NIOBIUM IN RAIL STEEL

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Abstract

The present paper reviews the key developments that have taken place in the production of niobium containing rail steels. An overall perspective is given on the fundamental metallurgical principals behind such steels together with the process developments that have taken place in Europe, the USA and Japan. A number of strategies are described for the production of as-rolled high strength alloy rail steels; the options of adding further alloying elements is compared to making a eutectoid carbon rail steel whose head is hardened by reheating and accelerated cooling (slack quenching). Furthermore, the recent developments in Japan in the development of niobium containing bainitic rail steels are also discussed. Specific attention is given to the need for improved wear resistance, shelling resistance, ductility and the weldability requirements of modern track systems. The role of niobium is found to consistently provide a fine austenite grain size at the start of the head hardening treatment even with a fairly wide range in the production parameters of time and temperature. The grain refining effect results in a finer pearlite colony size by reduction of the interlamellar spacing, which in turn leads to the prevention of rail head damage through the improvement in ductility.

Introduction

The multifunctional microalloying element niobium has turned out to be the most important microelement in low carbon structural steels. The example of line pipe steels show how the development in steelmaking and hot rolling led to structural steels that take full advantage of the metallurgical effects of niobium. These effects are; austenite and ferrite grain refinement, which increases both strength and toughness of a ferritic microstructure, precipitation hardening and retardation of recrystallisation which plays a key role in thermomechanical rolling (1, 2). The question is to what extent niobium may also have a beneficial effect in medium and high carbon rail steels.

Due to the increased requirements of railroads, in relation to axle loads and speeds, the development of rail sections and rail steels has been steadily pushed forward. The manufacture of rails systematically utilises the facilities modern steelmaking has to offer; hot rolling and finishing. On the basis of previous experience with niobium in rail steels, the benefit of niobium in the manufacture of rails, both with regard to steel composition and to rail head-hardening processes, is outlined.

Requirements

Within the system ‘wheel-rail’ the rail has to perform as a carrying element and as a guiding runway. Axle loads and track guidance demand special mechanical and technological properties from rail steels. The wear resistance, which is related to the tensile strength, generally governs the service life. Fatigue strength, toughness, stress crack and fracture resistance, as well as weldability, are also essential properties (3).

History of Rails - Sections, Steels and Production Processes

Since the beginning of railroad traffic, various rail sections have been developed to accommodate both commuter and industrial needs (4). Today, flat bottom rails, guide rails, grooved rails, crane rails and special rails are widely used. They are all manufactured from a type of steel that makes them fit for the purpose. Figure 1 shows the historical development of rail steels over the last one hundred and fifty years (5).

The characteristics of main rail steels are given in Table I. Crane rails are made of medium carbon steel with a 50% ferrite and 50% pearlite microstructure. The Flat Bottom Grade 700 rail steel also has a ferritic-pearlitic microstructure, whereas the high strength rail steels grade 900 and above, are completely pearlitic (6). There are also bainitic steels for special purposes (7), as will be outlined further in this paper.

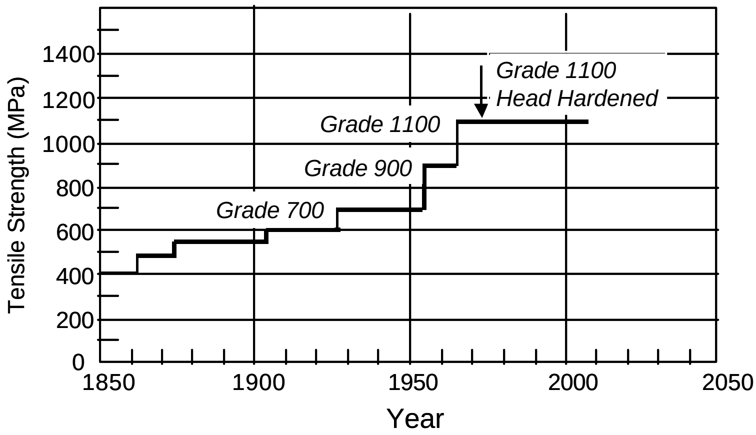

Figure 1: History of rail steels (5).

Table I Characteristics of the main rail steels

Rail Steels	**Chemical Composition (%)**			**Tensile Strength (MPa)**	**Microstructure**
	C	**Mn**	**Cr**		
Crane Rail	0.35	0.8	---	600	50% ferrite + 50% coarse pearlite
Flat Bottom Rails					
Grade 700	0.50	1.0	---	700	30% ferrite + 70% coarse pearlite
Grade 900	0.75	1.0	---	900	100% coarse pearlite
Grade 1100	0.75	1.1	0.9	1100	100% fine pearlite
HH 1100 (Head Hardened)	0.75	1.0	---	1100	100% fine pearlite

The production process comprises of steelmaking, hot rolling, heat treatment and finishing (8). Steelmaking of rail steel provides a clean steel due to modern secondary steelmaking practices (9). Achieving a high cleanliness markedly reduces rail damage through head checking and shelling (3, 10) and a low hydrogen content prevents the formation of flakes after rolling. The hot rolling process with grooved rolls must match the dimensional tolerances of the final product. After rolling the rails may cool down in still air (on the cooling bed) or be accelerated cooled, a process called direct head-hardening. Such an inline process (11, 12, 13) was developed after offline head-hardened rails proved to be successful (10, 14). The end-hardening of rails, as a preliminary process with regard to the treatment of the full length of rails, dates back to the time when the rails were still joined by fishplates. The hardened end should withstand the wheel bumping from one rail to the next. Therefore, only a small part of the rail had to be heat treated using a special facility. Today, rails are joined by welding, thus creating an endless track. Consequently, the idea of head-hardening was applied to the full length of the rail. At first, the heat treatment took place in offline installations which had far lower capacities than the rolling mill. Presently, inline processes offer such a high capacity that heat treatment is no longer the bottleneck. Further information on the principles of accelerated cooling of rails and a survey of offline and inline rail head-hardening installations has been given by Bramfitt (15).

Technological Properties and Microstructure

There is a clear relationship between wear resistance and tensile strength. Therefore, rail steel grades are classified according to their tensile strength, which is easy to test and certify. Pearlite is an important feature of the microstructure because it possesses good wear resistance, hence, making carbon an essential alloying element in rail steels. However, it is not only the amount of pearlite that is important but also its morphology, which means the shape and the distance between the cementite lamellae. The finer the structure of pearlite, the higher is its strength whilst still retaining reasonable toughness. Therefore, and understandably, the development of pearlitic rail steels has been focused on the refinement of pearlite. The formation of the microstructure of a steel product is basically the result of steel composition, deformation and heat treatment.

Grade 700 rails that used to be the main product for railroads, some 60 years ago, may be considered as the starting point for development which has since taken place. The Grade 700, with about 0.5%C, has a microstructure of about 30% ferrite and 70% pearlite within the rail head, which is the relevant location for comparison. Due to the rather slow cooling of the rail head on the cooling bed after rolling, the pearlite structure is relatively coarse. The first step to raise strength, and consequently wear resistance, was to increase the carbon content to achieve a 100% pearlitic microstructure (Figure 2) (16).

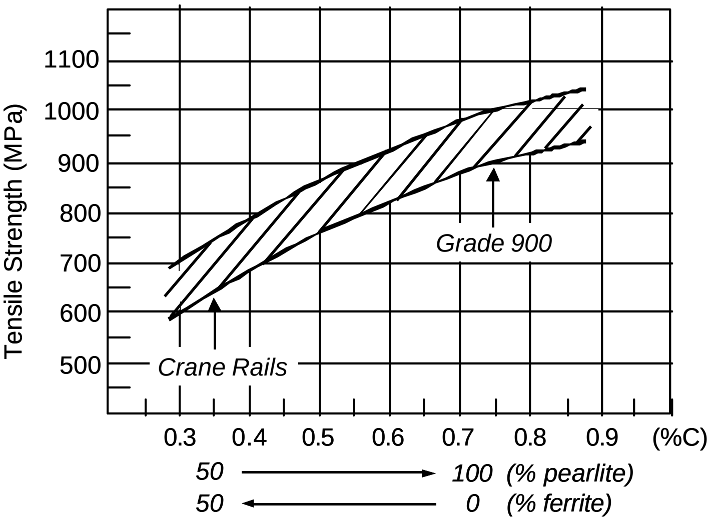

Figure 2: Effect of carbon content on microstructure and tensile strength.

The wear resistant rails of Grade 900 (see Table I) have a coarse pearlitic microstructure with sufficient ductility and toughness for general applications. Welding techniques were developed to replace fishplate connections and Grade 900 became the standard rail instead of Grade 700 for main lines (Figure 1). Nowadays Grade 700 rails are only used for tracks where low axle loads are applied, e.g. for trams. In some places like narrow curves and mountainous regions, but mainly for heavy haul ore and coal transportation, strengths greater than that exhibited by Grade 900 rails are needed; an increase in tensile strength of about 200MPa doubles the wear resistance of the rails and consequently their service life (3).

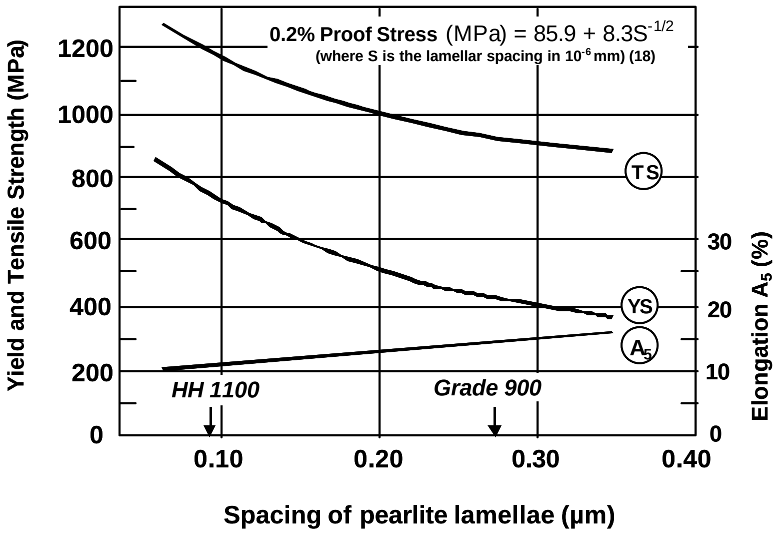

Figure 3: Effect of pearlite refinement on the propertiesof rails steels with 0.75%C and 1.0%Mn (Table I).

The further strengthening of pearlitic rails to 1100-1200MPa tensile strength is based on increased pearlite refinement (Figure 3) (17, 18, 19). The continuous cooling transformation (CTT) diagram of Grade 900 steel reveals that the maximum strength of the pearlitic microstructure is about 1200MPa and it shows two possibilities for achieving pearlite refinement. Firstly, the field of austenite to pearlite transformation may be moved, e.g. through chromium additions, to the right where air cooling of the rail head transforms the austenite into fine pearlite with narrow interlamellar spacing (Figure 4) (3).

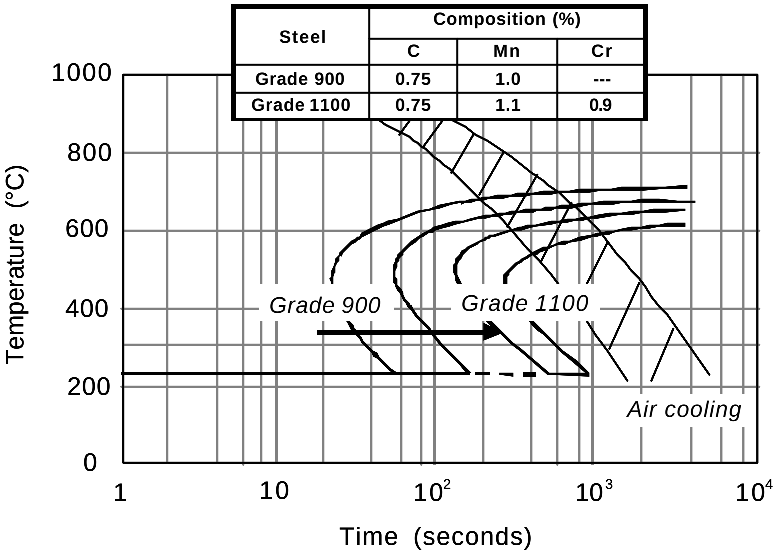
Steel	Composition (%)		
	C	Mn	Cr
Grade 900	0.75	1.0	---
Grade 1100	0.75	1.1	0.9

Figure 4. CCT – diagram showing the effect of alloying to achieve pearlite refinement.

This type is the high strength and highly wear resistant alloy Grade 1100, which cools still air after rolling. The second possibility is that the cooling speed of the rail head may be accelerated to move the austenite to pearlite transformation of the Grade 900 steel to the left in order to achieve a microstructure of fine pearlite; generating a 1100-1200MPa tensile strength with the same steel composition (Figure 5) (5). This type is head-hardened rail. The heat treatment and accelerated cooling of the rail head may be performed after reheating (offline) or using the still austenitic microstructure directly after rolling (inline).

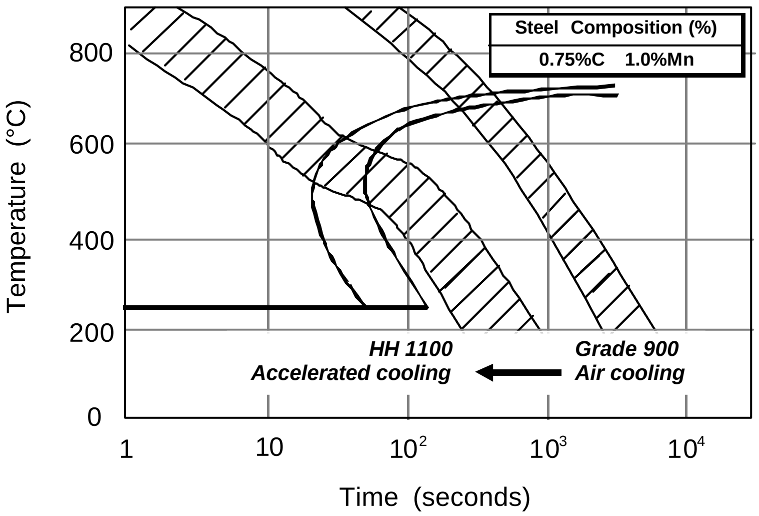

Figure 5: CCT-diagram showing the effect of cooling rate to achieve pearlite refinement.

This is a rough guide in the history of steel development for railroads. As there will always be the demand for further improvement there is the question whether microalloying with niobium can improve the quality of rails in a similar fashion to the successful alloying of structural steels.

Previous Experience with Niobium-Alloyed Rail Steels

Williams et al. (16) give a comprehensive compilation of the application of niobium in rail steels. The following statements have been extracted from the paper in order to evaluate the effect of niobium in rail steels and to find out where niobium will provide a beneficial contribution to the quality of rails:

- *Molycorp and the Colorado Fuel and Iron Company/USA*

  Compared to a basic rail steel with 0.74%C, 0.80%Mn, 0.14%Si, the additions of 0.015-0.047%Nb provided higher yield strength (11.4%) and tensile strength (4.0%) and better toughness. However, in-track tests showed no significantly improved performance over the basic rails.

- *Domnarvets Jernverk, Sweden*

  niobium increased the tensile strength by 98MPa which improved the wear resistance.

- *ISCOR, South Africa*

  Cr-Nb steel rails were investigated in order to improve the toughness through niobium. A combination of 1215MPa tensile strength along with a remarkable 14% elongation was achieved.

- In *Belgium* a rather low carbon Cu-Ni-Cr-Nb steel has been developed for crane rails. The range of carbon is 0.10-0.30% and the additions of niobium are between 0.04-0.06%. The tensile strength is about 1080MPa with a reasonable elongation of 12%.

The experience so far shows some advantages and no disadvantages with niobium additions with regards to the technological characteristics of rail steels. With completely pearlitic steels the key point is austenite grain refinement during rolling which leads to refinement of pearlite colonies and consequently, improved ductility of niobium-bearing rail steels. The specific merits in making additions of niobium have to be balanced by the requirements of individual cases. Williams makes two general remarks regarding niobium in rail steels:

- The lower the carbon content, the more pronounced the strengthening will be. Examples are given regarding the improvements in crane tracks and heavily loaded tracks at the steel plant of the Australian Iron and Steel Pty. Ltd.
- Irrespective of the carbon content benefits occur for additions up to 0.03%Nb (Figure. 6).

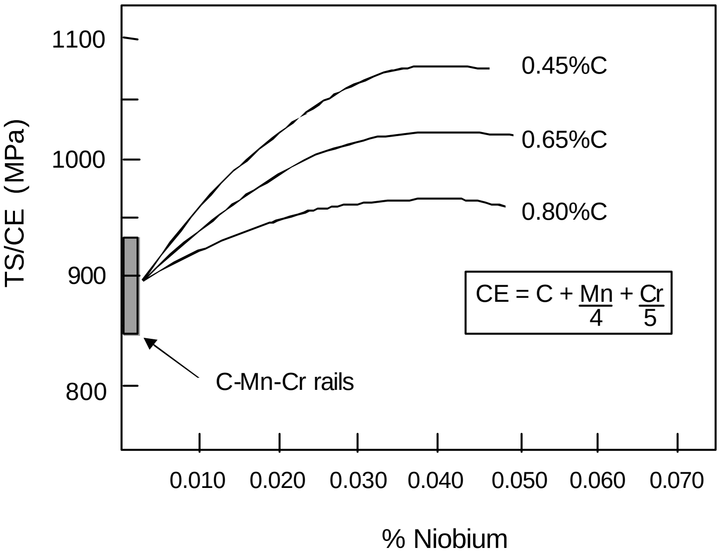

Figure 6: Effect of niobium content on the TS/CE in C-Mn-Cr-Nb rails.

Other authors found similar effects of niobium in rail steels or further results that are consistent with the experience gained so far. Some of them shall be mentioned to indicate the extent of the current knowledge regarding niobium in rail steels.

Hulka et al. (20) considered the metallurgical effects of niobium in eutectic rail steels (Fig. 7). Based on literature results they undertook mill trails where Grade 900 was microalloyed with niobium and finish rolled at various temperatures. This resulted in a slight increase in tensile strength and a marked improvement in toughness. The weldability remained unaffected.

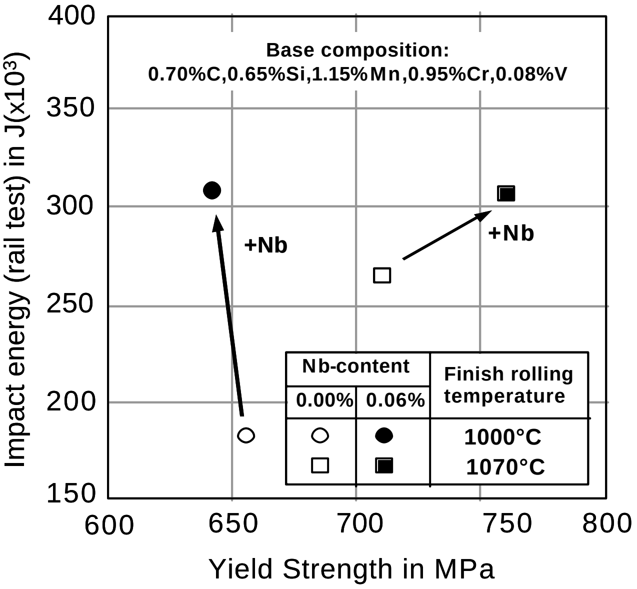

Figure 7: Influence of niobium addition on rail steel properties.

Laufer et al. (21) investigated the physical metallurgy of niobium- and V(C, N) precipitates in eutectic rail steels under various transformation conditions. They examined the influence of transformation speed on interlamellar spacing and characterized the precipitate size and distributions. Parsons et al. (22) modified two commercial rail steels (1%Cr and Cr-Nb steels) by additions of 0.1%V and nitrogen. The laboratory heats indicated an increase in yield strength providing acceptable ductility, fracture toughness and weldability. The addition of vanadium to the Cr-Nb steel showed no negative effect. The influence of microalloying niobium on fracture toughness and wear resistance of Mn-Cr-Nb rail steel was investigated by Singh et al. (23). They found improved rail properties through pearlite colony refinement and reduction of interlamellar spacing. There was an increase of about 40MPa in tensile strength without any deleterious effect on weldability. Suarez-Valdez (24) presented a detailed report about the testing of microalloyed rail steels with up to 0.06% Nb and up to 0.07% V. It was found possible to achieve more than 1080MPa in tensile strength with good ductility, elongation and reduction of area with a niobium and vanadium microalloyed pearlitic rail steel.

A very important contribution to niobium-bearing rail steels was the development of Niobras-200 in Brazil (25) where a rail steel with 0.75%C, 0.8%Si, 1.0%Mn and 0.02%Nb was designed. Here niobium acted as a grain refiner, which resulted in a fine pearlite colony size. Subsequently, the rails have improved mechanical properties and possess good weldability. Niobras-200 is a high strength rail steel with a tensile strength of about 1100 MPa. It was developed specifically to utilise Brazilian resources and has proven to be a great success in heavy haul iron ore service.

Improvement of Wear Resistance

Wear resistance of rail steel has been improved by the increase in strength through increases in the carbon content of rail steel. The CCT-diagram indicates that with lowering of transformation temperature the strength can be increased, and it is clear that transformation at about 600°C is necessary to achieve the required tensile strength of 1300MPa for heavy haul railroads. On the basis of this principle, two types of manufacturing processes have been applied to produce high strength pearlitic rail steels with fine lamellar spacing. One is to make the as-rolled high strength alloy steel rails whose hardenability is increased by the addition of alloying elements such as silicon, manganese, chromium, molybdenum and vanadium. The other is to make a eutectoid carbon steel rail whose head is hardened by reheating and accelerated cooling (slack quenching). Both of these strategies have been outlined earlier in this paper. Representative alloy steel rails and head-hardened carbon steel rails in Japan at the start of 1980's are listed in Table II.

Table II High strength alloyed steel rails and head hardened carbon steel rails

Steel		C	Si	Mn	Cr	Mo	V	Nb	0.2PS MPa	TS MPa	El. (%)	RE (%)
Std.C		0.80	0.20	0.90					510	920	11	18
As-rolled alloy steel	**Hi Si**	0.75	0.65	0.80					520	980	11	14
	Hi Si	0.75	0.90	1.40					565	1070	12	19
	Cr	0.75	0.25	0.65	1.15				650	1100	9	17
	Cr	0.75	0.35	1.25	1.15				690	1130	11	17
	Cr – Mo	0.75	0.20	0.80	0.75	0.16			800	1220	11	25
	Cr – V	0.75	0.30	1.30	0.80		0.12		740	1230	10	15
	Si – Cr	0.70	0.75	1.05	1.00				675	1140	12	20
	Si – Nb	0.70	0.80	1.20				0.03	705	1115	13	21
	Si – Cr – Nb	0.70	0.55	1.10	0.80			0.06	705	1140	10	16
	Si – Cr – V	0.65	0.60	1.05	1.15		0.20		680	1130	12	20
	Cr – Mo – V	0.65	0.30	0.80	1.00	0.10	0.10		705	1145	12	20
	Cr – Nb – V	0.60	0.10	1.30	0.50		0.06	0.04	640	1060	15	20
Heat treated carbon steel	**FH**	0.80	0.20	0.90					870	1220	13	30
	HH	0.76	0.20	0.80					910	1260	12	33
	HH (NHH)	0.75	0.20	0.85					880	1290	14	35
	FH	0.75	0.30	0.90					820	1250	14	40
	HH (HH)	0.65	0.20	0.90					830	1140	17	50

FH: Fully Hardened; HH: Head Hardened

The changes in pearlite transformation temperature in these two types of rails caused by changes in the cooling rate from the austenite region are schematically shown on the CCT diagram, Figure 8. To set the pearlite transformation temperature at about 600°C, slack quenching (cooling rate: 4~6°C/s) is required for the carbon steel rail, while natural air cooling (cooling rate: ~0.7°C/s) after hot rolling is sufficient for the alloy steel rail due to the high hardenability from alloying. These treatments could give the rails tensile strength higher than 1100MPa. Thus, at the beginning of the 1980's high strength wear resistant rails for heavy haul railroads appeared to be established.

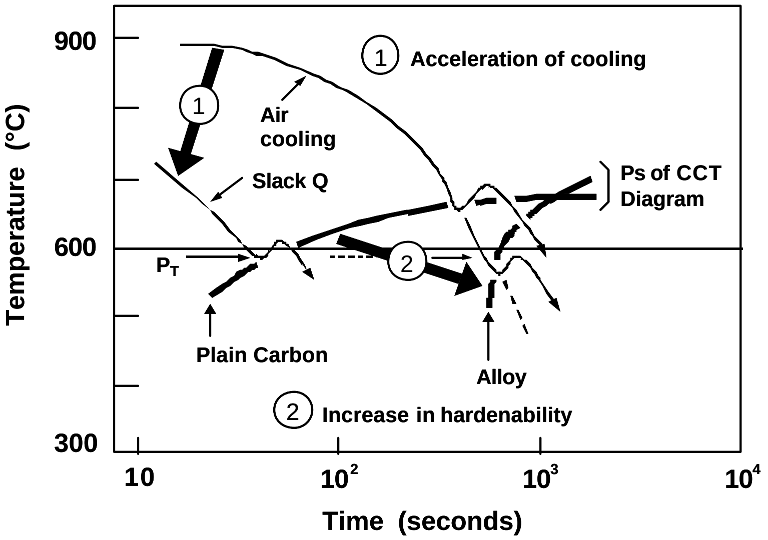

Figure 8: Pearlite transformation temperature of high strength rails depending on cooling rate and alloying content.

Improvement of Ductility

It has been established that the improvement in ductility is effective for the prevention of rail head damage due to plastic deformation. Therefore, the improvement in ductility of pearlite has been well established. The ductility of a pearlitic steel is determined by the pearlite colony size; a smaller size generating a higher ductility. In order to reduce the colony size, the austenite grain size must be refined before pearlite transformation. The relationship between austenite grain size (ASTM grain size No.) and reduction of area by tensile test of high strength rails is shown in Figure 9 (26).

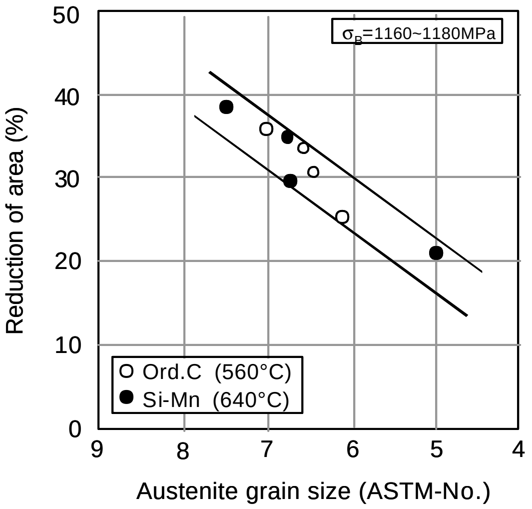

Figure 9: Relationship between reduction of area and austenite grain size (ASTM-No.) of rails with similar tensile strengths.

It is clear that the finer the austenite grain size, the higher the reduction of area. However, from a practical point of view, the improvement of ductility was not so much stressed as that of wear resistance. It should be noted that the improvement of strength by refinement of pearlite lamellar spacing and that of ductility by austenite grain refinement can be carried out separately (27).

Weldability

Most of the heavy haul railroads lay high strength rails as continuously welded rails joined by flash butt welding. With the extension in rail life, by improvement in wear resistance, damage at weld joints became more of a concern. The hardness distributions at the heat affected zone (HAZ) of flash butt welded joints of alloy steel rails and head-hardened carbon steel rails are shown in Figure 10 (28).

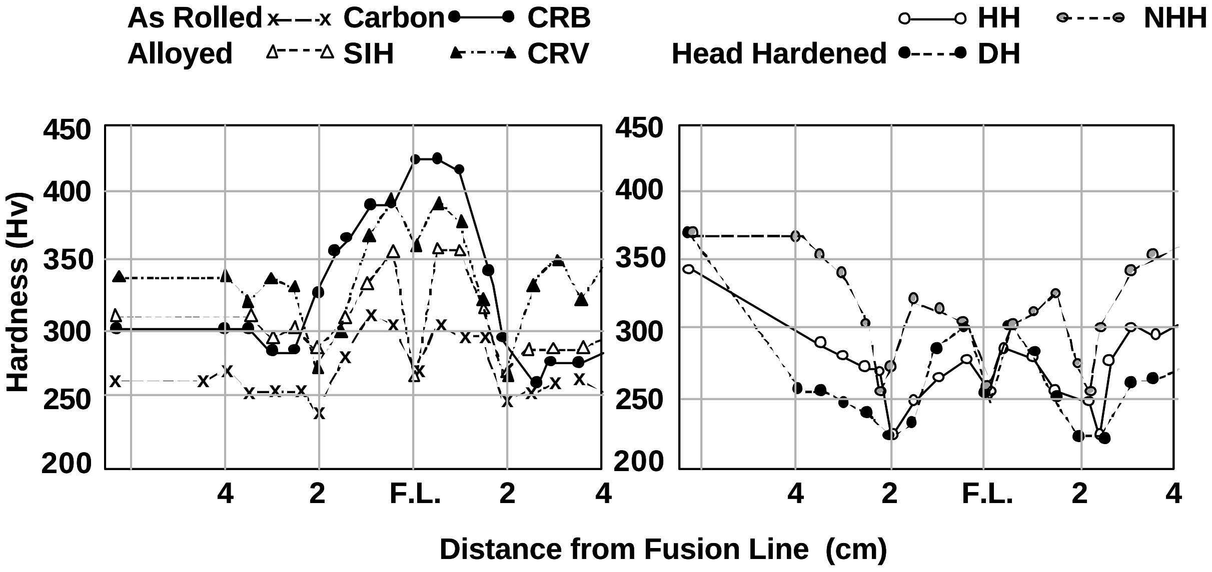

Figure 10: Hardness distributions at the HAZ of flash butt welded joints of high strength rails.

The hardness of the alloy steel rails rise up to HV400 in the presence of some brittle martensite, and those of the head hardened plain carbon steel rails drop rather low at the weld joints. It is these changes in hardness that have caused damage at the weld joints. The effect of cooling rate during welding on the pearlite transformation temperature at the weld joint is illustrated in Figure 11, together with that for a new alloy rail steel, which will be discussed later.

The cooling rate of flash butt welding (1~2°C/s) is higher than that of air cooling in still air after rolling and lower than that of slack quenching. Therefore, the pearlite transformation temperatures are different from those experienced in parent rail production. This difference has induced hardness changes at the HAZ of weld joints.

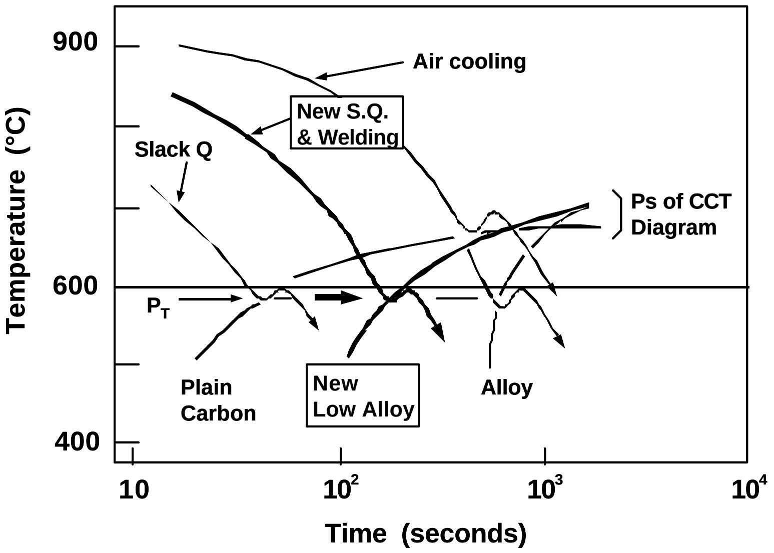

Figure 11: Effect of cooling rate during welding on the pearlite transformation temperature at the weld joint, and proposed pearlite transformation of a new low alloyed rail steel in production and welding.

Development of New Niobium Containing Low Alloy Head Hardened Rails.

To solve these problems Nippon Steel Corporation (NSC) developed a new process by which the head of a low alloy steel rail is hardened by suitable slack quenching (28). By this process, as shown in Figure 11, the chemical composition was designed so as to start the pearlite transformation at about 600°C during the cooling after flash butt welding to give a hardness of HV370. In rail production, the rail head was cooled after austenitising at the cooling rate equivalent to that of welding, thus allowing the pearlite transformation to start at about 600°C.

In total, two types of new low alloy steel rail chemical compositions were designed giving consideration to weldability as well as manufacturing procedures and costs (26, 29). Of the steels, one is a Si-Mn-Nb steel, NS-I, with a higher content of silicon and manganese than those of a normal carbon steel rail with a niobium addition. The other is a Si-Cr-Nb steel, NS-II, with higher silicon and chromium content, also with niobium addition. Chemical compositions and properties of these two rail steels are given in Table III (26). The hardenability of these steels is slightly greater than that of eutectoid carbon rail steel, but not so great as that of the alloy rail steel. The properties are as follows: 0.2% proof strength above 800MPa, tensile strength above 1250MPa, reduction of area above 35%, maximum hardness and martensite content at the HAZ above HV350 and below 5%, respectively. The purpose of the niobium additions is to refine the austenite grain size and increase the hardenability. Austenite grain refinement is effective for the prevention of rail head damage through the improvement of ductility. This improvement also favors the development of the rails for cold weather regions, which were specifically requested by the railroads in northern countries.

Table III Chemical compositions (in wt.%) and mechanical properties of as-rolled and heat treated rail steels of NS-I and NS-II

	C	Si	Mn	P	S	Cr	Nb
NS – I	0.76	0.84	1.24	0.023	0.009	--	0.006
NS - II	0.76	0.82	0.82	0.020	0.006	0.49	0.005

Rail Type	Heat Treatment	0.2% Proof Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of area (%)
NS – I	As rolled	608	1098	12	18
	Heat treated	873	1285	14	41
NS – II	As rolled	608	1127	14	19
	Heat treated	902	1324	19	50

From Table III the tensile strength of the head-hardened zone is approximately 1300MPa, and the reduction of area is remarkably improved, exceeding 40%. The austenite grain size (ASTM grain size No.) of the as rolled and rail head-hardened rails was measured by an ultrasonic device. Grain size change through a rail section is shown in Figure 12 compared with that of ordinary carbon rail steel (26). Even the as-rolled NS-II rail exhibits a finer grain size than that of the carbon rail steel, and the grain size becomes much finer by head hardening or reheating into the austenite region. These refinements are surely owing to niobium (NbC) and resulted in the improvement in ductility as mentioned above.

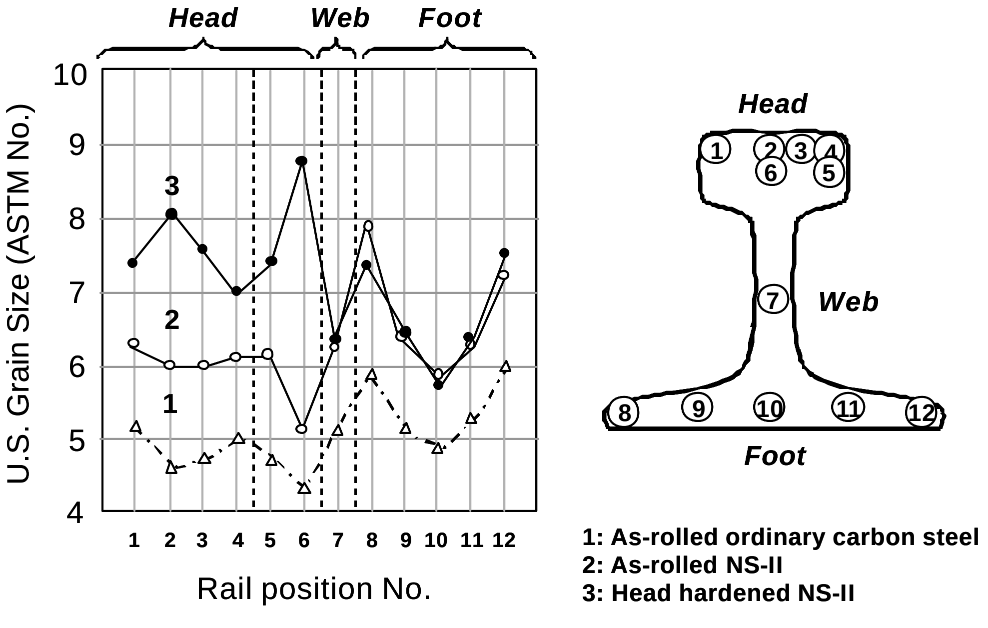

Figure 12: Ultra sonic grain size distribution in rail sections of ordinary C-steel & NS-II rails (26).

CCT diagrams of NS-I and NS-II are shown in Figure 13 (26). At the cooling rate equivalent to that of flash butt welding, pearlite transformation initiates at about 630°C and the resultant hardness achieves the aimed value of HV380.

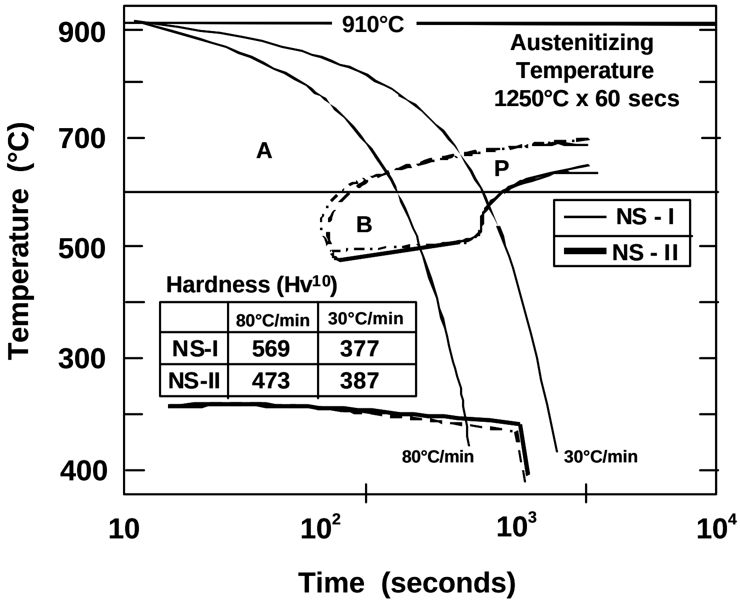

Figure 13: CCT diagrams of NS-I and NS-II rail steels.

The hardness distributions of flash butt weld joints are shown in Figure 14 (26). It is seen that the surface hardness change through the weld joint is smaller than that of ordinary high strength rails, and the HAZ hardness is kept at almost the same level as that of parent rail. The weld joint showed normal strength and fracture appearance in the bending test, and normal fatigue strength. Thus, it was successfully shown that these two new niobium-containing low alloy rail steels have better properties than those of the ordinary high strength rails.

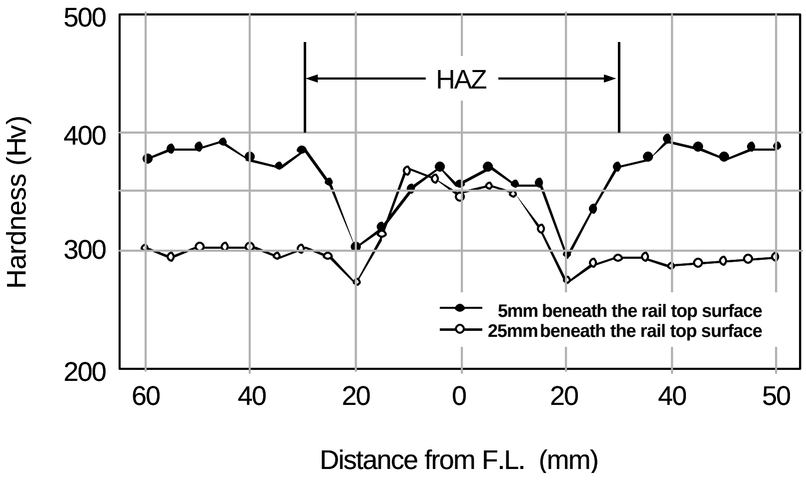

Figure 14: Hardness distributions on a longitudinal-vertical section of NS-II rail weld joint by flash butt welding.

The NS-II rail, including flash butt welded joints, were first offered to and installed on the FAST track (Facility for Accelerated Service Testing) of the Transportation Test Center (TTC) Department of Transportation (DOT, USA), in Pueblo, Colorado for the test of its performance in actual track. The test began in December 1979, in which NS-II was renamed SiCr(HH). The gauge face wear rates of the NS-II rail by running the tests without lubrication are shown in

Figure 15 together with the results of the other 10 test rails (30).

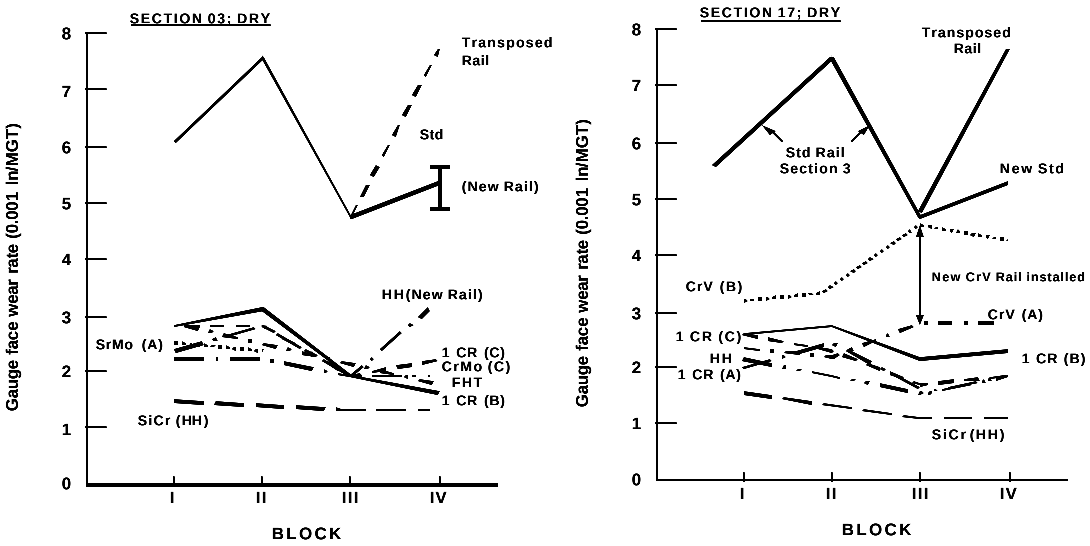

Figure 15: Comparison of gauge face wear rates of the test rails (30).

NS-II (SiCr(HH)) exhibited the lowest wear rates. The increases in the valley depth at the rail surface weld joint after traffic tonnage of about 160M gross ton are shown in Figure 16 (30). From Figure 16 NS-II is shown to have the smallest deformation at the weld joint. (Cr and CrV are the rails post heat treated after welding.) NS-II also exhibited the best performance against corrugation without grinding even after traffic tonnage of 35M gross ton (31). NS-II was finally recognized as the best rail among the rails examined due to its excellent wear resistance and good performance of weld joint without post weld heat treatment. The NS-II rail was widely used not only as the wear resistant rail with good weldability, but also a rail for use in cold climate countries such as Canada and Russia by virtue of its good ductility and toughness.

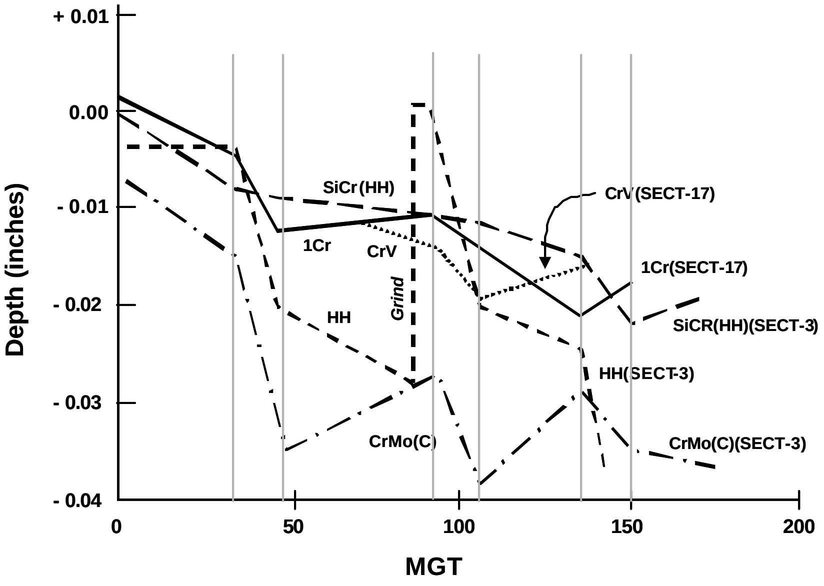

Figure 16: Comparison of the maximum valley depth at the weld joint of various rails.

Development of Niobium Containing Bainitic Rail Steels in Japan

The above-mentioned fine pearlitic rail steels, which were developed until the early 1980's possessed a tensile strength of 1300MPa and a hardness of HB370. These values were very high and reached the strength limit of a pearlitic structure. The wear resistance of outside rail has proved to be sufficient in practical use. However, with the extension of the rail life, rail surface damage by rolling contact fatigue came out as new challenge. In order to solve this new challenge, the applicability of a bainitic steel which has higher proof stress, ductility and fatigue strength than those of pearlitic steel was studied in Japan (32, 33). In the following, the experimental results on bainitic steels developed by NKK (Nippon Kokan) are summarized (34, 35, 36, 37).

The bainitic rail steel samples (0.20~0.55%C) were made from laboratory melts. For comparison, pearlitic rail steel samples (0.65~0.80%C) were also cut out of the head of commercially produced carbon steel rails. The range of the chemical compositions of both rail samples is listed in table IV (36).

Table IV Range of chemical compositions of steels studied (in wt.%)

	C	Si	Mn	Cr	Mo	Nb	V
Bainitic	0.20/0.55	0.40/0.45	0.40/2.10	0/2.0	0/2.0	0/0.15	0/0.1
Pearlitic	0.65/0.80	0.25/0.95	0.75/1.45	0/0.50	0	0	0/0.10

The tensile strengths of the bainitic steels were varied from 810 to 1430MPa by utilisation of chemical compositions within the range indicated in Table IV. In addition to manganese and chromium, niobium is also used as one of the strengthening elements to achieve the high strength. Niobium addition is considered to improve not only strength by precipitation hardening, but also toughness by microstructural refinement. In spite of a high tensile strength over 1300MPa, the bainitic steel had such good toughness that the absorbed energy of the u-notch Charpy impact test was twice of that of a pearlitic steel. The tensile strength of the pearlitic steel varied from 900 to 1300MPa by varying the alloy content and cooling rate after hot rolling. The properties investigated were wear resistance, fatigue strength, flaking resistance and shelling resistance.

Wear Resistance

The wear resistance of a bainitic steel with a tensile strength of 1400MPa is near to that of a pearlitic steel with a tensile strength of 1300MPa. The applied contact pressure of 1.4GPa was nearly equal to that experienced on the railroads in North America. The results indicated that the bainitic steel seemed to be a practical choice for heavy haul railroads.

Shelling Resistance

The initiation times for rolling contact fatigue damage (shelling) in high strength pearlitic and bainitic rail steels was measured by a Nishihara-type wear test machine with oil or water lubrication. The results obtained are plotted against tensile strength as shown in Figure 17 (34). The bainitic steel has a longer initiation time than that of pearlitic steel using both types of lubrication, and the initiation time is prolonged with an increase in tensile strength. The relationship between the initiation time and fatigue limit is quite similar (the fatigue limit at $2x10^6$ cycles is proportional to the proof stress irrespective of microstructure (34)).

The initiation time increases in proportion to the fatigue limit. This indicates that shelling initiates with plastic deformation of the surface, but resistance to shelling is predominantly decided by the fatigue limit in high strength rail steels.

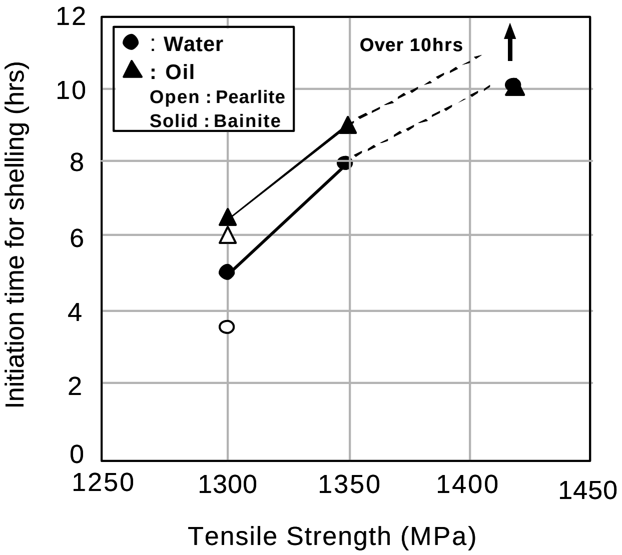

Figure 17: Relationship between tensile strength and initiation time for shelling.

It is the white layer on the rail surface which largely influences the initiation of shelling. The white layer is thought to be martensite resulting from rapidly cooled austenite formed by the temperature rise caused by slipping between wheel and rail. The rolling contact test machine was used to measure the thickness and hardness of the white layer on the contact surface. The relationship between carbon content and the white layer thickness is shown in Figure 18 (37).

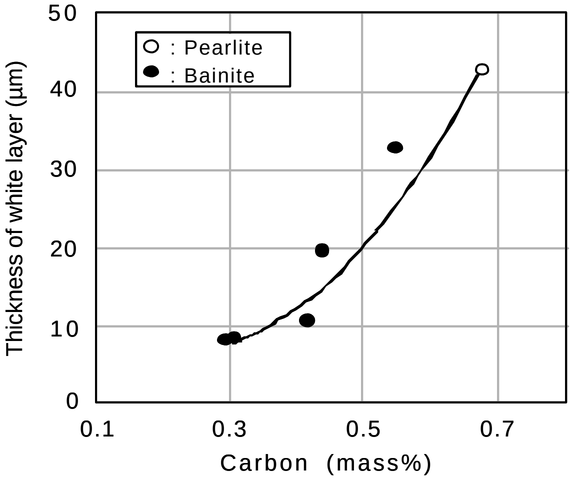

Figure 18: Relationship between C content and thickness of the white layer.

The bainitic steel with a relatively low carbon content shows reduced thickness compared to a pearlitic steel with high carbon content. This is owing to the fact that a bainitic steel has a higher Ac_3 point than a pearlitic steel due to its lower carbon content. As a result, bainite has smaller content of austenite and thinner white layer than pearlite at the same heat input caused by slipping. Additionally, the hardness of the martensitic white layer decreases with a decrease in carbon content (37). Therefore, bainitic steels with low carbon content are more resistant to the initiation of shelling.

The initiation time for shelling among various rail steels is compared in Figure 19 (37). The bainitic steels exhibit a longer initiation time than the pearlitic steels. It should be noted that the low strength bainitic steel with tensile strength of 850MPa shows a very long initiation time. This is due to the removal of surface cracking by wear, with 2 to 3 times higher wear rate than the others.

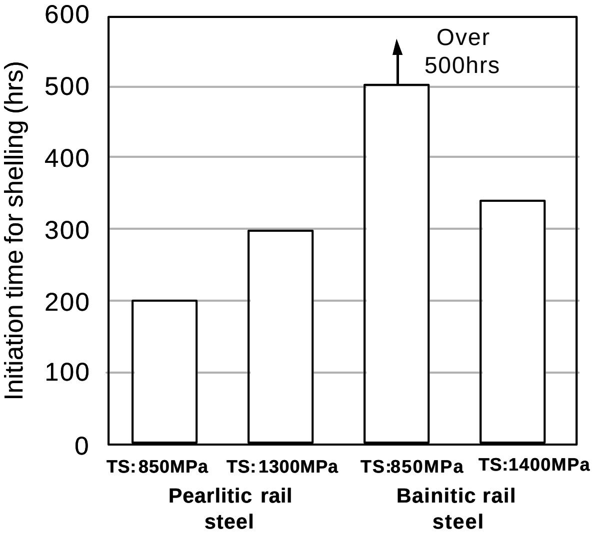

Figure 19: Initiation time for shelling in pearlitic and bainitic steels with various strength levels.

The effect of attack angle on the initiation of shelling was examined by a newly developed rolling–contact fatigue test machine under oil lubrication with the change of contact load and rolling speed. Carbon contents of pearlitic steel specimens ranged from 0.65~0.80%, and bainitic steel specimens contained such alloying elements as chromium, molybdenum, niobium and vanadium and half the carbon content of pearlitic steels. The Mechanical properties of the test steels are listed in Table V (38).

Table V Mechanical properties of steels studied

Code	Type of microstructure	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (Hv)
P1	Pearlite	401	855	15.3	270
P2	Pearlite	900	1303	13.3	390
P3	Bainite	645	823	19.6	270
P4	Bainite	1079	1421	14.0	420

Initiation time for shelling was detected by the vibration test machine and specimen surface inspection. Microstructures on the cross-section and hardness were examined simultaneously with the initiation, and work hardening, plastic deformation and crack behaviour were also investigated. The relationship between shelling initiation time and attack angle is shown in Figure 20 (38). Initiation time is reduced with an increase in attack angle, especially between 1 to 3 degrees.

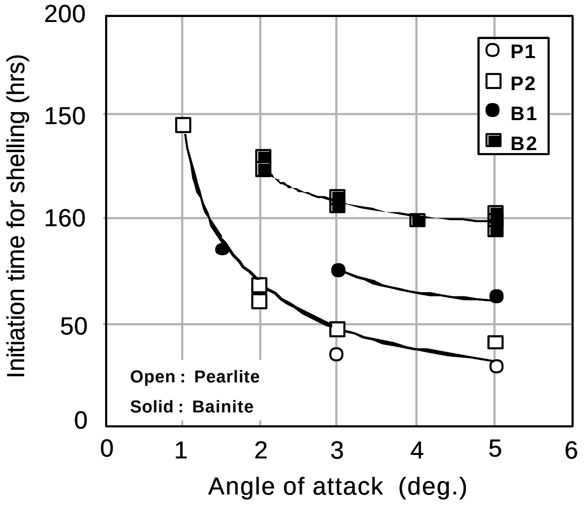

Figure 20: Effect of the attack angle on the life span before shelling.

However, wear is increased by a greater attack angle, and a bainitic steel shows more weight loss than that of a pearlitic steel. This difference brought about the above mentioned removal of surface damage by wear and resulted in the extension of the shelling initiation time of bainite. The retardation of initiation to shelling of bainite is also owing to its high fatigue strength and lack of such anisotropy due to a lamellar structure as that of pearlite.

On the basis of these fundamental investigations, the high strength bainitic rail with 0.35% carbon was produced on a commercial scale, and its characteristics were examined and compared with those of an ordinary high strength pearlitic steel rail (35, 36). The mechanical properties are given in Table VI (35).

Table VI Typical mechanical properties of developed bainitic steel rail.

	Tensile Strength (MPa)	**Tensile Elongation (%)**	**Fracture Toughness K_{IC} (MPam$^{1/2}$)**	**Absorbed energy: u-notch Charpy test (20°C) (J)**	**Fatigue Strength (MPa)**	**Wear (g/2h)**
The developed bainitic steel rail	1420	15.5	98	39	870	0.77
The premium pearlitic steel rail	1300	13.5	43	20	750	0.76

The resulting bainitic rail steel has a high tensile strength of 1420MPa, and a large elongation. Both fracture toughness and absorbed energy by u-notch Charpy impact test are twice as high as those of head-hardened pearlitic rails. Wear resistance is nearly the same as head-hardened pearlitic rails. Very long life span before shelling, about twice as long as those of head-hardened pearlitic rails, was also observed supporting the results obtained in laboratory scale tests (35). The developed bainitic rail is expected to exhibit excellent performance in heavy haul railroads.

Summary and Conclusion

In Japan, two types of new high strength niobium containing rail steels have been developed with improved performance. One type is a head-hardened low alloy rail steel which has a fully pearlitic microstructure with narrow lamellae spacing and a small pearlite colony size developed via a fine austenite grain size. Additions of niobium not only contributed to improvements in wear resistance and weldability, but also to ductility and toughness which enabled this rail to be successfully used in cold environments. The rail exhibited excellent performance in a test track. The other rail steel is a medium carbon bainitic steel in which niobium improved the strength and resistance against head checking and shelling (initiation of rail surface damage). This rail is also expected to show good performance in actual track service.

A significant advantage of niobium additions to rail steels relates to modern rail manufacturing, especially to the inline head hardening of rails. As long as only offline head hardening was available, only small quantities for special purposes could be treated. However, the capacity of an inline process offers the possibility of treating the rolling capacity of standard grades.

The head hardening of the Grade 900 rail steel leads to the special Grade HH 1100. Today it is possible to treat Grade 700 rails to produce standard HH 900 rails, which have superior toughness. The main role of niobium in rail steels that are head hardened by an inline process is the grain refinement of austenite and the prevention of grain growth during rolling. This means a conditioning of the austenitic state which the offline process achieves through the reheating of the rail head. Thus, austenite grain conditioning by niobium will ease the need for inline heat treatment with regard to consistency. The effect of niobium will consistently provide a fine austenite grain size at the start of the head hardening treatment even with a fairly wide range in the production parameters of time and temperature, thus, leading to consistently good mechanical properties. Even with some scatter in the processing conditions the mechanical properties are expected to stay within a narrow range due to the metallurgical influence of niobium. Therefore, the final message points to the fact that even if there is no stringent need to increase the mechanical properties of rail steels there remains the central idea of quality management, that of keeping the product tolerances narrow (39). This is a role provided by niobium to support the steelmaker and consequently be of benefit to the customer.

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