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Railway Rail Material Quality Tests

Ireneusz MIKŁASZEWICZ[1] Małgorzata FRELEK-KOZAK[2]

Summary
The article presents the obligatory qualitative tests of the material of railway rails, performed for the railway industry and having the status of qualifying tests, to which railway rails are subjected. They include tests of fracture mechanics (determination of the critical stress intensity factor K_{IC}, determination of the fatigue crack development velocity da / dN), determination of stresses in rail feet and fatigue tests. The article presents the results of tests of standard-gauge rails type 60E1, rolled from R260 steel by selected European producers, and an analysis of the results was carried out based on the guidelines of the PN-EN 13674-1 + A1: 2017-07 standard.

Keywords: quality tests of rails, K_{IC} coefficient, propagation da/dN, stress

1. Introduction

Rails are among the key components of the railway infrastructure affecting transport safety. Their reliable operation and low failure rate are decisive factors for the operability of the entire railway system in a given area. When in motion, a railway vehicle weighing several tens of tonnes exerts pressure on the rails through the wheel-rail interaction process. This interaction is dynamic, causing variability in the loads on these components. Railway rails therefore operate in an environment of very high, variable loads of a cyclical nature [5]. The result of these interactions is the formation of defects in the material – mainly in the form of discontinuities, such as cracks.

The appearance of the first cracks significantly reduces the load-bearing cross-section of the rail. This process fundamentally changes the stress distribution throughout the component. The presence of a discontinuity in the material, i.e. a reduction in its cross-sectional area at the same load level, increases the effective stresses in the material, causing it to degrade more quickly. In addition, it should be emphasised that a change in the stress distribution around the resulting defect in a working component causes further headcheck progression. Exploitation of such material causes a further increase in discontinuity, correlated with a progressive decrease in the specific cross-section of the component. Under these conditions, the rate of crack growth continues to increase with time in service, leading to excessive allowable stresses and consequent uncontrolled catastrophic cracking or fracture of the rail. For this reason, the rails are subjected to numerous tests to determine the quality of the material before it is put into service. These tests have two main objectives of:
1) minimising the risk of cracking,
2) determining the behaviour of the material in a system with a structural defect.

Considering the above assumptions, the rail qualification tests include mechanical tests of the material's fracture toughness K_{IC} [4] and determination of the fatigue crack growth rate da/dN. Both of these methods are sample tests in which the behaviour of a material with an artificial headcheck is recorded. In addition, the determination of the stress level in the rail foot and the distribution of sulphur on the cross-section of the finished rails is performed using the Baumann test – as a factor favouring the formation of cracks. Fatigue tests are also performed on samples taken from rail heads. Rail manufacturers also determine statistical, predictive material strength equations based on the assumed production period, depending on the content of alloying elements in the melts of the produced rails.

[1] Eng.; Railway Research Institute, Materials and Structure Laboratory; e-mail: imiklaszewicz@ikolej.pl.
[2] M.Sc. Eng.; National Centre for Nuclear Research, Material Testing Laboratory; e-mail: Malgorzata.Frelek@ncbj.gov.pl.

2. Material and testing methodology

The material for the tests consisted of rails made of R260 grade steel, 60E1 profile, manufactured in steel mills by four major rail manufacturers in Europe, marked with the letters A, B, C and D. Selected, representative chemical compositions of the melts and the obtained strength properties of the rail material are given in Table 1. The tests were performed based on the requirements of the current European standard PN-EN 13674-1+A1:2017-07 [7].

3. Rail quality tests

3.1. Rail material fracture toughness test K_{IC}

The material fracture toughness tests were performed according to the requirements of ASTM E399-19 [1], PN EN ISO 12737:2011 [8] and PN-EN 13674-1+A1:2017-07 [7]. These tests consist of fracturing a sample with a fatigue crack while recording the force and crack opening. The test is designed to induce a plane state of strain in the sample. For this reason, the geometrical dependencies of the tested sample are extremely important (i.e. the ratio of thickness to height and the ratio of the fatigue crack to the height of the sample) [5]. The test allows users to determine the critical value of the K_C coefficient in the type I stress system (hence the symbol K_{IC}), in which the crack tip is loaded with opening forces (i.e. tensile forces act in the direction perpendicular to the crack tip) [4]. This parameter is one of the basic quality data components used to predict the critical, from the point of view of cracking, condition of the structure [1]. The K_{IC} value corresponds to the stress intensity coefficient beyond which the crack increases in a component of any thickness – hence the greater the value of K_{IC}, the greater the load the component with the crack can carry [5].

Measurements were performed on beam SE(B) type samples with the dimensions: 45×25×230 mm (W×B×L), Figure 1. In order to create a fatigue crack, a Chevron mechanical notch was cut on the samples using the ***W****ire* ***E****lectric* ***D****ischarge* ***M****achining* (WEDM) method. The sample was then subjected to cyclic bending loads in a three-point bending system. A sinusoidal load variation with an amplitude of 20 Hz and a constant stress intensity factor amplitude ΔK was used. Fatigue crack propagation was performed until the ratio of the crack length “a” to the sample height a/W ≈ 0.50 was achieved. This process was carried out at room temperature. The fracture toughness tests were conducted on such samples at the negative temperature T = −20°C by bending each sample until it was destroyed. The force and opening of the crack was recorded during the test. The analysis of the data obtained was performed in accordance with EN 13674-1+A1:2017-07 [7].

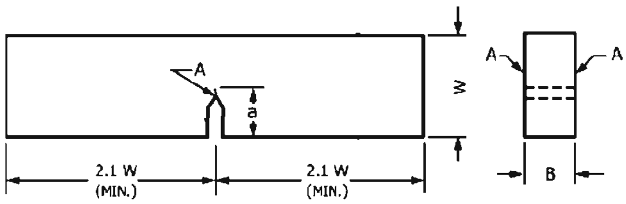

Fig. 1. The SE(B) type sample for fracture mechanics measurements [1]

Table 1

Chemical composition and mechanical properties of tested rails of R260 grade with 60E1 profile

Sample (steel grade)	Chemical composition [%]												Properties of the tested rails		
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	0_2 [ppm]	H_2 [ppm]	Rm [Mpa]	A5 [%]	HBW
A Rail	0.74	0.95	0.40	0.018	0.012	0.012	0.010	0.010	0.004	0.005	10	1.1	988	11.6	281
B Rail	0.69	0.97	0.34	0.022	0.025	0.09	0.06	0.04	0.004	0.003	4	2.3	968	14.0	280
C Rail	0.76	1.01	0.31	0.014	0.017	0.08	0.02	–	0.002	–	–	1.0	955	11.4	287
D Rail	0.72	0.94	0.35	0.013	0.015	0.07	0.04	0.05	0.003	0.03	–	1.7	945	12.5	278
R260 according to EN 13674-1	0.60–0.82	0.65–1.25	0.13–0.60	max 0.030	max 0.030	≤ 0,15	–	–	max 0.004	max 0.030	max 20	max 2.5	min 880	min 10.0	260–300

[Author’s study].

3.2. Fatigue crack growth rate test da/dN

The da/dN tests determine the rate of crack growth in an environment of cyclically varying loads. The K_{IC} measurements described earlier are intended to determine the maximum static load that can be applied to a rail so that an existing crack of a specified length in the rail does not widen. Changing the nature of the load from constant to cyclically varying fundamentally affects the ability to safely use a component. The decisive factor in this case is not the load, but its variability. Stresses not exceeding even half of the allowable static loads, but of a variable nature, have been proven to significantly reduce the service life of structural components [5].

For this reason, the tests on the rate of fatigue crack growth da/dN are intended to simulate the effects of fatigue damage. Fatigue damage processes are divided into several smaller stages, depending primarily on the geometry, the stresses present and their variation, the mechanical and structural parameters of the structural material and the geometry of the crack. The complexity of these aspects makes it difficult to identify general patterns. For this reason, the determination of the fatigue crack growth rate is performed taking into account the value of the stress factor amplitude ΔK, present at the time of testing [3–5]. The sample is subjected to a cyclical load of constant amplitude (Fig. 2a). The crack length and the number of cycles are recorded during the test (Fig. 2b). From the data obtained, the rate of fatigue crack development is determined for a specified value of the stress intensity factor K (Fig. 2c).

The da/dN measurements were performed with a constant load amplitude with a load cycle asymmetry of R = 0.5 and a frequency of 20 Hz. The SE(B) type samples (Fig. 1) with dimensions 45×20×230 mm (W×B×L), in which straight mechanical notches were cut using the WEDM method, were tested. The development rate of fatigue cracks was determined for two ranges of stress intensity factor K = 10 MPa·m$^{0.5}$ and K = 13.5 MPa·m$^{0.5}$, according to the requirements of the standard [7]. The da/dN values for each range were determined using the polynomial method.

3.3. Rail foot stress test

The process of stress formation in rails during their manufacture can be divided into two periods:

1. After the rail rolling and cooling process. These treatments result in structural stresses, associated with plastic deformation and phase transformations in the material. This manifests itself on the grates of the rail manufacturer's cold storage facility primarily by a lack of straightness after cooling.
2. After cold straightening of the rail in the XX and YY system. This process results in internal stresses, caused by the multi-plane strain of the rails, which changes the course and type of stress. The highest stress values are recorded at the rail foot, which is why these areas are subjected to qualification stress measurements [6].

On six 1-m-long samples of finished rails from each manufacturer, stress measurements were taken by placing strain gauges with a resistance of 120 Ω on the rail feet (Figures 3 and 4), then cutting a disc 20 mm thick. The released stresses in the rails were recorded during the cutting. According to the requirements of EN 13674-1+A1:2017(E), the stresses must not exceed 250 MPa.

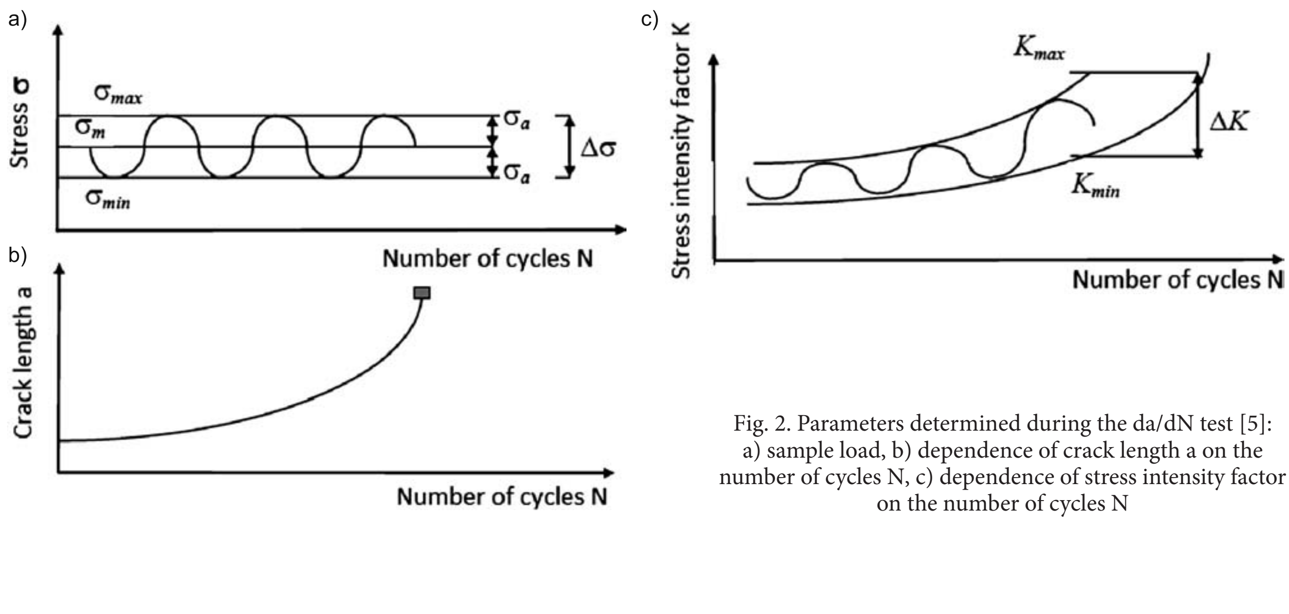

Fig. 2. Parameters determined during the da/dN test [5]: a) sample load, b) dependence of crack length a on the number of cycles N, c) dependence of stress intensity factor on the number of cycles N

Fig. 3. Rail with strain gauges in place [photo by the authors]

Fig. 4. Rails with stresses released [photo by the authors]

In accordance with the recommendations of this standard, during the test, the strain gauge method was used, which involves measuring the released own stresses while cutting rail sections with strain gauges installed. This method enables very accurate strain measurements to be made, as well as the calculation of stress values. At the same time, very precise placement of strain gauges on the surface of the test piece is required.

3.4. Fatigue tests

Due to the required high quality of the rail material, especially the fatigue toughness under varying operating load conditions, fatigue testing of the material was performed on samples cut from rail heads, machined on CNC cutting machines to ensure high dimensional accuracy. The samples prepared in this way were subjected to a fatigue loading cycle with a zero crossing of 5 million at a frequency of 10 Hz (Fig. 5). This means that, during the tests, the samples were subjected to alternating compressive and tensile forces at a high frequency of change. The test was designed to determine the strength of the rail structure formed during cooling to the varying strength of the material under operating conditions in the track. The criterion for completed fatigue tests according to the standard [7] is the absence of parting cracks in the samples after a load of 5 million cycles.

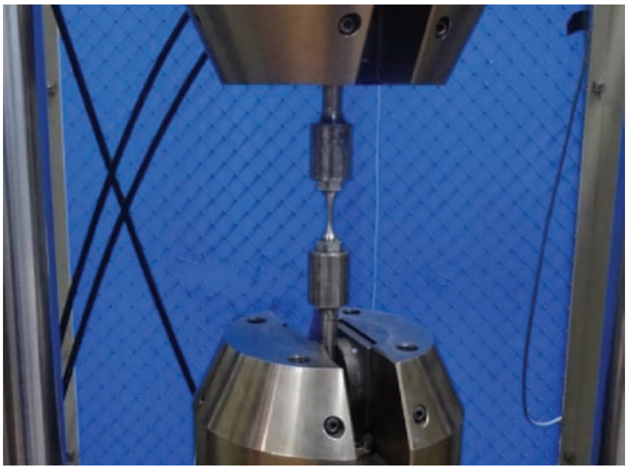

Fig. 5. Fatigue testing of a rail sample [photo by the authors]

3.5. Sulphur decomposition test

The presence of increased sulphur, i.e. above 0.030%, adversely affects the properties of steel. During the smelting of steel, the sulphur present in the material forms chemical compounds with manganese in the form of MnS and its variants [3]. These compounds, known as non-metallic inclusions, adversely affect the strength of steel. The sulphur content in rails should comply with the requirements of the standard [7], i.e. max. 0.030%, or the relevant reference documents. This standard defines the permissible sulphur content and its distribution on the rail cross-section in the form of Baumann print standards with an assigned qualification depending on the density and distribution of sulphur on the rail cross-section. In accordance with the qualification requirements, samples were taken and Baumann prints were made from the selected batches of five melts from six casting strands, from each melt after rolling the rails. An example of a Baumann print with the segregation distribution of sulphur in the rail is shown in Figure 6, graded to the D2 standard. The control and classification of the material were performed by comparing the Baumann print of the tested rail with the benchmarks included in the standard [7] or reference documents.

Fig. 6. Print of Bauman's sample of the rail assessed for the D2 standard [photo by the authors]

3.6. Prognostic tests

The introduction of prognostic equations in rail production was probably intended to assist producers in controlling the quality of production and its trends in the set of melts intended for rails. The prognostic equations describe the dependencies of tensile and elongation properties on chemical composition for individual rail steel grades. To statistically calculate these dependencies, the standard [7] recommends that a minimum of 100 melts be made by the rail manufacturer and that strength tests be performed. At the same time, the standard allows a limit for strength equations of Rm = 12.5 MPa and elongation A5 = 1.0%. The prognostic equations were made individually by each manufacturer (not published) and reflected the quality results obtained on the qualification test samples.

4. Test results

The results of the fracture mechanics measurements are presented in Fig. 7, which also indicates the minimum requirements of PN-EN 13674-1+A1:2017-07 for R260 grade steel [7], i.e. 26.0 MPa·m$^{0.5}$ for the single stress intensity factor value (black line) and 29 MPa·m$^{0.5}$ for the average stress intensity factor value (red line). Data marked with the K_Q symbol represents values that did not meet all the criteria for considering the result as a K_{IC} value. Analysing the data presented, it is easy to see that all the results obtained met the minimum requirements of the standard [7]. In addition, the test materials have similar mechanical properties, regardless of the manufacturer.

Figure 8 shows the results of fatigue crack growth rate for two measurement ranges: ΔK = 10 MPa·m$^{0.5}$ and ΔK = 13.5 MPa·m$^{0.5}$. The figure also indicates the maximum qualification values allowed by the standard [7], i.e. 17 m/Gcycle for ΔK = 10 MPa·m$^{0.5}$ (black line) and 55 m/Gcycle for ΔK = 13.5 MPa·m$^{0.5}$ (red line). It can clearly be observed that all melts (regardless of the manufacturer), obtain values well below the maximum value permitted by the standards.

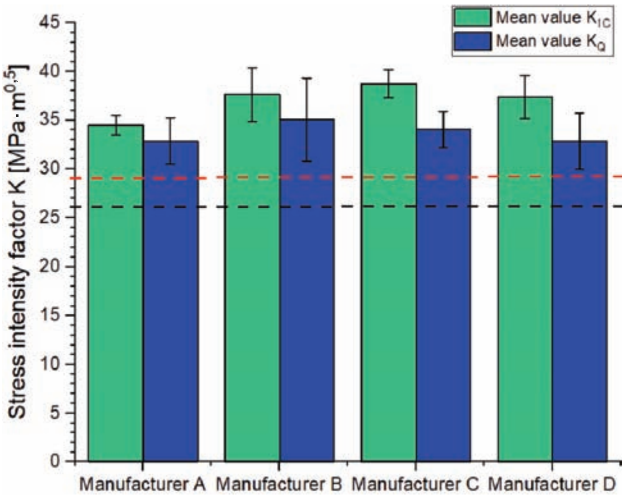

Fig. 7. Measurement results of K_Q and K_{IC} of R260 steel for the melts of individual manufacturers: the black line indicates the minimum value of a single measurement, while the red line indicates the minimum mean value of K_{IC} for the measurement series according to PN-EN 13674-1+A1:2017-07 [author's study]

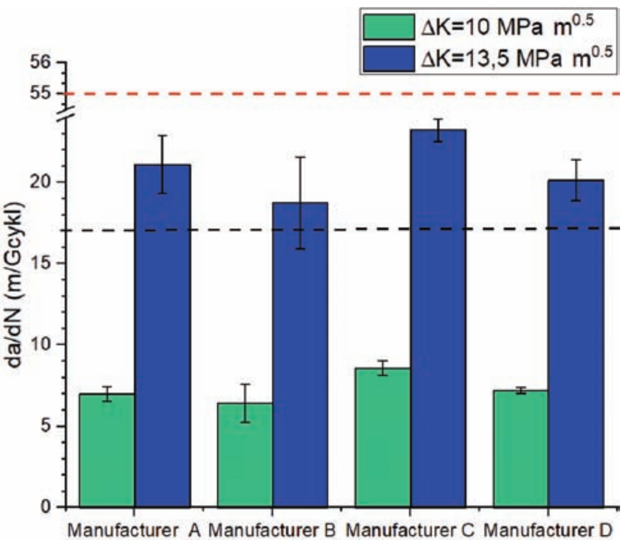

Fig. 8. Measurements of fatigue crack growth rate da/dN for two measurement ranges ΔK, obtained for samples of R260 steel produced by different manufacturers; the black line indicates the maximum value of crack growth rate for the range ΔK = 10 MPa·m$^{0.5}$, and the red line for the range ΔK = 13.5 MPa·m$^{0.5}$ [author's study]

Based on fatigue tests of rail samples according to the guidelines of PN-EN 13674-1+A1:2017-07 p.8.4 [7], it was concluded that all tested samples subjected to cyclic dynamic loading endured 5 million cycles and fulfilled the requirements of the above-mentioned standard, i.e. no parting cracks were found on the samples. The results are shown in Table 2.

Table 2

Fatigue test results on rail samples

Rail manufacturer code	Amplitude	Force range [kN]	Number of cycles [mil]
A	0.00135	±10.5 – ±10.7	5.0 – positive result
B		±10.1 – ±10.5	5.0 – positive result
C		±8.24 – ±10.08	5.0 – positive result
D		±8.91 – ±9.92	5.0 – positive result
PN-EN 13674-1	0.00135	–	5.0 million (without parting cracks)

[Author's study].

The results of the measurements of internal stresses in the rail feet are presented in Figure 9. Their analysis showed that, regardless of the manufacturer, the internal stresses did not exceed the values permitted by the standard. The rails of the A, B and C producers were characterised by stresses well below the intended limit, while the measurements obtained on the samples of producer D were in the upper acceptable range, well above the values obtained by competitors. However, these differences do not affect the qualification of the rails – all the melts were characterised by stresses that met the criterion of the PN-EN 13674-1+A1:2017-07 standard [7].

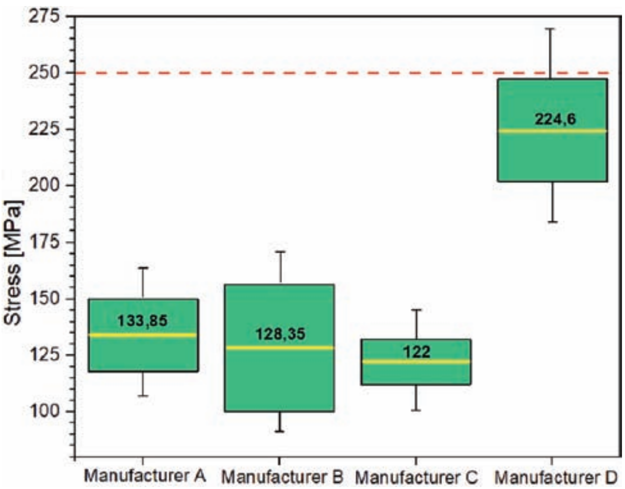

Fig. 9. Results of stress measurements in rail feet: the green area represents the scatter of the recorded measurement results, the yellow line shows the average value, while the red line shows the maximum stress value allowed by the standard [author's study]

In accordance with the qualification requirements, cross-sectional samples were taken from selected batches of five melts from six casting strands and Baumann prints were made from each melt after the rails were rolled. An example of a Baumann print with the distribution of sulphur segregation in the rail is shown in Figure 6.

The distribution of sulphur segregation, found in the Baumann test, in rail melts from all manufacturers, gave positive results in accordance with the requirements of PN-EN 13674-1+A1:2017-07 [7]. The vast majority of sulphur segregation, in rails from cast strands, was qualified on patterns D2 to D4 with a small number of patterns D5 and D9.

5. Conclusions

The presented results of qualification tests for rails of four major manufacturers in Europe in terms of fracture toughness K_{IC}, fatigue crack growth rate da/dN, stress magnitude in rail feet and fatigue tests met the requirements of the PN-EN 13674-1+A1:2017-07 [7] 1standard. The sulphur content and segregation of the finished rails were also classified as complying with this standard. In addition, regardless of the manufacturer, all materials had similar mechanical properties – no significant differences were recorded between the steels supplied by different manufacturers. Statistical prognostic equations calculated by the manufacturers on a set of more than 100 melts confirmed mechanical properties in accordance with the requirements of the standard [7] falling within the permissible range of strength Rm and elongation A5.

References

1. ASTM, E399: Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIC of Metallic Materials, Annu. B. ASTM Stand, 2012.
2. Blicharski M.: *Inżynieria Materiałowa. Stale* [Material Engineering. Constant], Wydawnictwo WNT, Warszawa, 2010.
3. Donahue R.J. et al.: *Crack Opening Displacement and The Rate of Fatigue Crack Growth*, Defense Technical Information Center, 1972.
4. Elber W.: *Fatigue crack closure under cyclic tension*, Eng. Fract. Mech. 2 (1970) 37–44, WWW https://doi.org/10.1016/0013-7944(70)90028-7.
5. German J.: *Podstawy mechaniki pękania* [Fundamentals of fracture mechanics], Wydawnictwo Politechniki Krakowskiej, Kraków, 2001.
6. Mikłaszewicz I., Siwiec J.: *Badanie naprężeń wewnętrznych w złączach zgrzewanych szyn kolejowych* [Examination of internal stresses in welded joints of railway rails], Problemy Kolejnictwa, 2019, z. 185.
7. PN-EN 13674-1+A1:2017-07: Kolejnictwo – Tor – Szyna – Część 1: Szyny kolejowe Vignole´a o masie 46 kg/m i większej [Railway industry – Track – Rail – Part 1: Vignole's railway rails of 46 kg/m and above].
8. PN-EN ISO 12737:2011: Metale – Określanie odporności na pękanie w płaskim stanie odkształcenia [Determination of fracture toughness in plane state of strain], 2011.