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Rails with Bainitic Microstructure

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Summary
The review article describes bainite as an example of a steel microstructure that can be successfully used in the production of railway rails. A comparison has been made between the key parameters to be met by railway rails: resistance to abrasive wear, resistance to flaking and presence of white etching layer for bainitic and pearlitic steel. The important role of residual austenite and the tempering process in shaping the mechanical properties of rails with bainitic microstructure has been discussed.

Keywords: bainite, railway rails, white etching layer, abrasive wear, residual austenite, tempering

1. Introduction

The rapid development of the railway sector requires the use of infrastructure having increasingly better strength properties. Improving, for example, rail strength will allow heavier trains to move at faster speeds. Traditional rails used in the railway sector are characterised by a pearlitic microstructure. With the right chemical composition and treatment process, the strength of approx. 1,300 MPa can be achieved; unfortunately, resistance to brittle fracture at stresses exceeding 1,180 MPa is very low [1].

The solution to this problem may be to use rails with a bainitic microstructure (rails of this type were used in 1980 for the first time). Bainitic rails can be very resistant (up to 1,400 MPa) and ductile (15–18%) with no reduction in resistance to brittle fracture. They also have better resistance to fatigue, but lower wear resistance compared to pearlitic rails. A higher chromium content or a higher content of other alloying elements makes it possible to increase resistance to abrasive wear of bainitic rails, which means that they can replace pearlitic rails in railway lines with heavy traffic [1–4].

2. Bainitic microstructure

Bainite is a microstructure that forms as a result of the bainite transformation. This transformation contains elements of both the diffusive and diffusionless transformation. Bainite is a mixture of dispersive carbides and carbon-rich ferrite. It is formed at temperatures lower than the temperature at which austenite is the least stable. The transformation starts with the formation of ferrite crystals at the boundary of austenite grains. Then, dispersive carbide particles are precipitated from ferrite. There are two types of bainite: upper and lower [5–7].

Upper bainite (Fig. 1) forms between 400–550°C. It contains thin and parallel ferrite plates with irregular precipitated carbides and is characterised by low strength, ductility and crack resistance [5–7].

Lower bainite (Fig. 2) forms at below 400°C. It contains laths of ferrite (similar to martensite in appearance) and parallel plate-shaped carbides. It is characterised by high hardness, wear and crack resistance as well as high ductility [5–7].

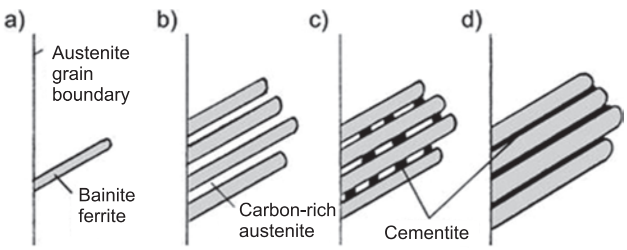

Fig. 1. Upper bainite formation diagram: a), b), c), d) transformation phases one by one [7]

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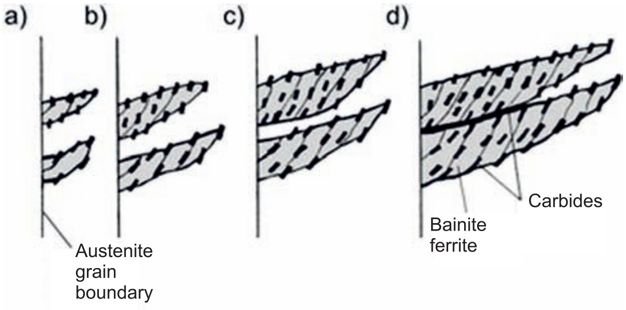

Fig. 2. Lower bainite formation diagram: a), b), c), d) transformation phases one by one [7]

If steel with a higher silicon or aluminium content is subject to the isothermic process of low-temperature bainitisation, the so-called nanobainite, i.e. a material having a nanocrystalline bainite structure, can be obtained. It contains nanoscale plates of bainitic ferrite, which are separated by thin layers of carbon-rich residual austenite. Adding aluminium or silicon hampers the precipitation of cementite during bainitisation, so the nanobainite structure does not contain carbides. Mechanical properties of nanobainite are similar to steel after transformation hardening and tempering at 150–250°C (low tempering) [8–12].

3. Resistance to flaking

On the running surface of the inner rail of the track section on a curve (Fig. 3), the direction of movement of a wheel does not coincide with the direction of a tangent to the railway, which results in a lateral force that causes side slip. This type of slip is one of the reasons why the rail flakes [1].

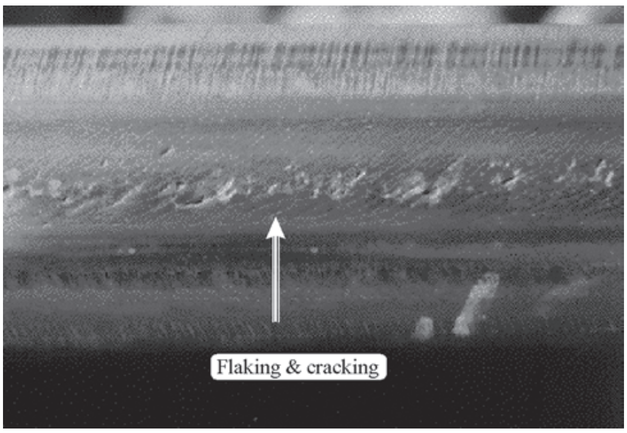

Fig. 3. View of railway rail flaking [1]

As the study showed [1], rails with a bainitic microstructure have higher resistance to flaking compared to rails with a pearlitic microstructure – and when both water and oil is used as a lubricant (Fig. 4). The higher rail strength, the longer flaking initiation time. Resistance to flaking of a bainitic rail able to withstand 1,400 MPa is more than twice higher than that of a pearlitic rail able to withstand 1,300 MPa.

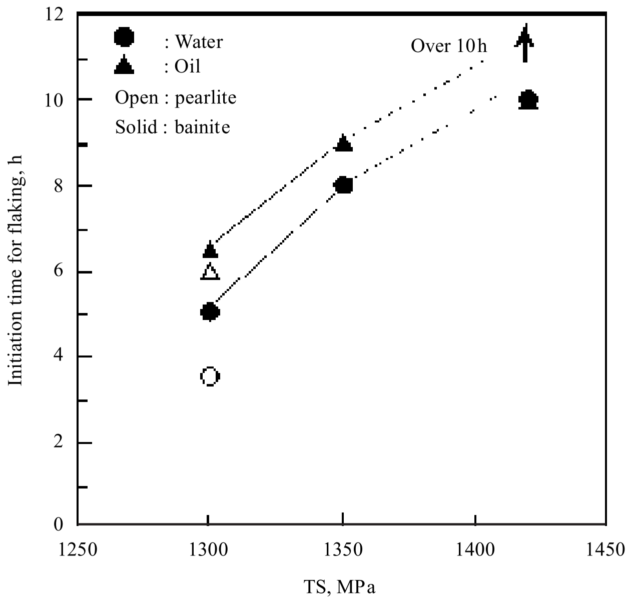

Fig. 4. Flaking resistance of bainitic and pearlitic steel [1]

As the tests of a microstructure of sections after flaking resistance testing revealed, pearlitic steel underwent plastic deformation – cracks are clearly visible, while bainitic steel underwent plastic deformation to a negligible extent – no significant crack was observed (Fig. 5).

4. White etching layer

Friction between wheels and the rail may cause a temperature increase in the rail above the iron austenitisation temperature. As a result, the surface of the rail may be covered with the so-called white etching layer with a martensitic structure (Fig. 6). This brittle white etching layer causes numerous faults of railway rails, especially cracks between the material layer and core. The thickness of the white etching layer depends on the carbon content in steel (the higher the content, the thicker the layer) and is independent of the microstructure [1, 13].

Steels with a lower carbon content have a higher iron austenitisation temperature, meaning that the white etching layer is thinner. Rails with a bainitic microstructure and a low carbon content form a thin white etching layer with low hardness (martensite thickness largely depends on carbon content, as

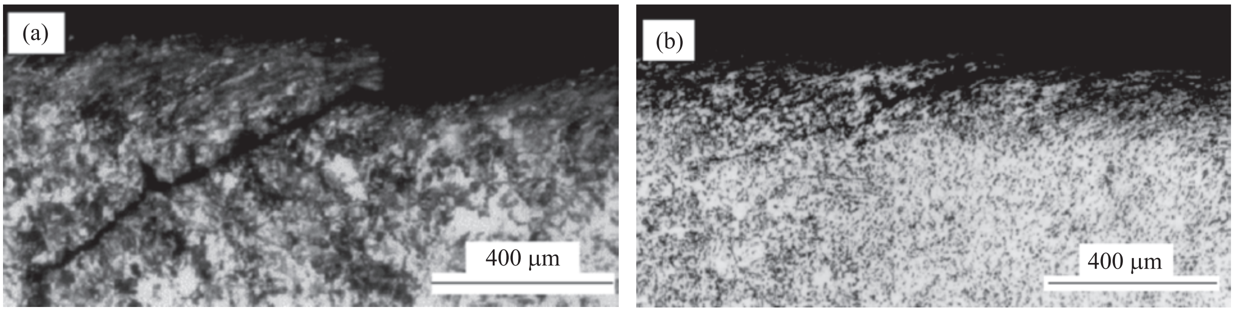

Fig. 5. Microstructure of sample sections after flaking resistance testing [1]; a) pearlite, b) bainite

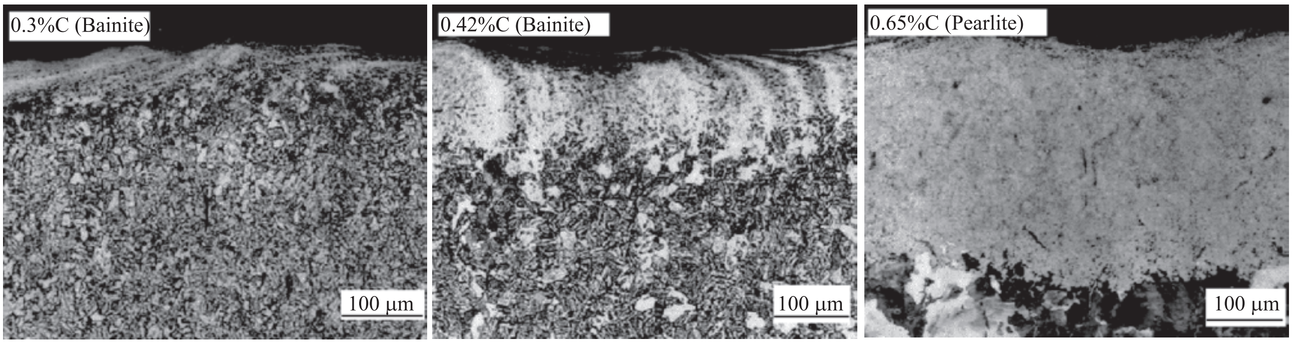

Fig. 6. Microstructure of sample sections depending on carbon content with visible white etching layer [1]

shown in Figure 7). For this reason, the propagation of fatigue cracks in such steel where the white etching layer and the rail core meet is contained [1, 13].

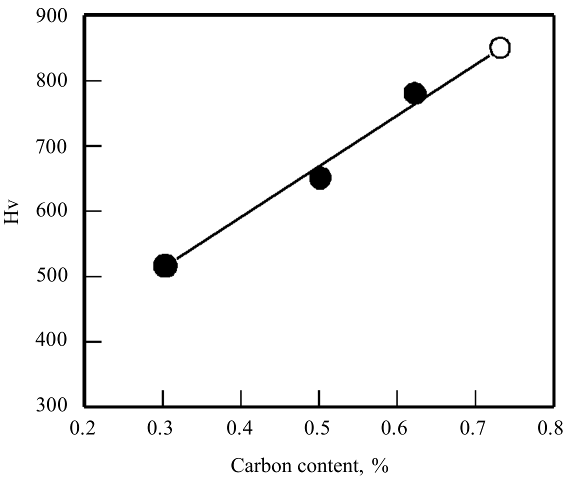

Fig. 7. Relationship between carbon content in the white etching layer and its hardness [1]

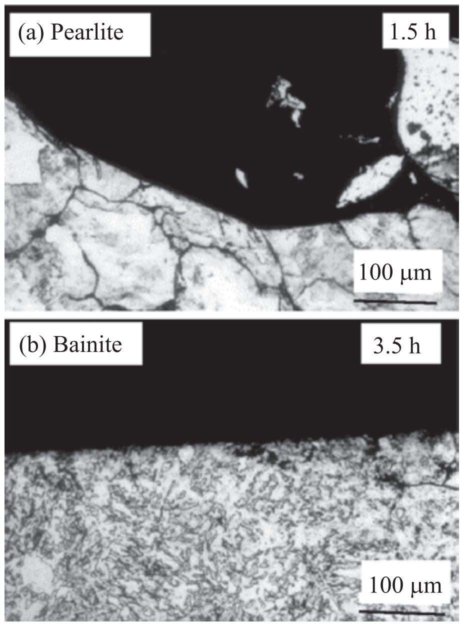

Fig. 8. Microstructure of samples with the white etching layer after flaking resistance testing [1]

Figure 8 shows the microstructure of sample sections after flaking resistance testing. For pearlitic steel, cracks at the point of contact between the white etching layer and the material core are visible. For bainitic steel, there are much fewer cracks.

5. Resistance to abrasive wear

The study [1] on resistance to abrasive wear showed that pearlitic rails are much more resistant compared to bainitic rails with the same strength rating (Fig. 9). The higher the strength, the lower the differences between abrasive resistance of both types of steel. Bainitic steel able to withstand 1,400 MPa is very similar in strength to pearlitic steel with the maximum possible strength of 1,300 MPa.

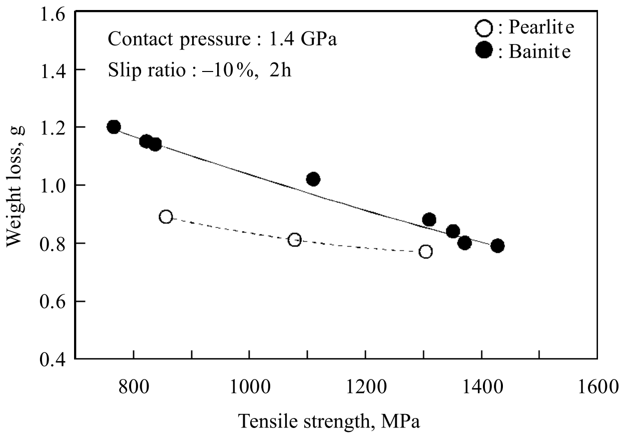

Fig. 9. Relationship between resistance to abrasive wear and strength [1]

6. Residual austenite

As far as mechanical properties are concerned, the amount and stability of residual austenite play a crucial role in rails with a nanobainitic structure. The stability of residual austenite depends on its size, morphology and carbon content. The presence of very stable austenite in bainitic steel contributes to its good plasticity (the so-called TRIP – transformation induced plasticity). Laths of austenite are much more stable than solid austenite – they also block crack propagation [2].

The tempering process plays a major role in shaping the mechanical properties of nanobainitic steel (Fig. 10). Changes to the microstructure during tempering affect the stability of residual austenite. Residual austenite can be stabilised by diffusing carbon from martensite to residual austenite. The study [2] showed that the optimum combination of strength and plasticity of steel characterised by the following chemical composition – 0.22C-2.0Mn-1.0Si-0.8Cr-0.8(Mo+Ni) (percentage by mass) can be obtained by tempering it at 280°C with the use of air cooling (strength: 1,388 MPa, elongation: 16%, shock resistance at room temperature: 130 J/cm^2). Once tempered, the stability of residual austenite is increased, which ensures excellent mechanical properties of a rail with a bainitic microstructure [2].

7. Conclusions

Rails with a bainitic microstructure can successfully replace traditional rails with a pearlitic microstructure, especially in railway lines with heavy traffic. Bainitic rails can be resistant to approx. 1,400 MPa, i.e. the value unobtainable for pearlitic steel. High-strength bainitic steel does not differ in resistance to abrasive wear from pearlitic steel. Higher resistance to flaking and lower white etching layer formation tendency are further arguments to support the use of this type of steel to make railway rails. The reliability of bainitic rails can be reflected by the ArcelorMittal

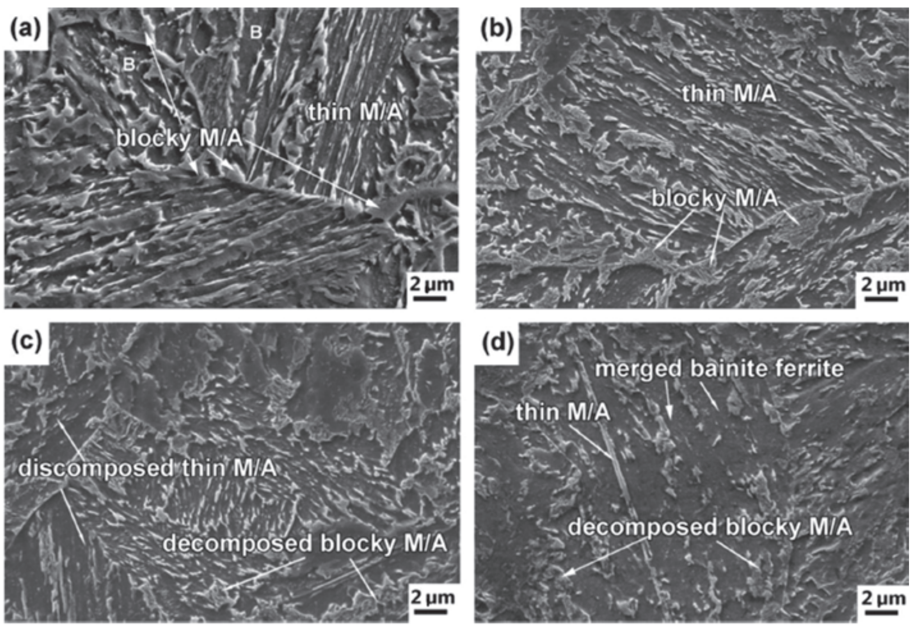

Fig. 10. Microstructure of bainitic steel without tempering (a), after tempering at: 280°C (b), 350°C (c), 400°C (d) [2]

steel mill located in Dąbrowa Górnicza, where the rails of the main railway track leading to the mill are made of bainitic steel – the rails have worked perfectly well since the track was built (4 years) [3].

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