THE DEVELOPMENT OF NEW TYPE OF 90 TON FORGING INGOT

Pavel MACHOVČÁK[a], Markéta TKADLEČKOVÁ[b], Aleš OPLER[a], Zdeněk CARBOL[a], Antonín TREFIL[a], Karel MICHALEK[b]

[a] *VÍTKOVICE HEAVY MACHINERY a.s., Ostrava, Czech Republic, EU, pavel.machovcak@vitkovice.cz*

[b] *VSB - Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Department of Metallurgy and Foundry and Regional Materials Science and Technology Centre, Ostrava, Czech Republic, EU, marketa.tkadleckova@vsb.cz*

Abstract

A production of heavy forging ingots is usually accompanied by a segregation of elements in the structure of steel. The segregation of the elements causes anisotropy of mechanical properties. But these mechanical parts must meet the strictest criteria, and therefore must be practically free of defects. In order to achieve the best possible quality of heavy forging ingots, the project focused on improving the useful properties of special machine parts was solved. The experimental forging ingot weighing 90 tons was cast due to the performance a detailed analysis of the current state of casting and solidification. The ingot was cut and macrostructure and chemical heterogeneity of the ingot was evaluated in detail. Microcleanliness evaluation was also carried out on the samples from this ingot. To assess the composition of oxide non-metallic inclusions, ternary diagrams were used. The gained knowledge was also used to specification of the setting of boundary conditions of the numerical simulations, which should help to optimize the production technology of casting heavy forging ingots and minimize the range of porosity and segregation in ingots. The new type of 90 tons ingot was also designed and analyzed. In particular, the extent of porosity and macrosegregation were evaluated. This article describes performance of the experimental ingots casting, the way of cutting, the methodology of chemical analysis and the results of that investigation. The results obtained in the analysis of two different types of 90 tons ingots are here compared.

Keywords: heavy steel ingot, macro - segregation, macrostructure, porosity, microcleanliness

1. INTRODUCTION

VÍTKOVICE HEAVY MACHINERY a.s. (further also VHM a.s.) is the traditional producer of large engineering components with a strong position in selected segments of machinery production. These include especially shafts for hydroelectric power plants, rotor shafts for wind power plants, crankshafts, parts for the container of pressurisers, steam generators, heat exchangers and collectors for both conventional and nuclear power engineering. These parts have to be uniformly structured and perfectly balanced, and therefore defect-free. Heavy forging ingots weighing up to 200 tons are used for this production. These are mainly carbon, low and medium-alloy structural steel as well as tool steel. Due the fact that the production of these heavy forging ingots is usually accompanied by a segregation of several elements, it was decided to initiate work focused on reducing of the occurrence of these undesirable segregations. The 90-ton forging ingot was cast and cut for the determination of the current state of distribution of segregation of individual elements in the cast ingot. This project has been solved mainly in cooperation VHM a.s. and Department of Metallurgy and Foundry at VSB. An integral part of the project was numerical simulations of casting and solidification of the ingots. These simulations were carried out in the ProCAST. This numerical analysis is a good way to optimize the casting technology virtually, shorten the trial casting stage and minimize the lead time [1 - 5].

2. DESCRIPTION OF PRODUCTION AND CUTTING OF THE EXPERIMENTAL INGOT 8K91SF

An experimental ingot 8K91SF was cast at steel plant VÍTKOVICE HEAVY MACHINERY a.s. so that the extent of the chemical heterogeneity and microcleanliness evaluation can be determined. It is octagonal forging steel ingot weighing 87.5 tons. The whole production process was completely monitored. The steel for this production was melted at EAF followed by processing at LF and VD. The EAF capacity is approximately 70 tons so the experimental ingot was cumulated from two heats. Structural carbon manganese steel (S355J2G3 according to EN 10 250) was chosen for this trial. Each of these two heats had intentionally different content of copper and nickel in order to determine mixing of these two heats in solidified ingot. Content of the other elements was target at the standard level. Chemical analyzes of both heats and the weighted average of the both heats is shown in **Table 1** [6]. The course of ingot casting and solidification was monitored using thermal camera. Ingot was removed from the mold in hot conditions as usual. It means after 20 hours after the end of ingot casting. The surface temperature of the ingot was from 530 °C (in the bottom part) up to 730 °C (in the top part) see **Fig. 1** [7]. Stress relieving annealing was carried out due to the elimination of occurrence of possible cracks during cutting.

Table 1 Chemical analysis of both used heats and the weighted average of these both heats [6]

Heat No.	weight (tons)	C	Mn	Si	P	S	Cr	Cu	Ni
52522	53.1	0.194	1.30	0.26	0.008	0.0008	0.11	0.13	0.51
52523	34.5	0.200	1.27	0.27	0.009	0.0010	0.14	0.46	0.12
w.average	87.6	0.196	1.28	0.26	0.009	0.0009	0.12	0.26	0.36

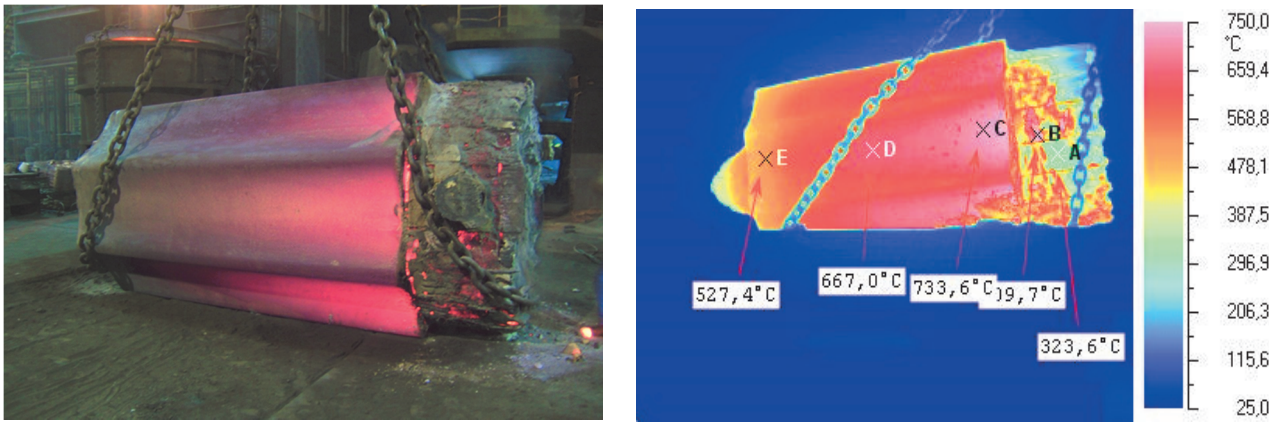


Fig. 1 Experimental ingot after removing from ingot mold and its picture from thermal camera [8]

To obtain a longitudinal cross section of the experimental ingot, at first the technology of band-saw cutting was considered to save processing time. Unfortunately band saw can hold a maximum dimension of work piece 1700 mm because the spacing of its columns, which is insufficient for our case because the maximum diameter of ingot is 1935 mm. Milling technology was finally chosen for cutting of the experimental ingot. The conventional horizontal boring machine WD250 was chosen for this procedure. The maximum speed of this machine was 630 min^{-1}. Special roughing milling with replaceable cutting edged was bought due to accelerate receive of large amounts of excess material. Cutting parameters were set with regard to the state of machine and clamping components. The processing time does not exceed 80 hours. The required quality of the machined surfaces was Ra 3,2 µm.

3. EVALUATION OF INGOT QUALITY

The evaluation of chemical composition, Baumann imprint, penetration test and microcleanliness evaluation were carried out on the cross section of the experimental ingot in order to find the extent of heterogeneity.

3.1 Macroscopic examination by sulfur prints and fluid penetration testing

Macroscopic examination by sulfur prints (Baumann imprint) is used to detect macroscopic distribution of sulfur in iron alloys. Sulfur in steel is excreted in the form of sulfides FeS and MnS. The principle of the imprint is based on the reaction of sulfides with sulfide acid (1). This reaction is accompanied by the formation of hydrogen sulfide, which acts on the surface of the photographic paper surface and react with silver bromide contained in this photographic paper to form very stable silver sulfide, which has a brown color (2).

$$FeS + H_2SO_4 = FeSO_4 + H_2S \quad (1)$$

$$H_2S + 2AgBr = Ag_2S + 2HBr \quad (2)$$

Performed Baumann imprint showed isolated significant sulfide segregations length up to 2 mm. These sulfides formed locally clusters or were directed into lines. The stronger lines of sulfides were occurred mainly in the head of ingot and in the quarters of the width, i.e. in expected areas of “A” segregations. In the lower third of the ingot height were sulfide segregations very weak and quite uniform.

Liquid penetration testing (further LPI) is a widely applied inspection method used to locate surface-breaking defects in all non-porous material. LPI is based upon capillary action, where fluid with low surface tension penetrates into clean and dry surface-breaking discontinuities. Penetrant may be applied to the test component by dipping, spraying or brushing. After adequate penetration time has been allowed, the excess penetrant is removed and developer is applied. The developer helps to draw penetrant out at the flow where an invisible indication becomes visible for the inspection. Inspection is performed under ultraviolet or white light depending upon the type of dye used - fluorescent or non-fluorescent (visible).

The small cavity especially in the upper half of the ingot in the central area and in the area of expected “A” segregations were detected after the performed penetration test, see **Fig. 2**. Dimension of identified cavity was relatively small.

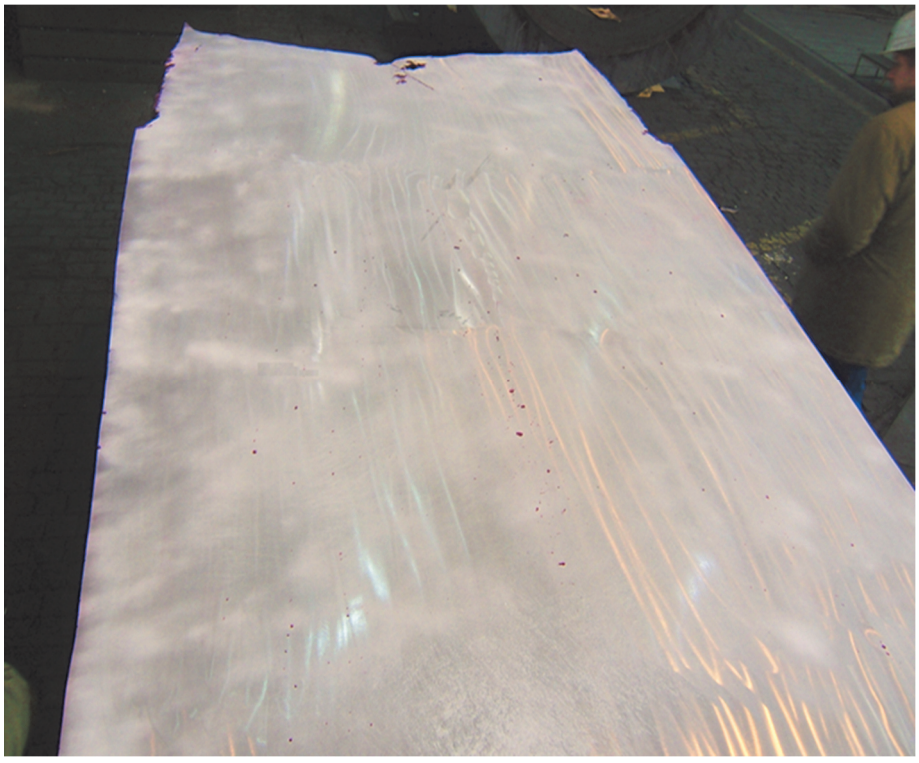


Fig. 2 Penetration test on the longitudinal section of the experimental ingot 8K91SF

3.2 Evaluation of chemical heterogeneity

Chemical analyses were performed on half the area of cut ingot as the ingot can be considered as rotation solid and the second half is the mirror image of the first half. Chemical analysis had two main aims. Firstly, determine the extent of segregation of the individual elements and secondly, mixing of both heats needed for experimental ingot casting. To achieve these aims has been chosen determination of the following elements: carbon, sulfur, manganese, copper, nickel, phosphorous and silicon. Chemical composition was analyzed along the height of the real axis of the ingot and then in the next four straight lines that were parallel to the axis. The distance of these parallel lines were 200, 450, 650 and 850 mm far from the central axis. Two main vertical lines to the ingot axis were chosen; at the interface of the body of the ingot and its head and at the interface of the body of the ingot and its heel. Other seven vertical lines were analyzed between these two main vertical lines. Other three vertical lines were analyzed through the head of the experimental ingot and other three vertical lines were analyzed through the heel of the ingot. Chemical analyses were performed totally at 15 vertical lines. Coordinate system was established due to a clear description of places that were analyzed. This system's starting point is at the intersection of ingot axis and the plane dividing the body and heel of the ingot. Analyzed places are shown in **Fig.3** [8].

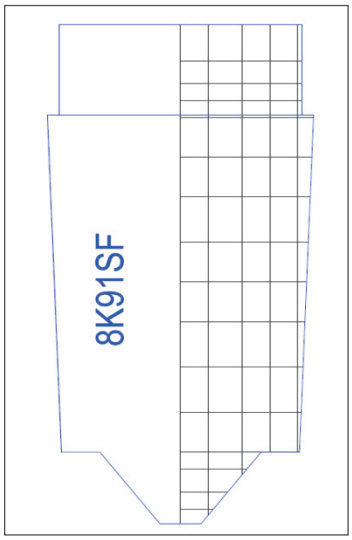


Fig. 3 The scheme of analyzed lines throughout the experimental ingot

The standard method used in metallurgical analytics - analyses using optical emission spectrometers - was not applicable due to the large number of required analyzes. Thus, the mobile optical spectrometer SPECRTOTEST was used for analysis of Mn, Si, Cu a Ni content. Its great advantage was that the analysis could be carried out directly on the ingot without sampling. Due to the low content of sulfur, from the very beginning was evident that there is no other alternative than to laboratory analysis of a combustion analyzer, with the lowest possible detection limit and the greatest accuracy. Sample of chips weighting from 0,5 to 2,0 g was need for this method. Thus the surface of ingot cross-section was drilled and chips were analyzed on an automatic analyzer LECO CS-600. Sulfur and carbon were analyzed on this unit. Phosphorus content was also determined on samples taken from the chips. The larger sample weight of chips was needed for this analysis, at least 2 gramms. A total of 1279 points were analyzed.

The main aim of this work was to determine the extent of segregation of individual elements over the cross section of the ingot. This evaluation was mainly focused on the contents of C, Mn, S and P. Contents of these elements along the height of the experimental ingot along the axis are shown in **Fig. 4 - 7**. In case of carbon content was found only small area with the minimal negative segregation in the bottom part of the ingot. Carbon content in the axis has increased from about the third of the ingot body height. Although, the melting analysis of carbon in the ladle was 0,196 %, there was found 0,292 % of carbon in the interface of the ingot body and the ingot hot top. Maximum coefficient of segregation of carbon in the ingot body was therefore 1,49. Carbon content further increases in the hot top up to maximum observed value 0,52 % and decreases in the direction from the ingot axis to the ingot wall.

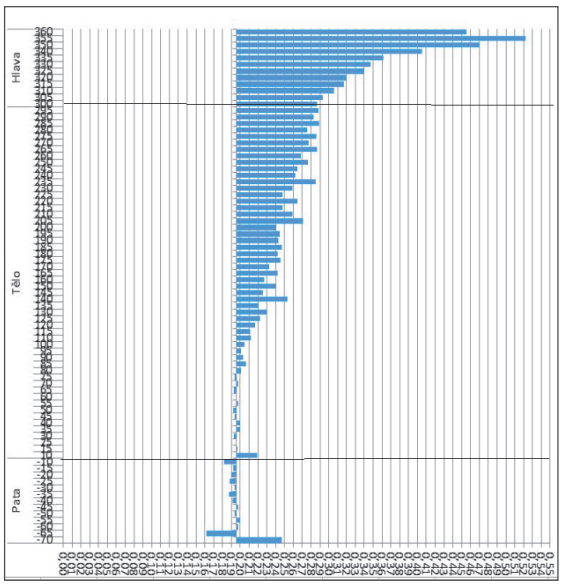


Fig. 4 Carbon content in the ingot axis

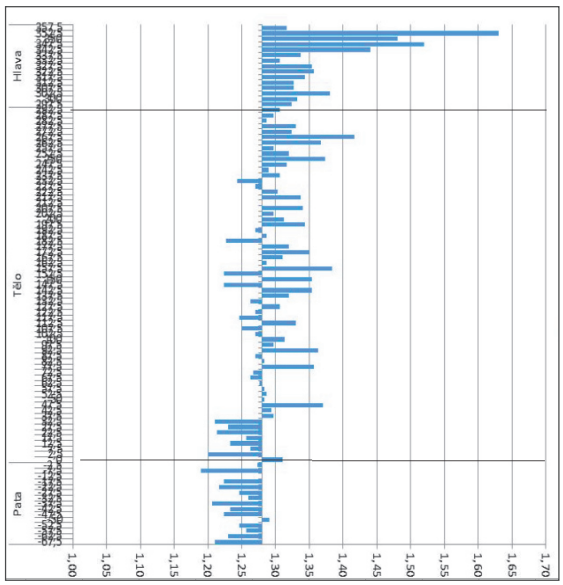


Fig. 5 Manganese content in the ingot axis

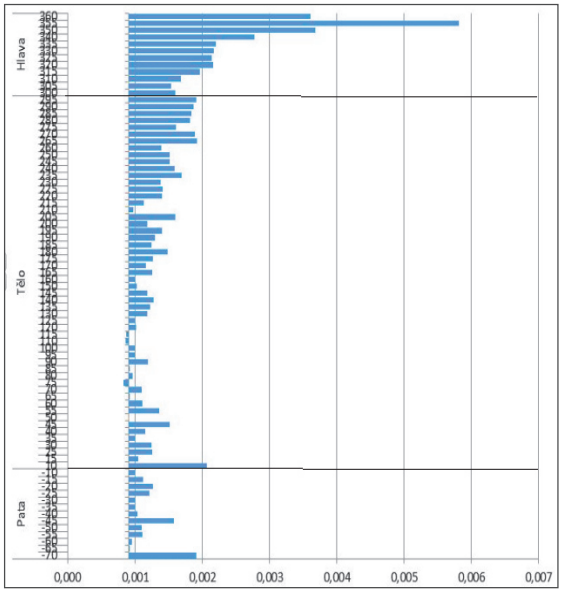


Fig. 6 Sulfur content in the ingot axis

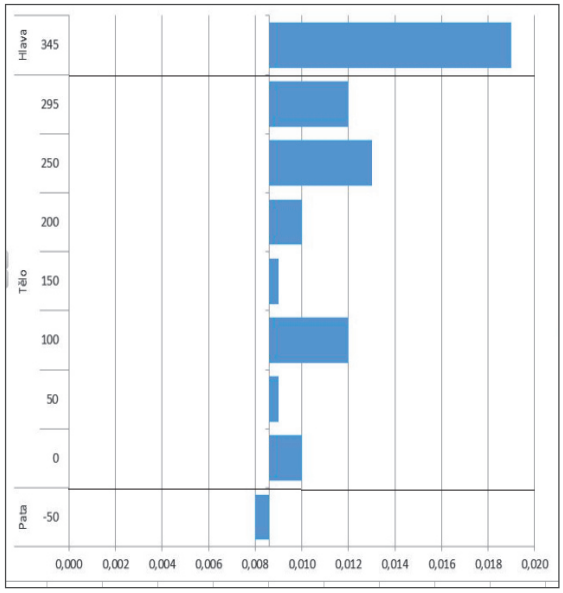


Fig. 7 Phosphorus content in the ingot axis

The final analysis of manganese from the ladle was 1,29 %. There was larger negative segregated zone at the bottom part of the experimental ingot than it was in case of carbon. Manganese content gradually increased with distance from the bottom toward the hot top of the ingot. Manganese content 1,37 % was detected at the interface of the ingot body and the hot top. The highest manganese content in the ingot body was not detected in the ingot axis, but it was found in ¼ of ingot diameter and at half of the height of the ingot body and it was 1,40 %. Maximum coefficient of segregation of manganese was therefore 1,09.

In the case of sulfur and phosphorus, only positive segregations of these elements in the ingot axis were detected. The highest sulfur content in the ingot body was found again in ¼ of ingot diameter and approximately at half of the height of the ingot body and it was 0,0023 %. The maximum coefficient of segregation was 2,55 with the respect to sulfur content in the ladle 0,0009 %. The highest content of phosphorus was found in the ingot axis at interface of the ingot body and the hot top. Here, the phosphorus content was detected in the

amount of 0,013 %. If the phosphorus content in the ladle was 0,009 %, so the maximum coefficient of phosphorous segregation was 1,44.

3.3 Evaluation of microcleanliness of collected samples

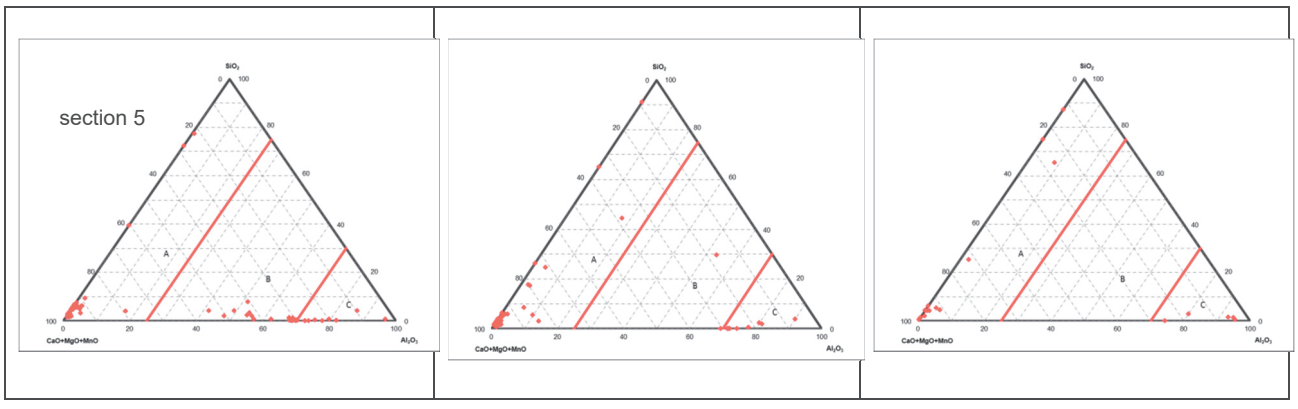
The microcleanliness evaluation was carried out on a Hitachi microanalytical complex equipped with an energy dispersive spectrometer Vantage in TŽ, a.s. Ninety visual fields at a magnification of 500x were evaluated on each sample, which represents a summary evaluation area 5,625 mm^2. A total number of inclusions, their density, division to distribution groups, and areal proportion of inclusions (summary area of inclusions / total area of evaluated sample*100) were evaluated. Due to the possibility to also generally evaluate the chemical composition of the inclusions, classification of oxide inclusions into the ternary diagrams CaO+MgO+MnO-Al_2O_3-SiO_2 was performed. The oxide inclusions were also in the given ternary diagram categorized into areas A, B and C, where A is the area limited by the Al_2O_3 content of up to 30%, area B then includes inclusions containing 30-70% Al_2O_3; and area C the inclusions with Al_2O_3 content exceeding 70%. This classification is consistent with the microcleanliness assessment of carbon steels according to the Pirelli norm using the HW method. As for the sulfide inclusions due to their complex composition the ternary diagrams CaO+MgO+MnO+Al_2O_3-SiO_2-MnS were used [9].

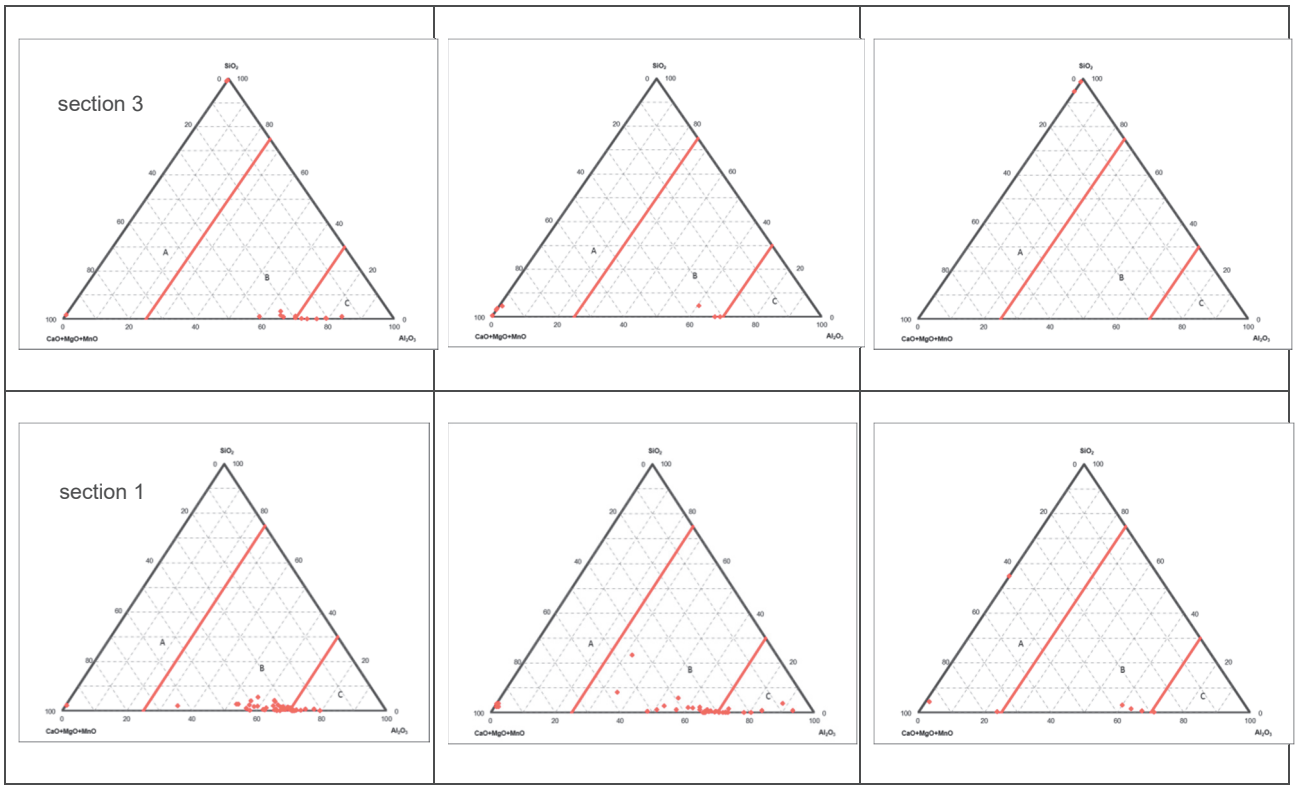
To start this evaluation, it is necessary to state that almost all the samples showed very good microcleanliness, measured areal proportions of oxide inclusions rarely exceeded a value of 0.015%, sulphide ones then 0.010%, especially in the central regions of the ingot. It shows, among other things a mastery of the production technology and casting of the steel as well as favorable conditions for the separation of inclusions during the steel solidification. It is therefore difficult to find a stronger connection between microcleanliness and, for example chemical composition of the steel, or other parameters.

To assess the composition of oxide non-metallic inclusions, the above-mentioned ternary diagrams CaO + MgO + MnO - Al_2O_3 - SiO_2 were used. As for the sulphide inclusions, the ternary diagrams CaO + MgO + MnO + Al_2O_3 - SiO_2 - MnS were used due to their complex structure. **Fig. 8** shows examples of a ternary diagrams of the composition of oxide inclusions in the ”central” samples marked No. 3, 8 and 13 from sections 1, 3 and 5. Similar characters of these diagrams were also obtained from other samples.

Based on the analyses of all ternary diagrams the obtained findings can be summarized as follows:

- The samples contain complex oxide inclusions based on oxides of Ca, Mg and Al
- Heterogeneous inclusions with a higher proportion of CaO were detected in the top part of the ingot
- The diagrams show that there are no significant differences between the compositions of sulphide inclusions. They were mostly Mn-Ca-S-based sulphides that excreted on the oxide particles based on Al, Mg and Ca





Obr. 8 Ternary diagram of composition in the ”central” samples marked No. 3, 8 and 13 from sections 1, 3 and 5

4. DESIGN AND EVALUATION OF NEW TYPE 90 TON FORGING INGOT

The results mentioned above were also used for the verification of numerical simulations and to specification of the setting of boundary conditions of the numerical simulations which should help to optimize the production technology of casting heavy forging ingots. A large number of simulations of partial tasks were carried out during the project. These simulations shows that macrosegregation and volume of porosity can be minimize by optimizing the ingot design.

On the basis of a detailed investigation and on the basis of carried out numerical simulations, new type of 90 ton forging ingot was designed. This new type is mainly characterized by lower height diameter ratio, increased number of ingot walls (16 instead of 8), increased bevel of wall ingot and modified ingot mold thickness. These changes were primarily designed to reduce the central porosity and to reduce the extent of „A“ macro-segregations. These „A“ segregations cause more problems during final ultrasonic testing of forgings than the central „V“ segregations. These problems are significant mainly in case of forgings like rollers or thick plates. In these cases the detected defect area is located in the annulus of forging, while the middle of the forging is defect free.

Also in this case the experimental ingot was cast from the same steel grade and its evaluation was very similar. Steel grade S355J2G3 with increased nickel content in first heat and with increased cupper content in second heat was used. New type of 90 ton forging ingot, now 16K91SF, was cast and longitudinally divided and analyzed. Performed penetration test confirm the lower extent of the central porosity. Also distribution of macro-segregation of individual elements was significantly different when compared to original type of ingot. According to expectations, due to the larger diameter of new ingot type, the higher content of carbon and sulfur was detected in the ingot axis. Maximum coefficient of carbon segregation in the axis of the new ingot type was 1,55 while this value in case of original ingot type was 1,49, see **Table 2.** The similar situation is in case

of sulfur. Maximum coefficient of sulfur segregation in the axis of the new ingot type was 2,86 while this value in case of original ingot type was 2,11. However, significantly lower segregations of monitored elements were detected in ¼ of the ingot diameter, i.e. in area of expected "A" segregation. In case of new type of ingot, maximum coefficient of carbon segregation was here 1,08, while this value in case of original ingot type was 1,28. The same situation is again in case of sulfur. Maximum coefficient of sulfur segregation in ¼ of the new type ingot diameter was 1,71 while this value in case of original ingot type was 2,56. The similar situation is in case of manganese.

Table 2 Comparison of maximum segregation coefficients of selected elements in the original and a new type 90 ton ingot

	8K91SF (original type)			16K91SF (new type)		
	ladle analysis	ingot axis	1/4 of diameter	ladle analysis	ingot axis	1/4 of diameter
C	0,196	1,49	1,28	0,213	1,55	1,08
Mn	1,28	1,07	1,08	1,27	1,05	1,02
S	0,0009	2,11	2,56	0,0014	2,86	1,71

Two others new type of heavy forging ingot were also designed and verified based on these results. It is 50 and 150 ton forging ingots. These new types of ingots are used during common orders, where the main parameter for evaluation of the impact of these changes on the quality is ultrasonic testing. Based on the last experience, it can be stated, that the change in the shape of ingot help improve of quality of production.

CONCLUSION

Evaluation of the chemical composition, microcleanliness, and structure of the 90-ton ingot cast from two heats, which had an intentionally modified Cu and Ni content was carried out in order to assess the degree of mutual mixing of both heats in the ingot volume during its casting and solidification. The evaluation showed that during casting of the ingot from two successive heats, in case of their different composition, a certain degree of inhomogeneity of chemical composition can be assumed, which will especially show in a lower half of the ingot where there is no mutual mixing of the two heats. Also, a greater segregation of carbon, sulfur and phosphorus in the central top part of the ingot was recorded. From the standpoint of achieved microcleanliness, some differences along the cross-section of the ingot and increased incidence of sulphides in a top central part can also be reported. However, in general, microcleanliness of the entire ingot is very good with low areal proportions of the non-metallic inclusions. The results of this experiment were also used to improve the accuracy of numerical simulation of casting and solidification of heavy forging ingot. New type of ingot was also proposed and evaluated based on these numerical simulations. Lower extent of porosity and lower level of carbon, sulfur and manganese segregation in ¼ of ingot diameter were found out. This improvement of these parameters will help increase the quality of forgings from these ingots.

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