



ARCHIVES  
of  
FOUNDRY ENGINEERING

ISSN (2299-2944)  
Volume 2023  
Issue 4/2023

127 – 136

15/4



10.24425/afe.2023.146687

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

# The Effect of Microalloying (Nb, V) and Interstitial (C, N) Elements on Mechanical Properties of Microalloyed Steels

P. Marynowski \* , M. Hojny , T. Dębiński 

AGH University of Krakow, Poland

\* Corresponding author: E-mail address: pmarynow@agh.edu.pl

Received 07.10.2023; accepted in revised form 21.11.2023; available online 22.12.2023

## Abstract

The microalloying elements such as Nb, V are added to control the microstructure and mechanical properties of microalloyed (HSLA) steels. High chemical affinity of these elements for interstitials (N, C) results in precipitation of binary compound, nitrides and carbides and products of their mutual solubility – carbonitrides. The chemical composition of austenite, as well as the content and geometric parameters of undissolved precipitates inhibiting the growth of austenite grains is important for predicting the microstructure, and thus the mechanical properties of the material. Proper selection of the chemical composition of the steel makes it possible to achieve the required properties of the steel at the lowest possible manufacturing cost. The developed numerical model of carbonitrides precipitation process was used to simulate and predict the mechanical properties of HSLA steels. The effect of Nb and V content to change the yield strength of these steels was described. Some comparison with literature was done.

**Keywords:** Microalloyed steels, Mechanical properties, Precipitations, Carbonitrides

## 1. Introduction

Low alloy steels are alloys on the matrix of iron, containing alloying elements, which content does not exceed few percent. In the group of alloy steels, microalloyed steels are the most common. **High Strength Low Alloy Steels (HSLA)** are widely used for the manufacture of structural components such as: pressure vessels, fuel tanks, automotive parts, bridges, elements of building structures or oil pipelines.

Basic requirements for microalloyed steels [1]:

- High yield strength,  $R_{p0.2}$ , in the range of 450-600 MPa.
- Good plastic properties.
- Resistance to cracking.
- Good weldability, when carbon content is from 0.02% to 0.2%.

High yield strength levels above 550 MPa are required when talking about Advanced High Strength Low Alloy Steels (AHSLAS). When yield strength above 780 MPa are achieved, the term Ultra High Strength Low Alloy Steels (UHSLAS) is used. Nowadays, yield strength above 1000 MPa are typical for UHSLAS is the result of various strengthening mechanisms like grain refinement, solid-solution strengthening, precipitation strengthening, and deformation substructure formation [2, 3].

In the production of HSLA steels, important role is played by the processes of controlled rolling and rolling with controlled recrystallization. The goal of these processes is to obtain a fine grained structure immediately after rolling with the elimination of costly heat treatment processes. To obtain the fine grained structure of HSLA steels, heat treatment in the form of controlled rolling and rolling with controlled recrystallization, combined with controlled cooling, is used [1].



The high mechanical properties of HSLA steels are achieved through small additions of elements such as Nb or V introduced separately or comprehensively in amounts not exceeding 0.15% with only elevated Mn content 1.5-1.6%, when appropriate manufacturing technology is used [1, 4]. Niobium primarily forms NbC, which is fully dissolved in austenite solid solution during reheating before hot rolling. Nb in solid solution retards the grain boundary migration and recrystallization kinetics. NbC precipitates pin dislocations and austenite grain boundaries, thus additionally retarding recrystallization. In subsequent heat treatment, NbC precipitates remain undissolved. Nevertheless, the precipitates can coarsen during re-austenitization, thus diminishing grain size control, as also possible strengthening. Even higher solubility in austenite is typical for vanadium, which primarily forms fine nitrides or carbides that precipitate around the austenite to ferrite transformation temperature, providing precipitation strengthening and inhibiting static recrystallization during final rolling passes. Caution needs to be taken during simultaneous Ti and V addition because Ti forms TiN which is more stable than VN or VC, thus Ti and V addition needs to be carefully planned concerning the N content in steel. In the case of simultaneous Ti and Nb addition co-precipitation of niobium-rich particles on existing TiN is also possible. Titanium forms small and stable TiN that pin the austenite grain boundaries, thus limiting grain boundary mobility during reheating and hot rolling. Ti is also used as a N binding agent for B protection, because of its high affinity to N. Ti addition is limited in respect to nitrogen, not only as of the Ti/N ratio but also as the total product of TiN, due to the risk of coarse primary TiN formation. In the case of higher total TiN product TiN forms non-metallic inclusions in the last solidification front. These coarse non-metallic inclusions do not provide prior austenite grain size control, furthermore, they degrade fatigue properties, weldability, and impact toughness of the final product.

Boron is another important microalloying element, used to increase hardenability. During austenitization before quenching, B should be in austenite solution, so it can segregate to austenite grain boundaries during quenching. Grain boundary segregation of B lowers the austenite grain boundary energy, thus retards the austenite to ferrite transformation. If B is in form of borides like BN, it cannot be fully dissolved during austenitization, that is why Ti is commonly used for B protection, to bind the excess nitrogen. Excess Al and a combination of Al and Ti, as also a combination of up to 0.1% Al and under 0.03% Nb is used for B protection, latter is also used to prevent coarse TiN formation.

HSLA steels can also contain small amounts of such elements as Mo, Cr, Ni and Cu. Their mechanical properties are also affected by such elements as N, O, S and P [5]. Microalloying elements such as Nb, V significantly affect the microstructure and mechanical properties of HSLA steels. High chemical affinity of these elements for interstitials (N, C) results in precipitation of binary compound, nitrides and carbides and products of their mutual solubility – carbonitrides. In steel containing one of the microalloying elements, the carbonitride described by chemical formula  $MC_yN_{1-y}$  is formed, where  $y$  means atomic fraction of carbon in carbonitride. The carbides and nitrides of these elements have the same crystalline structure, regularly wall-centered B1-type NaCl, so that their mutual dissolution is possible. Typically HSLA steels contain a small amount of aluminum, which is a metallurgical additive in the deoxidation of the steel. Aluminum has a high affinity for nitrogen, forming aluminum nitride. Because it has a

hexagonal crystal structure, aluminum nitride does not dissolve into carbonitride. The carbonitride precipitations of alloying elements and aluminum nitride formed in the microstructure, due to the wide range of dissolution temperatures, affect the microstructure and the properties of HSLA steels through [1]:

- Controlling the grain size of austenite by undissolved precipitations at high temperatures.
- Changing the kinetics of recrystallization and phase transformations induced by dissolved elements and precipitations.
- Obtaining a strengthening effect by finely dispersed carbonitride precipitations formed at lower temperatures.

Dissolved elements in austenite inhibit its decomposition, increasing the hardenability of steel. Knowledge of the chemical composition of austenite, as well as the content and geometric parameters of undissolved precipitates inhibiting the growth of austenite grains is important for predicting the microstructure, and thus the mechanical properties of the material. Proper selection of the chemical composition of the steel makes it possible to achieve the required mechanical properties at the lowest possible manufacturing cost. The largest share in the production of HSLA steels is held by a group of steels with a ferritic-pearlite structure. The chemical composition of typical ferritic-pearlite HSLA steels [1]: 0.05-0.12% C, 1.4-1.7% Mn, 0.25% Si (max), 0.008% P, 0.002-0.005% S, 0.008% N (max), 0.02-0.04% Al and microalloying elements Nb, V.

## 2. Research methodology

The research methodology involved the use of a developed numerical model of the carbonitrides precipitation process in HSLA steels. The model has been described and verified in [6 - 8]. The model allows to simulate the image of the microstructure formed during the carbonitrides precipitation process in HSLA steels and the stereological parameters of precipitates such as: volume fraction and mean radius of precipitations, or chemical composition of carbonitrides. These data can be used to identify the mechanical properties of the steel (e.g. increase in yield strength, effect of precipitation hardening, hardenability of the steel). The main objective of this work was to use the numerical model to simulate the carbonitrides precipitation process in microalloyed steels containing different values of microadditives Nb, V at varying C and N contents. Some of the simulation results were used for comparison with experimental results from the literature. In addition, the extra simulations were done as a presentation of the model ability to show the effect of the carbonitrides precipitation process on the change in yield strength values. The literature comparison and the extra simulations were used to present the final conclusions of the study and further research and development opportunities. **Fig. 1** shows the graphical presentation of the research methodology.

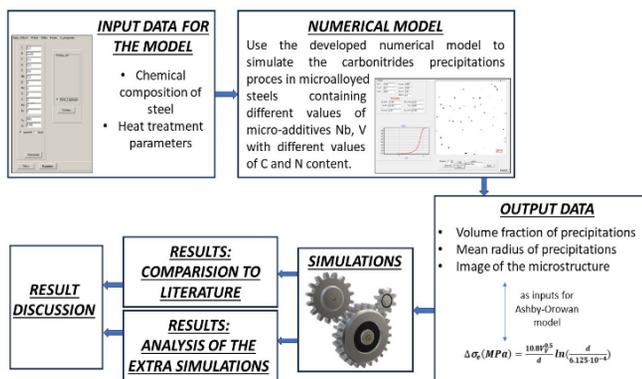


Fig. 1. Graphical presentation of the research methodology

### 3. Numerical model - the effect of chemical composition and grain size on the mechanical properties

The size of the ferrite grain,  $d_\alpha$ , depends on the size of the austenite grain,  $d_\gamma$ , and the cooling rate during austenite decomposition,  $\frac{dT}{dt}$ , according to the relation [1, 4]:

$$d_\alpha = Ad_\gamma + B\left(\frac{dT}{dt}\right)^{-0.5} + C \quad (1)$$

where: A, B, C - constants.

From equation (1), the smaller the austenite grain size and the higher the cooling rate, the smaller the grain size of the resulting ferrite. Therefore, to reduce the size of the ferrite grain,  $d_\alpha$ , it is necessary to refining the austenite grain,  $d_\gamma$ , or increase the cooling rate,  $\frac{dT}{dt}$ .

A quantitative description of the effect of steel chemical composition and grain size on the mechanical properties of ferritic-pearlite microalloyed steels is presented by the following formulas [4]:

a. The effect of strengthening is contained in the relationship between the yield strength,  $R_{p0.2}$ , and the chemical composition and grain size of ferrite,  $d_\alpha$ :

$$R_{p0.2}(MPa) = 88 + 37(\%Mn) + 83(\%Si) + 2918(\%N) + 15.1(d_\alpha)^{-0.5} \quad (2)$$

b. Brittle transition temperature,  $T_{kr}$ :

$$T_{kr}[^\circ C] = -19 + 44(\%Si) + 700(\%N)^{0.5} + 2.2(\%pearlite) - 11.5(d_\alpha)^{-0.5} \quad (3)$$

where: (%Mn), (%Si), (%N) - the content of individual elements dissolved in ferrite,  $d_\alpha$  ( $\mu m$ ).

From equations (2) and (3), it can be seen that grain refining is the most favorable mechanism of strengthening, as it results in higher

strength and lowers the transition temperature to the brittle state. Equation (2) shows that a reduction in the size of the ferrite grain, has a favorable effect on increasing the yield strength of the steel. The effect of strengthening, which is given by dissolved elements Mn, Si and N, is beneficial only in the case of Mn, as it is not accompanied by the decrease in impact strength that is observed in the case of the other elements. The addition of Mn lowers the decomposition temperature of the overcooled austenite, which also has a beneficial effect on reducing the grain size of the ferrite. A favorable effect of precipitation strengthening, i.e. an increase in yield strength,  $R_{p0.2}$ , while maintaining ductility, is given by undissolved particles of carbide and nitride precipitations of alloying elements.

The one of the most important factor influencing the mechanical properties of microalloyed steel is the effect of strengthening of ferrite by dispersed carbonitrides precipitations formed during the transformation austenite-ferrite as a result of reactions between elements dissolved in austenite. This effect is described by Ashby and Orowan model [9, 10]:

$$\Delta\sigma_e = \frac{10.8\sqrt{V_v}}{d} \ln\left(\frac{d}{6.125 \cdot 10^{-4}}\right) \quad (4)$$

where:  $\Delta\sigma_e$  – increase of yield strength, MPa,  $V_v$ - volume fraction of precipitations, d – mean diameter of carbonitride precipitations,  $\mu m$ .

The influence of the parameters of the precipitations on the effect of strengthening is presented in Fig. 2. As can be seen, the effect of precipitation strengthening increases with increasing precipitations content,  $V_v$ , but for a given content a strong increase in  $\Delta\sigma_e$  is observed with increasing precipitations dispersion.

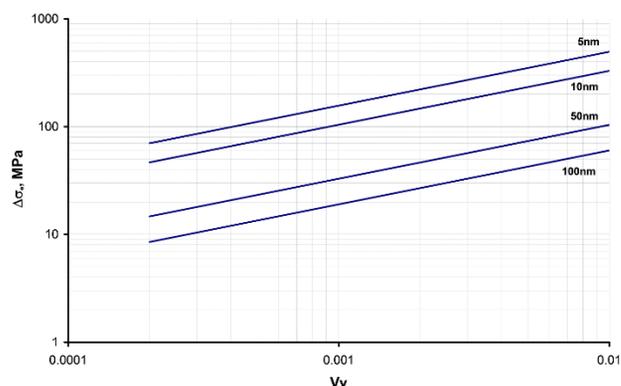


Fig. 2. Effect of precipitation parameters ( $V_v$ ,  $d$ ) on the effect of precipitation strengthening [1]

Knowledge of the chemical composition of austenite and the amount and parameters of undissolved precipitations inhibiting the growth of austenite grains is important in predicting the microstructure, and thus the mechanical properties of the material. Properly selected chemical composition of steels makes it possible to achieve the required steel properties at the lowest possible manufacturing cost. Among other things, the introduction of alloying elements increases the hardenability of the steel, which is required for tempered steels. However, the most widespread use of micro alloy steels has been in low-carbon steels, containing up to

0.2%C and an elevated manganese content of about 2%. Due to their low carbon content, these steels have good weldability. The effect of micro-elements is related to the ferrite grain size,  $d_\alpha$ , which depends on the austenite grain size,  $d_\gamma$ , and the cooling rate during austenite decomposition **equation (1)**. Alloying micro elements are introduced into the steel mainly for the purpose of grain refining and the effect of ferrite precipitation strengthening. These effects are caused by the presence of carbide, nitride and carbonitrides precipitations of alloying elements in the steel. The fine grain is the main advantage of micro-alloyed steels because it increases ductility and strength while maintaining weldability and ductility.

### 3.1. Effect of temperature and microalloying elements on austenite grain size

Grain size distribution can be achieved through three types of precipitations:

- Small undissolved particles of precipitations, cause a blocking effect on austenite grain boundaries during the heating process, mainly carbides and nitrides of titanium and niobium.
- Precipitations that are dissolved during heating, emitted in austenite during the rolling process, prevent recrystallization and/or austenite grain growth, mainly niobium and vanadium compounds.
- Precipitations after the rolling process, during the transformation of austenite into ferrite, cause the effect of precipitation strengthening.

**Fig. 3** shows the effect of temperature and alloying micro-elements V, Nb and Al on austenite grain size [11 - 15]. For comparison, the temperature dependence of grain size for carbon-manganese steel is included. A strong increase in austenite grain size above the dissolution temperature of the compound that inhibits grain growth can be observed.

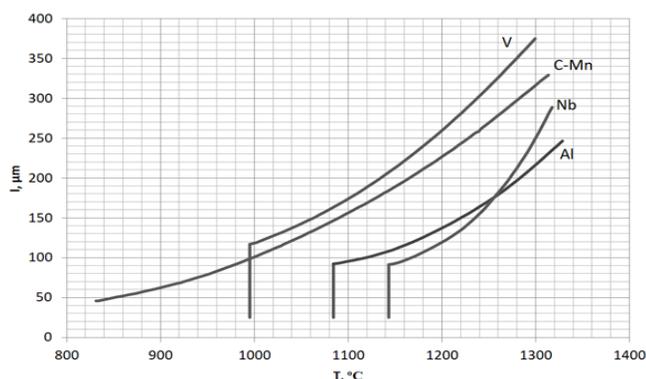


Fig. 3. Effect of temperature and microalloying elements on austenite grain size in HSLA steels [14]

### 3.2. Effect of microalloying elements on recrystallization temperature

Microalloying micro elements such as V, Nb dissolved in austenite affect the recrystallization temperature and decay kinetics of the overcooled austenite. Niobium has the greatest effect on the increase in recrystallization temperature,  $T_r$ , while vanadium has the least effect (**Fig. 4**). Plastic working should be carried out below the recrystallization temperature. Raising the  $T_r$  of the material gives the possibility to conduct plastic working in a wider temperature range. A recrystallization temperature that is too low can make plastic working of the material impossible due to the need to apply significant force, resulting from the decrease in plasticity of the material. The range between the recrystallization temperature,  $T_r$ , and  $A_3$  also decreases. Inhibition of recrystallization during plastic working results in fragmentation of the ferritic-pearlite microstructure due to the preservation of the most important features of deformed austenite, namely: elongated grain size, increased dislocation density and the occurrence of slip bands up to the austenite decomposition temperature. The controlled rolling process takes advantage of the effect of increasing recrystallization temperature.

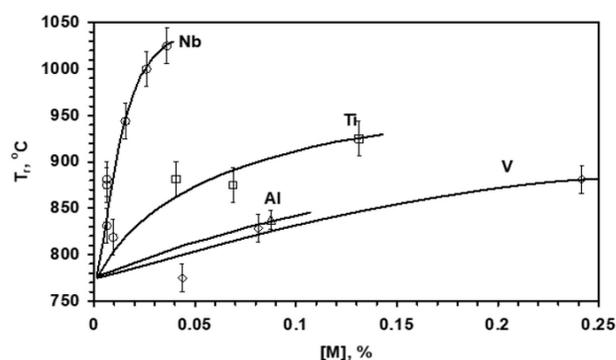


Fig. 4. Effect of microalloying elements, dissolved in austenite on the recrystallization temperature,  $T_r$  [1, 14]

### 3.3. Effect of carbonitrides precipitations on austenite grain size

Undissolved second-phase precipitations significantly affect austenite grain size. Compounds of microalloying elements with carbon and/or nitrogen, as well as aluminum nitride, are inhibitors of austenite grain growth at high temperatures. Their effectiveness is influenced by the chemical composition of the steel, on which depend: the content of precipitations and their stereological parameters, such as grains size and volume fraction. Effect of the carbonitride parameters, volume fraction,  $V_v$ , and the average radius of the precipitations,  $r$ , on the average radius of the austenite grains,  $R_a$ , describes the Smith-Zener equation [1]:

$$R_a = \frac{4r}{3V_v} \quad (5)$$

where:  $R_a$  – average radius of austenite grains,  $r$  – average radius of precipitations,  $V_v$  – the volume fraction of precipitations.

**Equation (5)** shows that the smaller the radius of precipitations,  $r$ , and the larger the volume fraction of precipitations,  $V_v$ , the smaller the austenite grain size, and thus the greater the degree of grain refining of the microstructure formed during austenite cooling. The volume fraction,  $V_v$ , under thermodynamic equilibrium conditions, for a given austenitisation temperature, remains constant. As a result of the coagulation process, the average radius of precipitations increases at elevated temperatures. Such a situation is a characteristic feature of all metallic systems. The kinetics of the process of coagulation of precipitations is described by the Lifshitz-Slyozov-Wagner (LSW) equation [15, 16]:

$$r^3 - r_0^3 = \frac{8\gamma D C_0 V_m^2}{9RT} \tau \quad (6)$$

where:  $r, r_0$  - initial, final size of precipitations,  $D, C_0$  - diffusion coefficient, concentration in austenite of element controlling coagulation process,  $T$  - temperature,  $\tau$  - annealing time,  $\gamma$  - energy of the austenite-precipitation interfacial boundary,  $V_m$  - molar volume of the precipitations.

The faster the coagulation process takes place, the effectiveness of precipitations as inhibitors of austenite grain growth is lower. As can be seen from **equation (6)**, the rate of coagulation of precipitations is affected by many factors. The value of the radius of the precipitations,  $r$ , depends most strongly on  $r_0$ , and  $C_0$ . The value of the average initial size of precipitations depends on the precipitation temperature of the compound, and on the cooling rate of the steel during casting. The higher the cooling rate of the steel, the lower the precipitation temperature and smaller the size of the precipitations. Compounds formed at high temperatures, in the liquid phase, due to their large size, are the least effective for inhibiting the growth of austenite grains. The microalloying element compounds V, Nb with carbon and nitrogen and AlN, are formed at lower temperatures in the solid phase. The rate of coagulation at a given austenitisation temperature is affected by the concentration in the austenite of the element controlling the process. This element is the substitutional element, or in the case of complex carbonitrides, the metallic elements that make up the precipitations. The lower the value of  $C_0$  in austenite, the lower the tendency of the precipitations to coagulate. A decrease in the concentration of the substitutional element at a given  $T$  can be achieved by increasing the content of the non-metallic element included in the precipitations. The effect of the content of a dissolved metallic element in austenite on the propensity of precipitations to coagulate can be qualitatively illustrated using vanadium nitride as an example. Analysis of the effect of nitrogen content on the amount of vanadium dissolved in austenite was carried out for steel containing 0.06% V (constant value) and 0.0165, 0.0195% N (real values obtained from experiment and assumed values: 0.01, 0.02% N), heated to 950°C. The nitrogen contents corresponded successively to the sub-stoichiometric and supra-stoichiometric contents relative to the vanadium content. The effect of nitrogen content on the amount of dissolved vanadium is illustrated in **Fig. 5**.

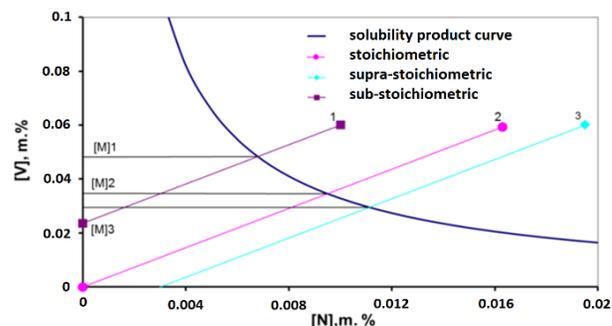


Fig. 5. Illustration of the effect of nitrogen content on the amount of dissolved vanadium [V], at 950°C

The amount of nitrogen and vanadium dissolved in the steel for each case is determined by the intersection of the stoichiometric line passing through the steel composition point with the solubility product curve. The remaining nitrogen and vanadium are present in bound form, namely vanadium nitride. A change in the content of a non-metallic element affects the amount of a substitutional element dissolved in austenite, the content of which affects the tendency of precipitations to coagulate. In the case of a supra-stoichiometric content of nitrogen (the composition of the steel denoted by point (3)), the amount of dissolved in the austenite of vanadium is equal to 0.03% (the [M]3 level) is significantly lower compared to the case in which the nitrogen content is at the sub-stoichiometric level (the steel composition corresponds to point (1) in **Fig. 4**) and is equal to 0.048% (level [M]1). For steel marked with point (2) with stoichiometric nitrogen content relative to vanadium, the amount of vanadium, [V] dissolved in austenite is equal to 0.035%. Thus, the VN precipitations in steel with a chemical composition corresponding to point (3) will more effectively inhibit the growth of austenite grains compared with the compositions corresponding to points (1) and (2). However, it should be noted that the excessive content of a non-metallic element can significantly increase the temperature of the compound precipitation, and then the resulting precipitations have a large size and are ineffective for inhibiting the growth of austenite grains. Therefore, there should be a reasonable compromise between the requirements of coagulation resistance and the precipitation temperature of the compound (the precipitations should not be formed in the liquid phase). Thus, for the effectiveness of inhibition of austenite grain growth by precipitations to be as high as possible, conditions are necessary:

- Possibly small radius of precipitations,  $r$ .
- Adequate content of precipitations,  $V_v$ .
- Resistance of the precipitations to coagulation (low concentration of metallic element,  $C_0$ ).

## 4. Experimental verification

In the literature is very hard to find any information about effect of Nb and V content to change of the yield strength of microalloyed steels. Some data was found and used to verify developed and implemented model. Zajac et. al. [17] studied steel with a

composition of 0.013% N, 0.12% V and variable carbon content: 0.004, 0.1 and 0.22% C. Heat treatment included heating to 1200°C and cooling to 650°C with subsequent holding at this temperature for 500s. The paper [17] also studied the effect of carbon and nitrogen content on the mechanical properties of a low-alloy steel after supersaturation and isothermal holding. The yield strength increases,  $\Delta\sigma_e$ , calculated for this steel after heat treatment are shown in Fig. 6. Fig. 7 shows the change in average radius of precipitations after heat treatment.

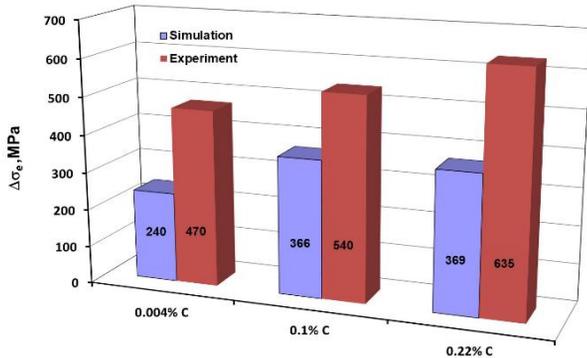


Fig. 6. Change in yield strength of steel after holding at assumed temperature, in addition, the value of yield strength for steel according to [17]

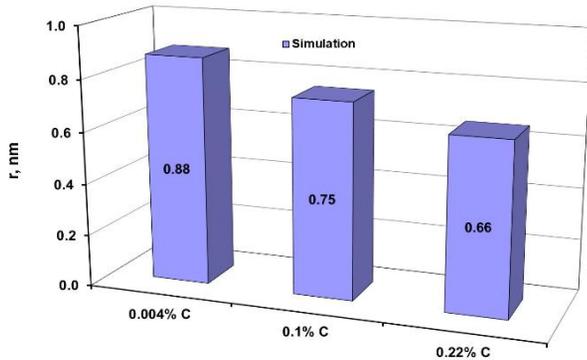


Fig. 7. Change in average radius of precipitations after holding at assumed temperature for steel according to [17]

## 4.1. Simulations

Using the numerical model of the kinetics of carbonitrides precipitation process, the influence of carbon, nitrogen and alloying elements vanadium and niobium on the kinetics of the carbonitrides precipitation process was studied. The analysis of the effect of vanadium was carried out for four steels with the composition shown in Table 1. The steels considered contained 0.005/0.010% N and 0.1/0.15% V at a constant carbon content of 0.2%. The heat treatment included heating to 1200°C, cooling to 800°C and holding at this temperature for up to 21 h allows the alloying element to fully dissolve in the austenite. The process parameters are for simulation purposes only, in real process much shorter holding time is used. The results obtained are presented in Fig. 8-12.

Table 1.

Chemical composition of steels subjected to nitrogen and vanadium influence analysis

Steels	C	N	V
steel I	0.2	0.005	0.1
steel II	0.2	0.005	0.15
steel III	0.2	0.01	0.1
steel IV	0.2	0.01	0.15

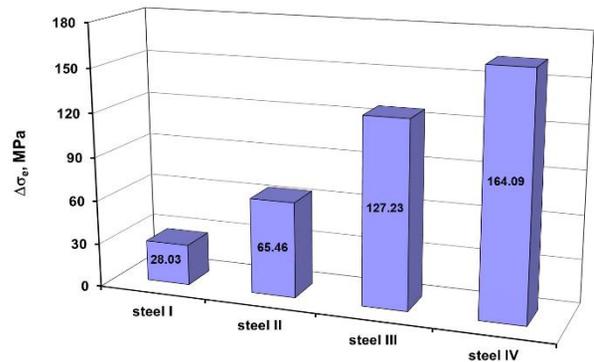


Fig. 8. Change in yield strength of steel after holding at assumed temperature (21h)

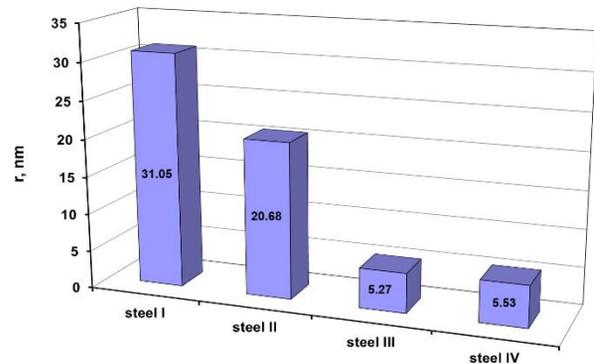


Fig. 9. Average radius of precipitation after holding at the assumed temperature (21h)

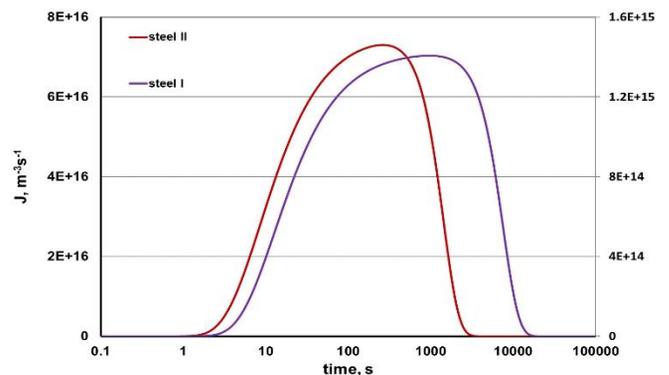


Fig. 10. Rate of nucleation of precipitations from holding time

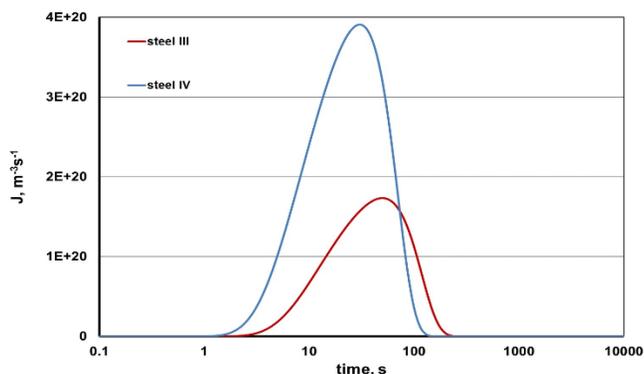


Fig. 11. Rate of nucleation of precipitations from holding time

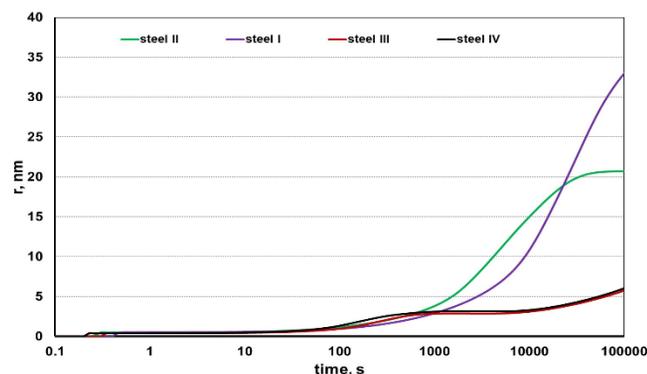


Fig. 12. Dependence of the average radius of precipitation on the holding time at the assumed temperature

The effects of Nb and interstitial elements were analyzed for eight steels with compositions listed in **Table 2**. Two levels of carbon (0.2/0.4%), nitrogen (0.005/0.010%) and Nb (0.03/0.05%) were considered. Heat treatment included heating to 1250°C and cooling to 900°C and holding for 21 h. The results obtained are presented in **Fig. 13-20**.

Table 2.

Chemical composition of steels subjected to carbon and niobium influence analysis

Steels	C	N	Nb
steel I	0.2	0.005	0.03
steel II	0.2	0.005	0.05
steel III	0.2	0.01	0.03
steel IV	0.2	0.01	0.05
steel V	0.4	0.005	0.03
steel VI	0.4	0.005	0.05
steel VII	0.4	0.01	0.03
steel VIII	0.4	0.01	0.05

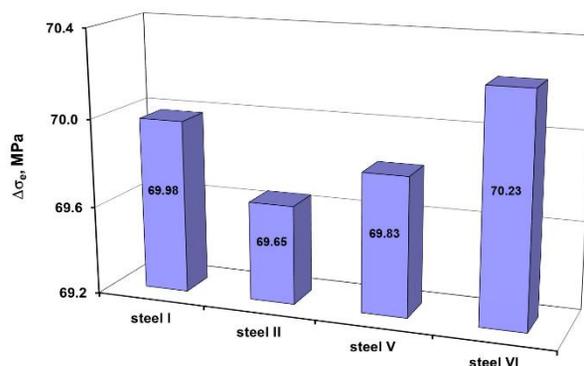


Fig. 13. Change in yield strength of steel after holding at assumed temperature (21h)

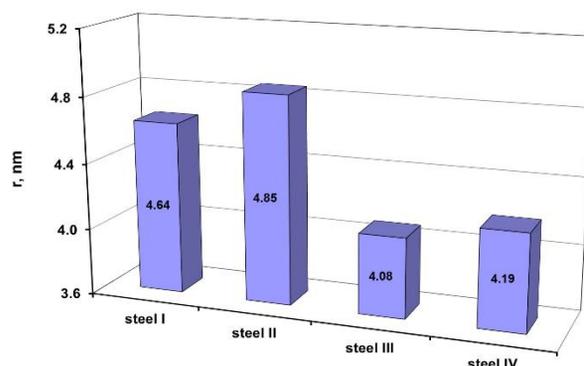


Fig. 14. Average radius of precipitation after holding at the assumed temperature (21h)

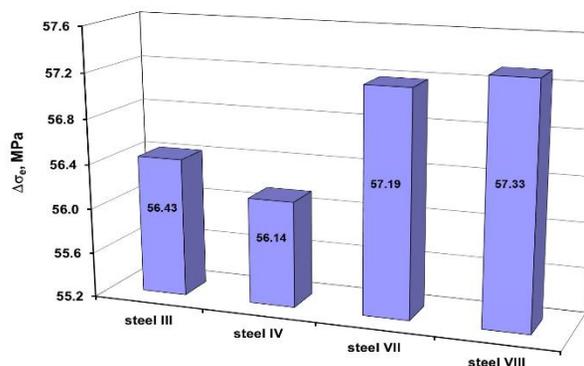


Fig. 15. Change in yield strength of steel after holding at assumed temperature (21h)

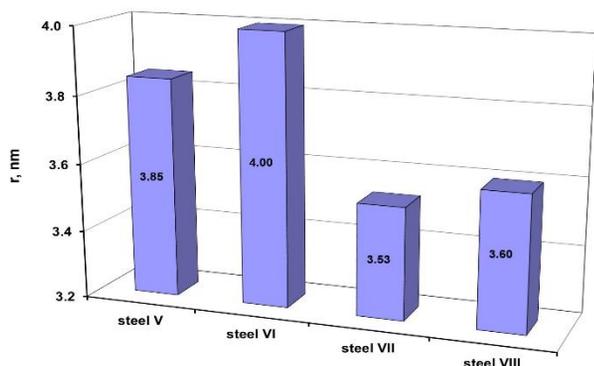


Fig. 16. Average radius of precipitation after holding at the assumed temperature (21h)

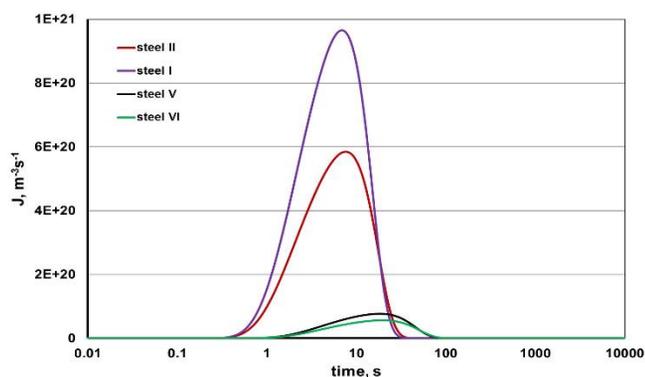


Fig. 17. Rate of nucleation of precipitations from holding time

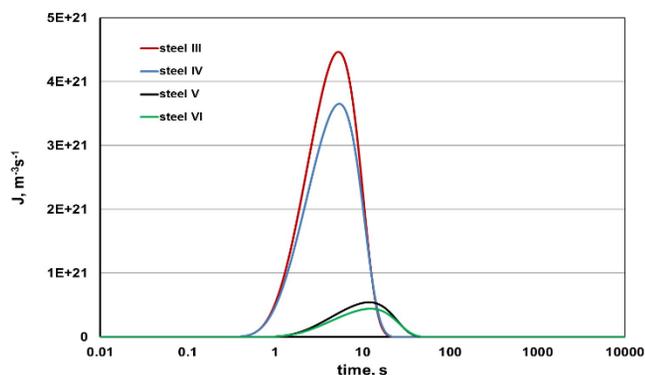


Fig. 18. Rate of nucleation of precipitations from holding time

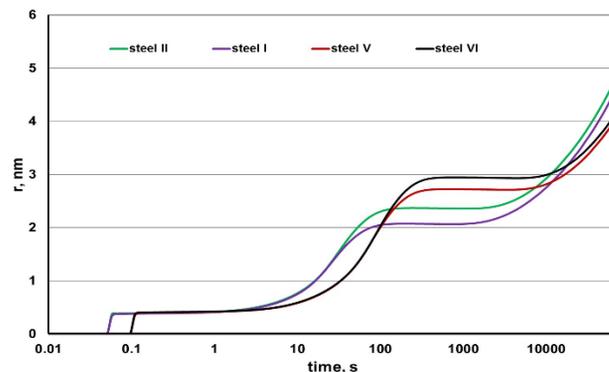


Fig. 19. Dependence of the average radius of precipitation on the holding time at the assumed temperature

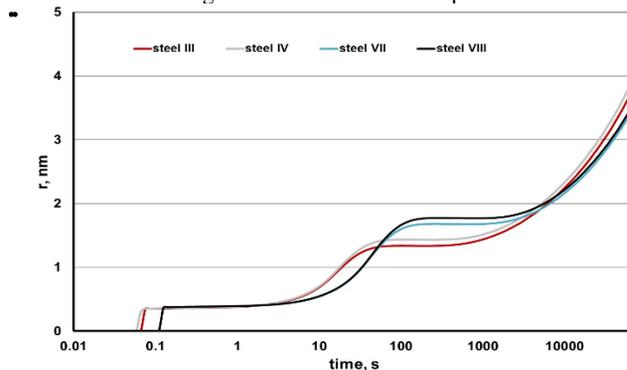


Fig. 20. Dependence of the average radius of precipitation on the holding time at the assumed temperature

## 5. Results discussion

In the literature is very hard to find any information about effect of Nb and V content to change of the yield strength of microalloyed steels. One was found [17] and some comparison between simulation and experiment was done. Lagneborg et. al. [18] describes only information about role of vanadium in microalloyed steels. Some the same conclusions were obtained in present paper.

Comparison of simulation and experiment are on **Fig. 6** and **Fig. 7**. **Fig. 6** shows the dependence of yield strength,  $R_{p0.2}$ , on carbon content. It can be seen that there is a satisfactory correspondence between the changes in  $R_{p0.2}$  and  $\Delta\sigma_e$  with increasing carbon content. These changes are associated with increasing carbon content and with decreasing average radius of vanadium carbide precipitations, V(C,N) (**Fig. 7**). The C content strongly affect the change in strength properties. At lower carbon content 0.004% C,  $\Delta\sigma_e$  increases from 240 to 369MPa with an increase in C content from 0.1 to 0.2%. Simulation shows the same correlation of results,  $\Delta\sigma_e$  increases from 470 to 635MPa with an increase in C content. Differences in simulation and experimental results can be due the  $\Delta\sigma_e$  calculated using Ashby and Orowan model. In this model the main parameter is mean diameter of carbonitride precipitations,  $\mu\text{m}$ . The influence of the parameters of the precipitations on the effect of strengthening is presented in **Fig. 2**. The effect of precipitation strengthening increases with

increasing precipitations content,  $V_p$ , but for a given content a strong increase in  $\Delta\sigma_e$  is observed with increasing precipitations dispersion.

In literature [18] there is many information about the influence of carbon and nitrogen content to mechanical properties of steel, but there is no any data about full chemical composition of steels and heat treatment parameters that can be useful to make simulations to compare the results. It can be seen that there is a satisfactory correspondence between the changes in  $R_{p0.2}$  and  $\Delta\sigma_e$  with increasing carbon content, both simulation and experiment, so decided to make more simulations using the numerical model of the kinetics of carbonitrides precipitation process to show the influence of carbon, nitrogen and alloying elements vanadium and niobium on the kinetics of the carbonitrides precipitation process.

As can be seen from **Fig. 8-12**, increasing the nitrogen content decreases the value of the average radius of nucleation. In addition, higher nitrogen content increases the value of the nucleation rate,  $J$ , by several orders of magnitude. The nucleation rate,  $J$ , is also affected by vanadium content. Increased vanadium content, while holding nitrogen content constant, increases the nucleation rate. The N and V contents strongly affect the change in strength properties. At lower nitrogen content,  $\Delta\sigma_e$  increases from 30 to 70MPa with an increase in V content from 0.1 to 0.15%, while at higher  $\Delta\sigma_e$  changes from 130 to 165MPa, respectively.

As can be seen in **Fig. 13-22**, both carbon and niobium contents slightly affect the magnitude of the value of the average radius of nucleation. Carbon strongly affects the value of the nucleation rate,  $J$ .

A higher carbon content significantly reduces the nucleation rate. A similar situation exists for niobium. A higher niobium content slightly reduces the value of the nucleation rate. At higher niobium content with the same carbon and nitrogen content,  $\Delta\sigma_e$  decreases (steels I-II and III-IV). With the same carbon content with increase of nitrogen and niobium content,  $\Delta\sigma_e$  also decreases (steels I-IV). At higher carbon content and increase of nitrogen and niobium content,  $\Delta\sigma_e$  increases (steels V-VIII).

Obtained simulations results allow conclusion very close to the literature [16], which makes it possible to conclude that the used model is consistent and obtained results are correct. Further comparison of the simulations results requires more experiments.

## 6. Conclusions

Carbonitrides precipitations strongly influence on mechanical properties of HSLA steels after heat treatment. In iron-carbon alloys, an important group are microalloyed steels, in which the small content of elements such as V, Nb provide the required mechanical properties due to the formation of carbide, nitride and carbonitrides, achieved in conventional steels with a similar chemical composition but without microalloying elements, after additional heat treatment (usually quenching + medium or high tempering). Mechanical properties of HSLA steels are shaped by their chemical composition and technological process parameters, which affect the size of carbonitrides precipitations. Carbonitrides precipitations play a dual role:

- In the austenite: they inhibit grain growth.
- In the ferrite: they cause the effect of precipitation strengthening.

The refining of the grain size of austenite decomposition products and the strengthening of the precipitation makes it possible to obtain high mechanical properties of steel after cooling, after plastic processing without additional heat treatment. The final effect of V, Nb introduced into the steel depends on two stereological characteristics of the resulting carbonitrides precipitations - their content and the size distribution, which can be calculated based on the chemical composition of the steel and the parameters of the technological process.

Derived numerical model can be a useful tool for chemical composition of steel and heat treatment parameters optimization for obtaining the required high mechanical properties. The model needs further development, which should include:

- Extending the range of chemical composition of steel for case of simultaneous addition of several microalloying elements in steel, on the carbonitride precipitation process.
- Including of calculation the temperature field during heat treatment processes and its effect on size distribution of carbonitride particles.
- More experimental data and samples to compare with numerical model.
- Calculation of final mechanical properties of steel after heat treatment.

## Acknowledgment

The work was completed as a part of fundamental research financed by the Ministry of Science and Higher Education, grant no. 16.16.110.663.

## References

- Adrian H. (2011). *Numerical modeling of heat treatment processes*. AGH Kraków. (in Polish).
- European Committee for Standardization (2019). *Hot Rolled Products of Structural Steels: Technical Delivery Conditions for Flat Products of High Yield Strength Structural Steels in the Quenched and Tempered Condition*
- Jan, F., Jaka, B. & Grega, K. (2021). Grain size evolution and mechanical properties of Nb, V-Nb, and Ti-Nb boron type S1100QL steels. *Metals*. 11(3), 492. <https://doi.org/10.3390/met11030492>.
- Gladman, T. (1997). *The physical metallurgy of microalloyed steels institute of materials*. vol. 363. London, UK. Search in.
- Blicharski, M. (2004). *Materials engineering: steel*. WNT: Warszawa. (in Polish).
- Marynowski, P., Adrian, H. & Głowacki, M. (2019) Modeling of the kinetics of carbonitride precipitation process in high-strength low-alloy steels using cellular automata method. *Journal of Materials Engineering and Performance*. 28(7), 4018-4025. <https://doi.org/10.1007/s11665-019-04170-4>.
- Marynowski, P., Adrian, H. & Głowacki, M. (2018). Cellular Automata model of carbonitrides precipitation process in steels. *Computer Methods in Materials Science*. 18(4), 120-128. ISSN 1641-8581.
- Marynowski, P., Adrian, H. & Głowacki, M. (2013). Cellular automata model of precipitation in microalloyed niobium

- steels. *Computer Methods in Materials Science*. 13(4), 452-459. ISSN 1641-8581.
- [9] Adrian, H. (1992). Thermodynamic model for precipitation of carbonitrides in high strength low alloy steels containing up to three microalloying elements with or without additions of aluminum. *Materials Science and Technology*. 8, 406-420. <https://doi.org/10.1179/mst.1992.8.5.406>.
- [10] Adrian, H. (1995). *Thermodynamic model of carbonitride precipitation in low-alloy steels with increased strength with application to hardenability tests*. Kraków: AGH. (in Polish).
- [11] Adrian, H. (1995). Thermodynamic calculations of carbonitride precipitation as a guide for alloy design of microalloyed steels. In Proceedings of the International Conference Microalloying'95, 11-14 June 1995(285-307). Pittsburgh.
- [12] Adrian, H. (1999). A mechanism for the effect of vanadium on the hardenability of medium carbon manganese steel. *Materials Science and Technology*. 15, 366-378. <https://doi.org/10.1179/026708399101505987>.
- [13] Cuddy, L.J. & Raley, J.C. (1987). Austenite grain coarsening in microalloyed steels. *Metallurgical Transactions A*. 14, 1989-1995. <https://doi.org/10.1007/BF02662366>.
- [14] Cuddy, L.J. (1984). The effect of micro alloy concentration on the recrystallization of austenite during hot deformation. *Processing of Microalloyed Austenite (Pittsburgh)* TMS-AIME Warrendale PA.
- [15] Goldschmidt, H.J. (1967). *Interstitial Alloys*. Butterworth-Heinemann.
- [16] Lifschitz, I.M. & Slyozov, V.V. (1961). The kinetics of precipitation from supersaturated solid solution. *Journal of Physics and Chemistry of Solids*. 19(1/2), 35-50. [https://doi.org/10.1016/0022-3697\(61\)90054-3](https://doi.org/10.1016/0022-3697(61)90054-3).
- [17] Zając, S., Siwecki, T. & Hutchinson, W.B. (1998). Lagneborg R. The role of carbon in enhancing precipitation strengthening of V-microalloyed steels. *Material Science Forum*. 284, 295-302. <https://doi.org/10.4028/www.scientific.net/MSF.284-286.295>.
- [18] Langberg, R., Hutchinson, W.B., Siwecki, T. & Zając, T. (2014). The role of vanadium in microalloyed steels. Sweden: Swerea KIMAB.