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# Chemical and structural inhomogeneity of the centrifugally casted Cr-Mo and Cr-Mo-V steel tubes

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**This study presents the casting conditions and experimental results of chemical elements distribution, their structure and hardness in axial direction and in the cross section of centrifugally casted tubes of different diameters and wall thicknesses made of Cr-Mo and Cr-Mo-V steel. Analyses of the chemical composition have shown that in centrifugally casted tubes the more intensive segregation of elements appears in the radial than in the axial direction. The apparent inhomogeneity of structure and hardness in the cross section has also been examined, as well as modelling of the radial hardness distribution.**

*Key words*: **centrifugal casting, steel Cr-Mo, steel Cr-Mo-V, tube, chemical composition, macrostructure, microstructure.**

## List of symbols

| | |
|---|---|
| $T_k$ | – Mould Temperature [K] |
| $T_1$ | – Pouring Temperature [K] |
| $\tau_1$ | – Pouring Time [sec] |
| $\tau_h$ | – Cooling Time [sec] |
| $n_k$ | – Mould Rotation Speed [r/min] |
| $k = F_c / F_g$ | – Gravity Coefficient |
| $F_c$ | – Centrifugal force [N] |
| $F_g$ | – Gravity force [N] |
| $d_s$ | – Outside Tube Diameter [mm] |
| $\delta$ | – Tube Wall Thickness [mm] |
| $\delta_k$ | – Mould Wall Thickness |
| $l$ | – Tube Length [mm] |

## Introduction

CENTRIFUGAL casting is a complex procedure in which, compared to the permanent mould casting, the crystallization of metal is achieved during the rotation of the mould, i.e. under the influence of the centrifugal force. The said force, which acts upon the metal while crystallization, is defined by the coefficient of gravity k, which denotes how many times this force $(Fc)$ is higher than the force of gravity $(Fg)$. The action of the centrifugal force, which is several decimal times higher than the force of gravity, induces the higher density metal structure creating. While pouring the liquid metal into the rotating mould, the centrifugal force pushes the metal towards the mould periphery, forming a hollow along the rotation axis of the casting. A relatively simple production of the casting without use of cores, gating of moulds and other parts, which are necessary in standard casting technology, has caused the wide use of centrifugal casting, especially for the making the castings of non-ferrous metals and grey iron. The centrifugal casting is significantly less applied in steel casting, what is justified by a range of disadvantages of this method [1-6].

One of the disadvantages is a possible segregation of the elements of different density in the casting cross section under centrifugal force influence. The elements of higher density (W, Nb, etc.) are pushed towards the periphery, and with these ones low density (C, Al, Ti and S) towards the inside region of the casting [2, 3]. The periodic crystallization of metals can lead to a complex distribution of segregation zones of said elements, i.e. the so-called "form of lamellar streaks" and cause the defective casting. Apart from the said, in centrifugally cast tubes, because of the centrifugal force action, other shortcomings influence the quality of castings. Among them the most common are flaws in the periphery, as well as forming of unsuitable macrostructure [2, 7]. The growing need for the quality castings as well as minimising the shortcomings have been the reason for this study.

The technological parameters, such as the number of rotations of the mould - n, the casting temperature - $T_1$ and the casting speed - $v_1$ [2, 3, 8], have the highest impact on the listed qualities of the final product, apart from the chemical composition and the dimensions of the casting. The number of the mould rotations shows the highest impact in the radial direction, which is very important in the forming of macro and microstructure and influences the quality of the casting crucially.

The object of this study is to examine the chemical composition, i.e. the axial distribution of chemical elements and the cross section of centrifugally casted tubes of different diameters and wall thicknesses made of Cr-Mo and Cr-Mo-V steel, with different number of mould rotations. The struc-

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tural analysis of the tubes has also been performed. The tube casting was produced in the centrifugal casting foundry "Vrsac" at Vrsac.

*Experimental Part*

Material

The tubes have been made of Cr-Mo and Cr-Mo-V steels of the chemical composition which is given in Table 1.

**Table 1**. Chemical Compositions of Cr - Mo and Cr-Mo-V Casting Steels

| Steel | Chemical composition, mass. % | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mark | C | Mn | Si | S | P | Cr | Mo | V | Ni | Cu | Al | O | N |
| Cr-Mo | 0.20 | 0.60 | 0.44 | 0.028 | 0.032 | 1.25 | 0.15 | | 0.160 | 0.140 | 0.080 | 0.0038 | 0.014 |
| Cr-Mo-V | 0.40 | 0.70 | 0.42 | 0.022 | 0.020 | 2.70 | 0.20 | 0.10 | 0.092 | 0.097 | 0.075 | 0.0370 | 0.020 |

The manufacture of the aforesaid steels has been performed in the medium-frequency induction furnace of 1000 kg capacity and 1 MW power. The tube casting was produced on the centrifugal machines with horizontal rotation axis in steel moulds, at the conditions given in Table 2.

**Table 2**. The Casting Conditions of the Centrifugally Cast Cr-Mo and Cr-Mo-V Steel Tubes

| Steel Mark | Casting Mark | $T_k$ (K) | $T_1$ (K) | $\tau_1$ (sec) | $\tau_h$ (sec) | $n_k$ (o/min) | $k$ | $d_s$ (mm) | $\delta$ (mm) | $l$ (mm) | $\delta_k/\delta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cr-Mo | C1 | 423 | 1863 | 35 | 700 | 1562 | 102 | 176 | 50 | 2000 | 0.82 |
| Cr-Mo | C2 | 423 | 1863 | 35 | 600 | 1315 | 101 | 172 | 33 | 2000 | 1.24 |
| Cr-Mo-V | A | 423 | 1873 | 25 | 420 | 1012 | 42 | 128 | 25 | 1400 | 2.44 |

The tubes C1 and C2 made of Cr-Mo steel were casted in the steel mould of dimensions $\phi$264/$\phi$182 × 2100 mm, and the tube A of Cr-Mo-V steel was casted in the steel mould of dimensions $\phi$260/$\phi$138 × 1405 mm. Before casting, the preheated moulds were dry-coated, the coating consisting of fine granulated $Al_2O_3$ and formaldehyde pitch (rezofen).

Fig.1 presents the image of the centrifugally casted tube A.

**Figure 1**. The centrifugally cast Cr-Mo-V steel tubes A

Chemical Elements Distribution

Chemical composition of the casting, chemical elements axial distribution and the cross-section of the tube have been obtained using the spectrometric method on the quantometre. The examination of chemical composition was done on specimens marked of 1 to 4 (Fig.2) in radial direction. The annular specimens were obtained by cutting from both ends and the middle of the tube. The contents of gasses (O2 and N2) were determined by the Leco apparatus.

Structure and Hardness

The examination of structure of the tube in as-cast condition was done on specimens in the shape of ring segments in radial direction, i.e. radially. Fig.2 presents the cutting scheme of the said specimens. The annular specimens were obtained by cutting from both ends and the middle of the tube.

Macrostructural examinations of the tubes in as-cast condition have been done on deeply etched specimens with Oberhoffer's solution lasting 30 seconds. Qualitative examination of microstructure was carried out using the light microscope with tube specimens which were metalographically prepared by standard procedure, and then etched in 3 % Nital. The radial hardness of the tube wall was measured by Vikers's method HV30 according to the JUS C.A4.030 standard on "Wolpert" hardness measuring device.

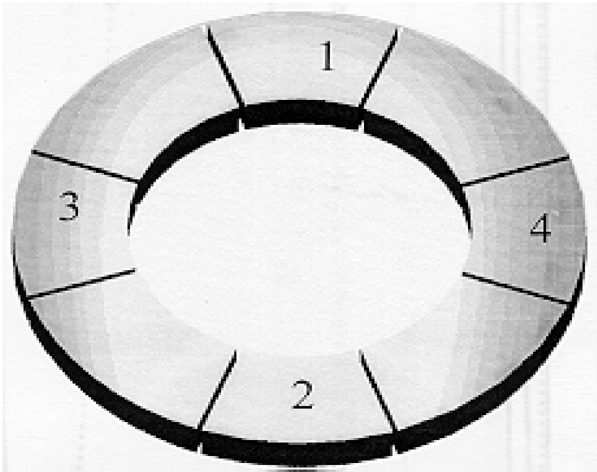
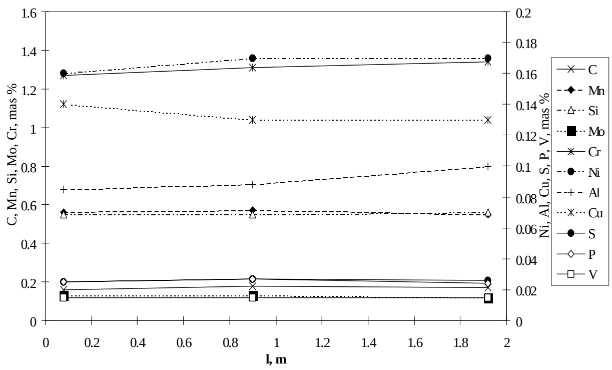



**Figure 2**. The cutting scheme of the samples for the analysis of the structure of the centrifugally cast steel tubes

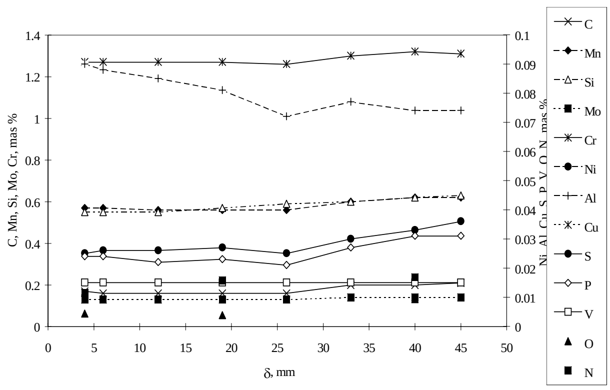
## Experimental results

*Chemical Elements Distribution*

The distribution of chemical elements, i.e. the axial and radial segregation of chemical composition across the length and walls of the tubes C1, C2 and A is presented in Figures 3 and 5.

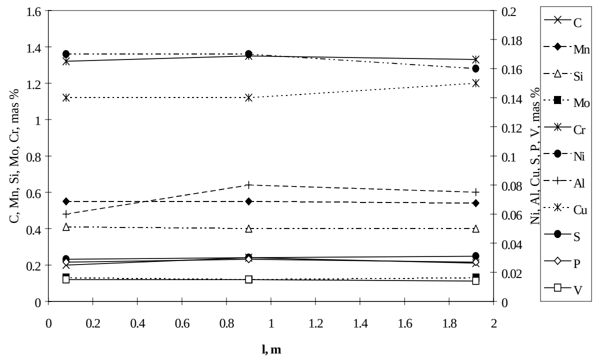



3a)

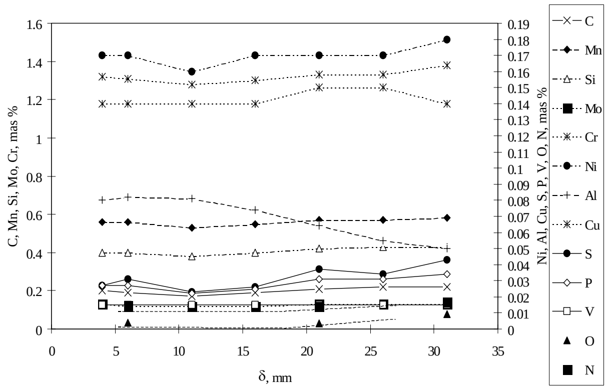



3b)

**Figure 3**. The distribution of chemical elements from both ends and the middle of the steel tube C1: a) along the tube; b) in radial direction the tube

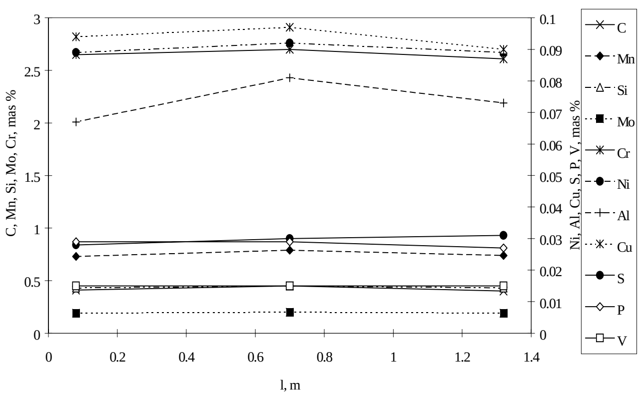



4a)

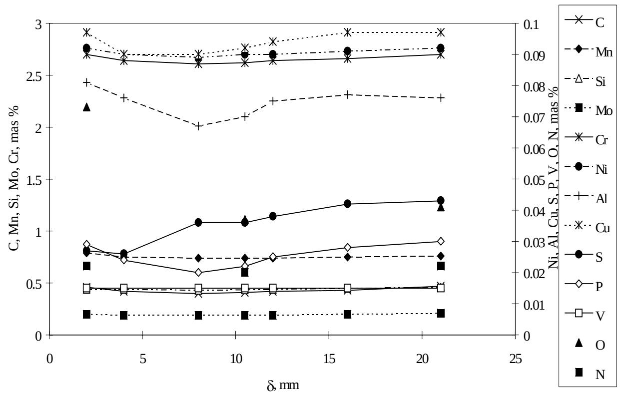



4b)

**Figure 4**. The distribution of chemical elements from both ends and the middle of the steel tube C2: a) along the tube; b) in radial direction the tube




5a)



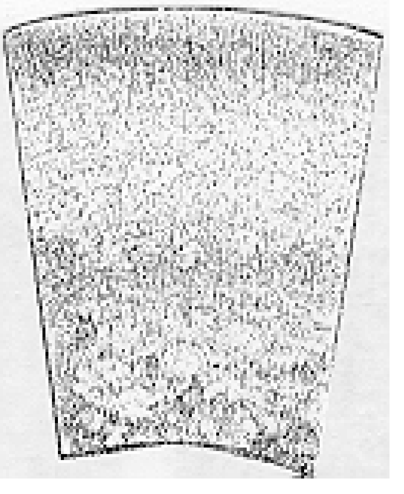

5b)

**Figure 5**. The distribution of chemical elements from both ends and the middle of the steel tube A: a) along the tube; b) in radial direction the tube

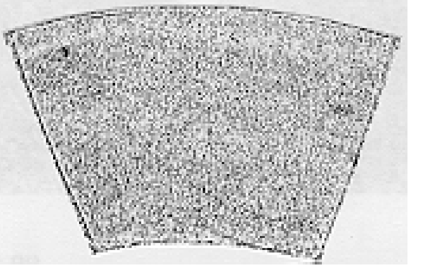
## *Structure and Hardness*

Macrostructure

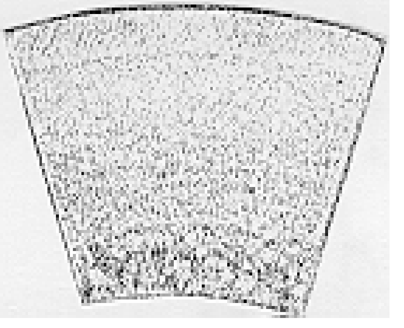
The macrostructure of the tube samples C1, A and C2 is presented in Fig.6, i.e. Figures 7 - 9.



6a)

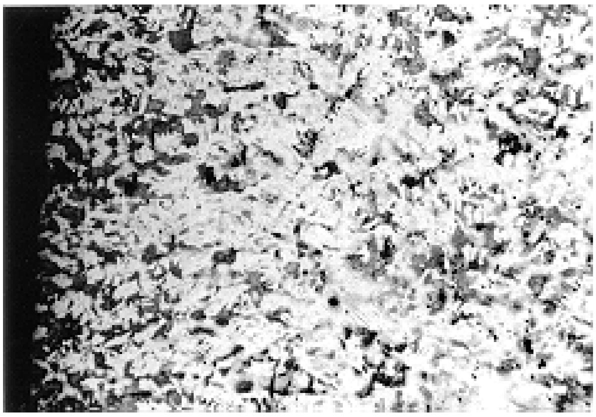


6b)

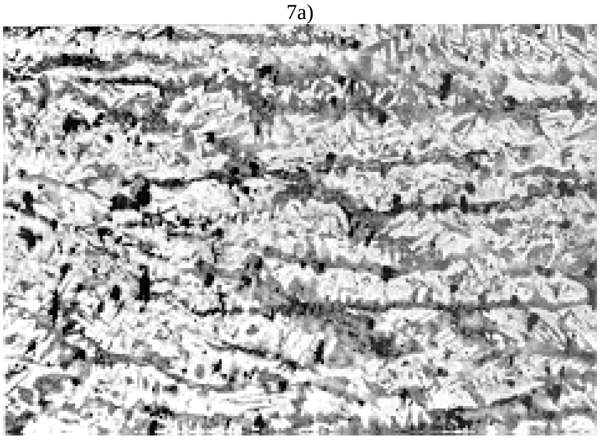


c)

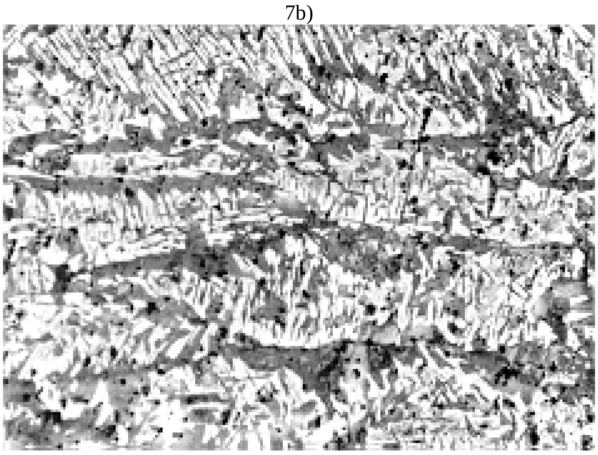
**Figure 6**. The macrostructure of the centrifugally cast tubes, etched by the Oberhoffer's reagent: a) tube C1; b) tube A; c) tube C2



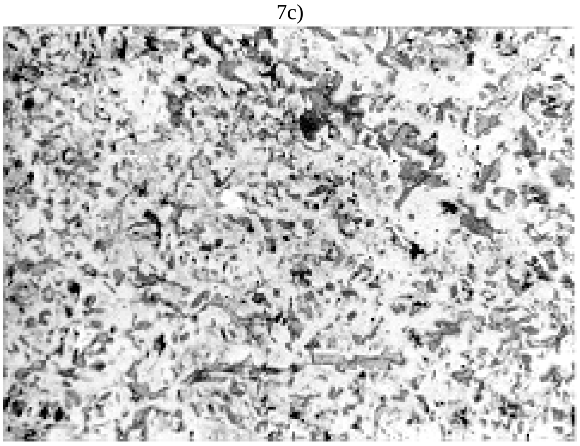
7a)



7b)

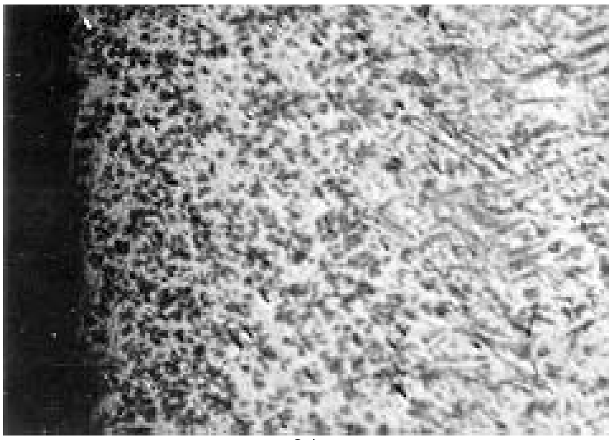


7c)

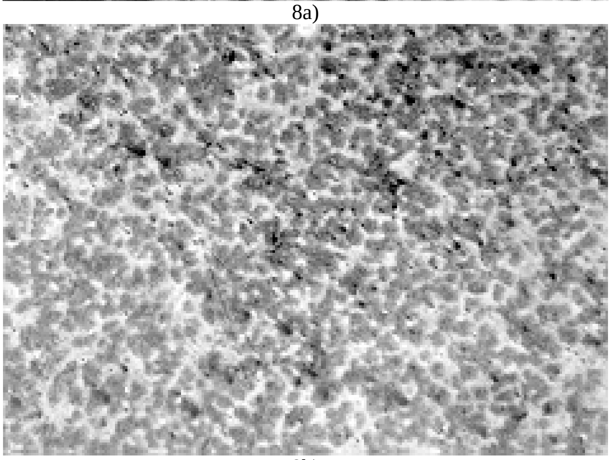


7d)

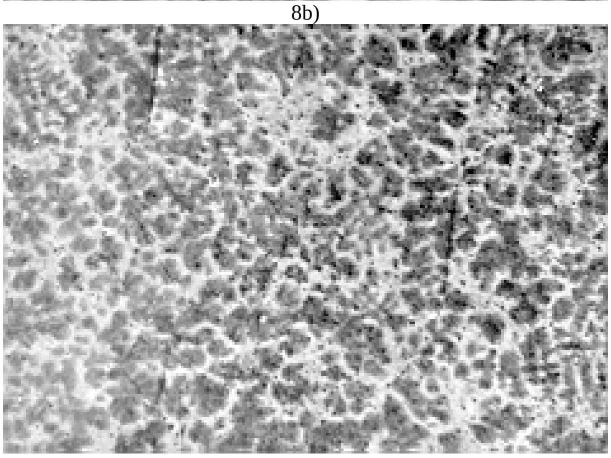
**Figure 7**. The radial macrostructure of the centrifugally cast steel tube C1, etched by the Oberhoffer's reagent: a) the 1-3 mm deep layer as peripheral; b) and c) the 3-40 mm deep layer as middle; d) the 40-46 mm deep layer as inside the tube region



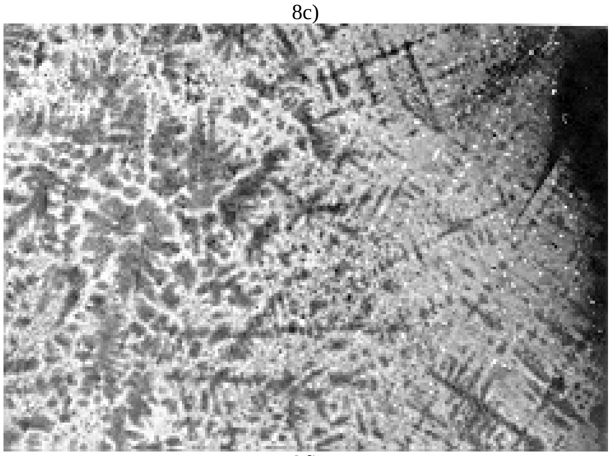
8a)



8b)

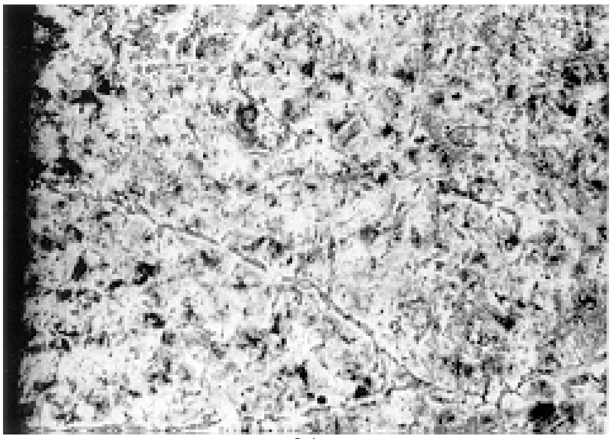


8c)

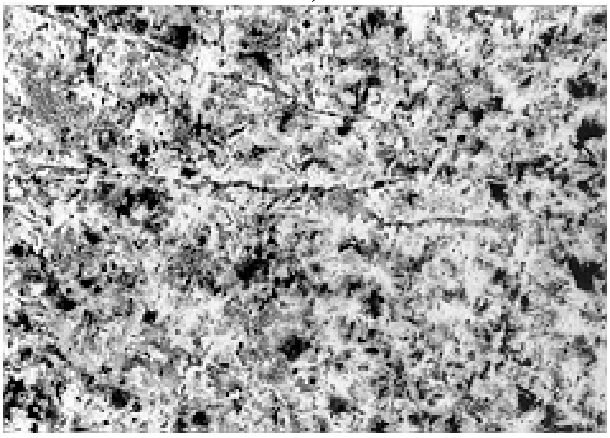


8d)

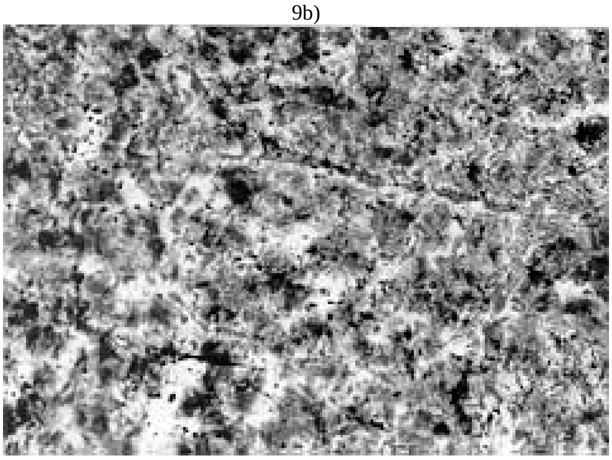
**Figure 8**. The radial macrostructure of the centrifugally cast steel tube A, etched by the Oberhoffer's reagent: a) the 1-3 mm deep layer as peripheral; b) and c) the 3-17 mm deep layer as middle; d) the 17-23 mm deep layer as inside the tube region



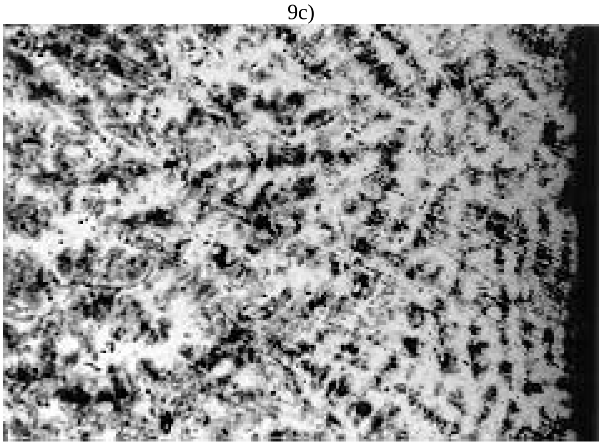
9a)



9b)



9c)

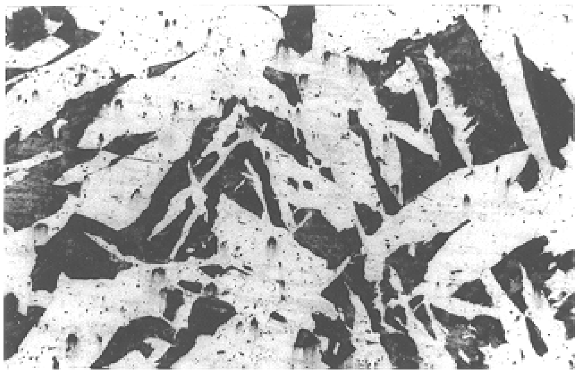


9d)

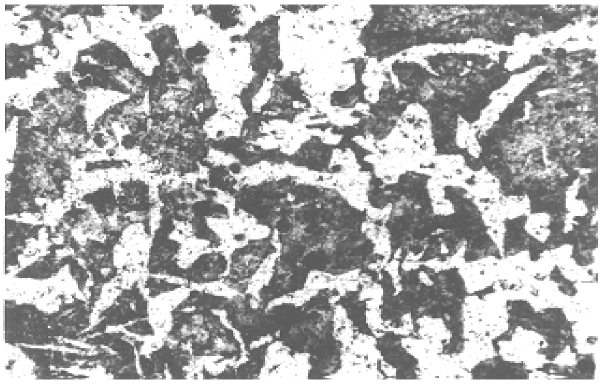
**Figure 9**. The radial macrostructure of the centrifugally cast steel tube C2, etched by the Oberhoffer's reagent: a) the 1-3 mm deep layer as peripheral; b) and c) the 3-28 mm deep layer as middle; d) the 28-31 mm deep layer as inside the tube region.

Microstructure

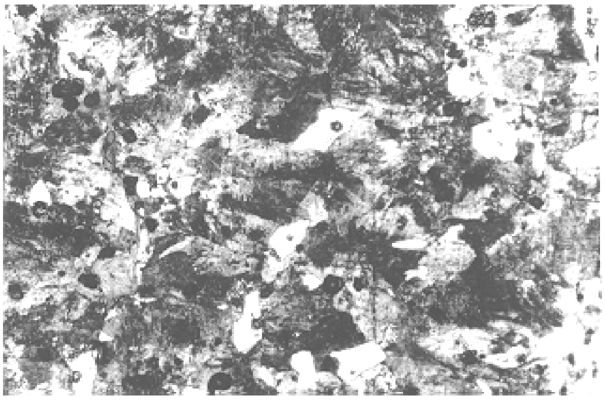
The microstructure of tube samples is presented in Figures 10 - 12.



10a)

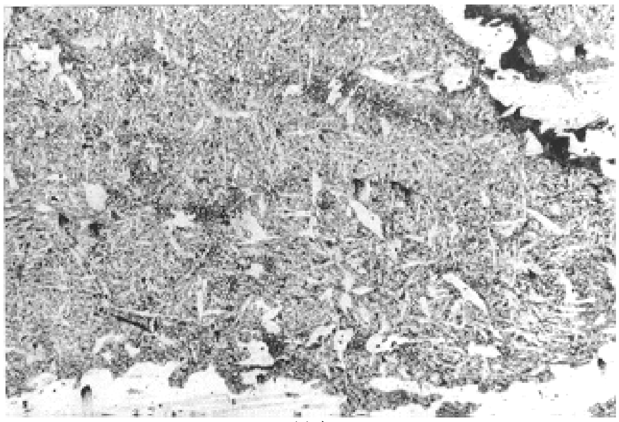


10b)

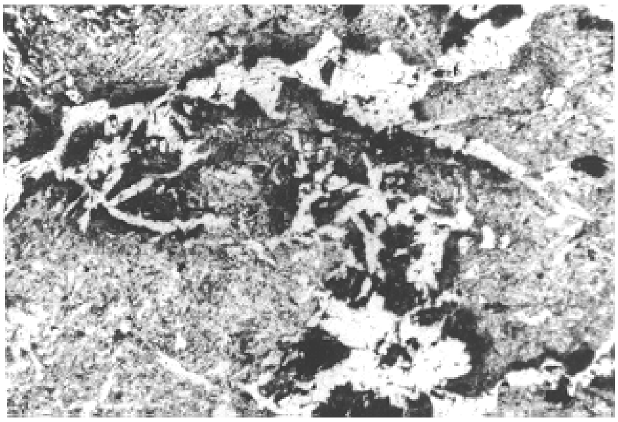


10c)

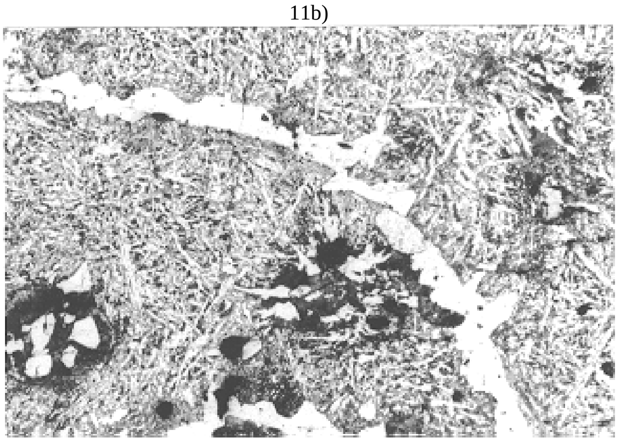
**Figure 10**. The radial microstructure of the centrifugally cast steel tube C1, etched by the 3% Nital reagent: a) the 1-3 mm deep layer as peripheral, b) the 3-40 mm deep layer as middle, c) the 40-46 mm deep layer as inside the tube region



11a)

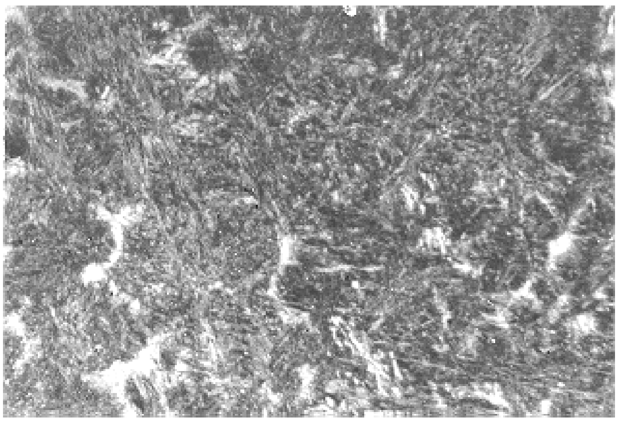


11b)

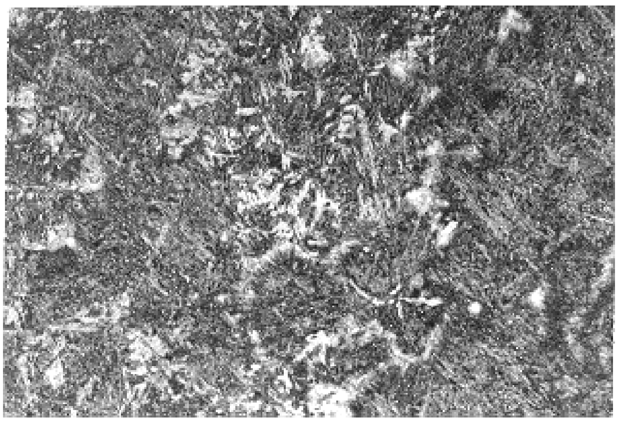


11c)

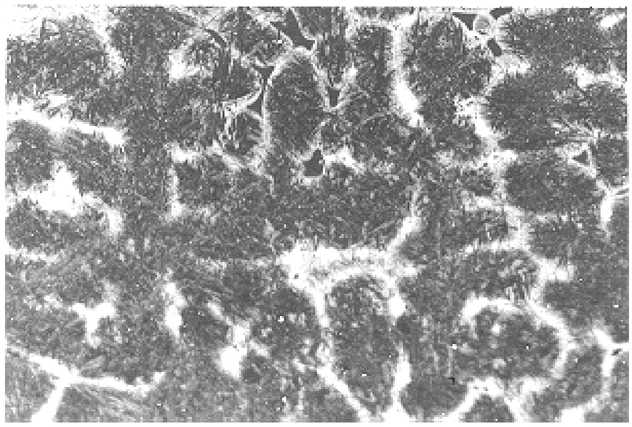
**Figure 11**. The radial microstructure of the centrifugally cast steel tube C2, etched by the 3% Nital reagent: a) the 1-3 mm deep layer as peripheral, b) the 3-28 mm deep layer as middle, c) the 28-31 mm deep layer as inside the tube region.



12a)



12b)



12c)

**Figure 12**. The radial microstructure of the centrifugally cast steel tube A, etched by the 3% Nital reagent: a) the 1-3 mm deep layer as peripheral, b) the 3-17 mm deep layer as middle, c) the 17-23 mm deep layer as inside the tube region.

Hardness Distribution

The curves of radial hardness distribution are given in Figures 13-15. The dependence of hardness distribution along the cross section of the tube wall in as-cast condition was derived by the 5th degree polynomial function that gives the highest correlation coefficient. The said dependencies are presented for the tube C1 by Poly curve (*curve 3*) in Fig.13 and for tubes C2 and A by curve 4 in Figures 14-15.

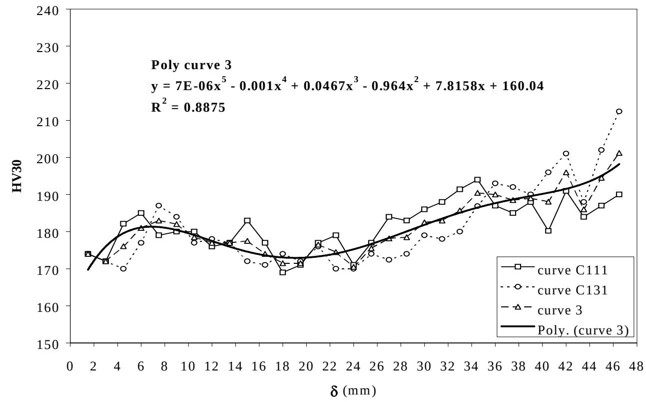



**Figure 13**. The distribution of hardness from both ends and the middle in radial direction the steel tube C1

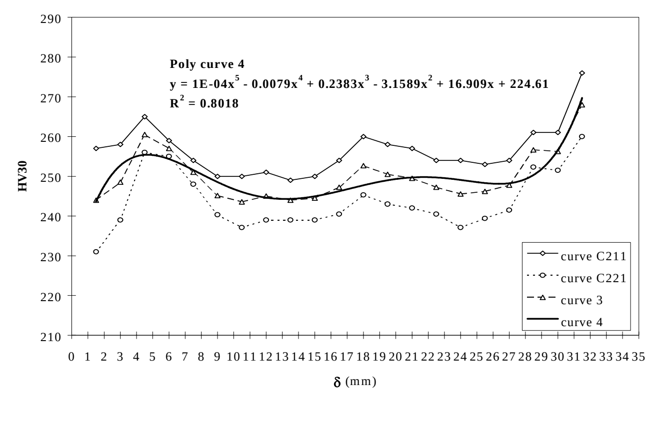



**Figure 14**. The distribution of hardness from both ends and the middle in radial direction of the steel tube C2

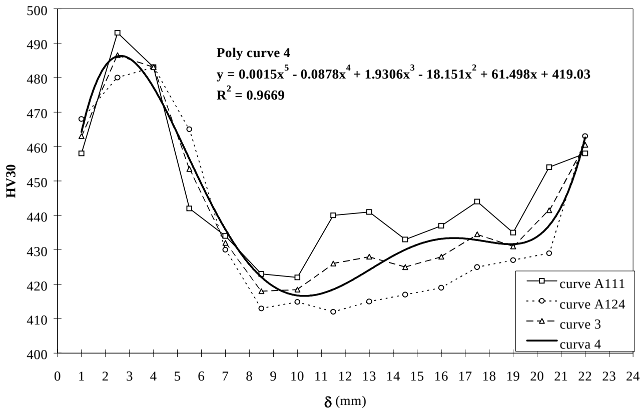



**Figure 15**. The distribution of hardness from both ends and the middle in the radial direction of the steel tube A

*Discussion*

Chemical Elements Distribution

The examination results of axial and radial chemical elements distribution demonstrate the occurrence of macro segregation in centrifugally casted tubes, Figures 3-5.

In tubes C1, C2 and A the axial segregation of the majority of elements (Figures 3a, 4a and 5a) either was not observed or it was insignificant. Somewhat more apparent difference in Al concentration is the consequence of more intensive oxidation at tube ends, rather than in the central part of the tube. More precisely, at higher rotation speed of the mould and higher ratio $d_s / l$ of the tube, the conditions for cold air suction and more intensive oxidation of elements are more favourable [2-4, 8].

More prominent segregation of elements is observed radially (Figures 3b, 4b and 5b). S and P segregate most apparently in tubes C1, C2 and A. The segregation of elements such as Cr, C, Mn, Si and Al is more prominent in tubes of larger diameters and wall thickness C1 and C2 (Figures 3b and 4b), than in the tubes of smaller diameter and wall thickness A (Fig.5b). However, the difference between the maximal and minimal concentration of these elements is within the required limits of chemical composition for steel casting. The segregation of the remaining elements is insignificant. In the existing crystallization conditions (cooling in the mould and in the centrifugal force activity field) the elements S, P and Cr segregate more intensively towards the inside region (direct segregation), while Al segregates towards the periphery of the tube (reverse segregation). The quick growth of dendrites, as a consequence of solidification conditions during the rotation casting causes the extrusion of residual solution with aluminium oxides and dissolved aluminium from the inside region towards the periphery of the tube and in that manner increases the concentration of total aluminium [3-5].

Macrostructure

The tube castings obtained by centrifugal casting at the conditions given in Table 2 are characterised by the first and the second type of macrostructure [2-4, 8].

The macrostructure of the first type is present in tube casting C1, consisting of three clearly apparent zones (Figures 6a and 7). On the casting surface, which is in contact with the mould, the first zone of approximate width of 2 mm, consisting of fine crystals (Fig.7a) is observed. This zone transforms into another zone formed of columnar crystals, orientated in the direction of maximal heat elimination (Figures 7b and c). In this zone, as coming closer to the inside region of the tube, an area of approximately 10 mm wide with shortened length and increased thickness of columnar dendrites (Fig.7c) is observed. The width of the second zone comprises 80% of the total tube wall thickness. This zone is followed by the zone of coarse equiaxed crystals, approximately 6 mm wide, which is of larger dimensions than the tubes C2 (Figures 7d and 9d). This zone spreads almost to the inside tube region, where somewhat more dispersive structure appears. Such tube structure is the result of directed crystallisation, the highest rotation speed of the mould and the lowest ratio of mould wall thickness and the tube wall thickness $\delta_k / \delta = 0,82$ (Table 2). The hardness distribution curve (Fig.13) confirms the least apparent dispersing of the cast tube structure C1, compared to the tube casting structure C2 (Figures 9 and 14) and A (Figures 8 and 15).

The second macrostructure type is present in tube casting A (Figures 6b and 8) characterised by homogeneity and the absence of the apparent crystallisation zones limits, i.e. the zone of equiaxed and columnar crystals (Fig.6b). In that case, the metal is of high density and it is practically with or without insignificant segregation of chemical elements in radial direction [3 - 5], as it is can be seen from Fig.5b. The tube macrostructure on the tube contact with the mould (Figures 6b and 8a), points to the small width of the zone of fine-grained equiaxed crystals, of approximately 2 mm, and also to the transfer of the dispersal columnar crystals into a narrow zone, of approximately 2 mm, (Fig.8b). However, at the inside region of the tube the columnar crystals are coarser (Fig.8d). In the remaining part of the casting macrostructure a wider and homogenous zone of fine-grained equiaxed crystals prevails (Fig.8c). The obtained structure is a result of the crystallisation conditions. More precisely, at higher crystallisation speed, which is the consequence of higher ratio of the mould wall thickness and the tube wall thickness $\delta_k / \delta = 2,44$ and lower rotation speed of the mould compared to the tubes C1 and C2 (Table 2), expression of "the explosive mechanism of the nuclei formation" is reached. In a very short time, in the entire volume of the casting, this mechanism causes the forming of crystal nuclei, the number and the growth speed of which prevent the genesis and development of coarse dendrites and forming of the bigger crystal grains [2, 3, 6, 7]. The dispersity of the structure is also influenced by the micro alloying of the casting by vanadium. The radial hardness distribution curve of the cast tube (Fig.15) confirms the given characterisation of the structure.

In the tube casting C2 (Figures 6c and 9) the same type of microstructure as in the tube A (Figures 6b and 8) is noticed. The zone of equiaxed crystals, yet coarser in size, is of the approximately the same width as in the tube A (Fig.9a). The width of the zone of coarse and wide columnar crystals is of approximately 27 mm (Figures 6c, 9b and 9c). From inside the tube region the columnar crystals are more dispersive (Fig.9d). The obtained structure is the consequence of the crystallisation conditions that are given in Table 2. The radial hardness distribution curve in the tube C2 (Fig.14) points to the less apparent dispersity of the said structure compared to the structure of the tube casting A (Figures 8 and 15).

In centrifugal casting of these tubes, with the increase of the wall thickness of the castings, the width of the columnar crystals zone increases (dendrite structure). The dimension of the zone of fine equiaxed crystals on the peripheral of the casting (the zone of contact of the mould and the casting) remains practically the same [3, 8]. Contrary to that, depending upon the cooling conditions on the inside region (the zone of contact of the casting and the air) a narrow zone of equiaxed crystals and columnar crystals is present [8]. Generally speaking, any type of structure forming depends upon the casting regime, i.e. the number of rotations of the mould, the speed and temperature of casting [1 - 5]. A smaller number of rotations and lower casting speed enable the obtaining of the first-type structure, and the higher speed and number of rotations lead to the forming of the structure of the second type. It has been confirmed that the casting regime at which the minimal segregation of chemical elements in radial direction is present, enables forming of the most favourable types of macrostructure of the first and second types [3, 4, 8]. Apart from that, the castings have density macrostructure without defects caused by the shrinking.

Microstructure

The general microstructure of the tube C1 castings, consisting of ferrite and dispersive pearlite is presented in Fig.10. Within the ferrite grains and on their boundaries of irregular shape, the fine precipitates are observed. The pearlite grains are separate from the ferrite ones within the sharp-angle boundaries. Apart from that, the pearlite area is of irregular shape and size. Generally speaking, the microstructure in the casting zone, which is in contact with the mould, is different in morphology and the fraction of micro-constituents (Fig.10a) compared to the middle zone and to the zone from the inside region of the tube (Figures 10b and 10c). More precisely, the structure is more dispersive in the middle and in the inside region of the tube.

In tube C2 castings (Fig.11), a microstructure which basically consists of the polygonal ferrite grains and the beinite is noticed. Dark cementite fields, as well as light fields, which consist of the residual austenite or martensite, are also present. A more dispersive structure from the inside and the peripheral region of the tube are noticed.

The microstructure of the casting of the tube A, consisting of the martensite and the beinite (Fig.12), is characterised by the more apparent dispersity (more fine-grained structure) in the peripheral zones on the peripheral and the inside region of the tube (Figures 12a and 12c).

The Handnes Distribution curves in as-cast tubes C1 (Fig.13) and C2 (Fig.14), confirm the observed structure and less expressed dispersivity of structure of these tubes (Figures 7, 9, 10 and 11) compared to the structure of tube A casting (Figures 8 and 12). Precisely, the apparent inhomogeneity of hardness distribution over the cross-section of the tube A is present, with higher growth of hardness towards the inside region than towards the peripheral of the tube (Fig.15). This is pointed out by the structure (Figures 8 and 12) which is the consequence of more intensive cooling conditions from the inner than from the peripheral region of the tube, i.e. from the region of the contact of the tube and the mould. Apart from that, the said hardness distribution is also influenced by the higher segregation of C and Cr towards the inside region, i.e. the higher presence of carbides [8].

Hardness distribution over the cross section of the tube wall in cast condition has been derived by the fifth grade polynomial function giving the highest correlation coefficient.

## Conclusion

This study presents the examination results of the distribution of chemical elements, structure and hardness in centrifugally cast tubes of various wall thicknesses made of Cr-Mo and Cr-Mo-V steel castings. In centrifugal tube casting, a more intensive growth of radial than axial elements segregation is induced. The elements S, P and Cr segregate more intensively towards the inside region (*direct segregation*) and Al towards the tube peripheral (*reverse segregation*).

Macrostructure of the tube castings of the higher wall thickness made of Cr-Mo steel is of the first type and consists of three clearly distinguished zones. Contrary to that, in the tube of smaller wall thickness made of Cr-Mo and Cr-Mo-V steel the macrostructure of the second type without the apparent limits of zones is present. The tube casting microstructure with higher wall thickness is ferrite and pearlite, and with smaller wall thicknesses ferrite - beinite, or mainly martensite. The noticed structure is confirmed by the hardness distribution curves.

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# Hemijska i strukturna nehomogenost kod centrifugalno livenih cevi od Cr-Mo i Cr-Mo-V čelika

**U radu su prikazani rezultati ispitivanja uticaja uslova livenja na raspodelu hemijskih elemenata, strukturu i tvrdoću po dužini i po poprečnom preseku centrifugalno livenih cevi različitog prečnika i debljine zida od Cr-Mo i Cr-Mo-V čeličnog liva. Ispitivanja hemijskog sastava pokazala su da se kod centrifugalno livenih cevi javlja intezivnija segregacija elemenata po debljini zida cevi nego u aksijalnom pravcu. Ispitana je i izražena nehomogenost strukture i tvrdoće po poprečnom preseku i izvršeno je modelovanje raspodele tvrdoće po debljini zida cevi.**

*Kljucne reci*: **centrifugalno livenje, čelik Cr-Mo, čelik Cr-Mo-V, cev, hemijska struktura, mikrostruktura, makrostruktura**

# Химическая и структурная негомогеничности у центробежно литых труб из **Cr-Mo** и **Cr-Mo-V** стали

В этой работе показаны результаты исследований влияния условий литья на распределение химических элементов, на структуру и на жесткость по длине и по поперечному разрезу центробежно литых труб различного диаметра и толщины стены из **Cr-Mo** и **Cr-Mo-V** стального литья. Исследования химического состава показали, что у центробежно литых труб является более интенсивная сегрегация элементов по толщине стены труб чем в аксиальном направлении. Здесь исследована и выражена негомогеничность структуры и жесткости по поперечному разрезу и осуществлено моделирование распределения жесткости по толщине стены труб.

*Ключевые слова*: центробежное литье, сталь **Cr-Mo**, сталь **Cr-Mo-V**, труба, химическая структура, микроструктура, макроструктура

# La non-homogénéité chimique et structurale chez les tubes de fonte centrifuge de l'acier Cr-Mo et Cr-Mo-V

**Ce papier présente les résultats des recherches concernant les conditions de fonte sur la distribution des éléments chimiques, structure et dureté en longueur et en section transversale des tubes de fonte centrifuge ayant diamètre et épaisseur de parois variés, faits en acier fondu Cr-Mo et Cr-Mo-V. Les recherches sur la composition chimique ont démontré que la ségrégation des éléments sur l'épaisseur du paroi de tube est plus intense que celle sur la direction axiale. On a examiné la non-homogénéité de la structure et la dureté sur la section transversale. De même, on a effectué la modélisation de la distribution de dureté sur l'épaisseur du paroi de tube.**

*Mots clés*: **fonte centrifuge, acier Cr-Mo, acier Cr-Mo-V, tube, structure chimique, microstructure, macrostructure.**