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FINE-GRAINED STRUCTURAL STEEL WITH CONTROLLED HOT ROLLING

DROBNOZRNATA KONSTRUKCIJSKA JEKLA S KONTROLIRANIM VALJANJEM

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The effect of rolling temperature and the content of carbon, manganese and niobium on the ferrite-pearlite grain size in steels cooled from the finishing rolling temperature is presented. It is shown that very fine-grained steels can only be obtained with transformation of fine-grained recrystallised austenite and hindering the grain growth with strain-induced nitride and carbonitride precipitates.

Key words: structural steels, grains size, finishing rolling temperature, composition, interpass recrystallisation, austenite

Predstavljeni so vplivi temperature valjanja in vsebnosti ogljika, mangana ter niobija na velikost zrn ferita in perlita po ohladitvi konstrukcijskih jekel na zraku. Dokazano je, da je mogoče doseči zelo majhna zrna le s premeno drobnozrnatega rekristaliziranega avstenita in preprečenjem rasti zrn z deformacijsko induciranimi nitridnimi in karbonitridnimi izločki.

Ključne besede: konstrukcijska jekla, velikost zrn, končna temperatura valjanja, sestava, rekristalizacija, avstenit

1 INTRODUCTION

With decreasing ferrite grain size three essential properties of structural steels are improved: the yield stress and the Charpy notch toughness are strongly increased and the transition temperature for the ductile-to-brittle fracture is decreased [1,2]. With water-quenching and the tempering of plates of steels with different compositions, yield stress values up to 1000 MPa are achieved. In the steel with 0.08% C, 0.34 %Si, 0.36 %Mn, 0.54 %Cr, 0.27 %Ni and 0.058 %Nb the microstructure of distorted ferrite and pearlite, the average intercept grain size of 1.7 µm and the yield stress of 500 MPa are achieved. With similar heat treatments of a 0.14 %C steel with higher contents of chromium and nickel, and the addition of molybdenum, a microstructure of tempered martenzite is obtained with the intercept grain size below 1 µm, the yield stress of 1000 MPa, and good weldability. After normalising in a 0.17 %C, 0.32 %Si, 1.28 %Mn, 0.21 %Cr, 0.13 %Ni steel a microstructure of polygonal ferrite and pearlite with an intercept grain size of 16.6 µm and the yield stress of 377 MPa was obtained. In the three steels the share of yield stress contributed by the grain size was 254, 502 and 135 MPa, rsp. 36.3 %, 50.4 % and 51.7 % of the actual yield stress [1]. Thus, the industrial interest in achieving a greater yield stress for structural steels with small grain size is evident. In addition to the heat treatment of rolled plates, two processing routes for the elaboration of ultrafine-grained ferritic structural steels with a grain size in the range of 1 µm were investigated [3]:

Transformation grain refinement. In this procedure the austenite-ferrite transformation is used to achieve the refined ferrite from a previously fine-grained austenite. With double hot rolling and intermediate precipitation annealing as well as cold rolling of a 0.1 %C, 1.42 %Mn, 0.039 %Al, 0.005 %N and 0.035 %Nb steel the limit grain size of approximately 0.4 µm was obtained in the quoted investigation. With hot rolling and controlled austenite transformation in the steel with 0.05 %C and 1.5 %Mn the grain size from 3 to 8 µm and the yield stress of 690 MPa were achieved [4].

Recrystallisation grain refinement. This procedure involves the recrystallisation in the ferrite field. The processing is achieved with warm working at high temperature or with static recrystallisation of cold-deformed austenite.

Using the emerging ECAP (equal-channel angular pressing) processing [5] a grain size well below 1 µm can be achieved and a yield stress of 675 MPa can be obtained with an interstitial-free steel [6].

In this article the results of an investigation into the evolution of the microstructure during the hot rolling of several industrial steels are presented. The steels were selected with the aim to determine the effect of the interpass recrystallisation of austenite of the content of carbon, manganese and niobium; of the austenite-to-ferrite transformation austenite to ferrite during the rolling process and of the hindered interpass recrystallisation of austenite.

2 EXPERIMENTAL WORK

The composition of the investigated steels is presented in **table 1**. All the steels are aluminium killed and the content of aluminium and nitrogen is sufficient to induce the precipitation of aluminium nitride in the rolling-temperature interval. Billets of thickness 55 mm were heated to 1200 °C and rolled at this initial temperature or after cooling to a low temperature with the aim to obtain a rolling-temperature interval from 1050 °C to approximately 760 °C. The average per-pass deformation was 16 % and sufficient to induce the interpass recrystallisation of austenite at sufficient temperature [7,8]. The rolled plates of thickness 16 mm were cooled in air on a fireclay bed. Specimens for optical microscopy were prepared from the plates in the conventional way. The content of precipitates of aluminium-nitride (AlN) and niobium-carbonitride (NbC) was determined using a modified halogen-extraction method [9].

Table 1: Composition of the investigated steels
Tabela 1: Sestava raziskanih jekel

Steel	Element, mass%							
	C	Si	Mn	S	N	Al	Nb	V
S.	0.04	0.01	0.34	0.01	0.0049	0.025	-	-
K.	0.13	0.22	0.46	0.03	0.0053	0.032	-	-
B	0.16	0.33	1.24	0.026	0.0054	0.026	-	-
C	0.14	0.42	1.46	0.01	0.011	0.05	0.051	0.07

3 RESULTS AND DISCUSSION

In spite of the rolling in temperature range where austenite was supersaturated with AlN, according to the solubility product in [10], this compound did not precipitate in the 0.16 %C, 1.24 %Mn steel in significant quantity also when all the rolling was performed in austenite region in the temperature interval from 900 °C to 790 °C (**Figure 1**). This indicates that the rate of deformation and interpass recrystallisation were too fast to enhance in a significant way the precipitation process, which is accelerated by the plastic deformation and in deformed state of austenite to a great extent [11,12]. On the contrary, the precipitation of AlN and NbC was very significant in the 0.14 %C, 1.46 %Mn, 0.051 %Nb steel. With the finishing temperature of 830 °C and 790 °C virtually all the disponible AlN and NbC were in the form of precipitates. This is explained by the fact that niobium has the strongest delaying effect on interpass recrystallisation of austenite of all steel microalloying elements [13]. The explanation for the mechanism of the delaying effect of niobium is that strain-induced precipitates hinder the recrystallisation nuclei from reaching the critical size necessary for their growth in the deformed matrix. Within this context it is not clear why the effect of titanium is smaller than that of niobium. In terms of equal weight content the atomic content of titanium is greater and the solubility product of TiC in austenite is even smaller than that of NbC.

In the steel with 0.04 %C the grain size decreases regularly with the decreasing rolling temperature in the austenite range (**Figure 2**), as expected with interpass recrystallisation of austenite and slower grain growth because of the lower temperature [14]. A microstructure of polygonal ferrite and pearlite is obtained after transformation of the recrystallised austenite with air cooling (**Figure 3**) With a low rolling temperature, when a significant share of the rolling is performed in ferrite range, the grain size starts to increase and a microstructure consisting of two components is produced: coarse non-polygonal ferrite grains and smaller polygonal ferrite and pearlite grains (**Figure 4**). Such a microstructure indicates that the austenite-to-ferrite transformation did occur during the rolling. The presence of ferrite started to increase after the minimum grain size was achieved with transformation of recrystallised austenite. With a low rolling temperature the per-pass deformation was too low to induce the static recrystallisation of ferrite [15,16]. The interpass grain coarsening of ferrite occurs with strain-induced grain

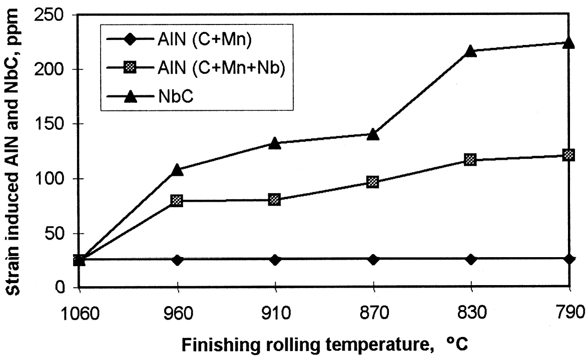

Figure 1: Content of AlN in the 0.16 %C, 1.24 %Mn and of AlN and NbC in the 0.14 %C, 1.46 %Mn, 0.051 % Nb steels in dependence of the finishing rolling temperature
Slika 1: Vsebnost AlN v 0,16 %C, 1,24 %Mn in AlN oz. NbC v 0,14 %C, 1,46 %Mn, 0,051 %Nb jeklih v odvisnosti od končne temperature valjanja

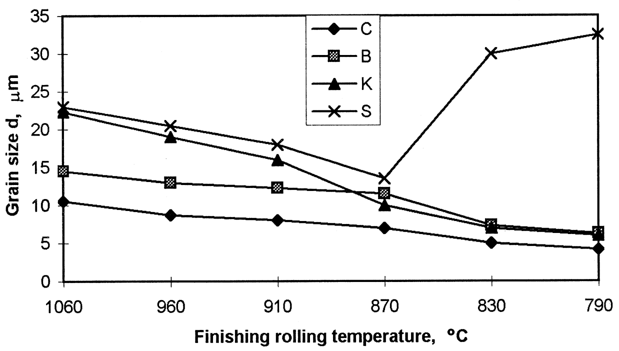

Figure 2: Linear intercept grain size of the steels in dependence of the rolling temperature
Slika 2: Linearna intercepcijska velikost zrn jekel v odvisnosti od končne temperature valjanja

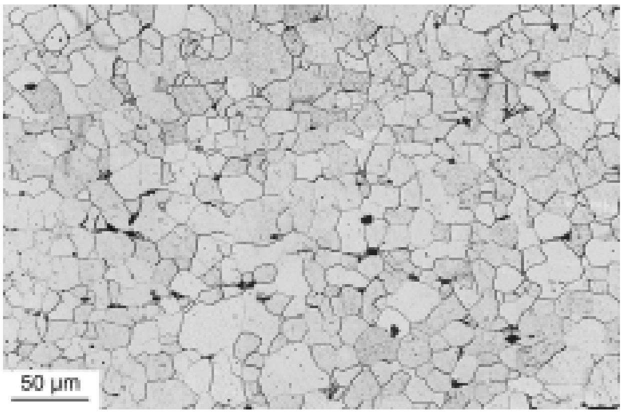

Figure 3: Microstructure of the 0.04 % C steel with finishing rolling temperature of 867 °C

Slika 3: Mikrostruktura 0,04 %C jekla pri končni temperaturi valjanja 867 °C

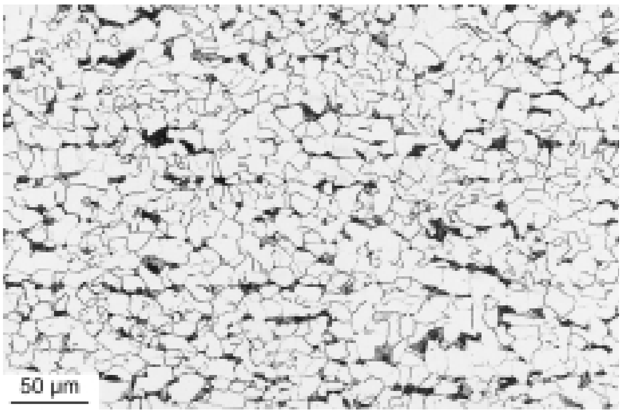

Figure 5: Microstructure of the 0.13 %C steel with finishing temperature of 820 °C

Slika 5: Mikrostruktura 0,13 %C jekla pri končni temperaturi valjanja 820 °C

growth and it is the greater, the greater part of the rolling is performed in the two-phase austenite+ferrite range and the greater is the share of ferrite in the microstructure. The investigation of this steel demonstrates that no decrease of grain size could be expected if the finishing rolling passes are performed significantly below the austenite-to-ferrite transformation temperature.

In the 0.13 %C steel the grain size decreases in a similar way as in the 0.04 %C steel down to the the temperature of the onset of the austenite-to-ferrite transformation during the rolling, and it changes little when the temperature is further decreased. In the range of static recrystallisation of austenite the microstructure was similar to that in **Figure 2**, with a higher share of pearlite (**Figure 5**). With low temperature two constituents of the microstructure are found (**Figure 6**) again: a matrix of partially polygonal small ferrite pearlite grains in areas where the plastic deformation was sufficient to induce the static recrystallisation of ferrite formed during the rolling, and lens-shaped colonies of coarser non-polygonal ferrite and pearlite grains produced, evidently, through high-temperaure transformation of non-recrystallised austenite. In this steel the intercept grain size in fine-grained areas was of 7.5 µm and of 12.4 µm in coarse-grained areas with the finishing temperature of 820 °C. The sizes were 6.3 µm and 11.2 µm, respectively, for a finishing temperature of 774 °C.

Also with the carbon content of 0.13 %, no significant decrease in the grain size can be achieved when the rolling is performed to a significant extent in the austenite+ferrite range of temperature. It is important to note that the grain size of this steel, with rolling in austenite range, is smaller than that of the 0.04 % C steel. It is assumed that the difference cannot be ascribed to the effect of carbon on the interpass recrystallisation but to the lower austenite-to-ferrite transformation temperature.

By rolling the 0.16 %C - 1.2 %Mn steel a still lower grain size is obtained with air- cooling from the finishing temperature because of the still lower austenite-to-ferrite transformation temperature due to the effect of the

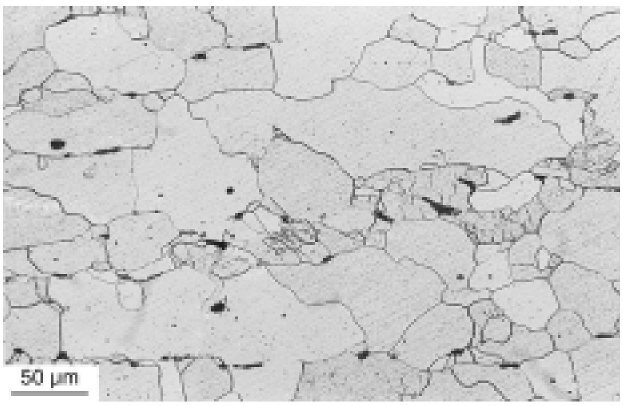

Figure 4: Microstructure of the 0.04 % C steel with finishing temperature of 817 °C

Slika 4: Mikrostruktura 0,04 %C jekla pri končni temperaturi valjanja 817 °C

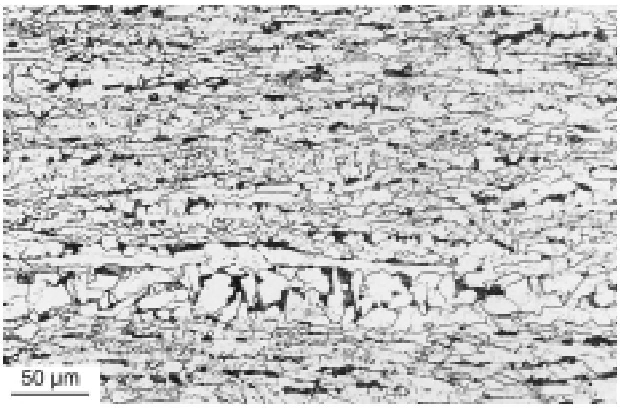

Figure 6: Microstructure of the 0.13 %C steel with finishing temperature of 774 °C

Slika 6: Mikrostruktura 0,13 %C jekla pri končni temperauri valjanja 774 °C

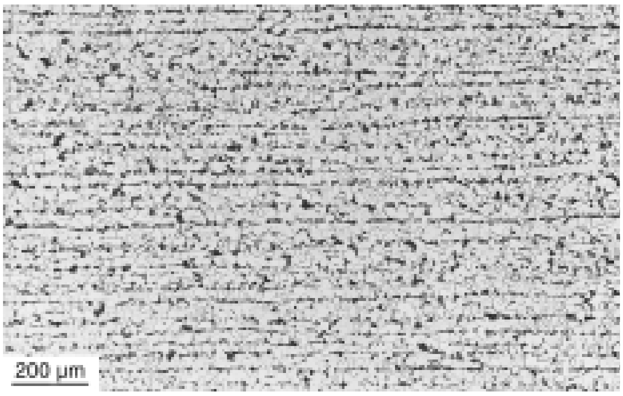

Figure 7: Microstructure of the 0.16 %C, 1.24 %Mn steel with finishing temperature of 910 °C

Slika 7: Mikrostruktura 0,16 %C, 1,24 %Mn jekla pri končni temperaturi valjanja 910 °C

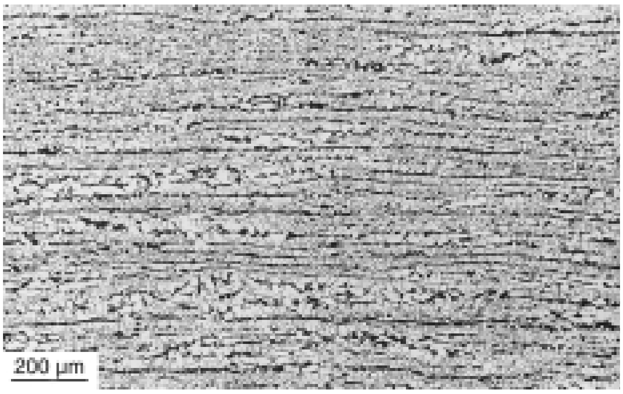

Figure 8: Microstructure of the 0.16 %C, 1.24 % Mn steel with finishing temperature of 790 °C

Slika 8: Mikrostruktura 0,16 %C, 1,24 %Mn jekla po končni temperaturi valjanja 790 °C

increased content of manganese. With a finishing temperature below approximately 870 °C the grain size decreases faster with decreasing rolling temperature than above this level as a result of the transformation of the non-recrystallised austenite at lower temperature With high rolling temperature the microstructure consists of fine polygonal ferrite and pearlite grains produced by the transformation of recrystallised austenite (**Figure 7**). With a lower temperature the interpass recrystallisation of austenite is not completed and lens- shaped colonies of coarser non-polygonal ferrite grains are found in a matrix of fine- grained ferrite and pearlite grains (**Figure 8**). The colonies are formed with high-temperature transformation of austenite, which remained unrecrystallised after several passes, while the fine-grained matrix was formed with the transformation of recrystallised austenite.

It is conclude that with this type of steel a grain size below 5 µm could be obtained with the optimal combination of rolling temperature and cooling rate.

Due to the delaying effect of niobium on interpass recrystallisation as well as on the recrystallised grains

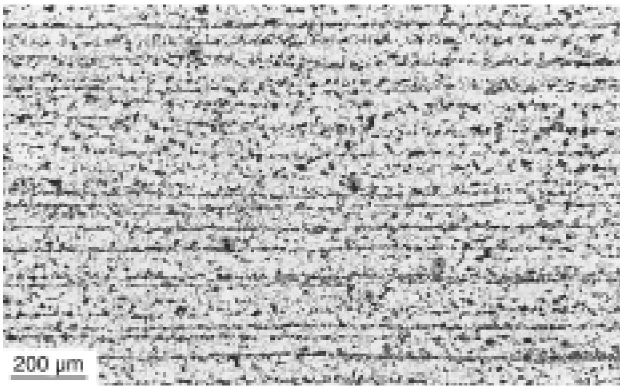

Figure 9: Microstructure of the 0.14 %C, 1.46 % Mn, 0.051 %Nb steel with finishing temperature 960 °C

Slika 9: Mikrostruktura 0,14 %C, 1,46 %Mn, 0,051 %Nb jekla pri končni temperaturi valjanja 960 °C

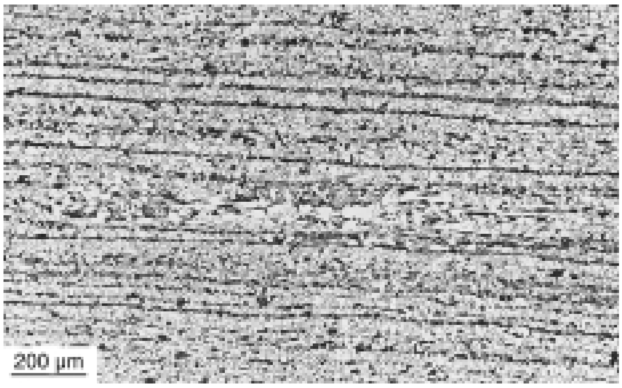

Figure 10: Microstructure of the 0.14 %C, 1.46 %Mn, 0.051 %Nb steel with finishing temperature 870 °C

Slika 10: Mikrostruktura 0,14 %C, 1,46 %Mn, 0,051 %Nb jekla pri končni temperaturi valjanja 870 °C

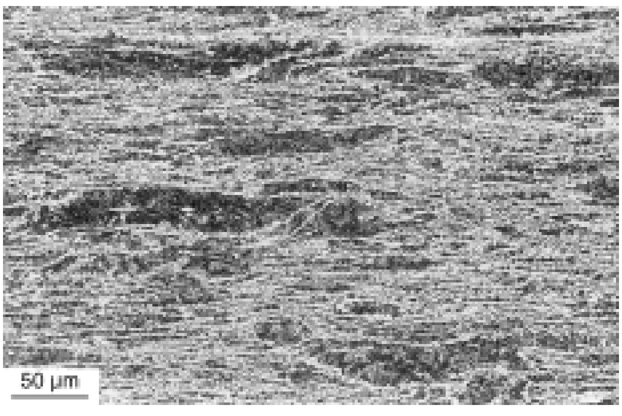

Figure 11: Microstructure of the 0.14 %C, 1.46 %Mn, 0.051 %Nb steel with finishing temperature 790°C

Slika 11: Mikrostruktura 0,14 %C, 1,46 %Mn, 0,051 %Nb jekla pri končni temperaturi valjanja 790 °C

nucleation and growth in interpass time the grain size is significantly smaller in the 0.14 %C - 1.46 %Mn - 0.051 %Nb steel than in the 0.16 %C - 1.24 %Mn steel in the whole rolling-temperature range. The microstructure is similar to that in the 0.16 %C - 1.24 %Mn steel. Only regular polygonal ferrite and pearlite grains are found after sufficient finishing temperature (**Figure 9**), lens-shaped colonies of non-polygonal and coarse grains in a fine-grained matrix at intermediate temperature (**Figure 10**) and still small-grained matrix and coarse ellongated grains of bainitic appearance at still lower temperatures (**Figure 11**).

It seems justified to conclude that with this steel a microstructure consisting of only a fine-grained matrix would be obtained with slower cooling from the finishing temperature or with holding the rolled plates at a temperature, which would prevent the transformation of non-recrystallised austenite grains to bainite if the recrystallisation of austenite was completed after several last passes. A grain size significantly below 5 μm would be obtained by optimisation of the rolling process and the transformation of the non-recrystallised austenite at a temperature of slow ferrite grain growth.

4 CONCLUSION

From the presented results it could be conclude that by optimisation of the hot rolling and cooling, the isothermal holding of the rolled steel at the appropriate finishing and lower temperature, a fine-grained micro-structure can be obtained by considering the following four provisions:

– the finishing rolling temperature should be low and the rolling performed above the austenite-to-ferrite transformation temperature,
– the recrystallisation of austenite should be completed after several last rolling passes,
– the austenite-to-ferrite transformation temperature should be low, and
– the recrystallised austenite and transformation ferrite grain growth should be hindered by a sufficient quantity of strain-induced precipitates.

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