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AS-ROLLED MULTI-PHASE MICROALLOYED STEEL BARS WITH IMPROVED PROPERTIES

VALJANE VEČFAZNE MIKROLEGIRANE JEKLENE PALICE Z IZBOLJŠANIMI LASTNOSTMI

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A series of experimental steels, based on a 0.3 C, 1.5 Mn, 0.1 V composition, with and without 0.01% Ti addition, was made by laboratory and full-scale casting, and fabricated into 22 mm dia bars by full-scale hot-rolling. Multi-phase Polygonal Ferrite-Pearlite-Non Polygonal Ferrite (PF-P-NPF) structures, with varying amount of NPF, are obtained in as-rolled bars. Acicular Ferrite (AF) and classical Bainite Sheaves (BS) are found to be dominant NPF morphologies in steels with a low (<30%) and a high (>40%) fraction of NPF, respectively. In Ti-bearing PF-P-AF steels, the PF-grain and P-colony size control, obtained through fine TiN particles, which also provide preferential sites for intragranular nucleation of AF, a tensile strength of 800/850 MPa and 900/950 MPa in 0.2 and 0.3 C steels was obtained, while maintaining the room temperature CVN impact energy at a level of 65/75 J and 40/50 J, respectively. A high fraction of grain boundary nucleated BS is promoted by increasing the content of Cr, Mo or Mn above the base level. The main effect of introducing BS into structure is a drop in impact toughness. Even so, in some BS dominated steels (notably Cr treated) an impact energy of 30/35 J is maintained at a tensile strength level of 1050/1100 MPa. These results have provided a bases for the development of as-rolled medium carbon microalloyed engineering bars, that achieve satisfactory properties in the as-rolled conditions without the need for subsequent heat treatment.

Key words: microalloying, bar-rolling, polygonal ferrite, pearlite, non-polygonal ferrite, bainite, acicular ferrite, strength, toughness

Vrsta eksperimentalnih jekel z osnovno sestavo 0.3 C, 1.5 Mn in 0.1 V z ali brez dodatka 0.01% Ti je bila izdelana z laboratorijskim in z industrijskim vlivanjem ter industrijsko izvaljana v 22 mm palice. Dosežene so več fazne poligonalni ferit-perlitne - poligonalni ferit (PF-P-NPF) mikrostrukture z različnim deležem NPF. Acikularni ferit (AF) in klasični bajnitni snopi (BS) so prevladujoče NPF morfologije v jeklih z majhnim (<30%) in velikim (>40%) deležem NPF. V PF-P-AF jeklih z dodatkom Ti, kjer je dosežena kontrola velikosti zrn PF in P kolonij z izločki TiN, ki so tudi prednostna mesta za intragranularno nukleacijo AF, je bila dosežena pri 0.2 in 0.3 C jeklih natezna trdnost 800/850 in 900/950 MPa. Pri tem je ostala CVN udarna energija pri temperaturi ambienta 65/75 oz. 40/50 J. Velik delež BS z nukleacijo na kristalnih mejah se doseže z dodatkom Cr, Mo ali Mn nad osnovno vsebnostjo. Glavna posledica prisotnosti BS v mikrostrukturi je zmanjšanje udarne žilavosti. Vendar je bila tudi v nekaterih jeklih s prevladujočo BS (predvsem z dodatkom Cr) ohranjena udarna energija 30/35 J pri trdnosti 1050/1100 MPa. Ti rezultati so bili osnova za razvoj srednje ogljičnih konstrukcijskih jekel, ki imajo v valjanem stanju dobre lastnosti brez dodatne toplotne obdelave.

Ključne besede: mikrolegiranje, valjane palice, poligonalni ferit, perlit, ne poligonalni ferit, bainit, acikularni ferit, trdnost, žilavost

1 INTRODUCTION

Medium-carbon microalloyed (MA) forging steels have been extensively studied over the past decade, and the results are reported at several international conferences (e.g.[1-3]). There are many examples to show that MA steels can replace Q&T steels in as-forged and air-cooled conditions, without subsequent heat treatment. However, in the ferrite-pearlite (FP) version, these steels suffer from inferiors notch toughness. In the last few years, bainite (B) and martensite (M) type grades, have received considerable attention as viable candidates to replace FP steels. Compared to M type (e.g.[4,5]) the air-hardened B-type grades need not quench, but the improvement in toughness is not as-spectacular[4,6-13], and in some instances a deterioration in toughness is claimed[14-16]. This as well as other disadvantage of B-grades, such as a low yield ratio[13,17] and poor machinability[7], may be among the reason why they are scarcely used[17].

The strength and toughness of as-hot rolled bars have been less extensively studied in comparison to forgings. However, while considerable work has been done to improve the toughness of conventionally or controlled rolled bars in FP version (e.g.[13,18,19]), little effort has been made to improve the toughness of bars by introducing B into structure. Improvements achieved in this work are mostly based on recent results which show[20,21] that, while some B-morphologies are beneficial, the other are detrimental to toughness.

2 EXPERIMENTAL DETAILS

2.1 Material

A series of experimental heats, based on 0.3% C, 1.5% Mn, 0.1% V composition (small variations among different heats are included in **Table 1**) with and without 0.01% Ti addition, is used in this work. A number of heats were modified by either reducing the content of some additions (e.g.: C to 0.2%; N to 15-60 PPM; V, Ni and Cu to traces) or increasing the content of other additions above the base level (e.g.: Mn to 1.55/1.65 or

1.72/1.78%; Cr to 0.37/0.38 or 0.57%; Mo to 0.21%; V to 0.16/19%; N to 160/240 ppm; S to 150/250 ppm).

Table 1: Steel compositions (in wt.%)
Tabela 1: Sestava jekel (v ut.%)

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	V
0.27	0.29	1.47	0.006	0.006	0.21	0.03	0.15	0.02	0.18	0.010	0.10
0.32	0.39	1.57	0.010	0.010	0.30	0.06	0.19	0.03	0.31	0.012	0.13

2.2 Casting and hot working of steels

Either laboratory vacuum or full-scale casting was used to produce 60 kg and 2630 kg ingots, labeled L and I-ingots, respectively. L-casting practice proved[20] to be effective in producing the fine TiN particles in Ti-bearing steel, capable of imposing a pinning effect on austenite grain boundaries during subsequent reheating and rolling. The ingots were fabricated into 22 mm dia bars on production facilities. They were first fabricated into 120 mm (I-ingots) and 80 mm squares (L-ingots) by hot-rolling on a bloom mill or by press-forging, respectively. Then, the squares were hot-rolled to 22 mm bars, on either a continuous (120 mm squares) or a cross-country (80 mm squares) bar mill, using the conventional rolling practice, which involved soaking at 1150°C and finish-rolling above 950°C.

2.3 Testing

Room temperature properties are evaluated from round tensile (l_0 = 40 mm; d_0 = 8 mm) and standard Charpy V-notch (CVN) longitudinal specimens, which were taken mid-radius from the as-rolled bars. A few impact tests were run at -50°C. Conventional metallographic techniques were used for revealing the microstructure.

3 RESULTS

3.1 Structure

A multi-phase Polygonal Ferrite-Pearlite-Non Polygonal Ferrite (PF-P-NPF) structure, with varying amount of NPF, is developed in the as-hot rolled bars. Acicular Ferrite (AF) and classical Bainite Sheaves (BS) are found to be dominant NPF morphology in steels with a low (<30%) and a high (>40%) fraction of NPF (to be referred to as PF-P-AF and PF-P-BS steels), respectively.

Intragranularly nucleated, mostly needlelike plates, which radiate in many directions, referred to as AF, are shown in **Figure 1a**, and as a part of PF-P-AF structure, in **Figure 1b**. The former austenite grain boundaries are decorated by Grain Boundary Idiomorphs (GBI) in **Figure 1a**, but Grain Boundary Alotriomorphs (GBA) or Widmanstatten Sideplates (WSP) are also frequently observed[20]. Grain boundary nucleated parallel ferrite plates, referred to as BS, are shown in **Figure 2a**, and as a part of a PF-P-BS structure, in **Figure 2b**.

AF is dominant NPF morphology in steels with composition within the limits given in **Table 1**, while a high fraction of BS is promoted by increasing Mn, Cr and Mo content above the base level. The two morphologies (including some transient variants) generally coexist in various proportions. In PF-P-AF steels, the addition of Ti increases the AF/BS ratio (Ti addition also refines the PF-grain and P-colony size). In PF-P-BS steels the BS/AF ratio depends upon the alloying addition. Thus, in 0.57% Cr and 0.21% Mo steels, BS coexist with a detectable fraction of AF (**Figure 3a**), while in 1.72/1.77% Mn steels BS are the only morphology present (**Figure 3b**). All three steels are L-cast and Ti-treated, but the two latter are virtually free of PF and P.

3.2 Structure-Property Relationship

Strength and Impact Properties (YS = Yield Strength; TS = Tensile Strength; CVN_{20} = Charpy V-Notch impact energy at 20°C) are, in terms of NPF fraction, shown in **Figures 4a and 4b**, respectively. Each data point represents an average of two (strength) and three to five tests (toughness). The TS remains virtually unchanged with increasing fraction of NPF up to about 70% and then

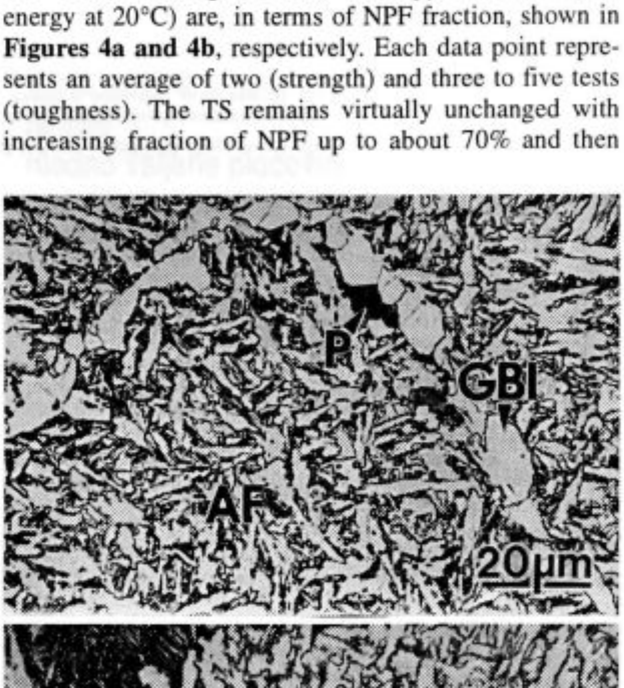

Figure 1: (a) Acicular Ferrite (AF), Grain Boundary Idiomorphs (GBI) and Pearlite(P); (b) Polygonal Ferrite-Pearlite-Acicular Ferrite (PF-P-AF)

Slika 1: (a) Acikularni ferit (AF), idiomorfi (GBI) in perlit (P) po kristalnih mejah; (b) poligonalni ferit perlit - acikularni ferit (PF-A-AF)

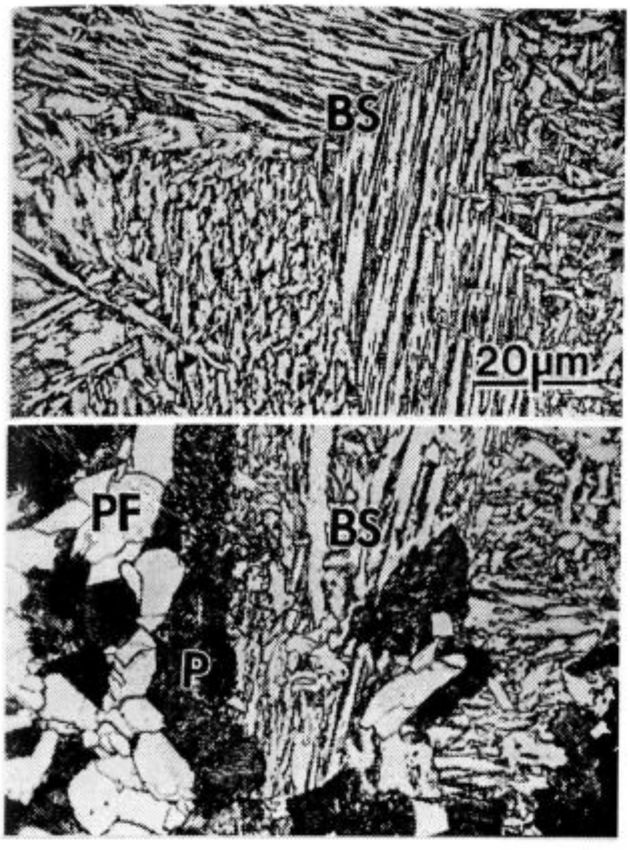

Figure 2: (a) Bainite Sheaves (BS); (b) Polygonal Ferrite-Pearlite-Bainite Sheaves (PF-P-BS)

Slika 2: (a) Bainitni snopi (BS); (b) poligonalni ferit perlit - bainitni snopi (PF-B-BS)

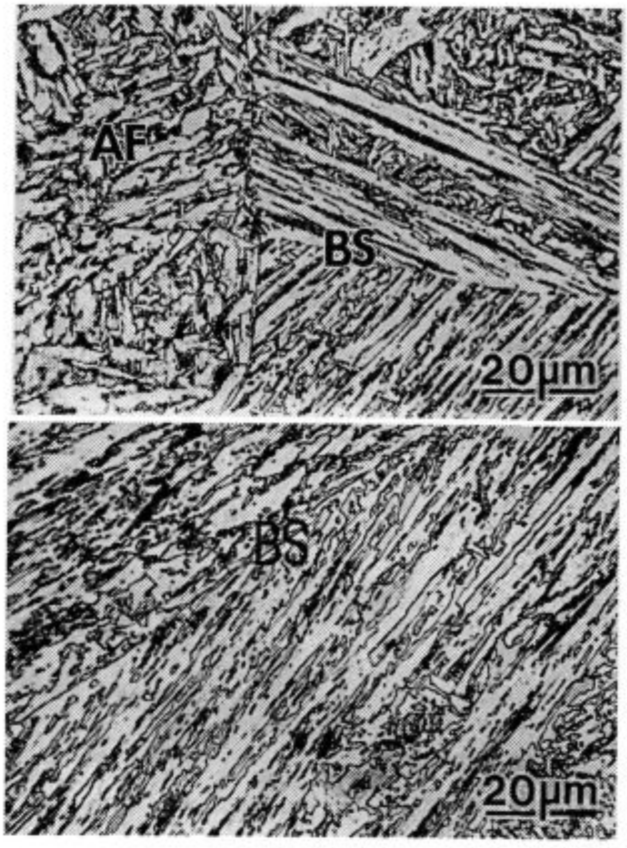

Figure 3: (a) Bainite Sheaves (BS) and Acicular Ferrite (AF); (b) Bainite Sheaves (BS)

Slika 3: (a) Bainitni snopi (B) in acikularni ferit (AF); (b) bainitni snopi (BS)

slightly increases, while the YS first decreases and than, at 30-40% of NPF, attain a constant level. These changes are neither consistent with variations in fraction nor in morphology of NPF (AF = open symbols; BS = closed symbols, in **Figure 4**). A relatively broad scatter band in **Figure 4a** is presumably a reflection of small variations in composition. For instance, decreasing C from 0.3% to 0.2% produces a drop in YS and TS from 600/650 to 550/600 and from 900/950 to 800/850 MPa, respectively. Moreover Ti, Cr and Mn produce an effect which can be discriminated within the scatter-band itself. Thus, Ti-free PF-P-AF steels (**Region 1a**) exhibit a higher strength level then Ti-bearing steels (**Region 1b**), while 0.57% Cr PF-P-BS and 1.72/1.77% Mn B-steels (**Region 2a**) exhibit a higher TS level (1050/1100 and 1150/1200 MPa, respectively) than the other PF-P-BS grades (**Region 2b**).

Data of **Figure 4b** show that an increase in impact energy with increasing fraction of NPF is interrupted by a pronounced drop on passing from AF dominated - **Region 1** to BS dominated - **Region 2**. Within the PF-P-AF **Region 1c**, the energy attains a level of 65/75 J at 20°C (33 J at -50°C), corresponding to YS = 550/600 MPa and TS = 800/850 MPa; and within the **Region 1b**, a level of 40/50 J at 20°C (32 J at -50°C), corresponding to YS = 600/650 MPa and TS = 900/950 MPa, in 0.2% C/10% AF and 0.3% C/30% AF steels, respectively. Both steels are L-cast and Ti-treated. In general, the L-cast/Ti-treated steels exhibit a higher impact energy level (+Ti band in **Figure 4b**) than the Ti-free steels (-Ti band). The I-cast/ Ti-treated steels take an intermediate position (open squares). Within the PF-P-BS **Region 2**, the energy attains a level of 30/35 J at 20°C (25/30 J at -20°C), corresponding to YS = 600 MPa and TS = 1050/1100 MPa; and within the **Region 2c**, a level of 15/25 J at 20°C, corresponding to YS = 550/600 MPa and TS = 1150/1200 MPa, in 0.57% Cr/70% BS and 1.75% Mn/98% BS steels, respectively. In 0.57% Cr steel, in addition to BS, the NPF morphology comprises a detectable fraction of AF (**Figure 3a**), while in 1.75% Mn steels, BS is the only NPF morphology present (**Figure 3b**).

4 DISCUSSION

4.1 Structure

A slight difference in composition of the steels studied in this work seems to be decisive in controlling not

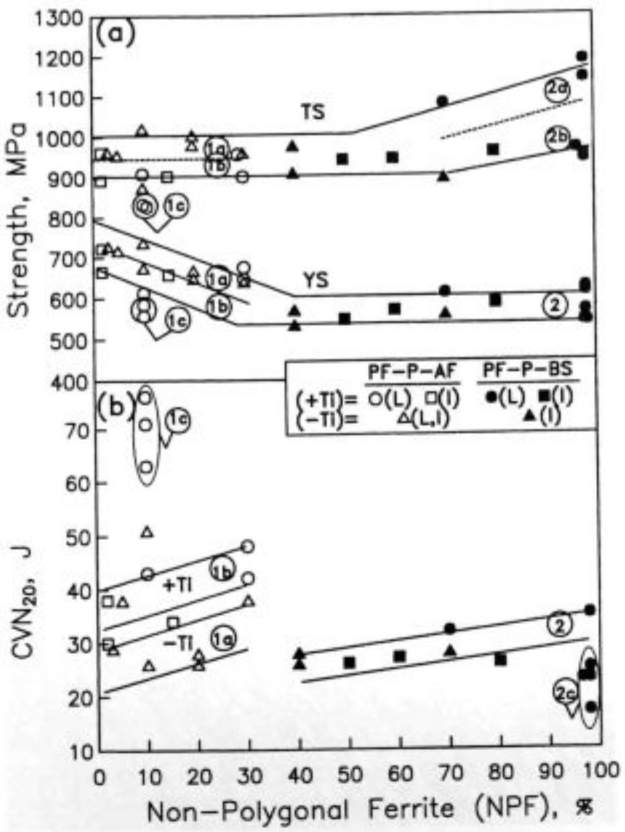

Figure 4: (a) Yield Strength (YS) and Tensile Strength (TS) as a Function of Non-Polygonal Ferrite (NPF) Fraction; (b) Charpy V-Notch Impact Energy at 20 (CVN_{20}) as a Function of NPF Fraction (PF = Polygonal Ferrite; P = Pearlite; AF = Acicular Ferrite; BS = Bainite Sheaves; L = L-Cast Ingots; I = I Cast-Ingots; +Ti = Ti-Bearing Steels; -Ti = Ti-Free Steels)

Slika 4: (a) Meja plastičnosti (YS) in natezna trdnost (TS) v odvisnosti od deleža ne poligonalnega ferita (NPF); (b) Charpy V udarna energija pri 20°C (CVN_{20}) v odvisnosti od deleža NPF (PF - poligonalni ferit, P - perlit, AF - acikularni ferit, BS - bainitni snopi, L-L - liti ingoti, I-I - liti ingoti, +Ti - jekla s Ti, -Ti - jekla brez Ti)

only the fraction of NPF but, together with inclusions, its morphology also.

Thus, the AF, which is assumed to be either intragranulary nucleated bainite[22] or Widmanstatten ferrite[23], together with various proportions of PF (e.g. Grain Boundary Idiomorphs, GBI) and pearlite, P (**Figure 1**), is produced in PF-P-AF grades, with a relatively low hardenability (<30% NPF). The Grain Boundary Ferrite (GBF) is assumed[24] to render austenite grain boundaries inactive in respect to intergranular nucleation of BS, what in turn promotes the intragranular nucleation of AF on TiN or MnS inclusions[20]. The nucleation potential of inclusions varies with composition, crystal structure and dispersion, i.e. with their number, size and spacing[22,25-29]. For example, a low degree of misfit between the ferrite matrix and the substrate crystal lattice is assumed[25-31] to increase the nucleation potential of inclusions. Therefore, TiN with a misfit ratio of 3.8[27] should be much more effective than MnS with misfit ratio of 8.8[25]. This could account for a higher fraction of AF observed in Ti-bearing (fine and coarse particles, which are presumably developed in L and I-cast ingots respectively, seems to be equally potent nucleation sites) than in Ti-free (high S) steels. However, in steels with high V and N, VN particles can be precipitated on MnS, before austenite is transformed to ferrite[30,31]. Since the misfit ratio of VN, estimated at 1.3 for (001) plane[27], is lower than that of TiN, the former particles, i.e. MnS coated by VN, should be more potent nucleation sites for AF. While the effect is not quite apparent in the present steel, the fact remains that the fraction of AF is higher in high-S than in low-S/Ti-free steels.

The BS are produced in PF-P-BS grades with relatively high hardenability (>40% NPF). The nucleation of GBF is considerably suppressed, and an abrupt transition from AF dominated to BS dominated NPF morphology occurs not only in Ti-free but also in Ti-bearing steels. This supports the assumption that removal of GBF frees the boundaries to nucleate BS concurrently with intragranular AF.

4.2 Properties

Yield and Tensile Strength (YS, TS). It is well known (e.g.[6-8]) that the YS of Polygonal Ferrite-Pearlite (PF-P) steels increases with increasing fraction of P. Additional strengthening is obtained by precipitation of V (C,N) particles in ferrite. Precipitation strengthening effect decreases with decreasing N-content. In Ti-bearing PF-P-AF steels tested in this work, Ti forms nitride particles which reduce the N available for VN precipitation and hence, reduce (from **Region 1a** to **1b** in **Figure 4a**) the strengthening associated with this precipitation. Gradual replacement of PF-P structure with NPF structure reduces the YS, as shown in **Figure 4a**, due to suppression of precipitation within the NPF phase (e.g.[8,11]). However, the TS is maintained at the same level (**Region 1**), and even increases (**Region 2a**) in some steels. This latter observation can be associated with a high strain-hardening rate imposed by bainite[32].

CVN_{20} Impact Toughness (CVN_{20}). The present results, together with data presented in previous papers[20,21], indicate that AF and BS are beneficial and detrimental to toughness, respectively. The brittle fracture of low-C bainites can be related to the cleavage facet size[33], which in the present steels can be related to either AF-plate or BS-packet size. AF-plates give rise to a finer facet size, and thus to a higher toughness, while BS, in addition to being coarser itself (individual laths within a sheaf have little effect, since the cleavage crack is deflected at the sheaf and not at the lath boundary[33]), contain coarse interlath carbides (a feature characteristic of upper bainite), which are detrimental to toughness[33].

The Ti-bearing PF-P-AF steels (**Region 1b** in **Figure 4b**) exhibit a considerably higher toughness in comparison to Ti-free steels (**Region 1a**). This is because the PF-grain and P-colony size is finer and the AF fraction is presumably higher in Ti-bearing steels which contain

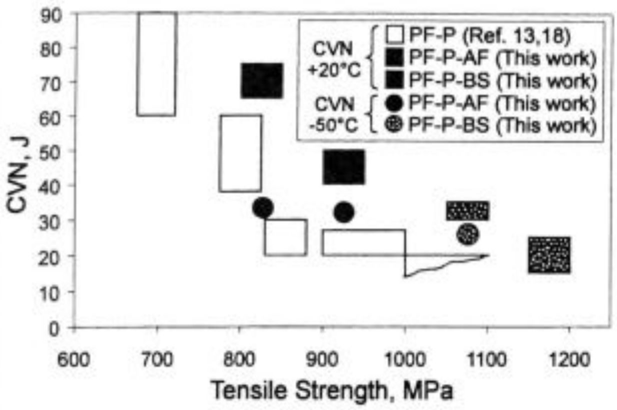

Figure 5: Tensile Strength (TS) vs. Charpy V-Notch Impact Energy (CVN_{20} = 20°C; CVN_{-50} = -50°C) of Conventionally Hot Rolled 0.2-0.5% C Polygonal Ferrite-Pearlite (PF-P), and 0.2-0.3% C Polygonal Ferrite-Pearlite-Acicular Ferrite (PF-P-AF) and Polygonal Ferrite- Pearlite- Bainite Sheaves (PF-P-BS) Bar Steels

Slika 5: Natezna trdnost (TS) v odvisnosti od Charpy V udarne energije (CVN_{20} = 20°C CVN_{50} = 50°C) pri konvencionalno vroče valjanih 0.2 - 0.5% C poligonalni ferit perlit (PF-P) in 0.2 - 0.3% C poligonalni ferit perlit - acikularni ferit (PF-P-AF) in poligonalni ferit perlit - bainitni snopi (PF-P-BS) jeklenih palicah

fine TiN particles. The role of particles is twofold, first they inhibit the austenite grain growth, and second, they provide the nucleation sites for intragranular nucleation of AF. However, Ti-bearing/I-cast steels exhibit a lower toughness than Ti-bearing/L-cast steels, in spite of AF is a dominant NPF morphology in both. Coarser TiN particles in I-cast steels are not as effective in pinning austenite grain boundaries as fine particles in L-cast steels and lead to a coarser austenite grain, and consequently coarser PF-grain and P-colony size.

5 CONCLUDING REMARKS

The conventionally hot-rolled and air-cooled multiphase Polygonal Ferrite-Pearlite-Non Polygonal Ferrite (PF-P-NPF) microalloyed Ti-bearing steels, tested in this work (closed and shaded symbols in **Figure 5**), exhibit improved impact properties in comparison to conventionally hot rolled Polygonal Ferrite-Pearlite (PF-P) steels (open symbols), tested previously (e.g.[18,19]).

The 0.2% C/10% AF and 0.3% C/30% AF PF-P-AF steels, based on a 1.5% Mn - 0.1% V - 0.01% Ti composition, with an impact energy level of 65/75 J and 40/50 J at 20°C (33 and 32 J at -50°C), and tensile strength level of 800/850 MPa and 900/950 MPa respectively, can replace Q&T steels which currently achieve these property levels.

The use of a higher Cr or Mn contents give rise to PF-P-BS structure with 70-98% BS and increased tensile strength level up to 1050/1200 MPa at the expense of reduced toughness.

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