Influence of the chemical composition on the mechanical properties of forged microalloyed steels

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The microalloying process applied to the steels is a common practice for obtaining high quality grades of steels that can be used in the production of parts for the automotive industry. The most significant chemical elements used for micro-alloying are: vanadium, niobium, titanium and zirconium. Microalloying of carbon steels with small amounts of elements having high affinity to carbon and nitrogen (usually less than 0.1%), results in a significant improvement of the mechanical properties. By microalloying process, stable compounds as carbides, carbo-nitrides or nitrides in the form of finely dispersed particles are formed in the solid solution of the solidified steel. These precipitates can slow the austenite grain growth and can block the dislocations movement during deformation process. The microalloying process of steels allows the increasing of some mechanical properties at lower cost compared with those of low and medium alloyed steels. If the metallurgical processes are appropriate (obtaining, refining and thermo mechanical processing such as rolling, forging etc.), the precipitates reaches the appropriate dimensions and dispersion, being localized mostly in the grain volume and not on the grain boundary, and can act as reinforcement elements in the metallic matrix, by blocking the grains growth and by increasing the local tension at the site level, which increase the hardness and can improve the thermal stability characteristics, at high temperatures. In the paper are presented and discussed several results of research, related to the obtaining of the micro-alloyed steels using a vacuum induction furnace, the selection of the alloying elements according the particular type of metallurgical treatment, the establishment of the optimal V/Nb ratio and the analyze of the cooling speed after deformation, in order to optimize the final characteristics of the experimental steels.

1. Introduction

The automotive industry is one of the most dynamic industries having a wide opening to innovation and rapid uptake of advanced materials and technologies. The intense competition between car manufacturers in order to conquer specialized markets involves increasing functional performance of products (parts and subassemblies), and reducing manufacturing costs.

For this purpose it is necessary to find solutions for the replacement of alloyed steels with microalloyed steels, in order to increase sustainability and functional performance of components from the automotive industry subjected to wear and / or fatigue. Also, concerns are directed to reduce manufacturing costs, the target being the manufacturing of competitive and reliable components.

Microalloying of carbon steels with small amounts (usually, less than 0.1%) of chemical elements with high affinity to carbon and nitrogen, such as Nb, Ti and V, resulted in a significant improvement in the mechanical properties [1, 2, 3, 4, 5, 6]. Microalloying with Nb, Ti or V results in the formation of stable precipitates of carbides, carbonitrides or nitrides (of these elements) finely dispersed in steel matrix. The presence of these dispersed particles slows the growth of austenite grain and blocks the movement of dislocations. The addition of carbide

forming elements leads to strengthening of austenite grain boundaries with precipitates which have also a grain refining role. Most of precipitates are nitrides and carbonitrides, which crystallize in the f.c.c. system and have a good mutual solubility. The solubility of precipitates in austenite is influenced by their chemical composition, nitrides having a lower solubility than carbides. Also, the dissolution temperature is dependent of the precipitate chemistry: vanadium carbide dissolves at the lowest temperature while niobium carbide has the highest stability. This is why NbC has an important role in controlling of the grain growth during high temperature processes as hot rolling. In addition, niobium forms with carbon and nitrogen simple compounds such as NbC, NbN. These compounds have total mutual solubility, leading to the formation of NbCN type carbonitrides. With the increasing of heating temperature (prior forging) both a gradual dissolution and a process of coalescence of the precipitates takes place thus affecting their role in blocking the boundaries migration and in the grain refining. Microalloying with such elements leads to a high mechanical strength and good toughness at a lower cost compared to common alloyed steels. The improvement of mechanical characteristics is the result of several factors among which the most important are:

- grain refining and fine microstructure formation, containing fine acicular ferrite [7-9];
- increasing of ferrite strength by forming fine precipitates of carbides, nitrides and / or carbonitrides of microalloying elements during the transformation of the austenite in ferrite, at cooling during thermomechanical processing [10, 11].

The refining effect of microalloying elements (particularly, niobium) on the microstructure has been studied by many researchers [12, 13, 14]. The studies have been directed, in particular, to highlight the effect of microalloying elements on the size and shape of the austenite grains at temperatures in the hot plastic deformation domain (900...1300 °C). However, it has to be mentioned that also in the case of microalloyed steels, superior mechanical characteristics can be obtained only by applying specific thermomechanical treatments, such as controlled rolling with well defined technological parameters (controlled temperature at start and end of the thermomechanical processing, deformation degree, cooling conditions) [15-18]. The values of these technological parameters are chosen according to the chemical composition of the steel produced.

The determining factor in the design of thermomechanical treatment regime for microalloyed steels is the ability to control the microstructure obtained after the completion of all stages of the treatment. The required superior mechanical characteristics (tensile strength, yield strength, toughness, fatigue resistance) might be obtained through optimum selection of thermomechanical process parameters without applying further heat treatments.

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Thus can be obtained microalloyed steels with enhanced toughness, able to replace heat treatable low and medium alloyed steels. The development of these steels has a large potential for cost saving by eliminating the final heat treatment stage. The setting or choosing of the chemical element which has the best behavior in microalloying process is based on the maximum value of heating temperature of the steel during hot processing. Thus, in case of steels forged at high temperature (1200...1300 °C) is preferable the microalloying with Ti or Ti and Nb, while for the steels processed in the range 900...1200 °C is preferable microalloying with vanadium [19, 20, 21].

2. Obtaining of microalloyed steels

The aim of experimental program was the study of the microalloying elements effect on mechanical and microstructural characteristics, resulting from the application of controlled mechanical treatments. The microalloying elements have been introduced in various combinations in quasi-identical matrices of carbon steel.

For this purpose, were obtained mini-ingots of C-Mn steel, as-casted, which have been microalloyed with V and Nb in different weight proportions, and then were thermomechanical processed, by forging. The samples cut from these ingots were then tested for tensile test, impact bending test and metallographic analysis to highlight the role of microalloying elements on the mechanical properties. The experimental program was based on previous research conducted by members of the research team [21-24] regarding the influence of chemical composition on the microstructure and the mechanical properties (microhardness) of steels microalloyed with niobium and vanadium.

For the design of the experimental metal matrix, as reference, was chosen the 38MnVS6 steel mark (International Steel Grade BS, AFNOR, SAE), with chemical compositions placed in the ranges of values: C = 0.34 - 0.41%, Si = 0.15 - 0.80%, Mn = 1.20 - 1.75%, P <0.025%, S = 0.02 - 0.06%, Cr <0.30%, Mo <0.080%, V = 0.08 - 0.20% Nb = 0.12 - 0.20%, N = 0.01 - 0.02%. After that, keeping the constant metallic matrix, some changes in the content of microalloying elements were made.

The microalloyed steel samples were obtained in a 12 kg vacuum induction furnace HU-40-25-40-04 Balzers type, from the endowment of Faculty of Materials Science and Engineering, POLITEHNICA University of Bucharest, laboratory ERAMET (www.eramet.ro), with 50 Hz frequency and 40 kW nominal power [25].

The steels microalloyed with vanadium and niobium have been obtained starting from S 235JR steel (EN 10025:2004), with the following chemical composition: C = 0.168 %; Si = 0.138 %; Mn = 0.485 %; P = 0.013 %; S = 0.03 %; Fe - balance. The following materials have been used for alloying: technical silicon (98 % Si), metallic manganese (99 % Mn), metallic Vanadium (99 % V), C (graphite) and FeNb (Nb = 65.6 %; Ta = 0.08 %; Al = 1.2 %; Fe - balance).

The main microalloying elements for the experimental samples of steel were chosen in the following limits:

- The content of Nb was varied in the range 0.12...0.203 wt%, with a degree of assimilation (from the ferroalloy) of 95 %;
- V content was varied in the range 0.142...0.176 wt% with a degree of assimilation of 90 %;
- The carbon content variation was in the range 0.29...0.387 wt%, the main concentration being around the value of 0.3 wt%. The degree of assimilation of carbon in the metal bath was between 50...70 %, depending on the degree of oxidation of the batches and the temperature of the refractory lining. Regarding the carbon, low corrections have been made, depending on the degree of oxidation of the batches and the temperature of the refractory lining. Also, the obtaining time has been kept constant, to prevent the excessive oxidation of some elements in the metal bath.
- The silicon content was varied in the range 0.461...0.67 wt% with a degree of assimilation of 75 %;

- The content of manganese has registered the greater variations (1.25…1.72 wt%) with a degree of assimilation of 70 % ;
- Sulfur and phosphorus have not generated any problems during obtaining process, their
- content in the matrix being extremely low, due to the basic material very clean (S 235JR steel) and controlled ferroalloys;
- Chromium content was kept in the constant range of 0.23...0.256 wt%, for a constant value of chromium content of about 0.26 wt % (imposed) and a degree of assimilation of 90 %.

For the first step of research, the experimental batches of steels were made in low-capacity induction furnace. Experimental batches, with different compositions, were cast into hexagonal ingots, in normal atmosphere. The mass of each sample was between 8.4…9.2 kg. Then, were thermomechanical processed by forging, for studying the

deformation behavior, the effects of the V/Nb ratio on the mechanical properties, in order to optimize the technology of plastic deformation.

3. Results and discussions regarding the obtaining process

During the experimental program have been obtained 6 batches of microalloyed steels with different chemical compositions (different content of V and Nb). The chemical composition of the experimental samples, determined by spectrometry (LISEOFRX laboratory, in the Faculty of Materials Science and Engineering, POLITEHNICA University of Bucharest) is presented in Table 1.

Table 1. Chemical composition of experimental samples

Sample code	Chemical composition, wt%									
	C	Si	Mn	P	S	Cr	Ni	Nb	V	V/Nb
TNMA8	0.29	0.69	1.72	0.006	0.0028	0.23	0.050	0.192	0.155	0.807
TNMA9	**0.30**	**0.67**	**1.73**	**0.007**	**0.0033**	**0.25**	**0.059**	**0.203**	**0.176**	**0.8669**
TNMA15	0.313	0.461	1.35	0.005	0.0023	0.27	0.098	0.12	0.146	1.21
TNMA16	0.387	0.55	1.32	0.009	0.006	0.252	0.046	0.176	0.145	0.82
TNMA17	0.345	0.457	1.25	0.008	0.004	0.248	0.066	0.162	0.164	1.01
TNMA18	**0.316**	**0.54**	**1.35**	**0.011**	**0.0052**	**0.256**	**0.051**	**0.169**	**0.142**	**0.84**

In terms of the obtaining process of experimental steels, using low-capacity induction furnaces, it can be appreciated that the working procedure was appropriate. The values of microalloying elements in the experimental steels (niobium and vanadium) were very close with those resulted from the calculation, due to appropriate dosage of batches and the right order of introduction in the melted bath.

4. Thermomechanical processing

The cast ingots have been formed (by hot forging), as bars with square section (20 mm side), and with circular section (20 mm diameter). The reduction degree for all the samples was 87%. The value of the reduction degree was established by preliminary experimental research dedicated to these steels, considering the low dimensions of the ingots. The heating of ingots was done in a gas chamber furnace. The plastic deformation was made both in dynamic regimes, with a hammer, and also in static regime, with a press. The values of the parameters used for plastic deformation are presented in table 2.

Table 2. Values of thermomechanical process parameters

Sample	Heating temperature, ^{o}C	Final temperature for forging process, ^{o}C	Reduction degree, %	Cooling speed, ^{o}C/min.
TNMA8	1200	950	87	110-130
TNMA9	1200	980	87	110-130
TNMA15	1200	920	87	80-90
TNMA16	1200	970	87	80-90
TNMA17	1200	950	87	80-90
TNMA18	1200	940	87	80-90

The thermomecanical process for the batches TNMA 8 and 9 is presented in fig.1 and for batches TNMA 15-18 in Fig. 2.
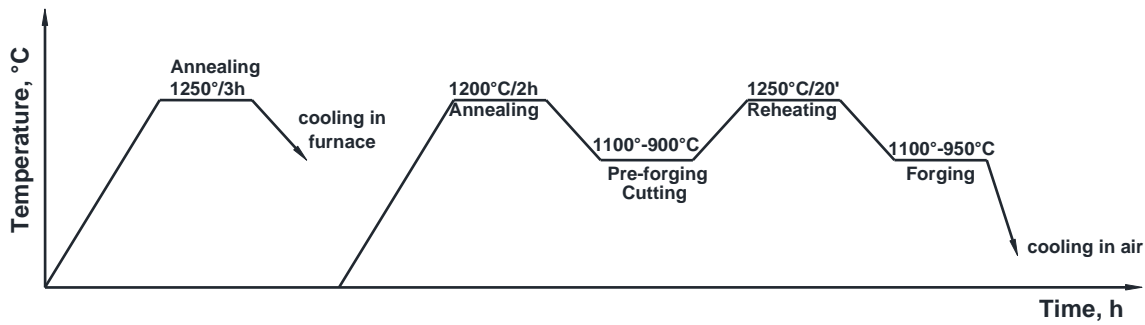
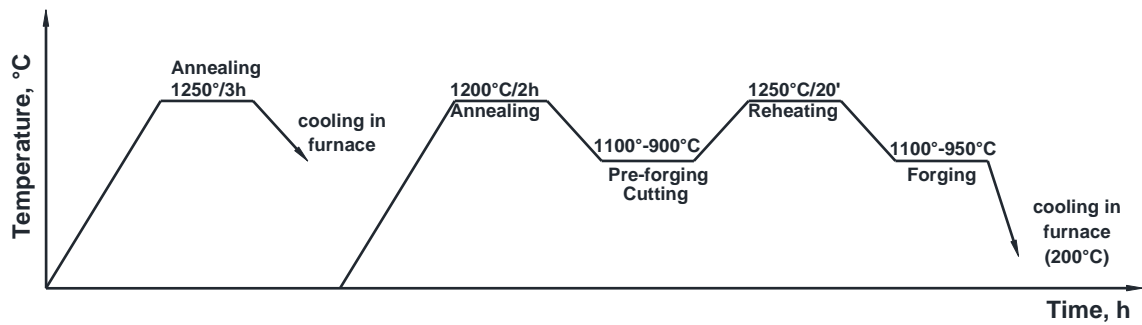*Fig. 1. Thermomechanical processing diagram for samples TNMA8 and TNMA 9.*

Fig. 2. Thermomechanical processing diagram for samples TNMA 15 - TNMA18.

5. Results and discussions

5.1. Thermomechanical processing

Samples cut from the forged bars have been mechanically tested (tensile and compression tests according to ASTM E8, E21 and Charpy impact test- according ASTM E 23, ISO 148) [26]. The results of mechanical tests are presented in table 3. The mechanical properties of microalloyed steels for the automotive industry are influenced by thermo mechanical treatment processes and also, by chemical composition.

The following observations can be made by analyzing the results of the mechanical tests for the batches TNMA 8 and 9:

Table 3. Values of mechanical tests

Sample	Mechanical properties							V/Nb ratio
	Tensile strength, Rm, MPa	Yield strength, $Rp_{0.2}$, MPa	Elongation, A, %	Reduction in area, Z, %	Impact energy, KU_2, J			
TNMA 8	948.29	476.14	12	-	73	57.1	52.3	0.807
	956.65	468.34	13	-	-	-	-	
	916.38	469.21	15	-	-	-	-	
TNMA 9	992.17	536.2	14	-	93	77.9	70.2	**0.8669**
	912.26	602.27	12	-	-	-	-	
	958.57	566.08	16.5	-	-	-	-	
TNMA 15	938	612	13.5	50.5	70.7	74.2	54.0	1.21
	940	619	14	45	43	51.6	60.9	
	1024	662	15	43.5				
TNMA 16	920	700	16.5	48.5	29.5	31.3	44.3	0.82
	1019	746	14	44	29.5			
	940	692	18	47.5				
TNMA 17	1007	662	15	41	59.2	68.4	84	1.01
	1059	695	14.5	36	27.9	44.2	55.4	
	980	663	15.8	43				
TNMA 18	854	652	18	59	76.3	86.2	100.5	**0.84**
	988	695	14	37	46.7	65.6	93.5	
	913	663	14.5	46	-	-	-	

- The values of tensile strength are in the range of 900 – 1000 MPa, the mean value for yield strength for sample TNMA 8 being around 470 MPa and for sample TNMA 9 around 600 MPa, while the elongation is approximately 12 % for both; it can be observed that sample TNMA9 has slightly superior values for mechanical resistance in comparison with TNMA 8;

- The compression test of sample TNMA 9 (bar with square section) resulted in compression resistance of 1200 MPa and a shortening at compression of approx. 18%;

- The values for absorbed energy for sample TNMA 9 are slightly higher (around 20 J plus) compared with those for batch TNMA 8, representing a plus for toughness of the sample TNMA 9. The high dispersion of values obtained for absorbed energy could be generated by inappropriate machining of the samples and the presence of internal micro-defects.

For TNMA 8 and 9 samples processed according with diagram from fig. 1, the microalloyed steels main compositional values are approximately constant, as: C = 0.29 to 0.30%, Si = 0.67 - 0.69%, Mn = 1.72 - 1.73% P = 0006-0007%, S = 0.0028 - 0.0033%, Cr = 0.23 - 0.25%, Ni = 0.05 - 0.059%. The content of micro alloying elements are moderate differentiated, from 0.192% (TNMA 8) to 0.203% (TNMA 9) Nb and 0.155% respectively (TNMA 8) to 0.176% (TNMA 9) V. From these results that the microalloyed elements values influence the mechanical properties of microalloyed steels used in the automotive industry. Also, the data extracted from the chemical composition values report an optimal value of V/Nb = 0.8669 for the mechanical properties of these forged steels..

For batches TNMA 15 – TNMA 18, at which the cooling after forging has been made in a furnace heated at 150 – 200°C, the following aspects can be noticed:

- The tensile tests show that the microalloyed steel presents values in the range of 850 – 1000 MPa for tensile strength and in the range of 600 – 700 MPa for yield strength, the values for mechanical characteristics for each batch being relatively close. Regarding the plasticity, the values for elongation A, are comprised in the field 14 – 18 % and values for the reduction in area Z, in the field of 36 – 59 %; obviously the highest value for plasticity were obtained for the lowest values of the mechanical resistance;

- The compression tests shows the similar mechanical properties for the batches TNMA 17 and TNMA 18, that have values for the yield strength higher than those of batches TNMA 15 and TNMA 16, but quite similar with the batches TNMA 9;

- The impact test clearly underlined that the batch TNMA18 has the best results, at which the mean value of impact energy, KU2, has been of 78J. Is a high value for this parameter, being close to those of the

medium alloyed steels, quenched and tempered. For all the samples from this batch, the values for impact energy have a high dispersion, due probably to the lack of accuracy during machining of the samples;

- Concluding, the batch TNMA 18 shows the best mechanical properties regarding the resistance, plasticity and toughness.

For batches TNMA 15 - 18 TNMA processed according diagram from fig. 2, the main compositional values of microalloyed steels are within the limits defined for microalloyed steels used in the automotive industry as follows: C = 0.313 to 0.387%, Si = 0457-0461%, Mn = 1.25 - 1.35%, P = 0005-0011%, S = 0.0023 - 0.0052%, Cr = 0.248 - 0.26%, Ni = 0046-0098%. The content of micro alloying elements are moderate differentiated from 0.12% (TNMA 15) to 0.176% (TNMA 16) for Nb and 0.142% respectively from (TNMA 18) to 0.164% (TNMA 17) for V. Also in this case the values of microalloying elements influence the mechanical properties of microalloyed steels used in the automotive industry. Also, the data extracted from the chemical composition values report an optimal value of V/Nb = 0.84 regarding the mechanical properties of these forged steels. These values are within the limits imposed for both types of thermomechanical treatments, which is why, based on experimental data, we can draw diagrams of correlation between the content values of alloying elements and mechanical properties of these types of forged steels.

Based on the data presented in table 1 and 3 diagrams have been drawn to evidence the correlation between the different parameters of the manufacturing process (considering the effects of main microalloying elements) and the mechanical properties of the microalloyed steels. Thus, fig. 3 – fig. 8 show the influence of the vanadium and niobium content on tensile strength and respectively, on the impact energy. There are highlighted the proportional increase of the mechanical characteristics values with the increase of vanadium content (fig 3 and 4) or niobium (fig 5 and 6) or the combination of vanadium and niobium (figure 7 and Figure 8).

These effects are due to the influence of the microalloying elements on the grain refining degree and the sub-grains network, microstructure of ferrite with very fine precipitates of carbides, nitrides and/or carbonitrides, formed during the austenite transformation at cooling. It is obvious that the proportion of these chemical elements in microalloyed steel grade cannot overcome the values imposed by product specifications. Introduction of some expensive materials leads also to increasing the steel price.

The influence of the V/Nb ratio on the mechanical properties of the microalloyed steels, hot deformed by forging, is represented in fig. 9 and fig. 10. It can be observed the parabolic distribution of the values, with maximal values in the interval 0.84 - 0.87.
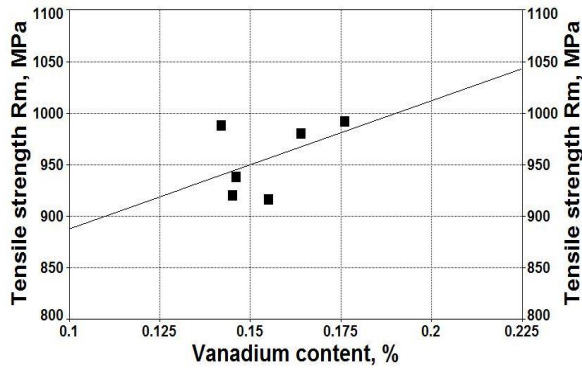
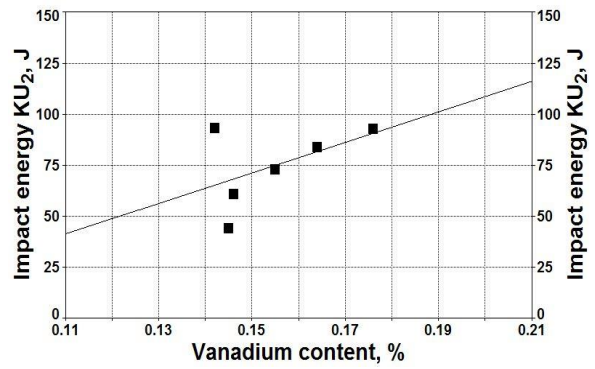Fig. 3. Influence of V content on the tensile strength.

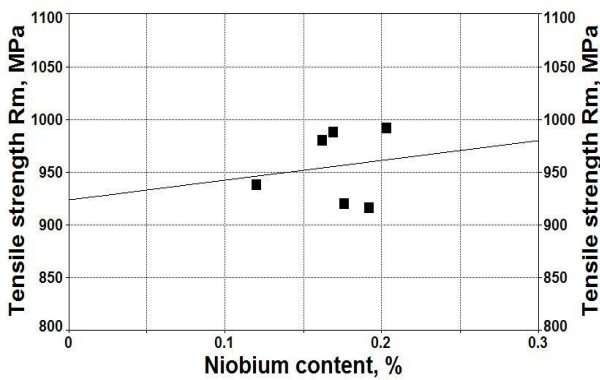Fig. 4. Influence of V content on the impact energy.

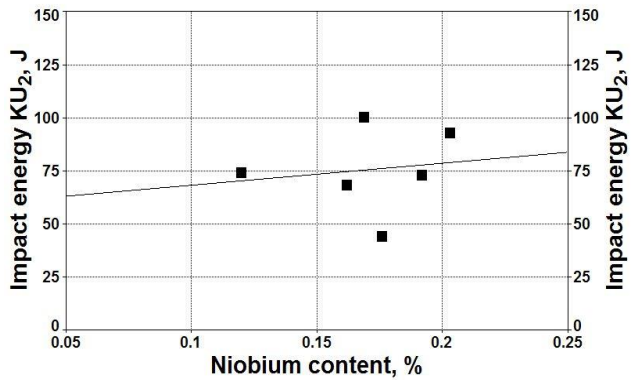Fig. 5. Influence of Nb content on the tensile strength.

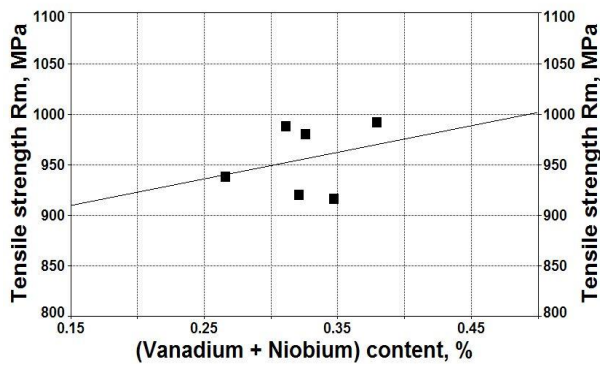Fig. 6. Influence of Nb content on the impact energy.

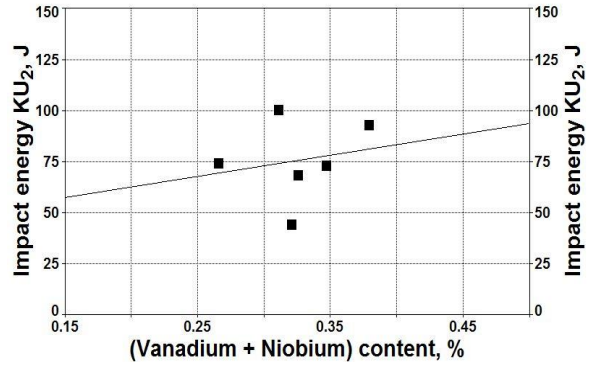Fig. 7. Influence of (V+Nb) content on the tensile strength.

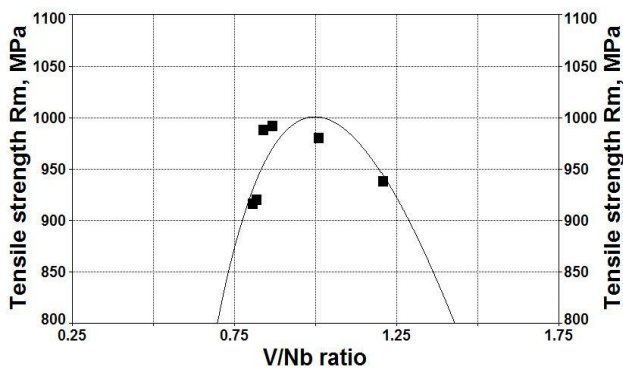Fig. 8. Influence of (V+Nb) content on the impact energy.

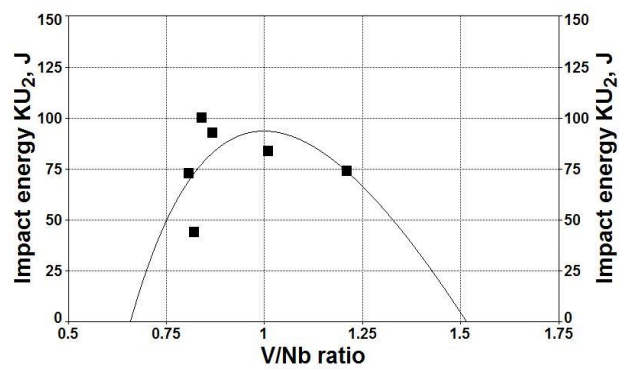Fig. 9. Influence of V/Nb ratio on the tensile strength.

Fig. 10. Influence of V/Nb ratio on the impact energy.

Under this aspect, from the comparison between the steels having the ratio V/Nb in the field of 0.84 – 0.87 it can be observed a similarity of the mechanical properties, although there are differences in the impact test results (values are higher in the case of TNMA 18 where KU_2 is 100 J, compared with the TNMA 9, where KU_2 is 93 J).

Due to the fact that the yield strength value is slightly higher in the case of batch TNMA 18 (670MPa) in comparison with TNMA 9 (568MPa) could be considered that, from the two analyzed materials, the microalloyied steel named TNMA 18 is preferred in engineering applications which implies, simultaneously, superior mechanical characteristics of resistance and toughness. Analyzing the chemical composition of the last 2 batches, it can be observed that the alloying degree with V and Nb is lower in case of batch TNMA 18, this representing an economical advantage for the obtaining of the metallic matrix.

The more favorable behavior, at the same mechanical tests, could be explained by the different cooling regime of the two batches, with practical consequences for toughness value.

6. Conclusions

The values of microalloying elements in the experimental steels (niobium and vanadium) were very close with those resulted from the calculation, due to appropriate dosage of charge and the right order of introduction in the melted bath.

Microalloying of steels with Nb and V followed by thermomechanical processing (annealing, forging, controlled cooling) ensures superior mechanical characteristics (values of the tensile strength in the interval of 900 – 1000 MPa and yield strength in the interval of 600 – 700 MPa), without applying subsequent heat treatments.

Similar values are obtained, in the case of low and medium alloyed steels, only after applying heat treatments (quenching/tempering).

For the microalloyed steels it is possible to obtain higher values of the mechanical properties by microstructure control, during the thermomechanical process and by controlling phase transformations, during cooling.

Replacing of low or medium alloyed steels with microalloyed steels contributes to lower manufacturing costs, by eliminating some technological operations linked to secondary heat treatment.

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