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## Analysis of macrosegregation in large size forged ingot of high strength steel

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**Abstract:** The macrosegregation levels of C, Mn, Ni, Cr and V were evaluated experimentally in large size forging made of high strength steel. The analysis was performed on a 2 cm thick slice cut along the longitudinal axis of a medium carbon steel bloc which has undergone casting, forging and heat treatment. The slice was then cut into small specimens. Chemical analysis was carried out on these specimens to obtain the chemical map of the different elements. Analysis of the macrosegregation mapping revealed the existence of positive and negative segregation types. The most segregated elements were C for positive segregation and Cr for negative segregation. V and Ni did not present an important segregation degree. Microstructure examination using optical microscopy revealed mostly a bainitic structure. The presence of retained austenite was not detected. Hardness measurements in two samples having high and low levels of macrosegregation did not reveal major differences.

**Keywords:** steel, large ingot, macrosegregation, homogeneity, carbon, chromium

In alloy castings, the chemical heterogeneity of solute elements is known as segregation defect. This defect is called macrosegregation if it is extended over a distance close to the casting dimensions. In the case of large ingots, this distance is in the order of centimeters or meters [1]. Macrosegregation could affect the microstructure and the mechanical properties of the final product [1,2]. Furthermore, the main problem with macrosegregation is that it cannot be removed particularly in large size ingots even after long heat treatments [3]. Therefore improving the quality of casting products requires a better understanding of macrosegregation formation mechanisms and consequences. The problem is more complex in large casting steels where the large dimensions complicate the macrosegregation analysis due to severe temperature gradients. Generally, macrosegregation characterization is performed in as cast steel where it is evaluated by the chemical analysis either as alloying elements profile or map.

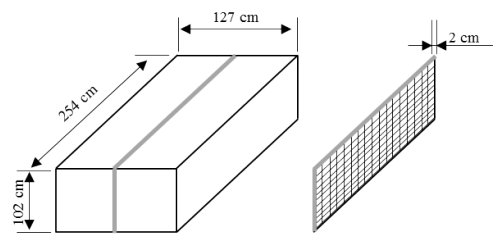
However, this kind of experiments is very expensive and time consuming. Moreover, such studies are fewer in the case of as forged and/or as heat treated products which implies a lack of information in the macrosegregation patterns behaviour during the different manufacturing steps. Thus, in the present study, the chemical heterogeneities were analysed at the last step of production, i.e. after casting, forging and quench and temper heat treatment cycle. The main objectives of the present study were to investigate the distribution and the degree of macrosegregation of some elements and to evaluate the effect of macrosegregation on the microstructure and hardness.

### 1 Experimental

The investigated material was a medium carbon low alloy steel with the nominal composition of Fe-0.35C-0.99Mn-0.5Ni-1.86Cr-0.149V (wt.%). After

solidification, a 40-ton ingot was forged in parallelepiped shape to reach the dimensions of  $102 \times 127 \times 254 \text{ cm}^3$ . The slab was then quenched and tempered. A 2 cm thick slice was cut along the longitudinal axis of the final product. The slice was then cut into small specimens:  $2 \times 4 \times 7 \text{ cm}^3$  (Fig.1). Chemical analysis using mass spectrometry were carried out to determine the chemical composition of each specimen and therefore to obtain the chemical map of the entire slice. In this study, we were interested to construct the chemical map of the elements cited above. To quantify the degree of

macrosegregation, the difference between the highest measured concentration of each element and its nominal concentration was calculated. In order to study the effect of macrosegregation on the microstructure and hardness, two samples presenting low and high degree of macrosegregation were characterized using optical microscopy, XRD and microhardness. The last technique was used to obtain information about the nature of the phases in presence. To this end, the Vickers method with 100 indentations ( $10 \times 10$ ) with an applied load of 10g was employed.



**Fig.1 Samples preparation for chemical mapping**

## 2 Results and discussion

### 2.1 Macrosegregation analysis

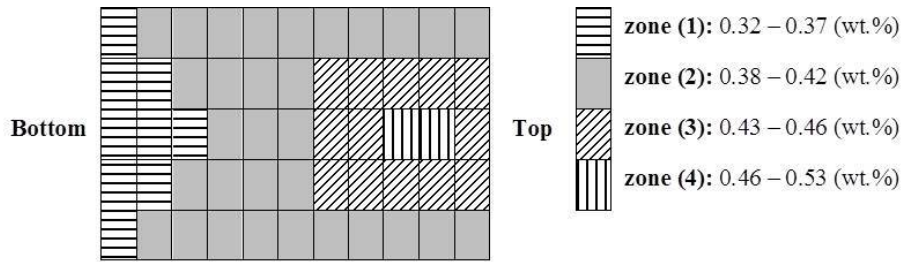
The general analysis of the different maps showed the existence of chemical heterogeneities depending on the sample locations in the ingot. In order to simplify the presentation of these maps and to draw trends, we assembled the samples having a close concentration with the same code. Two important regions were identified. The first one with positive macrosegregation was located close to the top of the ingot, and the second one with negative macrosegregation was situated in the bottom of the ingot. The level of macrosegregation was evaluated in these two zones, i.e. for positive macrosegregation the difference was calculated between the highest concentration and the nominal composition whereas for the negative macrosegregation the difference was calculated between the lowest concentration and the nominal composition. Table 1 gives the values of the maximum degree of macrosegregation. The segregations lines will not be considered in this work. The C map is presented in Fig.2. Four regions can be observed where the C concentrations increased from zone 1 to zone 4. Zone 1 was situated in the bottom of the ingot with a C concentration of 0.32–0.37 wt.%. Zone 2 (0.38–0.42 wt.%) starts above zone 1

and cover initially the entire section of the ingot and gradually becomes limited to regions adjacent to the surface of the ingot. Zone 3 (0.43–0.46 wt.%) was surrounded by zone 2. Concerning zone 4, it was located in the top of the ingot with the highest C content (0.46–0.53 wt.%). The degree of negative macrosegregation was  $-0.03 \text{ wt.}\%$  whereas that of positive macrosegregation was  $+0.18 \text{ wt.}\%$ .

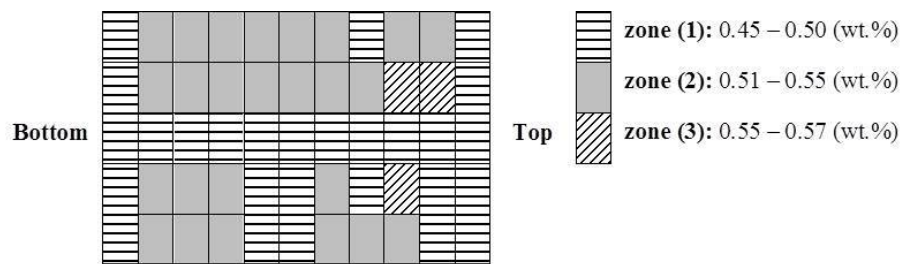
Fig.3 illustrates the map of Ni where three major zones can be distinguished. The concentration of Ni increased from zone 1 to zone 3. The Ni map did not exhibit the same configuration as the C one. Zone 1, with 0.45–0.50 wt.%, was observed in the bottom, top, the center and some places in the both sides of the ingot. Zone 2 was located in the sides of the ingot with a nickel content of 0.51–0.55 wt.%. Regarding zone 3 (0.55–0.57 wt.%), it was present in the top of the ingot between zones 1 and 2. Macrosegregation levels were  $-0.05$  and  $+0.07 \text{ wt.}\%$  for negative and positive types, respectively. The distribution of Cr is given in Fig.4. Four regions were revealed where also the concentrations of Cr increased from zone 1 to zone 4. The zone 1 which contained the lowest quantities of Cr (1.70–1.77 wt.%), was only present

in the bottom of the ingot. It was located also in the same regions in the two sides of the ingot far from its bottom. Zone 2 with 1.77–1.82 wt.% was located in the both sides of the ingot. For zone 3, it was surrounded by zones 1 and 2 with 1.71–1.85 wt.%. Concerning zone 4 (1.84–1.91 wt.%), it was located in the top of the ingot. The degrees of macrosegregation were  $-0.16$  and  $+0.05$  wt.% for

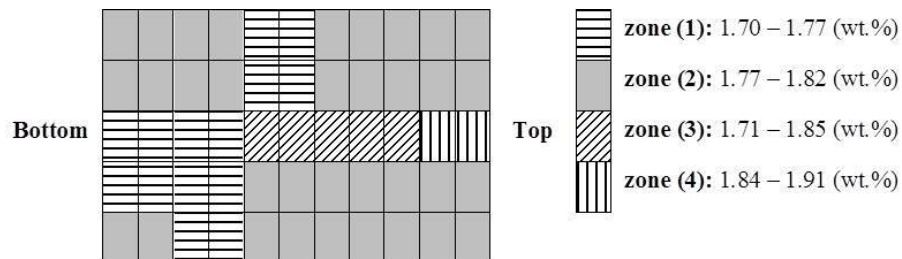
negative and positive types, respectively. In the case of Mn and V, four regions were also obtained with their contents increasing from zone 1 to zone 4. The distribution configurations of Mn and V were very close to that of C. The negative macrosegregation were more important for Mn compared to V while the contrary was true for positive macrosegregation.



**Fig.2 The distribution of C along the longitudinal slice of the large steel ingot**



**Fig.3 The distribution of Ni along the longitudinal slice of the large steel ingot**



**Fig.4 The distribution of Cr along the longitudinal slice of the large steel ingot**

The mapping analysis showed the existence of macrosegregation despite the deformation and heat treatments undergone by the ingot. The observed negative and positive macrosegregations are in good agreement with a directional solidification from the bottom to the top of the ingot. Comparison between the degree of segregation of the different elements showed that the C is the element having the highest level of positive macrosegregation. The degree of the positive segregation was very close for the other elements with the lowest value for vanadium. The highest degree of negative macrosegregation was attributed to Cr followed by Mn. The C and Ni had

approximately the same level. The lowest degree of negative macrosegregation was assigned to V. Moreover, regarding the distribution of the different elements, Ni and especially V present the maximum degree of chemical homogeneities. These differences in the distribution behaviour of the elements could be explained by different factors such as the type of the primary solidification microstructure, the diffusion coefficients, the cooling rates, dendrites arm spacing, etc. Among these, one of the most important factors is the type of the primary solidification. Depending on the initial chemical composition of the ingot, the solidification will either take place in delta ferrite ( $\delta$ )

or austenite ( $\gamma$ ). The type of the solidification mode will affect also the type and the content of the

elements present (alphagene or gammagene).

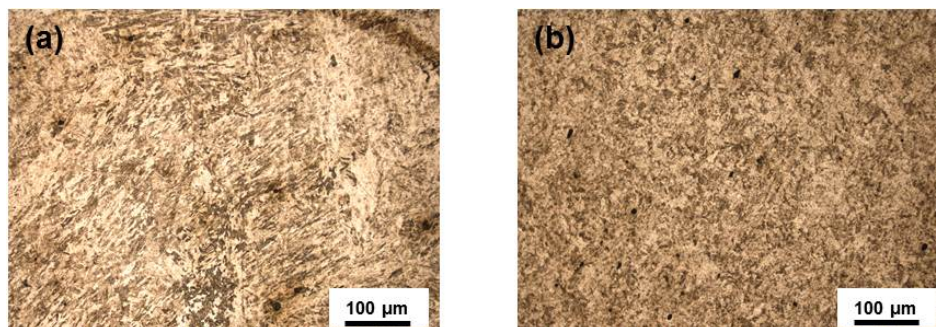
**Table 1 Macrosegregation level of the different elements**

	Nominal composition (wt.%)	Macrosegregation level (wt.%)	
		Negative type	Positive type
C	0.35	-0.03	+0.18
Ni	0.50	-0.05	+0.07
Mn	0.99	-0.11	+0.05
Cr	1.86	-0.16	+0.05
V	0.149	-0.001	+0.03

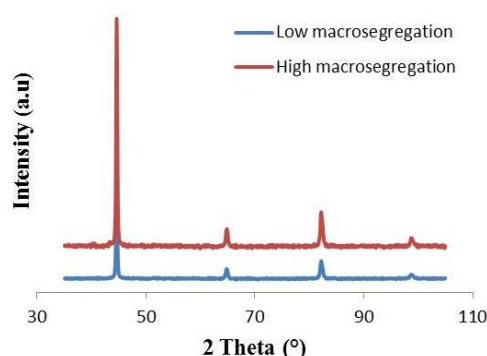
## 2.2 Microstructure and hardness properties

The characterizations were focused on two samples, with low (0.33 wt.%C) and high (0.48 wt.%C) degree of C macrosegregation. Fig.5 presents the microstructure of these two specimens. Both samples seem to have bainitic microstructure. XRD results, given in Fig.6, confirm the body centered cubic (bcc) structure which is in good agreement with that of bainitic microstructure. Furthermore, no retained austenite was detected in the two cases. Fig.7 presents an example of the microhardness map of the

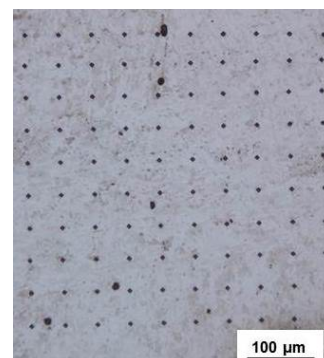
sample with low level of macrosegregation. The obtained values for both samples were in the range of 332–455 HV which is in good agreement with bainitic microhardness. Concerning the hardness, the values were  $276 \pm 9$  and  $286 \pm 5$  HV for the low and high level of macrosegregation, respectively. Chemical heterogeneities seem to do not affect the microstructure type and hardness in the case of these two samples.



**Fig.5 Microstructure of the two samples with a– high degree of macrosegregation; b– low degree of macrosegregation**



**Fig.6 XRD patterns of samples with low and high degree of macrosegregation**



**Fig.7 Microhardness measurements of the sample having low degree of macrosegregation**

## 3 Conclusions

The distributions of C, Ni, Mn, Cr and V were characterized in a 40-ton forged and heat treated steel

ingot. Regions of positive and negative macrosegregations were revealed. The C and Cr

presented, respectively, the highest degree of positive and negative macrosegregations whereas V presented the lowest level in both. V and Ni presented more homogeneous distributions. Macrosegregation seemed to do not have an important effect on the microstructure type and the hardness properties of the two samples presenting low and high degree of macrosegregation. Further characterizations, such as EBSD, in other locations in the ingot are necessary.

## **References**

- [1] Pickering EJ., Macrosegregation in steel ingot: the applicability of modelling and characterisation techniques, *ISIJ International*, 2013, 53(6): 935~949.
- [2] Peng F., Adverse impact and countermeasures of macro segregation for ring forging product, *Journal of Materials and Applications*, 2012, 17~20.
- [3] Beckermann C., Macrosegregation, *ASM Handbook, Casting*, 2008, 15: 348~352.