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The deformability and thermal treatment for the low alloyed Romanian steel of high resistance

[1]**IOAN ILCA**[*], [2]**DANIELA MILOŞTEAN**

[1]Member (c) of TECHNICAL SCIENCES ACADEMY OF ROMANIA,
University Politehnica Timisoara, Faculty of Engineering Hunedoara, Revoluţiei 5, Hunedoara, Romania
[2]University Politehnica Timisoara, Faculty of Engineering Hunedoara

Abstract: The studies made regarding the elaboration of some low alloyed steels of high resistance refer to the construction of some equipment that has maximum fatigue resistance on different directions, the steel having remarkable tenacity and ductility. In this category one can find the romanian steel 15VMoCr14X, pure in what concerns the gas content (azote, hydrogen) and non-metallic inclusions, having an advanced chemical and structural homogeneity. The characteristics of deformability are studied, which are represented by plasticity and deformation resistance, and the optimum temperature for heat processing is determined. After rolling the 3.6 tone ingots in half-finished products of blum □ shape of 250mm, a fist thermal treatment was applied to re-establish the resulted structure after deformation, which is formed out of ferrite and globular perlite with a bainitic orientation. The obtained granulation was inhomogeneous. Its correction to a more fine and uniform granulation was realized through a second thermal treatment after a previous rolling at a profile of □150mm. From the experimented secondary thermal treatments was chosen for the industrial practice the optimum one. A more homogeneous and finer granulation is observed, which determines an increase of the mechanical characteristics, especially resistance and fatigue resistance.

Keywords: low alloyed steels of big resistance, tenacity, ductility, weldability, resistance, fatigue resistance, deformability.

1. Introduction

Low alloyed steels of high-strength are successfully used in any building applications [1], with the aim of decreasing the weight or increasing the durability on the basis of the high resistance [2] that they have.

[*] Correspondence address: ilca@fih.upt.ro

Although these steels can be used in all known domains on the market, the principal one is that of equipment for transport [3], this is why they have to be more resistant and in many cases tougher than the construction carbon steels.
Also, they have to be sufficiently ductile, formable, weldable [4] and easy to work with using the workshop's usual methods.
The weight savings have a special importance in the case of mobile pieces, when they allow them to support high load capacities.
In addition, most of the times a bigger resistance to corrosion is asked in comparison to the construction carbon steel, so that the period of functioning of big resistance steel elements is higher [5].
This is why in the previous years the main focus was not on reducing the weight but on obtaining more powerful and lasting constructions with a low or non-increase in weight.
In this way some advantages were obtained in the construction of some important vehicles of land and space transport.
Also, in the construction of bridges the designers admit the big importance that the reduction of weight has. One of the solutions was represented by the use of low alloyed steels of high-strength, especially in the construction of bridges [5,6] with wide openings to which the reduction of weight of the central beam would allow some important weight savings in the construction of the legs.
Low alloyed steels of high-strength are successfully used in the construction of towers, to which can be used smaller sections than the ones corresponding to those of carbon steel constructions. This is an important advantage for the construction of high towers, where the forces resulted from wind resistance are decreased by using smaller sections and by reducing the weight which determines a significant price cut. These steels have a recent use in the construction of the columns for tall buildings. Important cost savings and a reduction of useful building area can be obtained through a judicious use of low alloyed steels of high-strength instead of carbon building steels and instead of any combination of them.
By using the low alloy steels with high-resistance there was considerable reduction of the weight of the portable containers for liquefied petroleum gases [7] like the ones destined to fulfil the requirements of heating appliances or for other similar goals, reducing in this way their handling and transport cost.

2. Content

In Romania the most important grade of low alloy construction steels of high-resistance is 15VMoCr14X; it is produced in the former Steel Mill from Hunedoara, which has multiple uses in the economy of the country. The main one represented the construction of the components for the airplane's landing gear of indigenous origin, succeeding in this way the replacement of expensive imported steel, because the qualitative performances of the Romanian steel are situated at the level of French steel (35NCD16), American steel (SEA4340 or 300M) and English steel (REX 539).

Our studies in the construction of these steels refer mainly at the realization of some equipment that has maximum fatigue resistance in different ways, the steel having remarkable tenacity and ductility. The requirements for superior resistance characteristics come from the harsh exploitation conditions, from the durability of some assemblies and sub-assemblies made from this steels, without affecting their properties of tenacity and ductility.

The elaboration of high-resistance steels in Great Britain and in USA were made in two ways. The first one represents the construction of low alloyed steels with a medium content of carbon and medium resistance, about 1400N/mm², which were used during the years, for example NCMV in Great Britain and SEA434 in USA with and without any modifications of the chemical composition. The second direction is characterized by the development of some steels with specially made chemical compositions, without applying any thermal treatments, like in the case of low alloyed steels.

The 35NCD16 French steel is successfully used in military applications. At quenching it is cooled down with air or gas and it doesn't have any internal tensions after the thermal treatment, having all the advantages of the Maraging steel but no its high cost.

The romanian steel 15VMoCr14X was made in electric oven of 50 tones, with alkaline lining, after the duplex system: electric oven-vacuum treatment facility (VAD, RH), because choosing the right making and casting process assures a clean steel regarding the gas content (azote, hydrogen), and the non-metallic inclusions in the ingot (or half-finished continuous casted) with advanced structure and chemical homogeneity.

The chemical composition of the Romanian steel is given in table 1.

This steel presents special mechanical characteristics; it is high-resistant and has tenacity over high temperatures range, for example +500°C÷ -75°C, big fatigue resistance and high reliability. Being used for the construction of some vital parts in engine making and most importantly in the structural frame system of the airplanes' landing gear, which is very used on three-dimensional directions, the steel needs to correspond to a high degree of isotropy of the mechanical characteristics.

Table 1. The chemical composition of 15VMoCr14X

Steel grade	C [%]	Mn [%]	Si [%]	S [%]	P [%]	Cr [%]	Mo [%]	V [%]	Cu [%]	Ni [%]
15VMoCr14X	0,13 0,18	0,80 1,10	max. 0,20	max. 0,015	max. 0,02	1,25 1,50	0,80 1,00	0,20 0,30	max. 0,20	max. 0,30

After all of these technical conditions it is observed the fact that the 15VMoCr14X steel is part both of the high-resistant class steels, and of the high tenacity class steels that is maintained high even at low temperatures.

In table 2 it is presented the chemical composition for batches made from 15VMoCr14X steel and in table 3 the resulted mechanical characteristics.

Table 2. The chemical composition for batches made from 15VMoCr14X steel

Number batch	Percent												P.P.M.	
	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	V	Al	As	O_2	N_2
Set under the existing standard	0,13 0,18	0,80 1,00	max. 0,20	max. 0,015	max. 0,020	1,25 1,50	max. 0,30	0,80 1,00	max. 0,20	0,20 0,30	-	-	max. 40	max. 100
1	0,15	1,01	0,2	0,015	0,019	1,37	0,08	0,88	0,15	0,30	0,060	0,016	34	109
2	0,15	0,86	0,14	0,018	0,020	1,36	0,08	0,88	0,22	0,26	0,064	0,008	34	123
3	0,15	0,89	0,13	0,012	0,018	1,34	0,13	0,89	0,15	0,27	0,068	0,016	32	126
4	0,15	0,90	0,11	0,015	0,022	1,32	0,07	0,89	0,13	0,24	0,088	0,016	31	129
5	0,15	0,77	0,17	0,014	0,020	1,30	0,08	0,86	0,15	0,24	0,071	0,007	34	134

Table 3. The mechanical characteristics of the batches made from 15VMoCr14X steel

Batch Number	Traction				Resilience		
	$Rp_{0,2}$ N/mm²	Rm N/ mm²	A5 %	Z %	KCU5 +20°C daJ/ cm²	KCU3 +20°C daJ/ cm²	KCU3 -50°C daJ/cm²
Set under the existing standard	930 -	1080 -	10 -	- -			
1	1130	1190	16,0	70,0	8,00	12,78	7,87
2	1100	1190	17,0	65,0	7,71	9,10	4,19
3	1170	1250	16,0	63,0	8,54	10,66	7,26
4	1040	1140	17,0	65,0	7,78	10,68	1,63
5	1020	1120	16,0	66,0	8,58	10,67	4,42

From the analysis of the presented batches it results that both chemical composition and their mechanical characteristics were within the accepted norms.

2.1. The effect of some elements from the composition

Carbon. It is one of the most efficient and economic elements which increase the resistance. It was noted that an increase of about 3,5N/mm² of the flow limit corresponds to an increase of the carbon content with 0, 01%. But the growth of resistance in this way is accompanied by a reduction of ductility, resilience and weldability this is why the carbon content of low alloyed steels of high-resistance is maintained under a certain maximum limit which depends on the destination of the steel.

In general it is better to maintain the carbon content under certain maximum limits when certain electric arc welding is needed to avoid the embrittlement of the area in the neighbourhood of the welding. The high content of carbon determines an increase of the hardenability so as to in the heat influenced area the tendency of hard and brittle martensite increases.

The addition of carbon improves the fatigue limit directly proportional with the value that increases the resistance to traction.

Manganese. Low alloyed steels of high-resistance have higher content of manganese than construction carbon steels. The effect of this element upon the resistance and fatigue limit is similar to the one of the carbon, but in a smaller measure. It was found that manganese improves the resilience.

For the steels destined to the uses that need welding it is necessary that the content of this element to be maintained under a certain maximum limit, which depends on the general composition, but especially on the carbon content.

Phosphorus. A lot of the actual low alloyed steels of high-resistance have phosphorus contents ranging between 0,04 -0,15%. The addition of phosphorus improves significantly the resistance properties of the steel, but this phenomenon is accompanied by a ductility decrease. In the past it was considered that in a bigger proportion than 0,10% phosphorus determines an embrittlement of the steel. It was found though that this effect is significantly influenced by carbon content at that is not that pronounced in low contents of carbon in low alloyed steels of high-resistance. It was also noted that the addition of aluminium that intervenes for example in the de-oxidation process with silicon-aluminium improves the resistance of the steels with phosphorus.

The phosphorus addition, like the carbon and manganese ones, increases the fatigue limit in approximately direct proportion with the growth of the traction's resistance. Also, if there are in the steel small quantities of copper the effect of the phosphorus is more pronounced, so that a certain proportion of phosphorus and copper, taken together, produce a more favourable effect bigger than the same proportion in each element.

Copper. In limited quantities, copper has a favourable effect upon low alloyed steel of high-resistance. Many of the actual steels of this type contain a percent of copper between 0.20-1,30%. The copper improves the resistance and hardness properties of steels with low and medium content of carbon, correspondent to small decrease of ductility. The fatigue limit is improved by the presence of the copper in the same proportion with the increase of the traction's resistance.

A favourable effect upon the quality of the surface of steels with copper is obtained by the addition of nickel in equal amount with at least half of the copper's content. Copper in usual concentrations, from all the elements obtained through alloying, is the most efficient from the point of view of the resistance improvement of the steel at atmospheric corrosion [8]. In a percent of 0,35% of the obtained carbon steel copper is very efficient. With a content of 1,00% Cu a continuous improvement can be reached, but the effect is not that emphasized like in the cases of 0,35% Cu adding.

Vanadium. It is used in a large amount as a resistance enhancing agent for low alloyed steels with high-resistance. This element, in an amount up to 0,12%, offers steel a higher strength [9], without having any unfavourable effect upon weldability and resilience. This is why low alloyed steels with high-resistance with vanadium are suitable especially for welded constructions, in which resilience is a key factor.

Other elements. From the chemical composition it is found that besides the above mentioned elements other elements are added for different low alloyed steels with high-resistance. Each was added with the aim of improving one or more of the important characteristics of the steels.

In general, obtaining a bigger mechanical resistance, a fatigue limit and superior wear resistances happens in the damage of the welding and even in the damage of the handling.

The specific combinations of the elements used for different steels determined some property and characteristic compromises.

2.2. The steel's deformability

Through deformability one can understand the property assembly which characterizes the plastic handling behaviour of the steel [10].
The appreciation of deformability is done through two technological properties: plasticity and deformability resistance.
These characteristics for steels are usually determined from 50 to 50°C and in the domains where structural or phase transformations occur, the temperature range shrinks to get the variation of the characteristics from a certain domain.
Each determination repeats itself at least three times and the obtained average of the values is taken into consideration. A few means of deformability determining are known: through traction, compression, and recently, the method through hot twisting.
The last mentioned one is the only one that allows the obtaining of big deformations on the whole length of the samples. Keeping in mind that the shearing tensions play an important role in the rolling and forging processes, the deformability obtained by twisting reflects quite accurately the steel's behaviour in deformation through these processes.
In this way, in the laboratory of Theory of metallic material deformation from the Faculty of Engineering Hunedoara, professor Ioan Ilca conceived and realized the hot-twisting deformability machine, shown in figure 1.

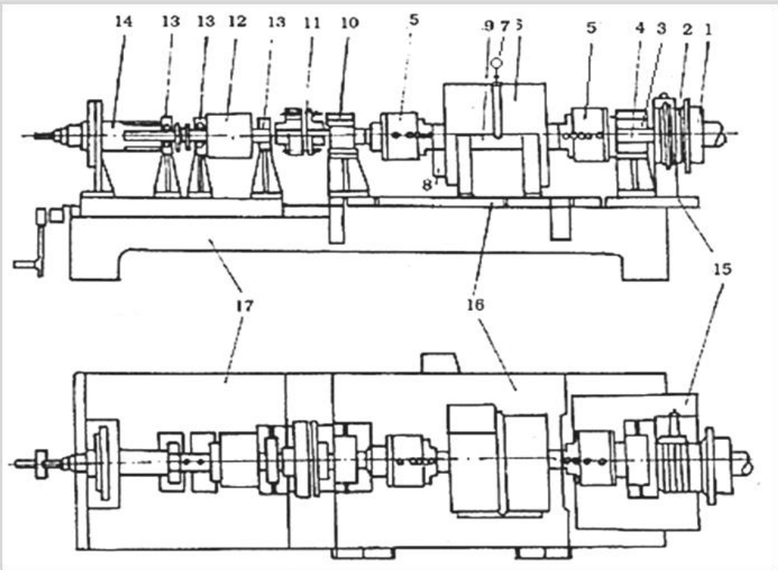


Fig. 1. Installation for the determination of deformability through hot twisting
1 - flange coupling on the motor spindle; 2 - electromagnetic coupling; 3 - fixed bearing; 4 - axis; 5 - sample fixation bins; 6 - heating oven; 7 - pyrometer with radiation; 8 - thermoregulator with resistance thermometer; 9 - sample; 10 - mobile bearing; 11 - mobile coupling; 12 - safety coupling; 13 - fixed bearing; 14 - cooling moment measuring bar; 15 - fixed plate; 16 - flapper; 17 - framework.

After approval, besides the didactic goal, the machine proved its many technological utility, being used by the author and collaborators in solving a large number of economic contracts with specialized units in metallurgy and machine building. Thus the field with optimal plasticity was determined for the rolling of steels developed in Hunedoara, for the thermonuclear Power Plant from Romania, of high resistance steels for deep sea drilling for the oil industry, of silicon steel grades for the electrotechnical industry, as well as of the steel for the industry aeronautics.

At this car, the samples are heated in a resistance furnace (silo bars) up to a maximum of 1300°C. The furnace temperature is kept constant with a 0.3°C error, with a thermoregulator with a resistance thermometer. To avoid oxidation of the sample, it is heated in a refractory steel tube through which purified nitrogen is circulated.

The machine develops three deformation rates, being applied for determinations similar to industrial preferences (rolling or forging). The determination is done on samples collected from the studied steel, of cylindrical shape, with a calibrated central sector, with smaller diameter, having the l/d=5 report corresponding to the part where the deformation takes place (figure 2).

The heating of the samples is done with high frequency currents and the deformation can be monitored visually. With the help of a radiation pyrometer the samples' temperature are measured.

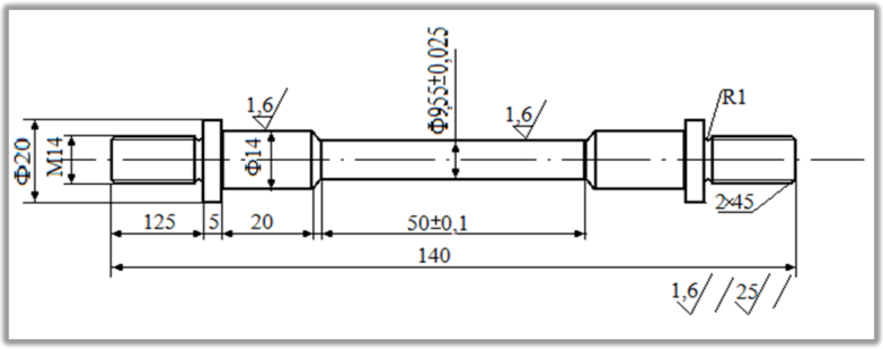


Fig. 2. The torsion test sample.

The experiments realized for 15VMoCr14X steel had a good reproducibility. In this way, when measuring the twisting moment the average deviation was of ±2% and for the number of twists until breaking from ±2% up to ±4%.

The twist deformation at the surface of the samples is given by the relation:

$$\gamma = r \cdot Q \cdot l$$

where: r = portion calibrated range surface, in mm; Q = the twist angle, in radian;
l = the length of the sample's calibrated part, in mm.

The speed of the surface deformation is given by the relation:

$$V_\gamma = \frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{\mathrm{d}\left(\frac{r}{l}Q\right)}{\mathrm{d}\theta} \cdot \frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{r}{l} \cdot \frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{r}{l} \cdot \frac{2\pi \cdot n}{60},$$

in which: n = the speed of the sample's spindle, in rotations per minute; dθ = the sample's twist speed

In this way, from industrial batches there were built samples of shapes and sizes mentioned in figure 2, which had to undergo heat twists between the range of 800-1200°C, from 50 to 50°C, using for each temperature 3 samples, at which the value average was considered.

With the technological characteristics obtained, ie the plasticity expressed by the number of twists to break (N) and the deformation resistance - expressed by the value of the torque corresponding to the breaking (M), is draw the diagram of the deformability of the steel depending on the temperature (figure 3), obligatory for the elaboration of hot processing technology.

Analyzing the chart, it is noted a continuous increase of plasticity (the N curve), together with the increase of temperature in the range 850-1150°C, simultaneously with the reduction of the deformation resistance (the M curve).

From this chart it results that the optimum rolling beginning temperature for the studied steel is placed in the range 1130-1150°C, when the plasticity is maximum and the deformation resistance is relatively low. The ending rolling temperature can be between the range 800-820°C, because the Ar3 point is situated at the temperature of 780°C, avoiding in this way the appearance of the biphasic in the structure.

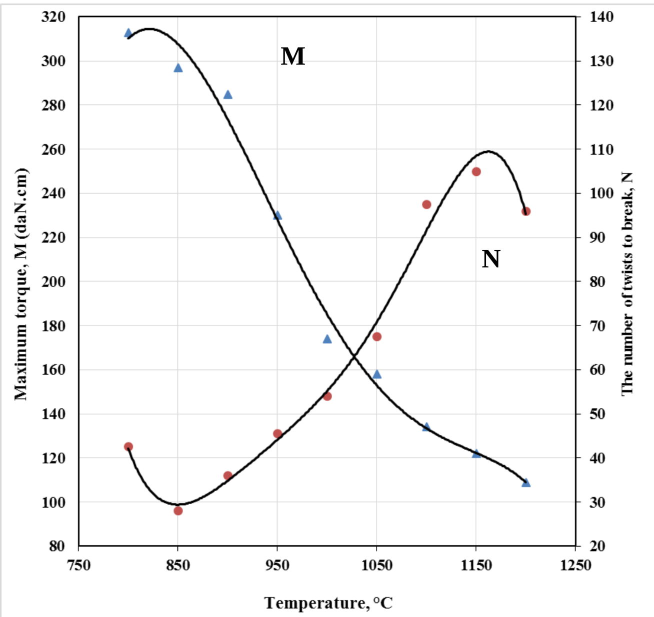
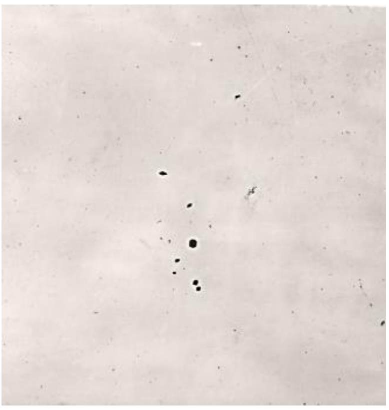


Fig. 3. The deformability diagram for 15VMoCr14X steel grade.

2.3. The applied thermal treatment

After hot rolling the ingots, to the resulted blums □ of 250 mm, a primary thermal treatment was applied to establish the isotropy degree of the mechanical properties. Analysing the Bauman mark of the blums it is noticed the lack of a square of segregation, the steel having high purity, fact highlighted by the microstructure from figure 4; which also emphasizes the inclusions resulting only sulphur of score 1 (according to the present STAS norms), and in figure 5 it is given the size of the austenite grain [11,12,13].

In what concerns the structural homogeneity, the microstructure of the blums was examined on their section.



200:1

Sulphur of score 1

Fig. 4

200:1

Attack, picric acid

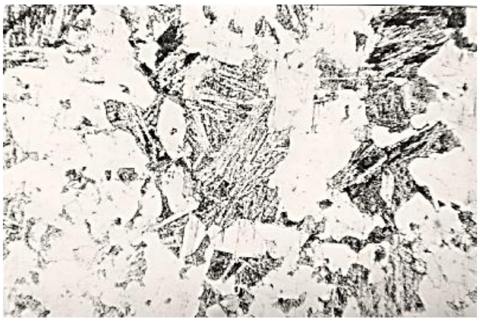
Fig. 5

Figure 6 emphasizes the recorded microstructures from different points in the section. It doesn't result any non-homogeneous structures on the section of the blums from their analysis.

The emphasis of the isotropic qualitative characteristics was realized by taking samples on longitudinal and transversal direction from blums □ of 250mm, previously thermal treated through quenching at 975°C ± 10°C with cooling in oil and tempering at 625°C ± 5°C, with air cooling.

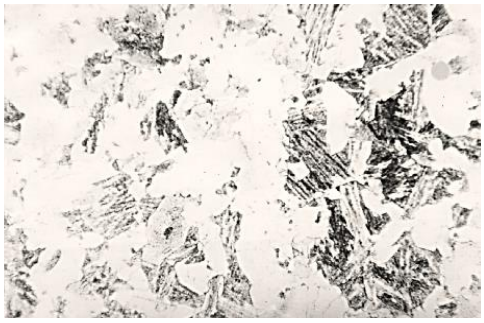
The results obtained for the mechanical structures as opposed to those imposed by the norms are presented in table 4.

To still obtain a half-finished □ of 150mm from the □ 250mm blum, these were reheated at 980-1000°C and underwent rolling. To improve the □ of 150mm half-finished mechanical processability the structure steel's annealing is imposed, the reason primary thermal treatment is applied.



200:1 Nital attack 2%

Microstructure in the centre of the Blum



200:1 Nital attack 2%

Microstructure at the ½ of the Blum's side

200:1 Nital attack 2%

Microstructure at the edge of the Blum.

Fig. 6. Structural homogeneity on the Blum section.

Table 4. The mechanical characteristics

Mechanical characteristics	$Rp_{0,2}$ N/ mm²	Rm N/ mm²	A5 %	WU5 J	KCU5 J/cm²	$R_1 \cdot 10^{-7}$ N/ mm²
imposed	930	1180-1280	10	39	80	50
longitudinal	1153-1170	1240-1238	17,5-15	54,8-55,8	140-152	55
transversal	1148-1148	1230-1240	15,75-17,5	47,1-48,1	72-50	51

The obtained steel's microstructure after rolling and primary thermal treatment is given in figure 7, being made out of globular ferrite and perlite with bainitic orientation.

Nital attack 200:1 Picric acid attac 200:1

Fig. 7. The structure after rolling
and primary thermal treatment.

It is observed that the grit is not homogeneous, its score being between the 5-8 limits. The cause is the unevenness of the heating for rolling, and the correction at a finer and uniformed grain will be done by applying a secondary thermal treatment.

2.4. Secondary thermal treatment

The secondary thermal treatment followed the influence of the austenitizing temperature for quenching and for the degree of transformation at tempering over the size and uniformity of the granulation and also on the mechanical characteristics, especially resilience.

The thermal treatment temperature was correlated with the one of the transformation points, which was dilatometer established. The necessary maintaining time for austenising and tempering was calculated depending on the dimensions of the samples, and the heating was done in an electric oven with azote atmosphere having permanent control over the temperature.

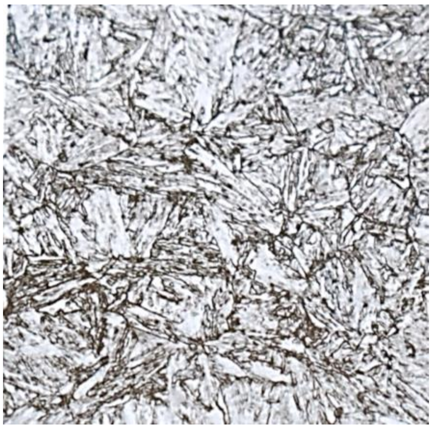
Alternatives of secondary thermal treatment have been tried after rolling at □ of 150mm. From them, the best one was chosen the alternative with technological parameters that consist in quenching the steel at 975°C and tempering in two alternatives at 615°C and 625°C. The resulted microstructures and grain size in this regime are presented in figure 8, in which it is noted a finer and homogeneous grain of 7-8 score, which determined the growth of the resilience’s values. The tempering at 625°C assures a complete transformation, also favouring the characteristics of high plasticity.

Nital attack 2% 500:1

*Microstructure after quenching at 970°*C

Picric acid attack 200:1

Size grain score 7-8



Nital attack 2% 500:1

Microstructure after quenching at 970° C and tempering at 615°C

Nital attack 2% 500:1

Microstructure after quenching at 970°C and tempering at 625°C

Fig. 8. The structure and the size of the grain after secondary thermal treatment.

3. Conclusions

From the analysis of the thermal conditions regarding the qualitative characteristics which the 15VMoCr14X steel must fulfil, it is noted the fact that the steel is part of the low alloyed steel of high-resistance class, but in the same time is part of the ones with high tenacity which is maintained at high values and low temperatures.

This steel presents special mechanical characteristics of high-resistance and tenacity, on a large range of temperatures, for example +500°C ÷ -75°C, fatigue resistance and very high reliability.

Knowing the 15VMoCr14X steel's deformability allows the establishment of the optimum hot processing domain. In this way the recommended optimum temperature for the beginning of the rolling is 1130-1150°C, and for the ending of the rolling 800-820°C, because the A3 point is located at temperatures of 780°C, avoiding the appearance of the biphasic in the structure.

The obtained microstructures through quenching and tempering lead to optimum properties for fatigue in the case of the studied steel.

The steel has though a limited domain of tempering temperature, being very sensitive at local overheating, at the increase of the grain size, both as at the heating for manufacture as well as for the thermal treatment.

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