

# Head-Hardened Rails Produced from Rolling Heat

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A process was developed by which rails are cooled immediately from the rolling heat in such a way that the fine pearlitic structure essential for optimum wear properties is achieved in practically the whole area of the head. Discussed are manufacturing parameters for heat treatment directly from rolling heat; criteria for the selection of rail qualities; structure, mechanical properties, and wear resistance results obtained during service; and production and inspection.

To enable faster rail transport of heavier loads at shorter service intervals, the use of rails with better wear resistance is of great importance. There has been a continuous tendency in the development of rails toward increasing the wear resistance. This is based on the knowledge that the wear resistance of rails with natural mill hardness is directly related to their strength. Substantially higher strength values than 1100 MPa are not attainable in rails with natural mill hardness because they are required to have a pearlitic structure in all their parts and the formation of martensite must be avoided under all circumstances. In the case of alloyed rails the chemical composition of the steel must be adjusted so that during self-cooling of the rail on the cooling bed no martensite is formed, not even in the web and the base of the rails. Therefore, a limitation exists in the strength attainable in this manner in the rail head.

A different approach to develop a higher strength in a comparatively low-alloyed steel has been reached by accelerated cooling from the austenitic range. Because such processes make it possible to perform accelerated cooling, especially in the rail head, an optimum combination of alloy composition and cooling rate can be adjusted, whereby strength levels of 1200 MPa can be obtained in the rail head. Attention must be paid to achieve these high strength levels by a fine pearlitic structure, because a fine pearlitic structure has a considerably higher resistance to wear than a quenched-and-tempered structure of equal strength. This applies in particular to abrasive wear in sharp curves under a high specific load per unit area.

From the metallurgical point of view this behavior is easy to understand. A quenched-and-tempered structure consists of ferrite with embedded, comparatively short, needlelike cementite, whereas the fine pearlitic structure consists of ferrite and cementite plates arranged in layers. If abrasion occurs, the cementite plates of the fine pearlite structure are far more resistant than the isolated cementite precipitations of the quenched-and-tempered structure.

There are in principle two different alternatives for adjusting a fine pearlitic structure in the rail head: by a process in which heat treatment of the rails takes place directly from the rolling temperature or one in which the rail, after normal rolling and cooling on the cooling bed, is reheated and subsequently subjected to accelerated cooling. Suitable coolants are hot water, compressed air, a water-air mixture, and water with synthetic additives. Therefore, in all cases a fine pearlitic structure, rather than a heat-treated structure (which is achieved by quenching and subsequent tempering), is the aim for a rail head. In spite of this fact, the term head-hardened rails is generally used for this product.

## HEAT TREATMENT FROM ROLLING TEMPERATURE

Currently, head-hardened rails are generally manufactured by using an additional heat treatment. After reheating the head of rail—usually by induction heating—accelerated cooling is used with a mixture of water and air. By this process, in principle, good results are achieved with regard to structure, strength, and wear characteristics.

For economical reasons, however, a heat treatment directly from the rolling temperature is preferred. The authors have therefore worked intensively on the development of an appropriate technique, for which the prescribed requirements were as follows:

- Heat treatment of the rails shall take place directly from the rolling temperature without causing pollution.
- A fine pearlitic structure shall be obtained, as far as possible, in the entire head area, but at least over a depth of 20 mm.
- The coolant shall have a homogeneous effect over the entire length of the rails, remaining unaffected by contaminations of the installation; it shall not be toxic or flammable.
- The chemical composition of the rail material shall be adjusted to ensure perfect weldability.

Starting from these requirements, first of all, a suitable quenching medium was obtained. Water with synthetic additives was selected. The medium is a high-polymeric compound used in hardening practice. As a result of this synthetic coolant admixture, a layer was formed on the rail and rail head that diminishes the cooling intensity with respect to water. The layer is of uniform thickness and remains unimpaired during heat treatment. It allows uniform cooling across the entire surface and over the entire length of rail and rail head.

TABLE 1 ALLOY COMPOSITION OF RAIL GRADES

Grade	Chemical Composition (Weight -%)						
	C	Si	Mn	Cr	Ni	Mo	Al
S900A <sup>a</sup>	0.60	0.10	0.80	n.s.	n.s.	n.s.	n.s.
	0.80	0.50	1.30				
S1100 <sup>a</sup>	0.60	0.30	0.80	n.s.	n.s.	n.s.	n.s.
	0.82	0.90	1.30				
≥ 286 BHN Standard Carbon <sup>b</sup>	0.72	0.10	0.80	n.s.	n.s.	n.s.	n.s.
	0.82	0.50	1.10				
≥ 341 BHN High Strength <sup>b</sup>	0.72	0.10	0.80	max	max	max	n.s.
	0.82	0.50	1.25				
HSH <sup>c</sup>	0.77	0.20	1.12	max	max	max	max
	0.79	0.30	1.20				

<sup>a</sup> Specification according to UIC860V

<sup>b</sup> Specification according to AREA

<sup>c</sup> Interne VOEST-ALPINE Specification

n.s.: not specified

The rail steel selection has to guarantee the perfect weldability as an essential condition. Of course, all rail grades presently in use can be welded. Nevertheless, it is necessary to weld alloyed grades, especially Grade S1100, with relatively expensive and time-consuming measures (e.g., intense pre-heating and postweld heat treatment.) Otherwise, martensite formation at the coarse grain boundaries is to be expected after subsequent cooling. For this reason, the heat treatment process was based on the unalloyed UIC Grade 900A. Table 1 presents the chemical composition of Grades S1100 and S900A due to UIC 860-V and AREA steel grades and for comparison the upper and lower limits of the most important elements of the steel for the head-hardened rails.

These head special hardened (HSH) rails correspond entirely to Grade 900A; only the concentrations of C and Mn are placed in the upper region of the allowed scatterband.

## PROPERTIES OF HEAT TREATED RAILS

The head areas of the rails heat treated by this process showed a fine pearlitic structure without amounts of ferrite, bainite, and martensite. In the area of head-to-web interface, the structure constantly changes to the usual basic pearlitic structure, which is characteristic of UIC Grade A rails after cooling on the cooling bed.

The hardness obtained in the rail-head is shown in Figure 1. The lines of hardness measurements have been executed vertically from the rail top surface, which is exposed to the

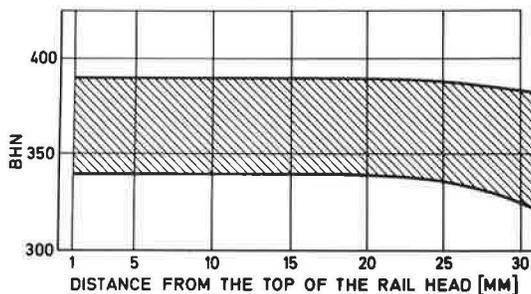


FIGURE 1 Hardness scatterband (measurements executed vertically from the top of the rail head).

highest stresses. All hardness values obtained from the HSH rails are positioned between the lower and upper lines in Figure 1. A minimum hardness of 341 Brinell hardness number (BHN) was guaranteed on the running surface. Figure 2 shows a probability plot of hardness values on the running surface, obtained during production series in 1990 for profile UIC 60 and AREA 136.

The minimum hardness of 351 BHN, which is required occasionally by some railway companies, was reached in a number of cases, but the authors are convinced that there will not be ill effects in case of a hardness scatterband on the surface down to 341 BHN.

In addition to dry abrasion wear, one of the most frequent results of wear is the shelling phenomenon, as a result of high axle loads, with subsequent overflow in the flow-stress in deeper parts of the rail head. Therefore, the most important property of a hardness curve should be securing constant high hardness values also in deeper areas of the rail head (Figure 3). The head top and lateral wheel contacts in daily traffic leads to rail shapes with lower heights and partially extreme lateral wear effects. So, these maximum stress-flow areas could reach depths of approximately 20 to 25 mm related to the original rail head profile.

An investigation of newer head hardening techniques revealed that various rail manufacturers all over the world offer deep-head-hardening with high hardness values as a big advantage in regard to service life. A comparison of the hardness curves in Figure 4 reveals similar properties in the deeper rail head regions for this purpose and comparable techniques of other firms. Additionally, there should be an advantage in the properties of the HSH rails discussed here because this hardness distribution was reached with a steel of Grade S900A according to UIC code, which is an unalloyed steel.

Furthermore, one can see in Figure 4 that head-hardened rails produced by off-line treatment show comparatively high hardness values in the surface area, but hardness decreases

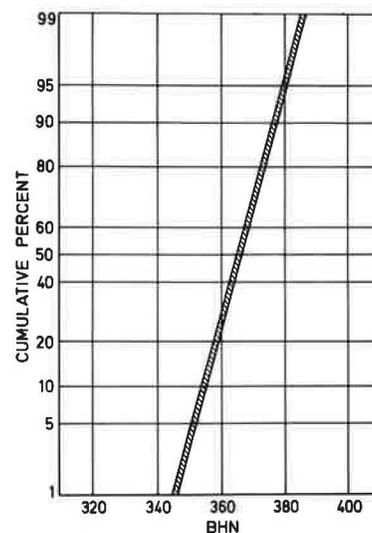
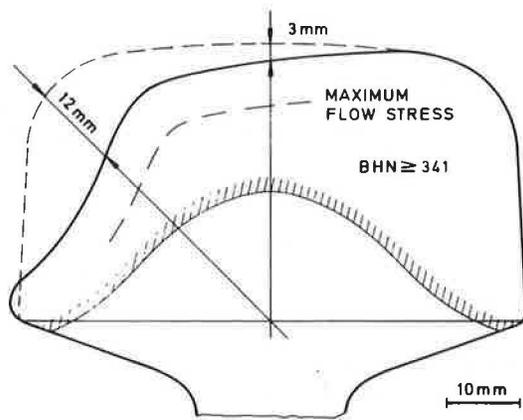


FIGURE 2 Probability plot of hardness on the top of the rail head: production series in June 1990, profiles UIC 60 and AREA 136.

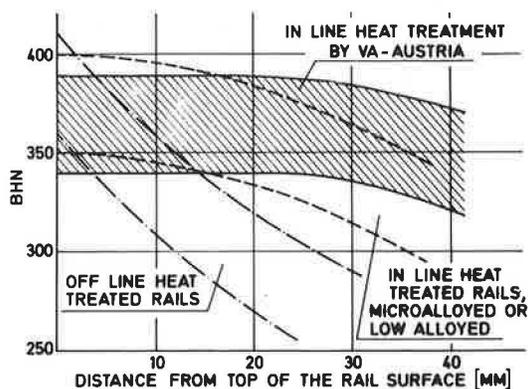


**FIGURE 3** Need of an even hardness distribution in the rail head because of the maximum possible wear profile.

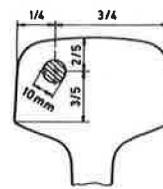
with a steep gradient toward the inner area of the rail head. Such rails would cause more problems in the stage of reaching these deeper regions caused by wear. Of course, the position of this hardness scatterband is dependent on the amount of heat, which is transferred into the rail head during heat treatment. More energy will produce deeper austenitic areas; the hardness curves will become more and more similar to those reached by in-line treatment. Nevertheless it is clear that such treatments will be more expensive and therefore perhaps uneconomical.

High-level hardness values that are constant down to deep rail head areas basically correspond with the different kinds of strength values. The strength values are determined on tensile test specimens taken in accordance with UIC specification. The required position of these test specimens is shown in Figure 5. On the basis of the HSH rails with a deep hardness-influence zone it is not necessary to choose special forms of tensile specimens which are normally only taken from rail surface areas and not for inner head controls. The following minimum values were obtained:

Tensile strength:  $R_m = 1170$  MPa minimum,  
 Yield strength:  $R_{p0.2} = 770$  MPa minimum, and  
 Elongation:  $A_5 = 9.5$  percent minimum.



**FIGURE 4** Comparison of hardness curves for in-line and off-line heat-treated rails.



	$R_m$ [MPa] min.	$R_{p0.2}$ [MPa] min.	$A_5$ [%] min.
HEAD	1170	770	9,5
WEB/ BASE	680	—	10

**FIGURE 5** Position of tensile specimen according to UIC 860-V and minimum strength values of HSH rails.

The properties of the untreated parts of the rail (web and base) meet from all viewpoints the conditions according to UIC for the Grade 900A.

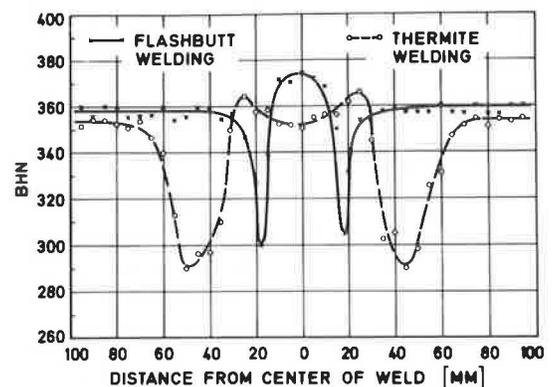
To test the toughness characteristics, drop tests were carried out in accordance with UIC specifications. All rails tested have met the specified requirement of withstanding one blow without breaking. In each case, fracture occurred only after two or more blows.

The welding behavior of the rails heat treated by this process also was tested. Tests were conducted with both flashbutt welding and Thermit welding. Welding was carried out in the usual way for UIC Grade A rails. However, after welding, the weld area was rapidly cooled to about 500°C by compressed air, thereby obtaining a favorable hardness variation in the weld area (Figure 6). In the middle of the welded joint, a fine pearlitic structure was observed, and the amount of martensite in all cases was definitely below 1 percent.

Some welding companies recently developed the use of special mixtures for Thermit welding to meet the hardness conditions in the welding area without the necessity of accelerated cooling of the welding joint after welding. The heat affected area is also diminished reasonably by this treatment. Head-hardened rails manufactured by our process can therefore be welded without difficulty.

**WEAR CHARACTERISTICS**

Of special importance, of course, was the testing of wear characteristics. It is realized that only results obtained during service provide final information in this respect. On the basis



**FIGURE 6** Hardness curve in the weld zone of head-hardened rails.

of a great number of wear tests on rails of various strength levels carried out over a long period of time, it is possible to obtain valuable information even from laboratory tests. The tests are abrasion tests (rolling and sliding friction) in which the behavior of rail steel is compared with an ordinary wheelsteel.

There exists a safe correlation between the resistance to wear and tensile strength, respectively hardness, for the common rail steels. The rails heat treated by this process fit in well with this correlation (Figure 7). Therefore, definitely better wear characteristics can be expected from them than from the highly wear-resistant qualities (e.g., S1100) that have been in common use until now.

These results were confirmed by tests in the rolling mill. In a pilot, plant rails up to lengths of 120 ft were heat treated. In each case the rails were taken from a normal rolling of UIC Grade 900A, section UIC 54 E.

In Switzerland these rails were employed in the construction of the outer part of a curve of a radius of about 900 ft on the St. Gotthard line in the valley track section. The curve is lubricated. The line load amounts to 59,000 gross tons per day. Because the lateral surface is exposed to heavy wear, it is necessary to use special rails (at present highly wear-resistant CrMn rails, Grade S1100) for this section of the track.

Figure 8 shows that the lateral wear of a rail in Grade S1100 already amounts to 8.5 mm after having been subjected to a total load of 38 MGT; at this time the rail was taken off the track. The HSH rail was built in at exactly at the same location. Recently this HSH rail was taken off with a lateral wear of 10 mm after a total load of 89 MGT; this corresponds to a wear rate of 22.4 mm/100 MGT for the S1100 rail and 11.2 mm/100 MGT for HSH rails. On this basis one can expect that the HSH rails approximately double the service life of UIC Grade S1100 rails.

The results were confirmed by a significantly different test run. In the Switzerland tests, abrasion was the dominant kind of wear. The tests in the special test track of Stscherbinka in

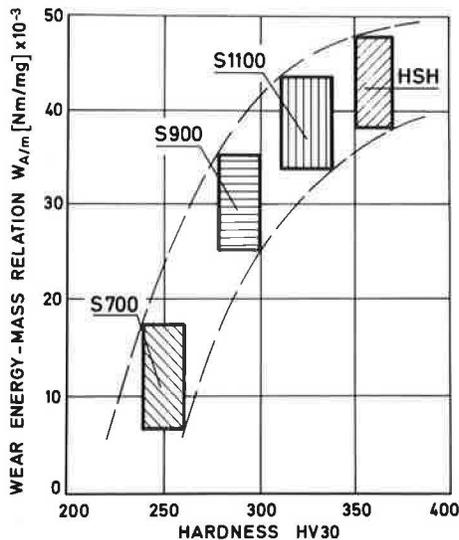


FIGURE 7 Rolling-sliding wear of rail material.

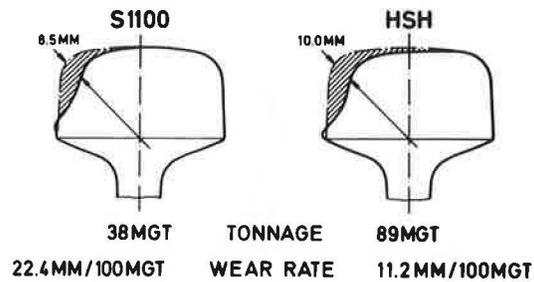


FIGURE 8 Wear of rails S1100 and HSH.

the Soviet Union were executed to receive clear results of the fatigue behavior of the HSH rails. The test was performed on a circular test track that is subjected to a monthly load of approximately 30 MGT with axle loads of 27 tons. Rail wear is only noted to a negligible extent because of heavy lubrication. Therefore, fractures of the running edges as a result of internal defects were the dominant kind of wear. These tests demonstrated that the behavior of HSH rails was by at least the factor 1.6 more favorable than rails of Grade S1100.

#### MANUFACTURE AND TESTING OF RAILS

The rail steel discussed here was manufactured by means of the basic oxygen furnace process. Before casting in a three-strand-bloom-caster, a vacuum treatment in an RH installation is carried out, thus ensuring that a hydrogen content well below a maximum of 2.5 ppm can be maintained. This practically excludes the appearance of flakes. Furthermore, this installation makes it possible that the deoxidation is carried out in such a way that the Al content is no more than 0.004 percent and the steel cleanliness (concerning the contents of aluminates) can be improved considerably.

The heat treatment of the rails was carried out on a new installation that was put into operation early 1990 together with a new flow line finishing shop. It was designed in such a way that the whole strand up to a length of 400 ft can be heat treated. The strand is automatically dipped into the cooling bath immediately after the last rail mill pass. The position of the rail in the bath is schematically shown in Figure 9.

The depth of immersion is adjusted so that the level of the bath reaches to edge of the head-web interface. This prevents the thinner area of the web from being cooled too drastically, which could lead to the formation of bainite and martensite.

Apart from tee rails, crane rails and special rail sections for turnouts can be heat treated on this installation. In the case of these special sections, the depth of immersion is changed, thus obtaining a fine pearlitic and consequently highly wear-resistant structure in all areas important for the special intended use.

After an immersion time of approximately 2.5 min the entire 400 ft rail is automatically transferred to a walking beam type cooling bed. From there the cooled rail passes through a roller-straightening machine. As again the whole strand is straightened in one piece, the proportion of unstraightened ends without output loss is reduced, and a rail strand with constant height over its total length is maintained. The rails are cut to lengths of no more than 200 ft after straightening

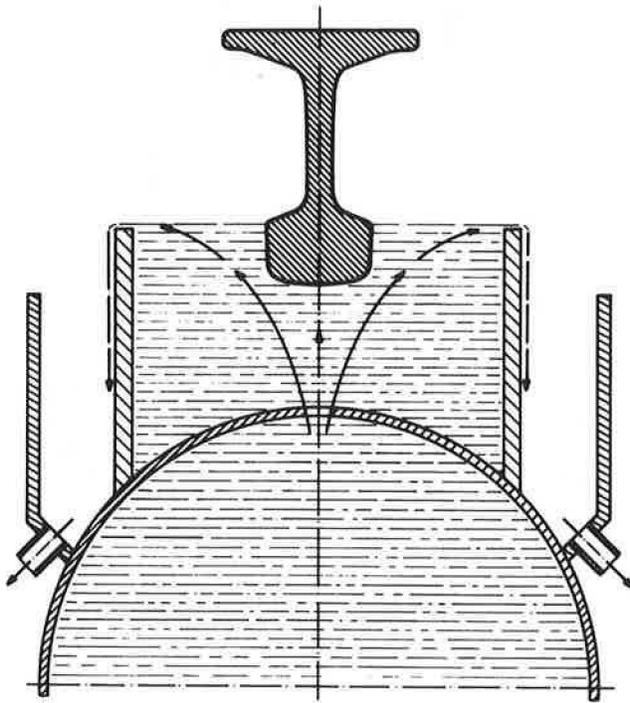


FIGURE 9 Position of the rail in bath.

with a high-performance saw equipped with hard alloy saw teeth.

After straightening, each rail is tested for internal defects in the head and web in a testing center with automatic ultrasonic equipment. The ultrasonic equipment is currently furnished with 6 probes that ensure that all critical areas of the rail cross section are scrutinized.

The measurement of the running surface straightness is executed without contact by 4 laser measuring probes. The results from these probes are evaluated according to the traveling fiber principle, and the values obtained for the total

length of the rails are printed in tabular as well as graphic form in test certificates.

## SUMMARY

Today head-hardened rails are used in tracks subjected to maximum stress. These rails are generally manufactured by induction heating of the rail head with subsequent accelerated cooling. In the opinion of the authors, this process has technical and, above all, economical disadvantages. Therefore, the authors developed a process by which rails of Grade 900A according to UIC 860-V are cooled down immediately from the rolling heat in such a way that the fine pearlitic structure essential for optimum wear properties is achieved in practically the whole area of the head. The heads of these rails have a minimum hardness of 341 BHN to a minimum depth of 20 mm. The web and base have a pearlitic structure typical of Grade 900A after normal cooling. For mechanical properties the rails fully correspond in these areas to the requirements of UIC 860-V for Grade 900A. Because they also comply with this grade in its chemical composition, the rails head hardened according to this technique can be welded without problems. To achieve an optimum structural shape, only the welded area must be cooled down with compressed air to approximately 500°C immediately after welding.

Results of comprehensive laboratory tests revealed that these rails have a wear behavior that is distinctly better than that of the common highly wear-resistant alloy Grade 1100. Field tests confirmed this favorable behavior of rails heat treated according to the procedure discussed here. This is why an automated plant was built and put into operation early in 1990 that permits heat treatment of rails up to 400 ft long. Together with the new flow line finishing shop, which was activated at the same time, head-hardened rails 200 ft long can be supplied. Because these rails are heat treated according to a special process and have especially favorable service properties, they are called HSH rails.

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