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NIOBIUM IN MICROALLOYED RAIL STEELS

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Abstract

Rails generally do not have a homogeneous austenite grain structure across their sections because the degree of plastic strain achieved during hot-rolling depends on location. Here we explore a philosophy in which niobium microalloying may be introduced in order to thermomechanically process the material so that pancaked and refined austenite grains may eventually be achieved in the critical regions of the rail. The essential principle in alloy design involves the avoidance of coarse niobium carbide precipitates in the regions of the steel that contain chemical segregation caused by non-equilibrium solidification. Both pearlitic and cementite-free bainitic rails have been studied. The work is of generic value to the design of high-carbon microalloyed steels.

Introduction

Rail steels rely primarily for their properties on wear and rolling-contact fatigue resistance [1–4]. The general characteristics of rail steels have been reviewed elsewhere [5]. It is, however, well known that the austenite grain structure of rails is not uniform, nor is it as refined in size as it could be. The purpose of the present work was to develop a niobium microalloying philosophy that would permit rails to be thermomechanically processed, resulting in a highly refined, pancaked austenite grain structure. There are many advantages to a fine austenite grain size, defined as a mean lineal intercept ($\overline{L_\gamma}$). A smaller $\overline{L_\gamma}$ leads ultimately to a finer microstucture following transformation. The influence of embrittling impurities is also reduced [6–8]. The thickness of cementite films or size of cementite particles at austenite grain surfaces is reduced as $\overline{L_\gamma}$ decreases.

Rails are hot-rolled starting beginning with slabs some 300×440×4700 mm size, reheated to 1200°C and then deformed into the required profile in less than twenty passes. The initial austenite grain size in the slab held at 1200°C for 4 h is greater than 460 μm [9], and reduces to about 50 μm during the first two passes, after which it remains at that value during subsequent passes. The lack of microalloying elements leads to the coarse structure at the reheating temperature and all of the subsequent deformation leaves the steel in a recrystallised state between passes. Conventional rails have an austenite grain size which varies dramatically as a function of position within the rail (Fig. 1), and with the processing parameters. The base of the web has a much more uniform and relatively fine austenite grain size, because of the greater extent of plastic work done during shaping.

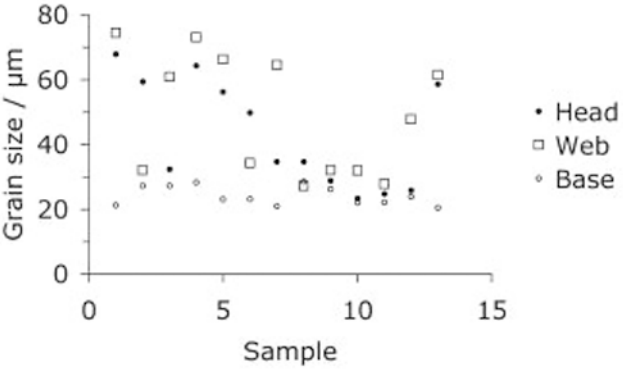

Figure 1: Variation in austenite grain size within rails, and between different alloys. The data are from [10] but neither the method of measurement nor the units, which here are assumed to be micrometres, were specified.

A controlled addition of microalloying elements would lead to substantial grain refinement for the lower degrees of deformation experienced by the head of the rail, if the austenite recrystallization process can be retarded. Such retardation is a well-established procedure in the controlled rolling of large quantities of lower strength materials so the technology is well established, albeit for the low-carbon alloys. There is an interesting aspect which has never before been explored in the context of rails, i.e., the creation of a pancaked austenite grain structure, especially in the head of the rail. Pancaking would lead to a dramatic increase in the amount of grain surface per unit volume because of the highly anisotropic grain shape (for quantitative details see [11]) and hence a more pronounced reduction in $\overline{L_\gamma}$ than if equiaxed grains are made finer. Similarly, there is the possibility of further refinement due to shear band formation in unrecrystallised austenite. Niobium present in solution, for example at the slab reheating temperature, would in itself retard recrystallisation during subsequent deformation if the latter stimulates precipitation [12].

Niobium in High-Carbon Steels

The solubility of niobium in austenite containing 0.8 wt% carbon which is in equilibrium with niobium carbide, is only about 0.01wt% at 1200°C [13]. This is one reason why there has been less activity in the microalloying of high-carbon steels. Nevertheless, promising work has been done on the development of microalloyed rail steels ([14, 15], cited in [16]). And the effect of niobium (0.04 wt%) on the austenite grain size after holding at 1200°C for 30 min was to reduce $\overline{L_\gamma}$ from 360 to 220 µm [16]. In spite of the small amount of dissolved niobium at the reheating temperature, the authors reported a strong effect on austenite processing and the subsequent pearlite reaction. This bodes well for rails since there would be a smaller austenite grain size entering the rolling mill from the slab reheating furnace.

Early experiments on the microalloying of rail-steels with niobium up to 0.047 wt% [17] established improved properties, particularly with accompanying adjustments in the chromium, carbon and silicon concentrations. Recent work [18] on the addition of niobium (up to 0.073 wt% but with an ‘optimum’ value of 0.053 wt%) to heavy-rail steel has proven that an equiaxed austenite grain size of just 7.2 μm can be achieved together with impressive fracture toughness values of 50 MPa $m^{1/2}$. The alloys studied were not from full scale production trials but rather, 50 kilogram melts. The authors also reported a refinement of the pearlite interlamellar spacing due to the niobium additions, and niobium-rich precipitates were apparently identified in both the ferritic and cementite phases of pearlite. Similar values of fracture toughness as reported in [18] have been observed in niobium microalloyed rails [19] but the full publication is not accessible. There is a claim in another publication which is not accessible [20] that the performance of a rail steel supplemented with niobium led to a greater strength and malleability, more so than when vanadium was used as a microalloying element.

High-carbon (0.85-1.01 wt%) and niobium (0-0.12 wt%) have been studied in the context of rolls [21]. Although metallographic details were not reported, the mechanical property data all show positive effects on strength, ductility and hardenability for niobium <0.05 wt%.

Alloy Design

Two alloys have been considered, one for pearlitic and the other for cementite-free bainitic steel rails with nominal compositions as in Table 1. The bainitic rail has a much larger silicon concentration to retard the precipitation of cementite from carbon-enriched austenite; its average carbon concentration is less than that of pearlite because it is possible to achieve the same hardness level due to its highly refined microstructure that results from the displacive mechanism of transformation.

To estimate the effect of chemical segregation during casting, the Gulliver-Scheil method [22, 23] was used, allowing the back diffusion of carbon since it is a fast diffusing solute at solidification temperatures. The model involves one-dimensional, continuous-cooling solidification with the partitioning of solutes between the homogeneous liquid and heterogeneous solid, implemented in MatCalc [24] using a 'mc_sample_fe.tdb' database. The composition of the last remaining 10% of the liquid is said to represent highly segregated regions of the casting, where coarse and difficult-to-dissolve particles of NbC may form. The phase fractions and compositions, and the temperature at which all the niobium would be in solid solution within the solute-enriched last 10% of the liquid to solidify (T_{diss}^{seg}), were then calculated.

The results are listed in Table 1 which shows surprisingly that the difference between the low-carbon bainitic and the high-carbon pearlitic steel is not large, indeed, T_{diss}^{seg} is in all cases greater for the bainitic alloy. It has been verified using thermodynamic calculations that this is because the large silicon concentration in the former alloy reduces the solubility of niobium in austenite. The results also indicate that if, in industrial practice, the maximum hot processing temperature is 1300°C then the maximum average niobium concentration ($\overline{w}_{\mathrm{Nb}}$) must be limited to less than 0.01 wt%. However, such a low concentration may not be conducive to grain size control during hot processing; it is also possible that the niobium carbide particles in the segregated zones may not be large enough to cause difficulties with respect to rolling contact fatigue.

To assess this, two 100 g experimental melts were cast, labelled "experimental pearlitic" steels in Table 1, and then assessed for niobium precipitate sizes. Fig. 2a shows the measured precipitate size distributions for the 0.009 and 0.016Nb wt% steels in the as-cast condition. The maximum size observed is in each case less than 3 μm, with the vast majority being much smaller in size. This augers well for the design of rail steels where conventional non-metallic inclusions can be much greater in size than observed here for the niobium-rich precipitates in the segregated zones. For example, average inclusion sizes have been reported to be from 18-28 μm in length and 4.9-6.2 μm in width depending on steel composition, with the maximum values ranging up to 300 μm long and 9 μm in width [25]. The nature of the niobium-rich precipitates is illustrated in Fig. 2b,c.

Table 1: Base compositions (wt%) for microalloying with niobium. $\overline{w}_{\mathrm{Nb}}$ represents the average wt% of niobium. T_{diss}^{seg} is the temperature at which all NbC can in principle be dissolved; values in brackets are calculated assuming the alloy is homogeneous.

	C	Si	Mn	Cr	Mo	Nb	T_{diss}^{seg} /°C
Pearlitic (average composition)	0.80	0.40	1.0	0.50			
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.005$	0.80	0.70	1.9	0.84		0.038	1300
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.010$	0.80	0.70	1.9	0.84		0.076	1351
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.020$	0.80	0.70	1.9	0.84		0.153	1372
cementite-free bainite (average composition)	0.40	1.50	2.00	1.00	0.30		
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.005$	0.40	2.22	2.67	1.23	0.97	0.035	1300
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.010$	0.40	2.23	2.68	1.24	0.99	0.072	1375
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.020$	0.40	2.22	2.67	1.23	0.98	0.140	1390
Experimental pearlitic (average composition)	0.70	0.40	1.02	0.65		0.009	(1137)
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.009$	0.70	0.72	1.91	1.05		0.070	1360
Experimental pearlitic (average composition)	0.72	0.42	1.02	0.61		0.016	(1180)
Segregated composition when $\overline{w}_{\mathrm{Nb}} = 0.016$	0.72	0.74	1.90	0.99		0.120	1373

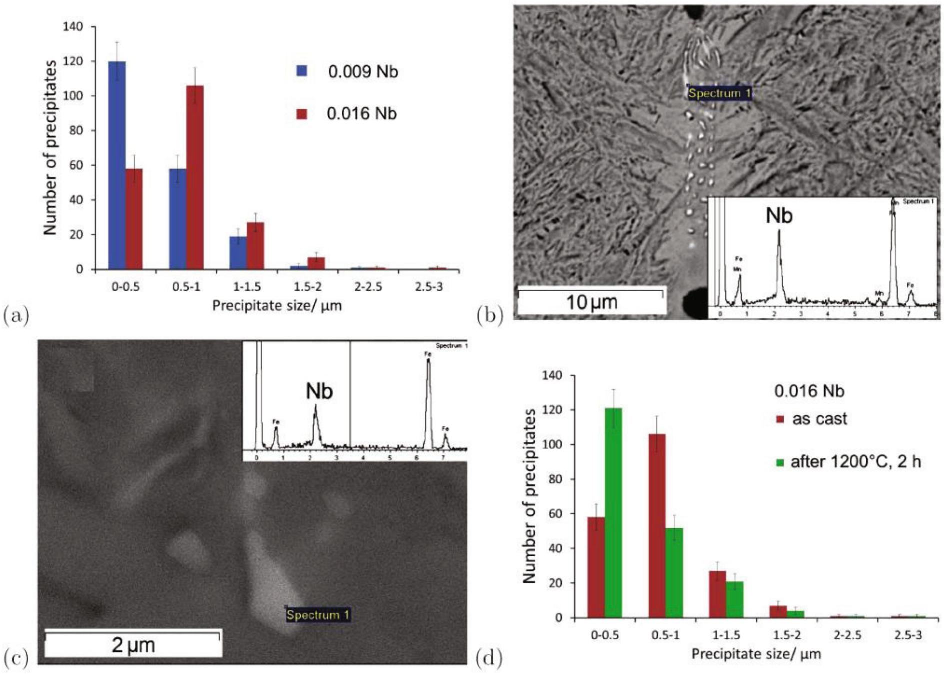

Figure 2: Scanning electron microscopy data on niobium-rich precipitates (identified using microanalysis). (a) As cast experimental pearlitic steels with $\overline{w}_{\rm Nb}$ = 0.009 and 0.016 et%. (b,c) Niobium-rich precipitates in the 0.016Nb wt% steel. (d) The 0.016Nb wt% alloy in as-cast and annealed conditions.

Some rail steels are rolled with the slabs heated to 1300°C whereas a more energy efficient process begins with the reheating furnace at 1200°C, where the steel may be held for about 2 h or more. To assess the role of this, the 0.016 Nb steel was annealed after casting at 1200°C for 2 h; Fig. 2d shows that there is a consequence, a very significant reduction in the size of the niobium-rich precipitates following the annealing treatment. Indeed, no particles were observed following annealing at 1250°C for 2 h.

Summary

Rail steels would benefit from thermomechanical processing that results in a fine, homogeneous austenite grain size throughout the rail section. A rationale has been developed for the niobium microalloying of pearlitic and cementite-free bainitic microstructures, based on the avoidance of coarse niobium carbides in the regions of the steel that contain chemical segregation resulting from the casting process. Gulliver-Scheil calculations are used to assess theoretically, the composition of the segregated regions, with subsequent thermodynamic analysis to estimate the temperature required to dissolve the carbides in the segregated zones (T_{diss}^{seg}). The concentration of niobium permitted is then reduced until T_{diss}^{seg} becomes less than that at which the steel begins its hot-rolling sequence.

We have demonstrated that it is possible to microalloy both classes of steel such that the carbide sizes in the segregated regions are much less than those normally encountered for non-metallic inclusions. It has been discovered that silicon has a large effect on reducing the solubility of niobium in austenite that is in equilibrium with NbC. This is important in the design of the cementite-free bainitic rail steel.

Our further work will focus on scaling up the castings and studying methods of further reducing the size of niobium-rich precipitates in the segregated zones. Mathematical models are at the same time being developed to calculate the size of these precipitate distributions.

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