

Pearlitic Interlamellar Spacing as a Tool for Evaluating Hot-Forged R260 Steel Frog Points

Małgorzata OSTROMEŃKA¹

Summary

The article presents an analysis of the usefulness of measuring pearlite interlamellar spacing in R260 steel frog points as a tool supporting the assessment of hot forging quality. The study was conducted using a digital light microscope. The work discusses the relationship between pearlite morphology and mechanical properties, highlighting the importance of quantitative microstructural evaluation in the context of technological process control of frog points.

Keywords: R260 steel, pearlite, interlamellar spacing, light microscopy, hardness, hot forging

1. Introduction

Grade R260 rail steels belong to the group of carbon pearlitic steels and are widely used in railway structures due to a favourable combination of strength, hardness, and wear resistance [1]. Rail infrastructure components, such as transition rails and frog point sections, are manufactured in a hot forging process involving intensive plastic deformation within the austenitic temperature range and controlled cooling after the completion of deformation. The parameters of this process, particularly the forging temperature, the degree of deformation, and the cooling conditions, significantly determine the final microstructure, its homogeneity, and the mechanical properties of the material, which directly affect the service life of track components [1, 15].

In the qualification practice for frog points and transition rails, direct microstructural evaluation is not routinely required. Hardness measurements, performed on the running surface, the foot and, in the case of frog points, also on cross-sections [14], are the primary tool for verifying compliance with the requirements of the PN-EN 16273 standard [14]. The obtained hardness values allow for the assessment of material homogeneity, the identification of local zones with altered mechanical properties, and an indirect evaluation of the correctness of the technological process, including thermomechanical processing.

At the same time, it is widely known that the hard-

ness of pearlitic steels is directly linked to microstructural features, particularly the pearlite interlamellar spacing, which depends on the pearlite transformation conditions after the completion of plastic deformation [1, 4, 18]. Changes in this parameter affect strengthening mechanisms and wear resistance, and its value is sometimes used as an indicator of cooling intensity and microstructural homogeneity after thermomechanical processing [15, 18].

From a classical metallographic perspective, microstructural analysis is the basis for interpreting the mechanical properties of steel products [1]. For track components, however, this approach is often limited to indirect testing, namely hardness testing, due to technological and organisational reasons. Consequently, it is reasonable to consider whether quantitative measurements of pearlite interlamellar spacing, performed using light microscopy (which is significantly more accessible than scanning or transmission electron microscopy), can serve as a supplementary tool for assessing the correctness of the hot forging process and the predictability of the mechanical properties of R260 steel, while maintaining compliance with standard requirements regarding hardness [4, 14, 16].

The aim of this article is therefore to analyse the usefulness of pearlite interlamellar spacing measurements as a microstructural parameter supporting the quality assessment of the manufacturing process for frog points made of R260 steel, in relation to standard hardness tests and normative criteria.

¹ Ph.D. Eng.; Railway Research Institute, Materials & Structure Laboratory; e-mail: mostromecka@ikolej.pl.

2. Pearlite – theoretical introduction

To properly evaluate the mechanical properties of track steels, it is essential to understand the pearlite microstructure, its structure, and the parameters determining the hardness and strength of the material. Pearlite is a eutectoid microstructure in carbon steels, composed of alternating lamellae of ferrite and cementite, forming colonies with varied crystallographic orientation. The key parameters shaping the properties of pearlitic steels are the interlamellar spacing (λ), colony size, and prior austenite grain size, which significantly determine the hardness, strength, and wear resistance of track components [1]. The lamellar structure of pearlite is illustrated in Figure 1 [19].

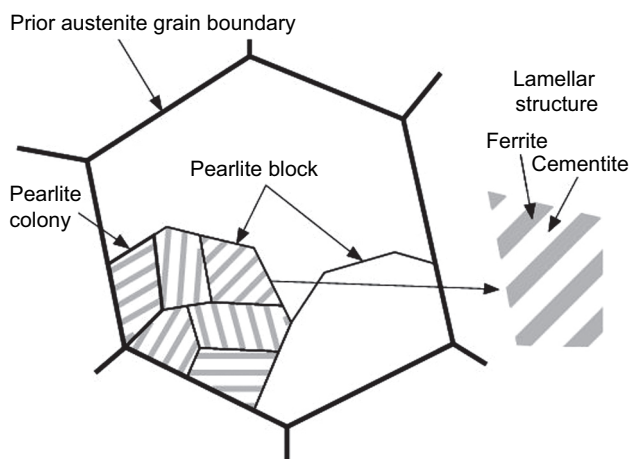


Fig. 1. Schematic of pearlitic steel microstructure [19]

Pearlite morphology largely depends on the kinetic conditions of austenite transformation during cooling [10]. At lower transformation temperatures and faster cooling rates, finer lamellae with smaller interlamellar spacing are formed, which is associated with an increase in the hardness and strength of the steel [1, 4, 11, 15]. The interlamellar spacing λ is strongly correlated with hardness: a larger λ indicates a wider distribution of cementite lamellae, which weakens the blocking of dislocation movement and leads to lower hardness [1].

Although the chemical composition of the steel, particularly the carbon content, influences the cementite fraction, in near-eutectoid steels, the main factor shaping mechanical properties remains the pearlite geometry rather than slight differences in composition [8]. Thermomechanical processing has a significant impact on the interlamellar spacing λ and colony size: the deformation of austenite increases dislocation density and alters nucleation conditions, which, with appropriate cooling, leads to a finer pearlite morphology and improved mechanical properties [8, 13]. In the forging process of track components,

three stages are key: austenitisation, deformation, and controlled cooling. Proper selection of parameters allows for a homogeneous pearlite with a low λ value to be obtained, while non-optimal conditions result in the formation of areas with coarser pearlite and reduced hardness [8].

Due to the nanoscale nature of the lamellae, reliable measurement of the spacing between them (λ) requires high-resolution techniques such as SEM, TEM, or 3D stereology [3, 4, 7] (Fig. 2). Classical light microscopy, with its limited resolution, primarily allows for the identification of pearlite colonies, whereas the precise determination of λ is only possible locally, in areas with coarser lamellar morphology. The use of KEYENCE digital microscopy at magnifications of 1000x and above enables the measurement of lamellar spacing in the coarsest part of the pearlite, which may serve as a valuable indicator for evaluating rail microstructure and supporting further comparative analyses.

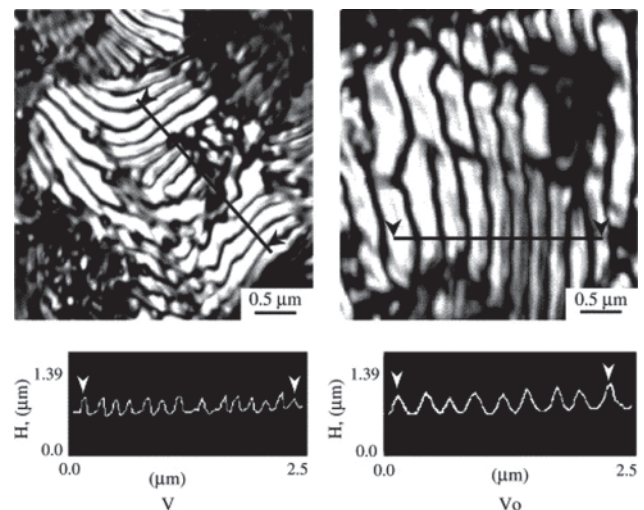


Fig. 2. Measurement of the mean interlamellar spacing (λ) presented in paper [4]

3. Methodology

3.1. Hardness testing

Hardness testing was conducted on R260 steel forgings, including frog point sections, in accordance with the requirements of the PN-EN 16273 standard [14], which specifies the location and method of hardness measurements for track components produced in a hot forging process.

Representative fragments of the various types of forgings were cut, and then ground and polished to ensure the appropriate quality of the measurement surface. Brinell hardness (HBW) measurements were performed in two areas: on the running surface and

Technical drawing of a rail cross-section showing measurement points and dimensions. The drawing includes a side view of the rail head and a cross-section of the rail foot. Key dimensions and measurement points are indicated:

- LG**: Length of the rail head.
- LF**: Length of the rail foot.
- a**: Boundary of the forged heat-affected zone (HAZ).
- 100**: Distance from the running surface to the measurement point in the rail head.
- 10**: Distance from the running surface to the measurement point in the rail foot.
- 50**: Distance from the running surface to the measurement point in the rail head.
- 100**: Distance from the running surface to the measurement point in the rail foot.
- 5**: Distance from the running surface to the measurement point in the rail head.
- 5**: Distance from the running surface to the measurement point in the rail foot.

Legend:

- ▼ – measurement point from the running surface
- ▲ – measurement point in the rail foot
- a – boundary of the forged heat-affected zone (HAZ)

The frog points were also subjected to measurements on cross-sections using the Vickers method (HV) (Fig. 4), which enabled the assessment of hardness changes through the depth of the section and the identification of potential effects resulting from the hot forging process.

The pearlite *interlamellar spacing* (λ) was calculated using the *test line method* [4, 18], in accordance with the commonly accepted procedure in the microstructural analysis of pearlitic materials. The obtained local values were used to determine the distribution and average value of the pearlite interlamellar spacing in the examined material. In each analysed microstructure, a line of a measured length L was drawn perpendicular to the pearlite lamellae, and the number of intersected lamellar boundaries, N , was then counted. The interlamellar spacing was calculated using the formula:

$$\lambda_m = L / N,$$

where λ_m is the local, measured pearlite interlamellar spacing in a given measurement field. This method, based on the number of lamellae intersections by a test line, is analogous to classical methods for analysing pearlite microstructure and has been extensively described in metallurgical literature. The accuracy of determining the mean interlamellar spacing using

Fig. 4. Schematic showing the distribution of measurement points on the cross-section of frog points according to PN-EN 16273 [14]

stereological methods and the sources of measurement errors have been discussed in detail in, among others [2].

Due to the random orientation of pearlite colonies relative to the measurement line, the measured interlamellar spacing values λ_m were corrected using the coefficient proposed by Vander Voort [18], according to the following relationship:

$$\lambda = \lambda_m / 2.$$

The corrected λ values are considered an approximation of the true interlamellar spacing.

5. Results

5.1. Hardness test results

The hardness distribution on the running surface of the frog points shows some fluctuations along the sample, with HBW hardness values ranging from approxi-

mately 253 to 283 HBW. In the foot of the frog points, the average hardness was 275.13 and 274.17 HBW, respectively, for the two tested samples. Vickers hardness measurements on the cross-sections revealed variations in values at individual measurement points, with the highest hardness observed near the running surface, reaching values up to approximately 289 HV30, whereas the lowest results, around 259 HV30, were recorded in regions closer to the rail head core of the sample. The general hardness distributions show relative homogeneity with local decreases and increases, indicating some material heterogeneity along the frog point. Detailed results are presented in Figures 5–9.

5.2. Pearlite interlamellar spacing measurement results

Selected observed microstructures are presented in Figure 10. Table 1 contains the measurement results for the line length L , the number of intersected lamellar boundaries N , and the calculated local pearlite interlamellar spacings λ .

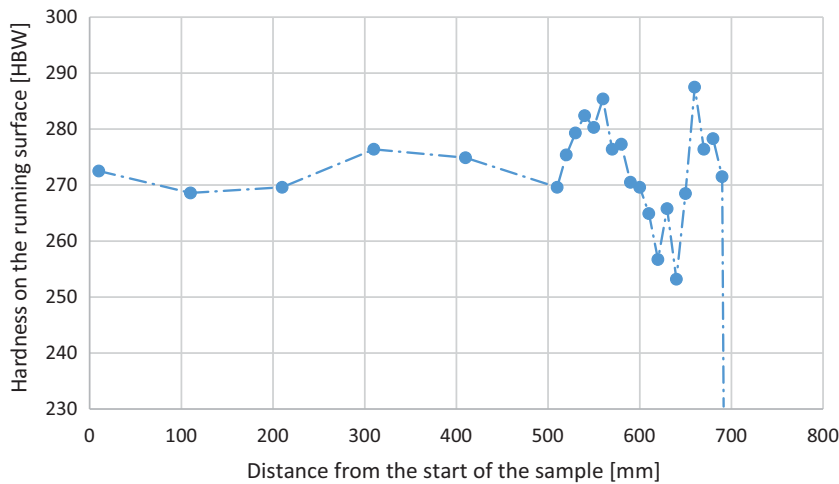


Fig. 5. Hardness distribution on the running surface of Frog Point 1 [Author's own work]

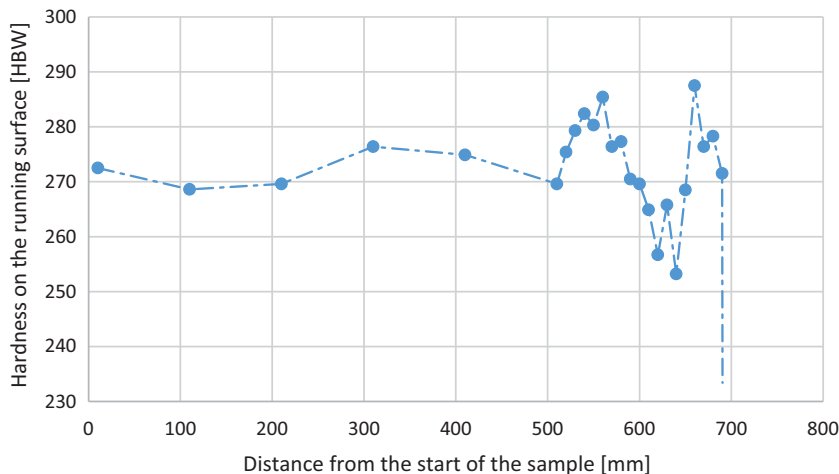


Fig. 6. Hardness distribution on the running surface of Frog Point 2 [Author's own work]

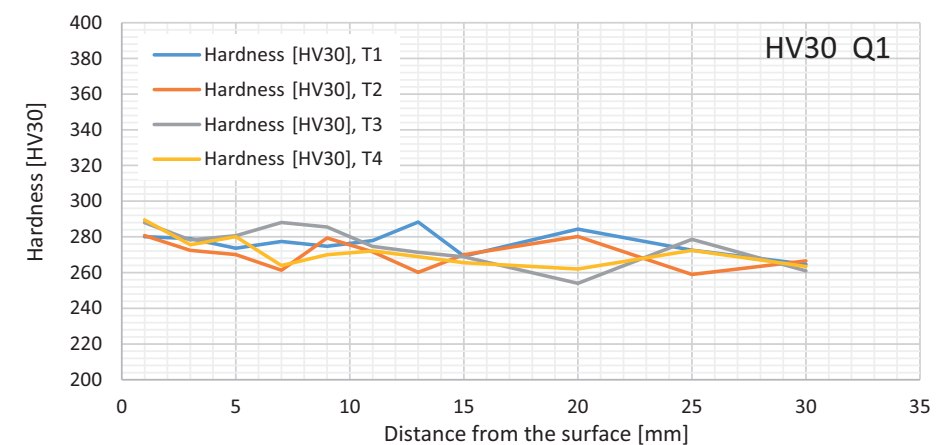


Fig. 7. Hardness measurement in cross-section Q1 of Frog Point 1 [Author’s own work]

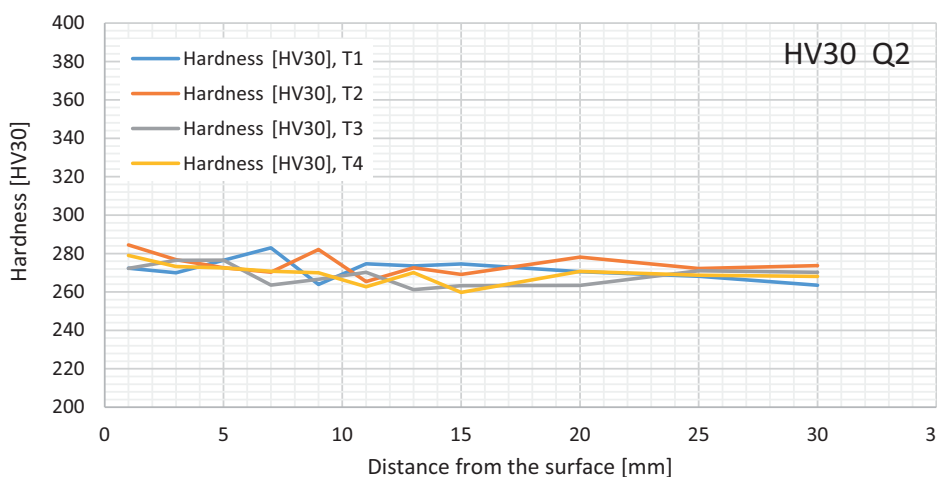


Fig. 8. Hardness measurement in cross-section Q2 of Frog Point 1 [Author’s own work]

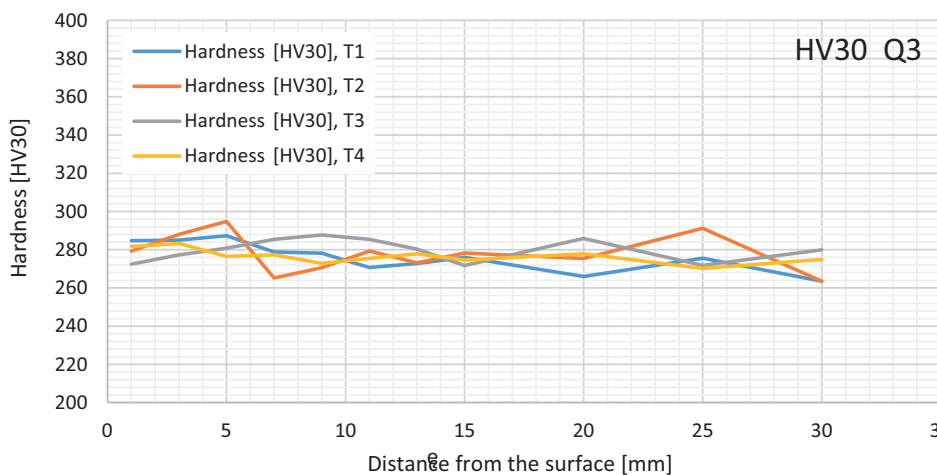


Fig. 9. Hardness measurement in cross-section Q3 of Frog Point 1 [Author’s own work]

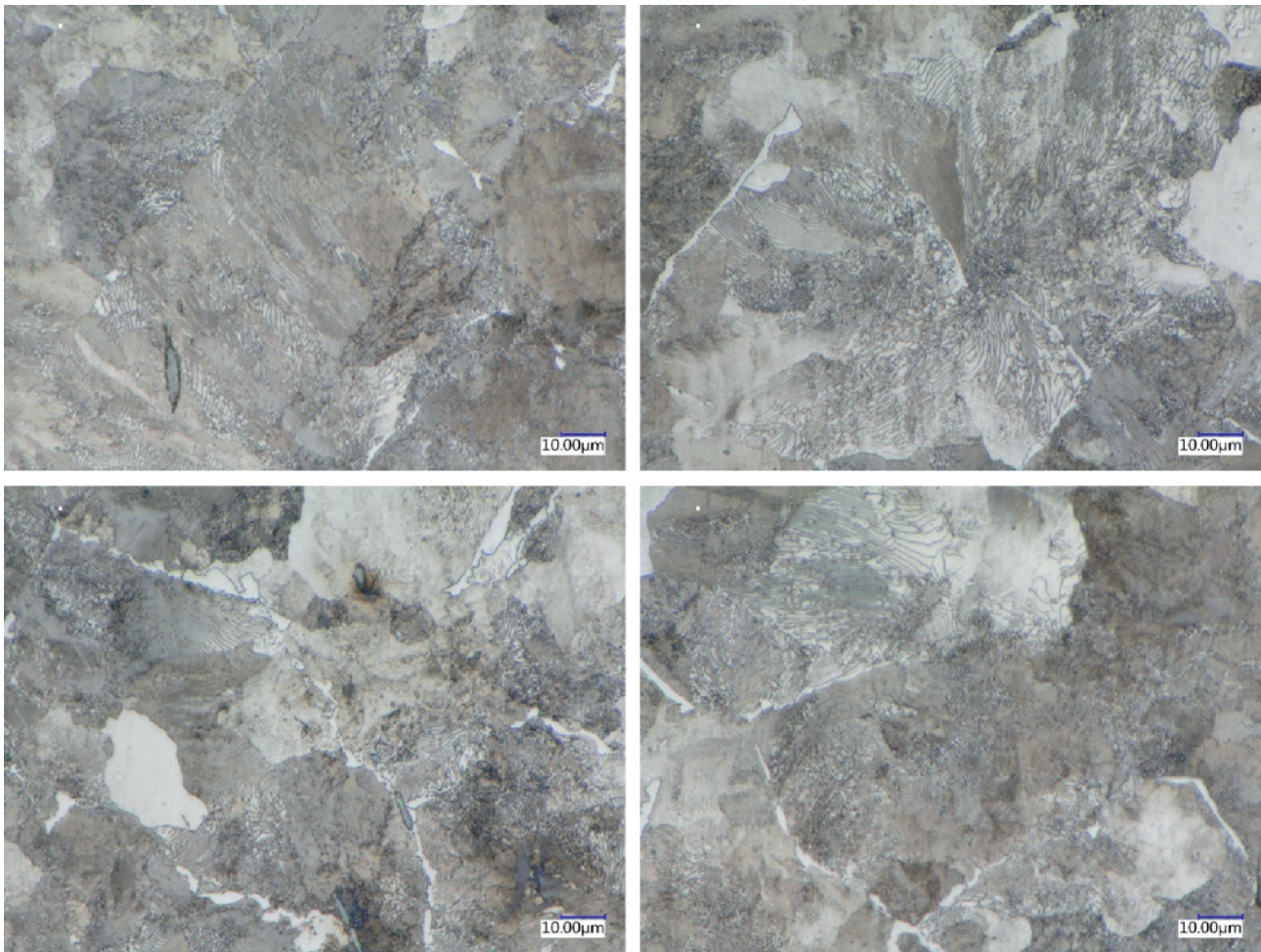


Fig. 10. Observed exemplary microstructures [Author's own work]

Table 1

Results of pearlite interlamellar spacing analysis

No.	L [μm]	N	λ_m [μm] = L / N	λ [μm] after correction
1	62.59	81	0.77	0.39
2	8.09	12	0.67	0.34
3	7.55	8	0.94	0.47
4	16.11	16	1.01	0.50
5	12.26	17	0.72	0.36
6	11.66	12	0.97	0.49
7	16.02	17	0.94	0.47
8	11.6	14	0.83	0.41
9	4.51	9	0.50	0.25
10	13.32	22	0.61	0.30
11	37.84	55	0.69	0.34
12	22.35	33	0.68	0.34

No.	L [μm]	N	λ_m [μm] = L / N	λ [μm] after correction
13	36.34	59	0.62	0.31
14	13.32	21	0.63	0.32
15	21.27	31	0.69	0.34
16	5.78	9	0.64	0.32
17	15.16	22	0.69	0.34
18	37.46	53	0.71	0.35
19	3.5	6	0.58	0.29
20	3.28	6	0.55	0.27
21	8.24	13	0.63	0.32
22	10.46	19	0.55	0.28
23	6.66	10	0.67	0.33
24	10.28	18	0.57	0.29
25	5.81	9	0.65	0.32

No.	L [μm]	N	λ_m [μm] = L / N	λ [μm] after correction
26	26.96	29	0.93	0.47
27	7.27	10	0.73	0.36
28	12.43	9	1.38	0.69
29	5.36	10	0.54	0.27
30	3.99	6	0.67	0.33
31	11.87	15	0.79	0.40
32	3.74	6	0.62	0.31
33	14.92	18	0.83	0.41
34	10.54	12	0.88	0.44
35	10.51	18	0.58	0.29
36	10.69	18	0.59	0.30
37	9.01	17	0.53	0.27
38	5.68	10	0.57	0.28
39	5.33	11	0.49	0.24
40	4.74	9	0.53	0.26
41	10.15	14	0.73	0.36

[Author's own work].

Where: L – measurement line length [μm], N – number of intersected lamellae, λ_m – interlamellar spacing measured by the test line method, λ – interlamellar spacing corrected according to Vander Voort.

Based on all 41 individual measurements, a statistical evaluation of the obtained results was performed in Table 2.

Table 2
Statistical evaluation of the obtained results

Statistics	λ_m [μm]	λ [μm] (corrected)
Mean value	0.71	0.35
Median	0.67	0.33
Minimum	0.49	0.24
Maximum	1.38	0.69

[Author's own work].

6. Discussion of the results

6.1. Hardness test results and their compliance with standards

The results of the Brinell hardness (253–283 HBW) and Vickers hardness (259–289 HV) measurements indicate that the majority of the results, as well as

the mean values, fall within the normative range, although isolated areas of reduced hardness (down to 253 HBW) were locally recorded. The observed local reduction in hardness may be associated with the presence of coarser pearlite colonies or local microstructural inhomogeneities. The average foot hardness of 274–275 HBW confirms the effectiveness of the hot forging process in achieving the desired level of strengthening, which results from the refinement of the pearlitic structure due to the dynamic recrystallisation of austenite and natural cooling.

Local hardness fluctuations, specifically drops to 253 HBW on the running surface, indicate a heterogeneity characteristic of forged sections made of R260 rail steel. The hardness gradient across the cross-section, with higher HV values in the surface layer (up to 289 HV30) and lower values in the core (259 HV30), reflects the natural thermokinetic cooling profile after forging, where external zones lose heat more rapidly, promoting the formation of finer pearlite [1, 4, 11].

6.2. Pearlite interlamellar spacing (λ) measurement results

Statistical analysis of 41 local interlamellar spacing measurements, after applying the Vander Voort correction, revealed a mean value of $\lambda = 0.35 \mu\text{m}$ (median $0.33 \mu\text{m}$), with a range from $0.24 \mu\text{m}$ to $0.69 \mu\text{m}$. The wide range of values indicates significant heterogeneity of the pearlite morphology, which is typical for R260 steel after hot forging and natural cooling. The coarsest colonies ($\lambda = 0.69 \mu\text{m}$), located in the central zones of the samples, reflect the slower cooling of the core.

The test line method (the number of lamellar intersections per unit length of a test line perpendicular to the lamellae) ensured the reliability of the data. The results refer to structures that can be analysed at $1000\times$ magnification and remain consistent with literature data obtained for rail steels with a composition similar to R260 (Table 3). The comparison also includes data for steels of a higher strength grade to demonstrate the scale of the influence of pearlite refinement on hardness [17].

Table 3 presents a summary of selected literature data regarding the relationship between pearlite interlamellar spacing (λ) and hardness for rail steels and similar alloys. A comparison of the present results with literature data allows for an assessment of the scale of pearlite refinement and its influence on mechanical properties.

Results by Herian [9] indicate that, for rail steel after rolling, the mean λ is $0.278 \mu\text{m}$ at a hardness of $\approx 296 \text{ HV}$ (285–290 HB), which is slightly lower than the value of $\lambda = 0.35 \mu\text{m}$ observed in this study. Research by Fei [6] on U75V steel showed $\lambda = 0.263 \mu\text{m}$ at a hardness of $\approx 330 \text{ HV}$ (315–320 HB), reflecting a higher degree of pearlite refinement and higher steel hardness.

Table 3
Comparison of corrected pearlite interlamellar spacing values (λ) with literature data

Source / Material condition	Mean λ	λ range	Hardness (HB / HV)
Present study / R260, hot forging	0.35	0.24–0.69	259–289 HV
Herian [9] / rail steel, after rolling	0.278	–	$\approx$ 296 HV (285–290 HB)
Fei [6] / U75V rail	0.263	–	$\approx$ 330 HV (315–320 HB)
Modi [12] / C0,65% steel,	0.54–0.79	–	220–270 HV
Toribio[17] / eutectoid wire/ rail-like	0.12	0.08–0.20	350–400 HV
Ferreira [5] / R260Mn, laboratory tests	0.15	–	292 HV

[Author's own work].

Ferreira et al. [5] report a mean $\lambda = 0.15 \mu\text{m}$ at a hardness of approximately 292 HV for R260Mn. It should be emphasised, however, that the materials studied by these authors were subjected to specific, controlled conditions of rapid heating and cooling in laboratory settings, which differs from the classic hot forging process and may affect the microstructure as well as the hardness and interlamellar spacing values.

Modi O.P. [12] and Toribio J. [17] present other steel grades, demonstrating a wide range of λ (0.12–0.79 μm) at various levels of strength and hardness, which confirms the influence of pearlite refinement on mechanical properties. A comparison of the present results with the literature shows that local hardness fluctuations and microstructural heterogeneity in the examined R260 frog points are consistent with observations for pearlitic steels in other scientific works.

7. Syntesis

This article analyses the usefulness of pearlite interlamellar spacing measurements as a microstructural parameter supporting the quality assessment of the hot forging process of R260 steel frog points. The research was conducted using light microscopy and standard hardness measurements compliant with the requirements of the PN-EN 16273 standard.

The obtained Brinell and Vickers hardness results confirmed the compliance of the examined frog points with the requirements of the PN-EN 16273 standard for R260 steel and demonstrated a characteristic hard-

ness gradient in the cross-sections, resulting from non-uniform cooling conditions after the hot forging process. Concurrent microstructural observations revealed a varied pearlite morphology, including areas with finer and coarser lamellar arrangements.

Pearlite interlamellar spacing measurements were performed using the test line method only in those microstructural areas where the lamellar structure was clearly recognisable at the applied light microscopy magnification. The corrected λ values should therefore be treated as a characterisation of local microstructural fragments rather than as a representation of the mean interlamellar spacing of the entire material cross-section.

Despite these limitations, the comparison of microstructural measurement results with the hardness distribution indicates the consistency of the observed trends and confirms the existence of a relationship between pearlite morphology and the mechanical properties of forged R260 steel frog points.

8. Conclusions

1. The research showed that the majority of the results and mean values fall within the normative range; however, isolated areas with reduced hardness (down to 253 HBW) occur locally, indicating the presence of local microstructural inhomogeneities. In the case of Vickers hardness testing, the observed hardness distribution across the cross-section is typical for hot-forged and uncontrollably cooled components, with higher values in surface zones and lower values in the core.
2. The pearlite microstructure exhibits distinct heterogeneity, which is reflected in both local hardness variations and the diversification of interlamellar spacing.
3. Pearlite interlamellar spacing measurements performed using light microscopy refer only to selected, most visible fragments of the microstructure (usually those with a coarser lamellar morphology) and do not constitute a complete characterisation of the entire material. The obtained values should be interpreted as an indicator of local cooling conditions after the forging process rather than a global average for the entire volume of the frog point.
4. Despite the limitations of the method, λ measurements can serve as a useful tool supporting the quality assessment of the hot forging process. In particular, they enable comparisons between production series, the identification of areas with potentially inhomogeneous microstructures, and the interpretation of local hardness deviations from mean values.
5. The application of quantitative pearlite microstructure assessment as a supplement to standard

hardness testing increases the sensitivity of quality control for hot-forged frog points. It can serve as a comparative and diagnostic tool for analysing the influence of changes in forging and cooling parameters on the microstructural homogeneity of R260 steel.

References

1. Bhadeshia H.K.D.H.: Honeycombe R.W.K.: *Steels: Microstructure and Properties*, 4th ed., Butterworth-Heinemann, 2017.
2. Czarski A., Matusiewicz P.: *Some aspects of estimation accuracy of mean true interlamellar spacing*, Metallurgy and Foundry Engineering, 38(2), 2012, WWW <https://doi.org/10.7494/mafe.2012.38.2.133> [dostęp 07.01.2026].
3. Dey I., Ghosh C., Saha S.: *Effects of cooling rate and strain on austenite decomposition during thermomechanical processed pearlitic steel*, JMR&T, 2019, 8, 2685–2698.
4. Elwazri A.M., Wanjara P., Yue S.: *Measurement of pearlite interlamellar spacing in hypereutectoid steels*, Materials Characterization, 54 (2005) 473–478, WWW <https://doi.org/10.1016/j.matchar.2005.02.002> [dostęp 07.01.2026].
5. Ferreira V. Mattos et al.: *Microstructure development of pearlitic railway steels subjected to different thermomechanical treatments*, TU Delft Repository, 2022.
6. Fei J. et.al.: *Research on the effect of pearlite lamellar spacing on rolling contact wear behavior of U75V rail steel*, Metals, 2023, 13(2), art. 237.
7. García-Caballero F., Capdevila C., de Andrés C.: *Modeling of the interlamellar spacing of isothermally formed pearlite in a eutectoid steel*, Scripta Materialia, 2000, 42(6), 537–542.
8. Hamada D., Sasaki M., Ueda H.: *Noguchi. Fatigue limit evaluation considering crack initiation for lamellar pearlitic steel*, Procedia Engineering, 10. 2011, 1467–1472, WWW <https://doi.org/10.1016/j.proeng.2011.04.245> [accessed 7 January 2026].
9. Herian J., Aniolek K.: *The structure and properties of steel with different pearlite morphology and its resistance to abrasive wear*, Archives of Materials Science and Engineering, 2008, 31(2), 83–86.
10. Jabłońska M. et.al.: *Advanced heat treatment of pearlitic rail steel*, Materials, 2023, 16(19).
11. Khan, A.R. et.al.: *Effect of cooling rate on microstructure and mechanical properties in the CGHAZ of electroslag welded pearlitic rail steels*, Metals, 2019, 9(10), 1070.
12. Modi O.P. et al.: *Effect of interlamellar spacing on the mechanical properties of 0.65% C steel*. Materials Characterization, 46(4), 347–352 (2001). DOI: 10.1016/S1044-5803(00)00113.
13. Nikas D.: *Influence of combined thermal and mechanical loadings on pearlitic steel microstructure in railway wheels and rails*. PhD Thesis, Chalmers University of Technology, Gothenburg, 2018.
14. PN-EN 16273: Railway applications – Measurement of hardness in rails and components.
15. Porter D.A., Easterling K.E., Sherif M.: *Phase Transformations in Metals and Alloys*, 3rd ed., CRC Press, 2009.
16. Solano-Álvarez W., Bhadeshia H. K.D.: *Rails - microstructure, toughness and fatigue*, Progress in Materials Science, 146 (2024), 101313.
17. Toribio J., Ovejero E.: *Microstructure evolution in pearlitic steels under fatigue*, Materials Science and Engineering A, 1997, 234–236, 579–582, WWW [https://doi.org/10.1016/S0921-5093\(97\)00257-5](https://doi.org/10.1016/S0921-5093(97)00257-5) [dostęp 07.01.2026].
18. Vander Voort G.F.: *The interlamellar spacing of pearlite*, Practical Metallography, 52 (2015) 466–475.
19. Zhang G., Enomoto M.: *Interlamellar spacing of pearlite in a near-eutectoid Fe-C alloy measured by serial sectioning*, ISIJ International, 2009, 49(1), 56–62.