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Silicon influence on the microstructure formation at cooling rates lower than the critical rate

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Materials

ABSTRACT

Purpose: On the bases of fundamental research [1], on the silicon influence on the kinetics of phase transformation of undercooled austenite in model ferrous alloys with carbon of a weak background of other alloying elements, it was found that up to the Si content of 1 mass % the steel hardenability decreases. The time before the start of the ferrite precipitation decreases as well as the time before the start of the pearlite and bainite formation. On the other hand in model ferrous alloys with carbon of a strong background of other elements, also in the range to app. 1 Si %, the time before the start of the ferrite precipitation and bainite formation is insignificantly prolonged (hardenability increases minimally), while the location of the start of the pearlitic transformation remains practically the same. This observation, being a part of designing the ferrous alloys structure, can be successfully utilised, among others, in steels for working rolls for plates cold-rolling. Due to that in these expensive tools we are able to soften the influence of the structural notch, which is formed - at a certain depth - by the upper bainite layer, in steels without silicon additions.
Design/methodology/approach: Dilatometric investigations were performed using a DT 1000 dilatometer of a French company Adamel.
Findings: An addition of 1 mass % of silicon causes a gradual vanishing of the steel bainitisation, being the bainite slipping in 'under pearlite', due to which the austenite, at continuous cooling, will be at first transformed into pearlite, on its grain boundaries, and only later - inside grains - into bainite. Even if it is the upper bainite its location inside grains, within the pearlite envelope, is less dangerous for the crack resistance than its location on grain boundaries.
Research limitations/implications: These observations can be utilized for steels in which the bainitic transformations are shifted in the direction of shorter times (e.g. in chromium - molybdenum steels). Especially when this is the upper bainite known for its low crack resistance.
Practical implications: Due to this work in expensive tools we are able to soften the influence of the structural notch, which is formed - at a certain depth - by the upper bainite layer, in steels without silicon additions.
Originality/value: Details descriptions of influence of the Si content on the kinetics of phase transformations during cooling in model ferrous carbon alloys with a weak background and also strong background of other alloying elements.
Keywords: Metallic materials; Hardening; Phase transformations; Microstructure formation

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1. Introduction

Metallurgical rolls belong to the most expensive tools applied in steel industry. A special attention, both in respect to materials and to technologies, is focused on working rolls production for cold-rolling mills [2]. A high hardness, to a depth up to 35 mm under the surface [at least 880 HV (94HS)] is required, good tribological properties - abrasion and surface wear resistance as well as a sufficient crack resistance also required, cause that the basic materials for these tools are high carbon (app. 0.80% C) chromium - molybdenum steels containing 1.70-3.00%Cr and 0.20-0.40% Mo. Sometimes, to increase their hardenability, small amounts of manganese (up to 0.50%) are added. Chromium and especially molybdenum (also manganese) favour the steel bainitisation [3,4,5] by their inclination to a grain boundary (austenite) segregation and lowering their energy. It renders difficult a nucleation of diffusive structures, it means ferrite and pearlite, on these boundaries by prolonging a nuclei formation time. Thus, within a certain range of cooling rates, it means at a certain depth under the roll surface, the bainite is formed. If it is steel with chromium, it is nearly certain that this will be the upper bainite. Morphologic features of this microstructure (carbides at the boundaries of supersaturated ferrite laths) cause its very low crack resistance (cracking at a relatively small stress) [6]. If during a roll operation such (small) stress is exceeded, then in the upper bainite zone, it means at a certain depth under the roll surface a cracking process starts, and more precisely: a spalling of the upper surface of the roll occurs. This is a quite common defect of rolls for cold-rolling of plates of a chromium - molybdenum composition.

Trials of eliminating the structural notch, formed by the upper bainite at a certain depth in each chromium - molybdenum roll, were as follows

1. Addition of manganese [7,8] - to lower the bainite start temperature, Bs. This admittedly eliminated (at a significantly large addition) the upper bainite, however increased the steel hardenability so strongly that rolls were cracking soon after starting operations.
2. Increasing of the molybdenum content in steel [3,4,5], since this element favours the steel bainitisation and simultaneously lowers (nearly so strongly as manganese) the bainite start temperature, Bs. However, the molybdenum content can be only increased to app. 0.40%. At higher contents this element starts forming sparingly soluble own carbides, which completely eliminates its influence on lowering the Bs temperature.
3. Increasing of the carbon content in steel [9], since it decreases the Bs temperature the most strongly. However, it favours a formation of large amounts of secondary carbides, which - remaining undissolved - significantly decrease the steel hardenability and all attempts for the austenitising temperature increase (even quite moderate) always lead to a strong increase of the retained austenite volume fraction [10] and consequently to the hardness decrease of rolls after quenching.

In this paper a special attention was directed towards silicon. This elements is not forming carbides in steels [11,12] and it is generally believed [13,14], that it increases the steel hardenability assessed by traditional indices, e.g. by the hardenability coefficient f, only insignificantly.

The influence of silicon - at the background of other alloying elements - on the hardenability coefficient f, in low and middle carbon steels according to A.F. Retana and D.V. Doane in [13] and in high-carbon steels acc. to C.F. Jatczak [14], are shown in Fig. 1.

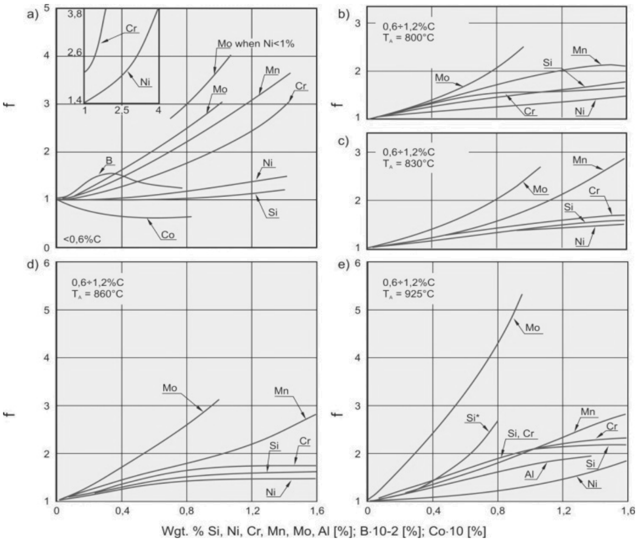


Fig. 1. Coefficients of hardenability f for steels: a) low- and medium carbon content, acc. to A.F. Retana and D.V. Doane in [13]; b, c, d, e) high carbon content, acc. to C.F. Jatczak [14]
Si* - concerns the medium alloy steels with bainitic output structure

However the silicon influence is more complex. It is known, on the basis of investigations [1], that this element behaves differently in ferrous alloys containing carbon of a weak background of other alloying elements and when the background of these other elements is strong. The results of investigations of A.F. Retana and D.V. Doane and C.F. Jatczak concern ferrous alloys with carbon (steel) of a strong background of other elements. In addition, they do not provide any information on a diversified silicon influence on the time before the ferrite precipitation or pearlite or bainite formation starts, while according to [1] this time is diversified.

In products of ferrous alloys, especially in metallurgical rolls for plates cold-rolling, in which a problem of the upper bainite formation occurs (at a certain small distance below the surface) the silicon influence on the starting time of the transformation, especially the pearlitic transformation, can have a fundamental meaning. If, due to silicon adding, times before the pearlitic transformation start were shorter, then at the cooling rates lower than the critical rate there would be a possibility of ‘covering’ the austenite transformation into the upper bainite by the austenite transformation in the pearlite (occurring at higher temperatures). Since the favoured places of the pearlite nucleation are austenite grain boundaries, only the insides of the austenite grains will be left for the bainite formation. Such location of the pearlite and bainite (even upper) is much better from the crack resistance point of view, since it softens the structural notch of the upper bainite at the austenite grain boundaries and eventually martensite inside them.

When investigating the possibility of silicon influencing the location of the pearlitic and bainitic transformation one should not forget that, when these transformations are finished, this element cumulates in ferrite of the pearlite, in supersaturated ferrite of the bainite or in martensite, decreasing their crack resistance (see data of A.P. Gulajev [15] in Fig. 2). Therefore additions of silicon to every steel, not only tool steels, should not be exaggerated. In structural steels the silicon content should not exceed 0.50 mass% [16], while in tool steels, especially for working rolls in cold-rolling mills, which after quenching achieve the highest possible hardness (in steels) the silicon content can be larger. This is so, since steel of the layer thickness of app. 35 mm is very hard and brittle and the silicon addition serve only to softening the structural notch formed by the upper bainite at its transformation from the martensitic structure to the pearlitic one.

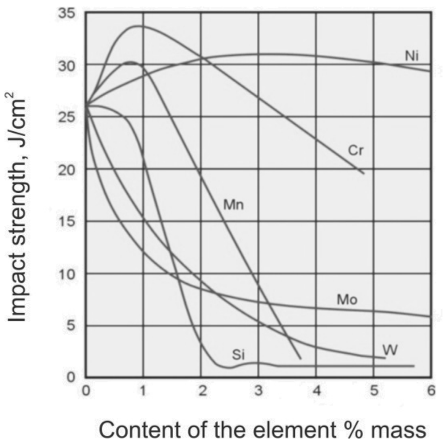


Fig. 2. Influence of alloying elements dissolved in ferrite on its impact strength, acc. A.P. Gulajev [15]

2. Silicon influence on the microstructure formation in model steel alloys

These investigations were performed within study [1]. They were carried out on two groups of model alloys. The first group consisted of four Fe alloys containing 0.32-0.33% C, a weak background of other alloying elements and an increasing Si content, in a range: 0.48-1.15%. The second group consisted of two Fe alloys containing also 0.32-0.33% C, but a strong background of other elements and an increasing Si content, in a range: 0.50-0.92%.

2.1. Silicon influence on the microstructure formation in model steel alloys of a weak background of other elements

Four Continuous Cooling Transformation diagrams (CCT) for model alloys of a weak background of other alloying elements but of an increasing Si content, quoted from paper [1], are presented in Fig. 3. It can be easily noticed that when the Si content increases from 0.48 to 1.02% (Fig. 3a,b,c) the hardenability of the investigated alloys decreases. The times before starting of the ferrite precipitation and the bainite formation shorten. Especially important is shortening of time before the start of the pearlite formation. Only when the Si content was increased to 1.15% the hardenability decreasing process stopped and a minimal increase occurred.

2.2. Silicon influence on the microstructure formation in model steel alloys of a strong background of other elements

Two CCT diagrams for model alloys of a strong background of other elements and of an increasing Si content, also quoted from paper [1], are presented in Fig. 4. In this case, an increase of Si content from 0.50 to 0.92% caused a small hardenability increase (decrease of the critical cooling rate) but simultaneously decreased the steel susceptibility for bainitisation and ferritisation by shortening times of these transformations, before the pearlitic transformation, the start of which remains nearly exactly in the same place. This creates hope for the possibility of decreasing - by Si additions - the susceptibility for bainitisation of tool Cr-Mo steels, including steel for working rolls in cold-rolling mills.

On the bases of the CCT diagrams shown in Figs. 3 and 4 the opinion can be risked that the Si content up to 1.02% in alloys of a weak background of other elements decreases the steel hardenability by shifting all transformations to the left, it means to the shorter times direction. However, at higher Si contents and in alloys of a strong background of other elements Si slightly increases the hardenability but simultaneously - contrary to Mo, Cr, Mn - significantly decreases the steel susceptibility for bainitisation. It manifests itself by the easy ferrite and pearlite nucleation on austenite grain boundaries (which can indicate e.g. their energy increase) and also by shortening the so-called nose of the bainitic transformation.

3. Silicon influence on the microstructure formation in tool steels intended for working rolls for plates cold-rolling

Two CCT diagrams for two steel grades intended for working rolls in cold-rolling plate mills, varying only in the silicon content are shown in Fig. 5. The first contained 0.30% Si and the second 0.87 mass%. As can be seen, the higher Si content shown in Fig. 5b, caused the shortening of the start of the pearlitic transformation at simultaneous prolongation the time before the start of the bainitic transformation (which means a decrease of the susceptibility to bainitisation). As the effect of these two influences, the bainitic transformation zone was nearly completely hidden from the pearlitic transformation, which caused that the crack resistant pearlite precipitated at the austenite grain boundaries as the first one.

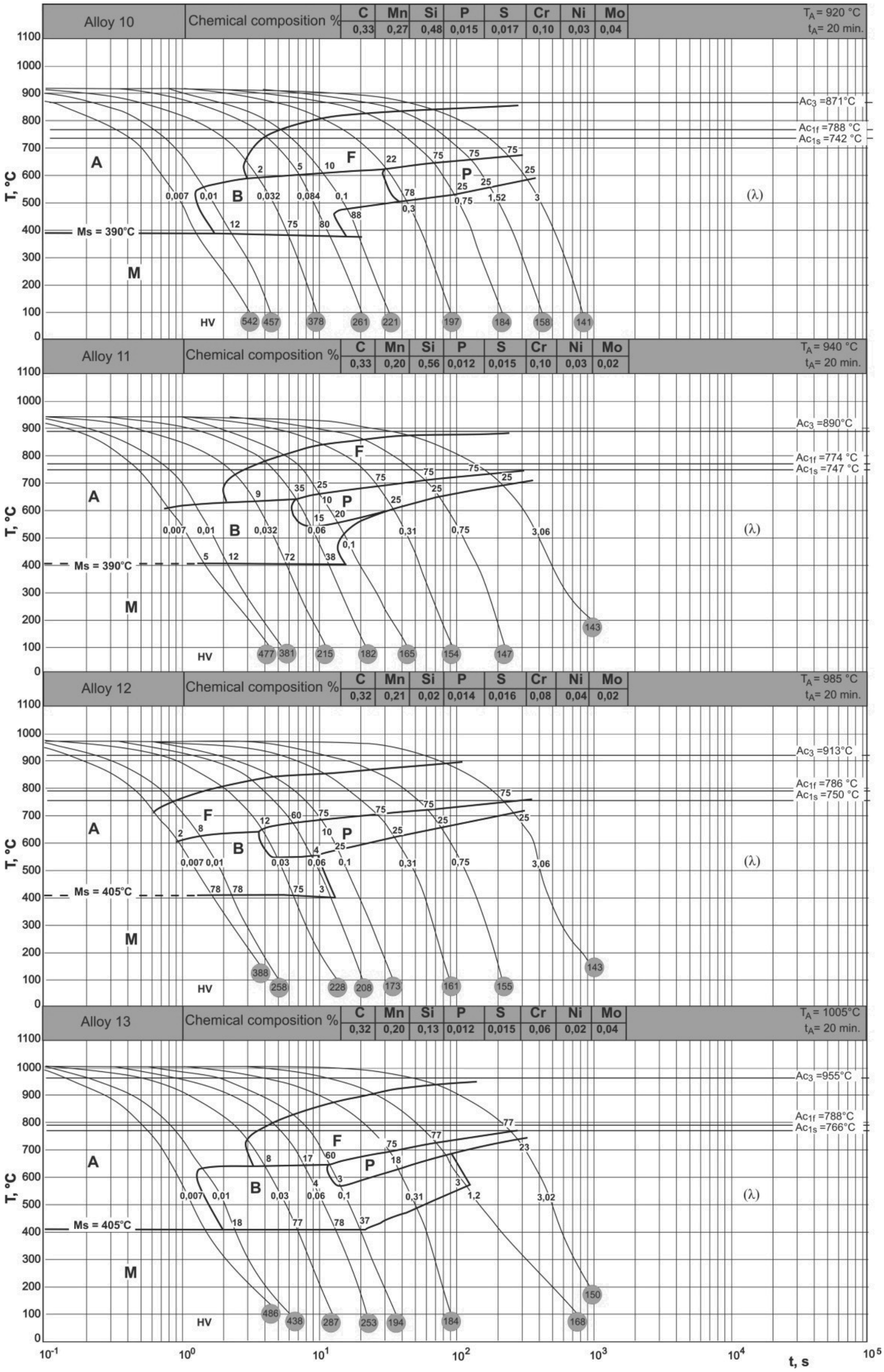


Fig. 3. Silicon influence on the kinetics of phase transformation of undercooled austenite in model alloys containing 0.32-0.33% C and a weak background of other elements [1]

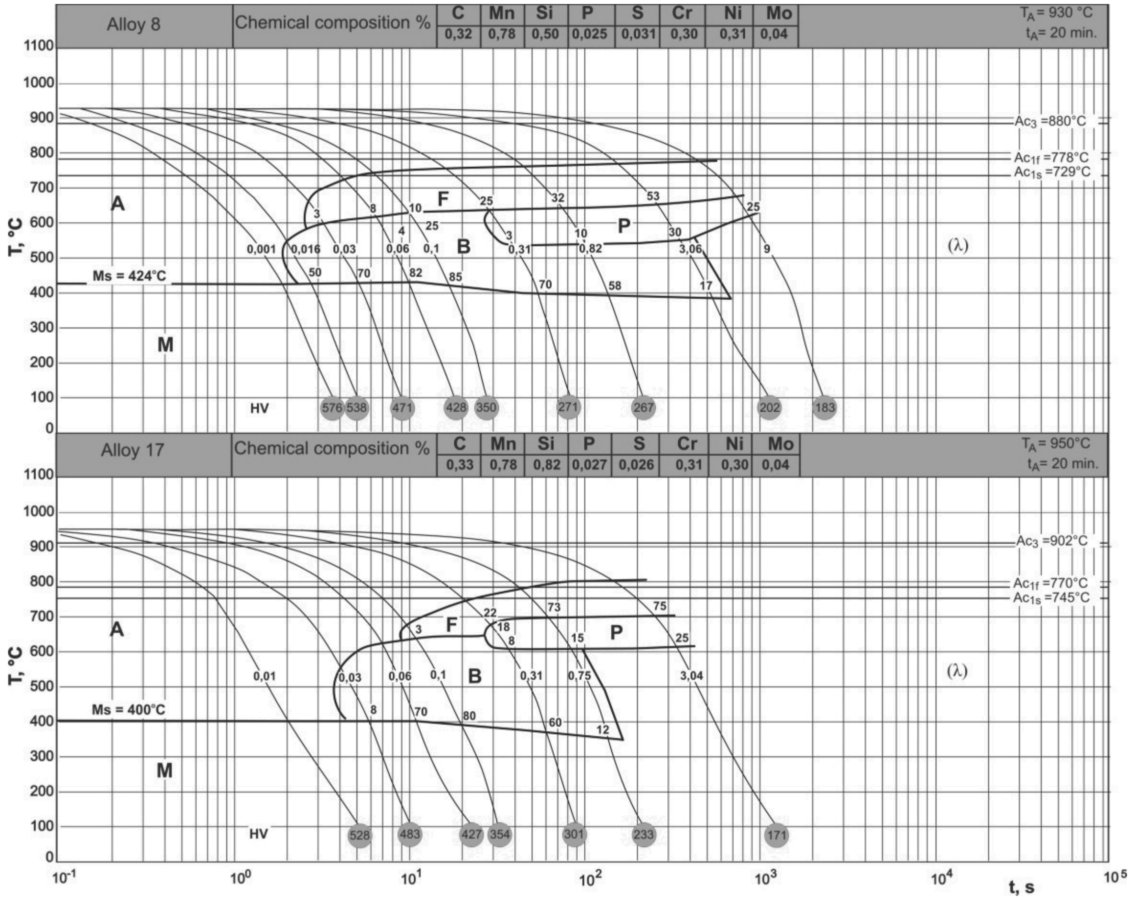


Fig. 4. Silicon influence on the kinetics of phase transformation of undercooled austenite in model alloys containing 0.32-0.33% C and a strong background of other elements [1]

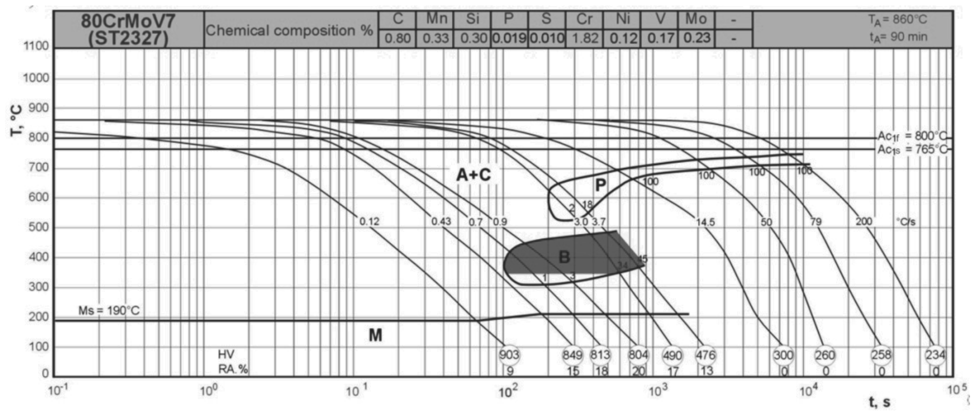
Admittedly the bainitic transformation nose sticks out a little bit in front of the start of the pearlitic transformation zone, in steel with silicon (Fig. 5b) but at a much smaller degree than in the case of steel with a lower Si content shown in Fig. 5a. Probably, if slightly more Si was added to steel shown in Fig. 5b (app. 1%), it would be possible to avoid completely the upper bainite zone on the roll cross-section.

The presented in the hereby paper influences on the steel microstructure, at cooling rates lower than the critical rate, to increase its crack resistance can be effectively applied for the quality improvement not only of tools (metallurgical rolls) but of all kinds of driving, transmission, wind power plant shafts and other shafts of such cross-sections on which there is a risk of the upper bainite formation, dangerous from the point of view of the crack resistance.

4. Conclusions

1. Silicon is an element which - at a content to app. 1 mass% - decreases the hardenability of ferrous alloys with carbon of a weak background of other elements. This concerns the ferrite precipitation range as well as the pearlitic and bainitic transformation ranges.
2. Silicon moderately increases the hardenability of ferrous alloys with carbon of a strong background of other elements. This concerns prolongation of times before the starts of the ferrite precipitation and bainitic transformation. However, it does not concern the pearlitic transformation and due to that, the steel inclination for bainitisation decreases.
3. It is possible to limit the structural notch occurrence by means of silicon via its influence on the location of the pearlitic and bainitic zones, in steels for working rolls for plates cold-rolling. The structural notch is caused by the formation of the upper bainite on the prior austenite grain boundaries at a certain depth under the surface of the quenched roll. This should improve the safety of these tools exploitation.
4. Silicon can be used for softening or liquidation of structural notches related to the formation of the upper bainite - at a certain depth under the surface - in all Cr-Mo steels intended for heavy forgings, which due to bainitising influence of Mo and Cr are prone to such notches formation during quenching.

a)



b)

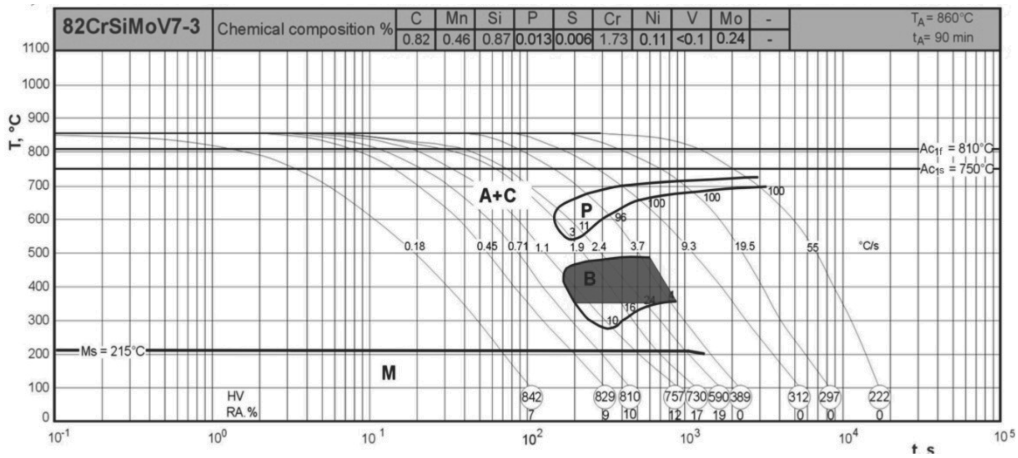


Fig. 5. The CCT diagrams for grade steels: a) 80CrMoV7, b) 82CrSiMoV7-3. The upper bainite area are marked

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