Microstructural Considerations Limiting the Mechanical Properties of HSLA Steel

Mikrostrukturne omejitve mehanskih lastnosti HSLA jekel

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The influence of chemical composition, grain and subgrain size, and precipitation on yield strength, transition temperature and the work strengthening exponent was analyzed for HSLA (high strength, low alloy) steel. The relationships are quantified and transferred to graphic charts - nomogram for steel with polygonal as well as non polygonal microstructure. The limits of mechanical properties (the highest combinations of yield strength and transition temperature) were quantified for the polygonal HSLA microstructure.

Key words: microstructure, mechanical properties, HSLA steels

Vpliv kemijske sestave, velikosti zrn in podzrn ter izločanja na mejo plastičnosti, prehodno temperaturo žilavosti in keficienta deformacijske utrditve je bil analiziran za HSLA jekla. Odvisnosti so kvantificirane in zapisane v grafih - nomogramih za jekla s poligonalno in acirkularno mikrostrukturo. Mejne mehanske lastnosti (kombinacije največje meje plastičnosti in prehodne temperature žilavosti) so bile kvantificirane za poligonalno mikrostrukturo.

Ključne besede: HSLA jekla, mikrostrukture, mehanske lastnosti

1 Introduction

At the development of new steel types the key problem is to understand the influence of chemical composition and obtainable parameters of microstructure on strength, plasticity and brittle fracture resistance. It is essential to obtain the quantitative description of the relation, and the description should be based on the knowledge concerning the nature of the mechanical properties in question. This way a valuable information can be obtained for the production technology, first for the prime chemical composition and heat treatment. In the presented work descriptions of correlations between chemical composition and parameters of microstructure on one side, and yield strength, work strengthening exponent, and transition temperature on the other, are compiled. They are quantified enabling direct application in engineering. In the second part of the work the limits of mechanical properties - combinations of strength, plasticity and brittle fracture resistance, are shown for the polygonal microstructure.

2 Microstructural essence of mechanical and fracture properties of microalloyed steels

Investigated were low-carbon microalloyed steels based on Ti, V, Nb, with eventual addition of Mo, in polygonal and non-polygonal microstructures. Introductory studies were devoted to the kinetics of precipitation of carbides, nitrides or carbonitrides of microalloying elements from the viewpoint of its intensity and effectiveness. Furthermore, investigated were also questions of laws of interphase precipitation and precipitation in austenite and ferrite. The main objective was to gain the knowledge of laws of the effect of precipitation states on strength as well as, plastic and brittle fracture properties. Analyses were carried out on several hundreds of structural states in the state after rolling at hot rolling mill in VSŽ JSC Košice, or in the state after thermal processing. Main attention was paid to the yield point, work strengthening exponent and transition temperature of notch toughness.

2.1 Yield point

The analyses were based on the assumption of an additive character of individual strengthening contributions to the yield point R_e and the following relationship was proposed for the studies set of steels:

$$R_e = R_{PN}+R_{IN}+R_G+R_{SG}+R_S+R_{PR}+R_P+R_D \qquad (1)$$

where R_{PN} - is the contribution of lattice friction stress; R_{IN} - contribution to strengthening on account of interstitially dissolved atoms of additives; R_D - contribution of dislocation strengthening; R_G - strengthening contribution resulting from the size of grains; R_{SG} - contribution resulting from the effect of subgrains; R_{PR} - pearlitic contribution; R_S - substitution contribution; R_P - precipitation contribution.

Their quantitative expression is based on relations comprised in [1].

Analyses provided a quantitative expression of the substitution effect of manganese R_{Mn} and confirmation of the effect of silicon and pearlite on strengthening contributions (R_{Si}, R_{PR}).

In addition to that a quantitative effect of polygonal ferrite grains d, or formations delimited by large angle boundaries (d_F) in non-polygonal microstructures was

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described. The quantitative expression of subgrain strengthening with intensity $R_{SG} = Gb \cdot d_{SG}^{-1} = 0.1 \cdot d_{SG}^{-1}$ (the size of a subgrain d_{SG} in mm) in a very good agreement with the Landford-Cohen relation, was used. The interchangeability of R_G and R_D was demonstrated, with R_D representing a contribution of transformation or of "geometrically inevitable" dislocations.

The analyses of the influence of precipitation on precipitation strengthening, employing all available theoretical models, were carried out. These analyses resulted in a quantitative relation for precipitation strengthening:

$$R_p = k_p^R \cdot \lambda^{-2} \quad (2)$$

where λ is the average planary interparticle distance of precipitates. The physical interpretation of this relation is following: Precipitation strengtheningis inversely proportional to the mean size of a free sliding area, corresponding to one precipitate (obstacle) standing in the way of the moving dislocation. The strengthening intensity constant k_p^R acquires a force dimension and can represent a mean value of force interaction phenomena between dislocations and precipitations, leading to a critical stress for the passing of dislocations trough obstacles. Its value $k_p^R = 76.8 \cdot 10^{-8}$ N is of the order corresponding to the size of an interaction of an edge dislocation with an elastic field of a particle $F \approx 10^{-7}$ N).

The quantitative behaviour of a thermaly dependent constituent of the yield point (R^*) was determined in the range -196 to +20°C, together with parameters C_1, B, appearing in the relation:

$$R^* = C_1 \cdot \exp(-T/B) \quad (3)$$

2.2 Transition temperature

Our analyses were based on Cottrell's energetic balance of cohesion of tough/brittle transition and Petch's condition of equality of the yield point R_e and fracture stress R_{FR} for determination of the transition temperature of brittleness T_K. Contrary to Petch's formulation, we have assumed a general interaction between individual parameters of microstructure and chemical composition and the friction stress R_{OFR}, appearing in the relation for fracture stress

$$R_{FR} = R_{OFR} + k_f \cdot d^{-1/2} \quad (4)$$

which resulted in the development of a corresponding model and analytical formulation. The k_f parameter represents a barrier effect of grain boundaries directed against the propagation of cracks across boundaries of grains.

The performed analyses provided the following relation for the transition temperature

$$T_{K(35)} = A - B \cdot \ln(d^{-1/2}) + \sum_{(i)} \Delta T_i \quad (5)$$

where A is the so-called threshold value of brittleness, dependent on the intensity of the thermal change of yield point B (relation (3)). The surface-plastic energy γ, shear modulus of elasticity G, parameters k_y, k_f and the mode of stressing q are connected to the values A and B in the relation

$$A = B \cdot \ln\left(\frac{4\gamma \cdot q \cdot G}{k_y} - k_f\right) \quad (6)$$

ΔT_i is the shift of transition temperature and depends from the structural parameter i or eventually from the chemical composition.

The positive effect of grain refining on an improvement of brittle fracture resistance has been demonstrated and a direct relationship of its intensity and a thermal change of the yield point has been observed. A good agreement of the parameter B in relations (3) and (5) was detected. An embrittlement effect of pearlite and silicon has been demonstrated.

The influence of precipitation on the shift of transition temperature was demonstrated to follow the relation

$$\Delta T_p = k_p^T \cdot \lambda^{-2} \quad (7)$$

An estimate of the barrier effect of grain boundaries against propagation of cleavage cracks ($k = 55$ Nmm$^{-3/2}$) was provided together with a value of surface plastic energy at T_K ($\gamma = 10^{-2}$ Nmm^{-1}). In case of polygonal microstructures analyses did not exclude a positive effect of manganese on the improvement of brittle fracture resistance and the quantitative expression corresponded to results of Pickering. In case of non-polygonal microstructures an absence of significant effect of subgrains on transition temperature changes was observed.

2.3 Complex relations

In our previous works[1,2,3] we presented simplified relations for the evaluation of the influence of microstructure on yield strength R_e, transition temperature T_{35} and work strengthening exponent n. For a polygonal microstructure it is expressed as:

$$R_e = R_G + R_{Mn} + \Delta R \quad (8)$$

$$T_{35} = A - B \cdot \ln(d^{-1/2}) + C \cdot \Delta R \quad (9)$$

$$n = a + \frac{b}{\Delta R} \quad (10)$$

where $R_G = 15 \cdot d^{-1/2}$ is the strengthening by ferrite grain size d (mm); $R_{Mn} = 50 \cdot x_{Mn}$ is the strengthening share of manganese x_{Mn} (%); ΔR is the part of embrittlement caused by strengthening, for microalloyed steel including mainly precipitation strengthening R_P, and also the influence of strengthening by silicon content R_{Si}, pearlite content R_{PR}, Peierls-Nabarro stress R_{PN}, and by interstitial strengthening R_{IN} ($\Delta R = R_P + R_{Si} + R_{PR} + R_{PN} + R_{IN}$); A = 147°C, B = 110°C, C = 0.4°C/MPa is an embrittlement constant, a, b are regression coefficients. For non polygonal microstructure similar relation were derived:

$$R_e = R_G + R_{SG} + R_{Mn} + \Delta R \quad (11)$$

$$T_{35} = A - B \cdot \ln(d^{-1/2}) + C \cdot \Delta R \quad (12)$$

where $R_G = 19 \cdot d^{-1/2}$; A = 143°C; B = 100°C, C = 0.4 °C/MPa while $R_{SG} = 0.1 \cdot d_{SG}^{-1}$ is the strengthening contribution of the subgrain size d_{SG} (mm).

The graphic interpretation of the relations is shown in **Fig.1** for the polygonal microstructure (eq. 8-10) and in **Fig.2** for the non-polygonal one (eq. 11-12).

It is important to note that the yield strength is controlled by a set of strengthening contributions with different influences on the brittle fracture resistance. The embrittlement from strengthening ΔR is resulting for every 100 MPa of strengthening a 40°C shift of the transition temperature into the wrong direction, causing the worsening of plastic properties, too, as shown by the work strengthening exponent. There is an influence of manganese content and subgrain size on strengthening too, though their influence on the transition temperature is not significant. Practically only one microstructural parameter is known, the increasing of the yield point together with the increase of brittle fracture resistance. It is the ferrite grain size d, or described more generally the size of the microstructural object limited by large angled borders. It is of prime importance to constitute the chemical composition and microstructure in the way to obtain first this microstructural parameter in the quality reflecting the desired complex of properties. The relations given in the work are simplified theoretical descriptions with coefficients calculated by regression analysis made on more than 300 microstructure types of steel produced in ironworks VSŽ, a.s. Košice, Slovakia.

3 Limits of polygonal microstructures

We decided to define the limits of the complex of mechanical properties for a steel with polygonal microstructure. With this aim the HSLA steel, with yield strength from 420 to 700 MPa were evaluated. The basic features of the evaluation are shown in the graphic chart in **Fig.3**, which was calculated for a 1% Mn content. The straight lines are representing the yield strength R_e. The nomo-

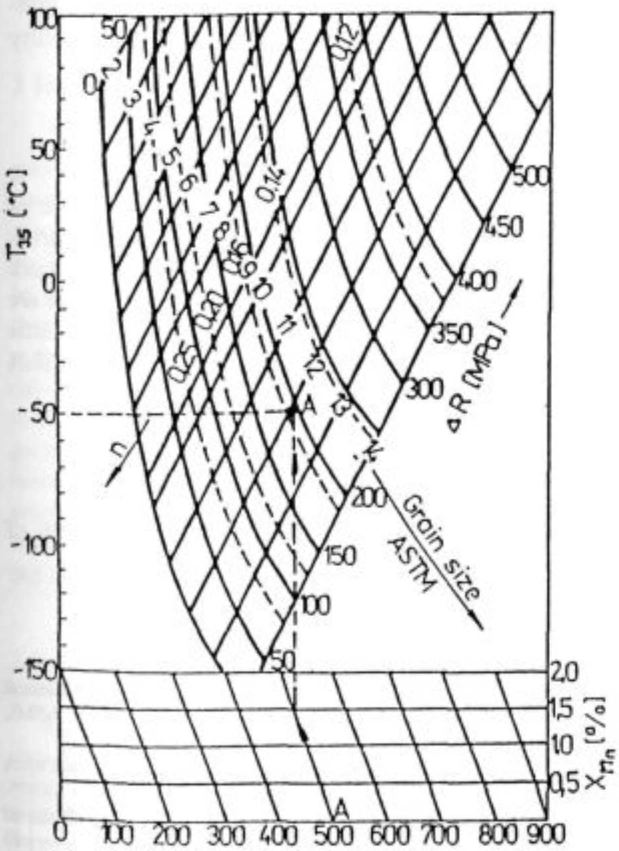

Figure 1: A complex nomogram for relation between microstructural parameters and mechanical properties of HSLA steels with polygonal microstructure

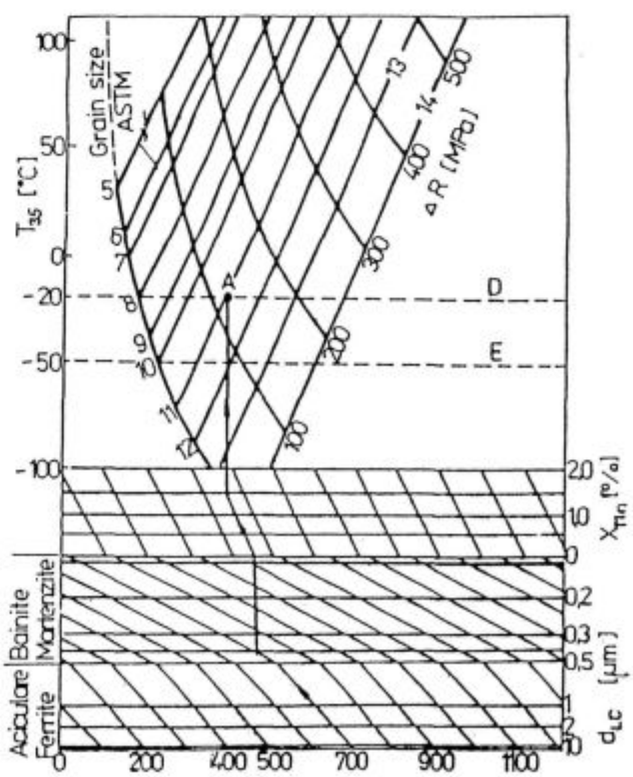

Figure 2: A complex nomogram for relation between microstructural parameters and mechanical properties of HSLA steels with non-polygonal microstructure

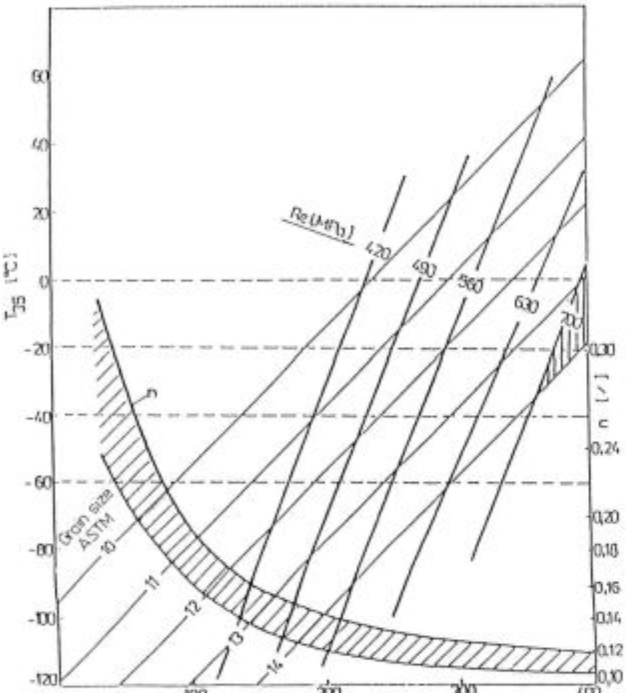

Figure 3: Microstructural considerations limiting mechanical properties of HSLA steels with polygonal microstructure

gram shows the possible combination of embrittlement ΔR and ferrite grain size d, necessary to obtain the selected yield point. The transition temperature T_{35} and the work strengthening exponent n are shown also.

In **Tab. 1** the combinations of embrittlement ΔR and ferrite grain size d in grades according to ASTM are shown, which are necessary for a steel with the desired combination of yield strength R_e and transition temperature T_{35}.

Table 1: Required ferrite grain size d and embrittlement by strengthening ΔR necessary for the combination of properties R_e and T_{35}

T_{35}(°C)	0		-20		-40		-60	
R_e (MPa)	d	ΔR (MPa)	d	ΔR (MPa)	d	ΔR (MPa)	d	ΔR (MPa)
420	10	230	11-10	220	11	190	11-12	170
490	11-10	275	11	260	12-11	230	12-13	210
560	11-12	320	12	290	12-13	270	13	250
630	12-13	370	13	340	13-14	320	14	290
700	13-14	420	14	400	14	350	?	?

In all cases a fine ferrite grain is required. Knowing the manufacturing technology and the limits of the wide strips hot rolling mill the production of steel with ferrite grain size under grade 14 cannot be experted. To obtain the grade 13 is very difficult, grade 12 is demanding, while the more coarse grains are currently obtained. Consequently, **Tab. 1** was simplified to **Tab. 2** which show that the elaboration of polygonal steel with the yield strength R_e = 700 MPa and the transition temperature T_{35} under -40°C, is not be reliable. It is also not realistic to desire expert a limit of elasticity R_e = 630 MPa with the transition temperature T_{35} better than -60°C.

Table 2: Limits of the polygonal microstructure for different combinations of R_e and T_{35}

R_e	T_{35} (°C)			
(MPa)	0	-20	-40	-60
420	1	1	1	1
490	1	1	2	2
560	1	2	2	3
630	2	3	3	4
700	3	3	4	4

The possibilities are denoted: 1 - realistic, 2 - demandig, 3 - very difficult, 4 - fiction.

In **Fig. 3** it can be also seen, that for the mentioned R_e and T_{35} values the ductility is very low, the work strengthening exponent in the range 0.10 to 0.16 (for the lower strength) because for high R_e values the embrittlement by ΔR is necessarily high, degrading the ductility and brittle fracture resistance.

4 Conclusion

Starting from theoretical relations the influence of chemical composition and parameters of the microstructure on strength, transition temperature and work strengthening exponent were investigated. The results are compiled and the limit combinations of strength, plastic properties and resistance to brittle fracture for HSLA steel with polygonal microstructure are calculat

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6 References

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