of a 0.13 C-1.41 Mn-0.027 Nb-0.012 Ti steel during reheating and after the subsequent deformation. The stability of the recrystallised structure and the uniformity of the final microstructure were also studied. The abnormally grown grains appear in a few minutes at reheating temperatures around 1200 °C. All grains in the bimodal grain structure recrystallised at 1100 °C for strains ≥ 0.2 within about 40 s. The coarse grains are refined, while the fine grains become slightly larger. Some abnormal grain growth can occur again in the recrystallised structure within 10 min. After cooling at 1° C/s the coarse austenite grains transform into large areas of upper bainite, while the finer grains transform to fine ferrite and pearlite. The transformed microstructure in specimens cooled at 1°C/s consists of large upper bainitic areas corresponding to the prior coarse austenite grains, surrounded by fine ferrite-pearlite grains.

Keywords Abnormal grain growth. Reheating. Recrystallisation. Grain size. Microalloyed steel.

Evolución de la estructura de grano irregular durante la deformación en caliente de un acero microaleado Nb-Ti

Resumen Se ha estudiado la recristalización y la evolución del crecimiento anormal de grano, durante el recalentamiento y tras deformaciones sucesivas, en un acero 0,13 C-1,41 Mn-0,027 Nb-0,012 Ti procedente de colada continua. Se ha estudiado, así mismo, la estabilidad de la estructura recristalizada y la uniformidad de la microestructura final. Para temperaturas de recalentamiento próximas a 1.200 °C, aparece crecimiento anormal de grano en unos pocos minutos. Todos los granos pertenecientes a la estructura bimodal resultante recristalizan durante, aproximadamente, 40 s, a 1.100 °C, para una deformación de 0,2. El tamaño de grano se afina en aquellas regiones con granos más gruesos de partida y crece, ligeramente, en las que tenían un grano más fino. En 10 min, se puede desencadenar, de nuevo, un cierto crecimiento anormal de grano en la estructura recristalizada. La microestructura final a temperatura ambiente tras enfriamiento a 1° C/s está constituida por amplias áreas de bainita superior, que se corresponden con los granos gruesos de la austenita previa o bien, por una estructura ferrito-perlítica fina, en el caso de partir de granos más finos.

Palabras clave Crecimiento anormal de grano. Recalentamiento. Recristalización. Tamaño de grano. Acero microaleado.

1. INTRODUCTION

Fine uniform ferrite grain size is a desirable feature of HSLA steels for providing high strength and toughness. In commercial practice, microalloying elements, in particular titanium, are added to suppress excess coarsening of austenite grains during the slab reheating and subsequent rolling. However, when these microalloyed steel slabs are reheated it may happen that a few of the grains

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grow excessively while the mean size of the others remains fine. This well-known phenomenon is called abnormal grain growth and the conditions leading to it have been discussed recently by Rios[1]. For abnormal grain growth to take place it is necessary that the growth rate of the "matrix" grains is small e.g. due to Zener pinning. Militzer[2] and Lechuk *et al.*[3] discussed the modelling aspects of the interaction of precipitation and grain growth incorporating a time-dependent pinning force due to dissolution or coarsening of particles in low-carbon and in Nb-Ti steels. Medina *et al.*[4] have investigated the abnormal grain growth in a medium-carbon microalloyed steel and calculated the pinning force by applying different models.

Non-uniform austenite grain size may result in a heterogeneous final microstructure, which may cause the harmful scatter in impact toughness values occasionally encountered in hot-rolled steel plates and sheets. However, the evolution of abnormally grown austenite grain structure during the course of rough rolling has not been reported in detail. Karjalainen and Perttula[5] have earlier investigated the recrystallisation of partially recrystallised austenite, i.e. in a dual-grain structure. The present paper reports stress relaxation and optical microscopy investigations of the recrystallisation and the grain size evolution of non-homogeneous reheated grain structures.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

A piece of a continuous cast slab of a Nb-Ti microalloyed steel with the chemical composition (wt %) 0.13 C-0.20 Si-1.41 Mn-0.037 Al-0.019 V-0.027 Nb-0.012 Ti-0.0054 N was used in the investigation. Specimens were taken from both close to the surface and the centre-line. Reheating and hot deformation were performed in a Gleeble 1500 thermo-mechanical simulator using cylindrical specimens with dimensions ø10 × 12 mm. After the reheating treatment, the specimens were cooled at 2° C/s to the deformation temperature and compressed at the true strain rate of 0.1 s^{-1}. The strain applied was 0.2 in most single pass tests. The recrystallisation kinetics were determined by the stress relaxation method, which is described elsewhere [5-7]. For non-uniform grain structure, a series of multiple-pass deformation tests were performed at 1,100 °C with pass intervals of 60 s. In some tests, the holding time after the last pass was extended up to 600 s to investigate the possible occurrence of abnormal grain growth. Additionally, some tests were performed to examine the effects of a bimodal grain structure on the final transformed microstructure. In these cases, testing was finished by cooling the specimens at 1 °C/s.

For revealing the prior austenite grain boundaries, the specimens were etched in saturated picral containing Teepol detergent at about 70 °C. The grain size was measured by the linear intercept method in the case of fine grains, while for the coarse grain structure the grain size was assessed by measuring the area occupied by a number of grains and computing the average diameter. For heterogeneous structures, an average grain size is inappropriate; rather, separate values for the coarse and fine grains should be given.

3 RESULTS AND DISCUSSION

3.1. Abnormal grain growth during short reheating

It was found that the studied steel in the as-cast condition was quite susceptible to abnormal grain growth. In the short times suitable for Gleeble simulation tests, holding 3 min at 1,175 °C revealed the first locally coarse grains (>50 μm), and within 10 min at 1,200 °C or in 2 min at 1,250 °C most of the grains were already coarse. Consequently, the reheating treatments at 1,200 °C and 1,250 °C for 2-5 min were selected to create the initial bimodal grain structure for the grain size evolution tests. Typical grain structures obtained after reheating at 1,100, 1,200 and 1,250 °C are displayed in figure 1. The average grain sizes were 16 and 1750 μm for reheating treatments 1,100 °C/10 min and 1,350 °C/5 min, respectively. Treating at 1,200-1,250 °C/2-5 min produced increasing numbers of 200-500 μm diameter coarse grains among 40 μm diameter fine grains.

It was evident that the coarse grains formed in solidification dendrite core regions, while the finer grains were located in the darker-etching interdendritic zones, obviously due to the segregation of microalloying elements. The maximum contents of Si and Mn, measured using SEM-EDS, were 0.74 % and 2.6 % respectively in the interdendritic regions.

3.2. Recrystallisation behaviour

In single pass deformation, the recrystallisation kinetics were determined using three different

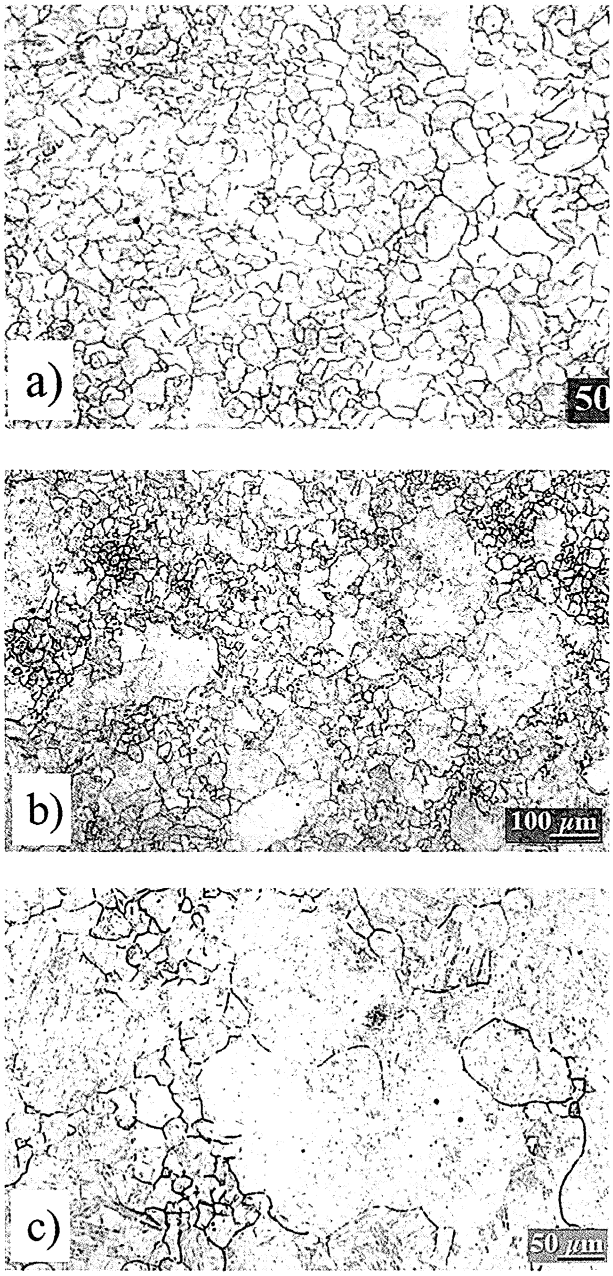

Figure 1. Austenite grain structures: a) 1,100 °C 10 min b) 1,200 °C 2 min c) 1,250 °C 2 min.

Figura 1. Estructura de granos de la austenita a) 1.100 °C 10 min b) 1.200 °C 2 min c) 1.250 °C 2 min.

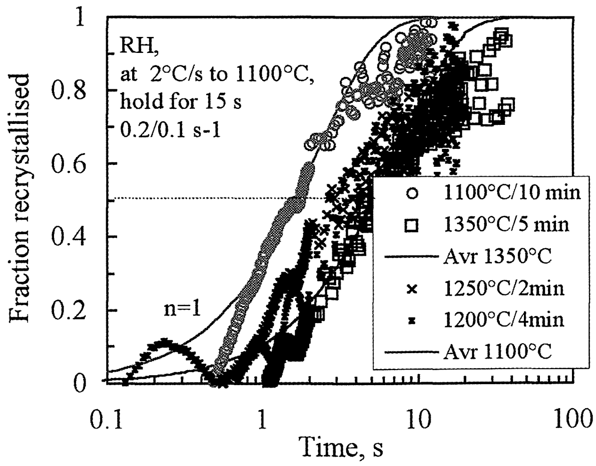

Figure 2. Fractional softening curves for specimens reheated at various temperatures.

Figura 2. Curvas correspondientes a la fracción de ablandamiento para muestras recalentadas a diferentes temperaturas.

grain structures, i.e. uniformly fine, uniformly coarse and heterogeneous, after reheating at 1,100 °C/10 min, 1,350 °C/5 min and 1,250 °C/2-5 min (and 1,200 °C/2-4 min). From the recorded relaxation data, fractional softening curves were computed and some of them are shown in figure 2. The determined times for 50 % recrystallised fraction t_{50} were widely scattered, but after deformation at 1,100 °C (0.2/0.1 s^{-1}) t_{50} values around 1-2.5, 2-4 and 5-7 s were obtained for specimens reheated at 1100, 1250 and 1350 °C respectively. For both the homogeneous fine-grained and the coarse-grained structures an Avrami exponent n ≈ 1 seemed to be appropriate. In the cases of bimodal structures, small softening fractions were reached in times between the t_{50} times for the fine and coarse-grained structures, but the final softening takes place in times more or less identical to those for the coarse grain structure.

Differences in the recrystallisation kinetics seem to be relatively small, in spite of the difference of two orders in the grain sizes. One reason is that applied strain was somewhat higher than the nominal one for the coarse-grained structure due to some barrelling of un-lubricated specimens, because the graphite foil, i.e. the lubricant, could not be used at the high 1,350 °C reheating temperature. The second reason is that the power of the grain size varies with the grain size, as shown elsewhere[8], being much lower than the quadratic power often suggested for fine grains[9]. Similarly, a weak dependence ($t_{50} \propto d^{0.7}$) has been recently observed by Fernánandez *et al.*[10] for coarse austenite grain sizes (>100 μm).

In multipass tests, interpass times of 60 s were mostly used, which, on the basis of the fractional softening curves (in Fig. 2), was long enough to complete the recrystallisation (95 % softening within ≈20-40 s). Full softening was also confirmed by comparing the flow stress curves of the passes. It was observed that for reheating at 1,200 °C for 2-4 min, while most of the grains were still fine (figure

1b), the recrystallisation rate was slightly reduced from pass to pass. This suggests that the fine grains, which mainly influence the kinetics, were somewhat coarsened rather than refined from pass to pass. The recrystallised grain size is mainly dependent on the prior grain size and strain [5, 7 and 9]. The power of 0.67 was given by Sellars[9] for both the grain size and strain for C-Mn steels. Airaksinen *et al.*[7] obtained the powers 0.4 and 0.55 for the grain size and strain respectively for Ti- and Nb-Ti bearing steels. For the measured homogeneous fine grain sizes in the present tests the following approximate relationship was obtained:

$$d_{rex} = 1.1\, d_o^{0.67} / \varepsilon^{0.8} \qquad (1)$$

where d_{rex} and d_o are the recrystallised and initial grain sizes respectively, and ε is the strain. The mean grain size of the matrix grains in the specimens reheated at 1,200 °C for 4 min was about 40 µm and the coarse grains roughly 400 µm. For three successive passes with a strain of 0.2, equation (1) predicts that the fine grains are coarsened in the sequence 40 → 47 → 53 → 57 µm, while the coarse grains are significantly refined: 400 → 221 → 148 → 114 µm.

In agreement with the predictions, it was observed that an initially bimodal grain structure such as in figure 1b became distinctly more uniform in the recrystallisation following single (Fig. 3a) or especially multipass deformation (Fig. 3b): the very coarse grains disappeared.

3.3. Isothermal holding after recrystallisation

Normal grain growth in the present steel is very restricted at temperatures ≤1,100 °C due to (Ti,Nb)C particles [3, 5 and 6], but there is the possibility of abnormal grain growth initiating at the same locations that were responsible for abnormal grain growth during reheating, i.e. in areas with sparse precipitation and low pinning force. Figure 4 shows a typical austenite grain structures after deformation and 600 s holding at 1,100 °C. Definitive conclusions are difficult to draw, but it seems that relative large grains again appear with a similar distribution to that after reheating. The considerable size advantage of certain grains may be a reason for this enhanced tendency to abnormal grain growth.

3.4. Final transformed microstructure

The influence of a bimodal austenite grain structure on the final microstructure was examined after continuous cooling. It was observed that at the rate of 1° C/s large austenite grains transformed into an upper bainite-like constituent, i.e. ferrite laths with aligned M-A-C particles, while the fine austenite grains decomposed into fine-grained polygonal ferrite with a minor fraction of pearlite (Fig. 5). This happens despite the segregation of Si and Mn in the interdendritic regions. The presence of prior abnormally grown grains are clearly detectable in the transformed microstructure (Fig. 5a). The marked refinement produced by

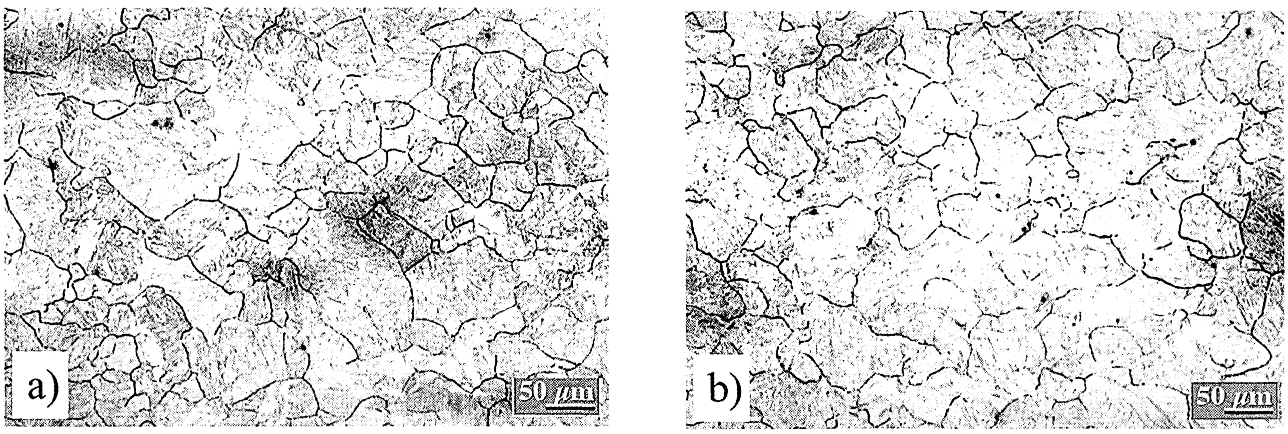

Figure 3. Austenite grain structures after reheating at 1,200 °C for 4 min: a) compression at 0.2 and held for 60 s b) 3 passes at 0.2 with 60 s interpass times.

Figura 3. Estructura de granos de la austenita después de un recalentamiento de 4 min a 1.200 °C: a) compresión hasta una deformación de 0,2 y mantenimiento durante 60 s b) 3 pasadas de 0,2 de deformación con tiempos entre pasada de 60 s.

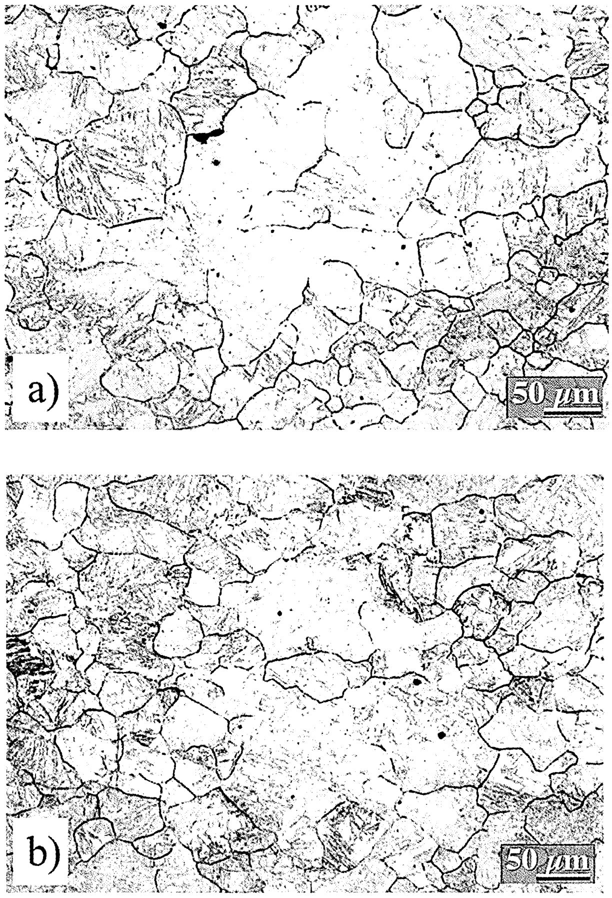

Figure 4. Austenite grain structures after reheating at 1,200 °C for 4 min: compression at 0.2 and held for 600 s at 1,100 °C b) 3 passes 0.2 each and held for 600s at 1,100 °C.

Figura 4. Estructura de granos de la austenita después de un recalentamiento de 4 min: a) 1.200 °C compresión hasta una deformación de 0,2 y mantenimiento durante 600 s a 1.100 °C b) 3 pasadas de 0,2 de deformación cada una y mantenimiento de 600 s a 1.100 °C.

recrystallisation can be seen in figure 5b and finally the tendence for coarse bainitic regions to reappear in after prolonged holding in figure 5c.

4. SUMMARY AND CONCLUSIONS

A bimodal austenite grain structure is formed by abnormal grain growth within minutes at 1,175-1,250 °C in the present C-Mn-Nb-Ti steel slab.

After deformation, static recrystallisation occurs in the non-homogeneous grain structure. At 1,100 °C, 0.2 strain and 0.1 s^{-1}, complete recrystallisation takes place within 40 s. Under these conditions, the coarse grains get considerably finer in successive deformation passes with a 60 s interpass times.

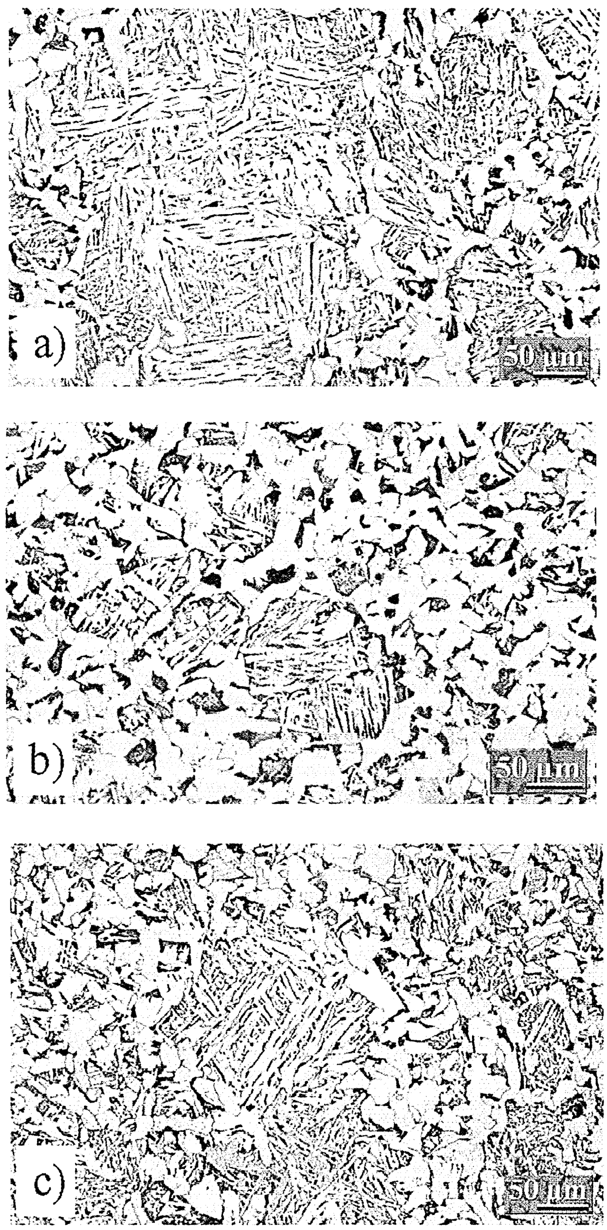

Figure 5. Microstructures after the cooling at 1 °C/s. Reheated at 1,200 °C for 3 min: a) undeformed b) 0.2 strain at 1,100 °C, held 60 s, c) 0.2 strain at 1,100 °C, held 600 s.

Figura 5. Microestructura tras el enfriamiento a 1 °C/s. Recalentamiento a 1.200 °C durante 3 min: a) muestra sin deformar, b) 0,2 de deformación a 1.100 °C y mantenimiento durante 60 s y c) 0,2 de deformación a 1.100 °C y mantenimiento de 600 s.

After the completion of recrystallisation, certain grains can, however, start to grow abnormally once again even at 1,100 °C.

Changes in austenite grain sizes are revealed in the transformed final microstructure after continuous cooling at 1° C/s: large upper bainitic areas form at the locations of the prior abnormally grown austenite grains and fine ferrite grains at the location of the prior fine matrix austenite grains.

To avoid large grains in the final microstructure, a proper hot rolling schedule is essential to refine the coarse grains by repeated recrystallisation events and the time before the start of the finishing rolling should be as short as possible.

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