Metallographic characterization by variographic analysis and geo-statistical simulation of local segregation microstructures in a heavy thickness forged part in SA508 Gr3 Cl2 type steel

Extended Abstract

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Introduction

In the field of mechanical characterization of large forgings in low alloy steel for nuclear components, it is usually considered that the classical specimen size for testing the material, and the repetition of the sampling by testing a few specimens is enough to provide a good vision of the measured properties and its variability in a given location in the forging (given by the position (azimuth and elevation and through thickness). As a matter of example, the RCC-M Code specifies that Charpy toughness specimens used for acceptance tests (standard size 8 mm x 10 mm in the tested section) are repeated 3 times in a given combination of position, heat treatment condition, and at a given test temperature. Testing such a small volume of material with a small number of replicate tests implicitly assumes that the material must be homogeneous at the scale where these specimens are taken. But the standards generally do not explicitly set what an inacceptable inhomogeneity at this scale is, nor the method to characterize it.

This question - the effect of the sampling specimen size and number on the toughness distribution, when the material is obviously not homogeneous at the scale of the specimen size - can be treated by means of the "local approach of fracture". One significant contribution needed in this analysis is a reliable description of the morphological distribution of the microstructure, and of its variability along the notch tip or crack front of the specimen. Geostatistics, i.e. the science of analysis the spatial distribution of some properties with statistical tools, can help solving this problem.

A method for the characterization of the heterogeneous structure of the local segregations, inherited from the ingot solidification and the forging processes, based on variographic analysis and geostatistical tools was developed. This paper presents the material characterization, by metallographic and micro-chemical analysis, and the variographic analysis, which was made of it, to finally generate a 3D model of the local segregations, which can be used in further works of mechanical modelling by the local approach of fracture.

Characterization of Local Segregations of the material

In this paper an example of a material with heterogeneous structures at the centimeter scale is given. The material comes from a forging, in SA 508Gr3 Cl 2 steel, which is highly segregated, and represents the central part of a large ingot (> 250t), which was not discarded by punching (since it is a solid forging) and remained embedded in the mid thickness of the forging. This test material, although not representative of an actual part existing in a nuclear component, presented clearly local segregations typical of some areas of ingots, made of this steel grade, which made it a good candidate to test the development of the methods which are presented in this paper to address the treatment of local segregations.

The resulting local segregation structure was studied by macrographs, in 3 perpendicular planes. Calling S the "Short" Direction (i.e. the direction of upsetting), R1, and R2 two perpendicular radial directions, in the plane normal to S, examples of macrographs in 3 planes normal to these 3 axes is shown in Fig. 1. Micro-analysis mapping with Castaing micro-probe were also performed. These mapping allowed to show that the contrast level of the macrographs (i.e. the grey level) can be correlated to the local Chemical composition: this is particularly clear with the Mo Content, as can be seen in Figure 2. One can see unambiguously in the S plane the dendritic structure of the solidification process, which resulted in a network of local segregations formed by micro-segregations (between dendrite arms of a single dendrite), and "inter-granular" meso-segregations (surrounding the equi-axial dendritic solidification grains), which appear after etching as dark areas. As shown in Fig. 2, the darker is the picture of the macrograph the higher is the Mo content (light areas in the Mo% mapping of Fig. 2).

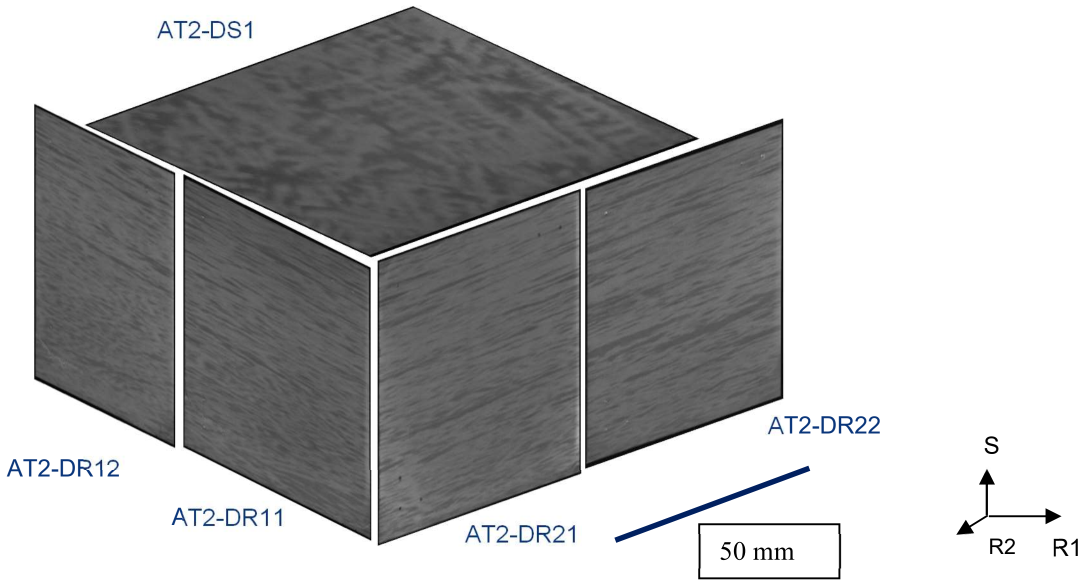

Figure 1: **Macrographs of the material in 3 planes normal to the principal axes of the forging process (Nital Etching)**

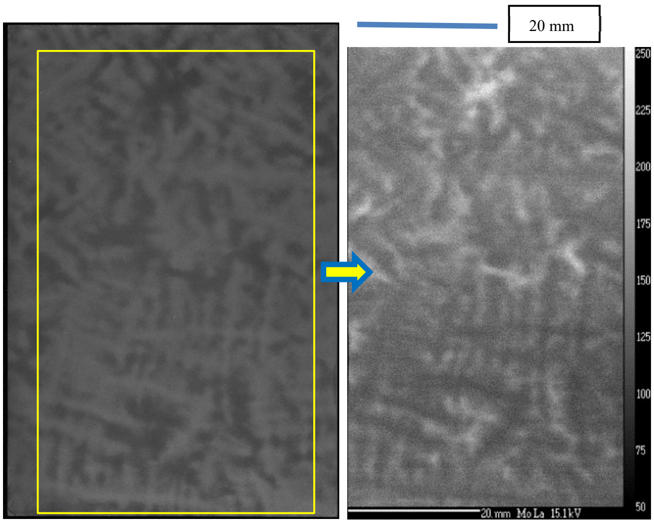

Figure 2: **Comparison of a Macrograph (Nital Etching) in the S plane (Left) with a Castaing Micro-probe-mapping (Molybdenum) of the same sample (Right)**

The variograms of the images of these structures were derived from different macrographs, and also completed with the analysis of the analytical mappings. In Geostatistics science, variogram, is a function of a vector which characterizes the dispersion (or the level of continuity) of the field of the studied parameter (here, the grey level at each pixel of a macrograph); it is formalized by the square of the difference between the value of the parameter at two points separated by the vector, averaged on the whole set of such couples of pixels in the whole macrograph. Examples are given in Fig. 3, for macrographs in two different planes, S and R2.

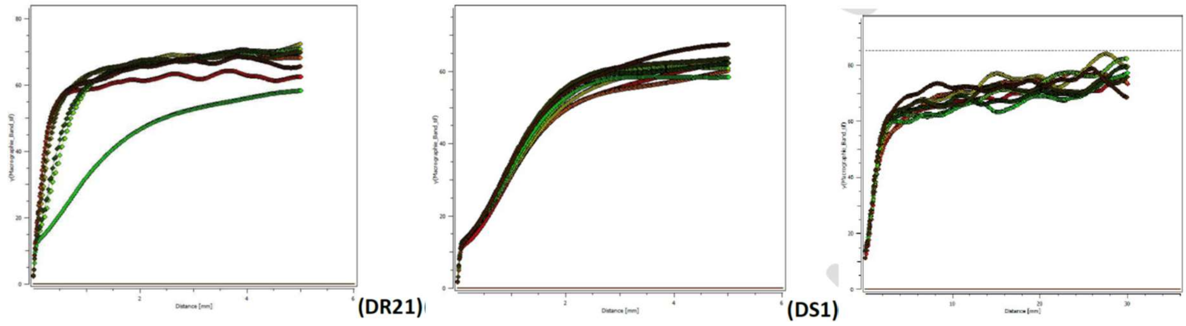

Figure 3: **Typical variograms obtained in the analysis of the macrographs: Left: in a R2 plane in various directions between the S direction (red curve) and the R1 direction (lower green curve) - Center :Short range variogram in the S plane in various directions between R1 (red curve) and R2 (green curve) – Right: Long range variogram in the S plane**

The analysis of these variograms clearly reflects the "stratified" and anisotropic structure observed in plane R2, with a characteristic distance much longer in the R1 direction (green curve – plateau not yet reached at 5 mm – in fact >7-8 mm) compared to the S direction (red curve) for which a plateau is reached at ~ 0.5 mm (characteristic thickness of the bands); the period of oscillations reflect the typical distance between segregated bands. At the opposite, in the plane normal to S, the variograms do not depend on the direction, which means that the structure is isotropic in this plane, with characteristic features (typically the segregated veins between dendritic grains) which extend over several (2 to 3) mm in size. The long range variogram in the same plane (see Fig. 3 Right) showed that some structures have a characteristic size of 7- 8 mm, which is the typical distance between two highly segregated zones in this plane.

3D Simulation of meso-segregation structures

Finally, a 3D segregation simplified model was developed, based on basic tools of geostatistics, Its parameters were adjusted on the basis of the previous experimental analysis, to generate sets of 3D segregation fields on a 3D regular mesh of 0.2 mm step), having essentially the same variographic characters as those experimentally determined in the three section planes before. Examples of sections through an R plane and the S plane are illustrated in Figure 4 (the color represents here the grey level of macrograph- which can be correlated to local chemical analysis as shown above). One simplification consisted in neglecting the micro-segregation of small amplitude and small wave-length, generated by the dendrite secondary arms in the S plane, and to focus on the higher amplitude "meso-segregation" between the grains with a long characteristic distance.

As said above, it is believed that this kind of model will be very useful for analyzing the risk of presence of local segregation at the notch tip in mechanical test specimens randomly located in the material, and the resulting scatter of the mechanical properties.

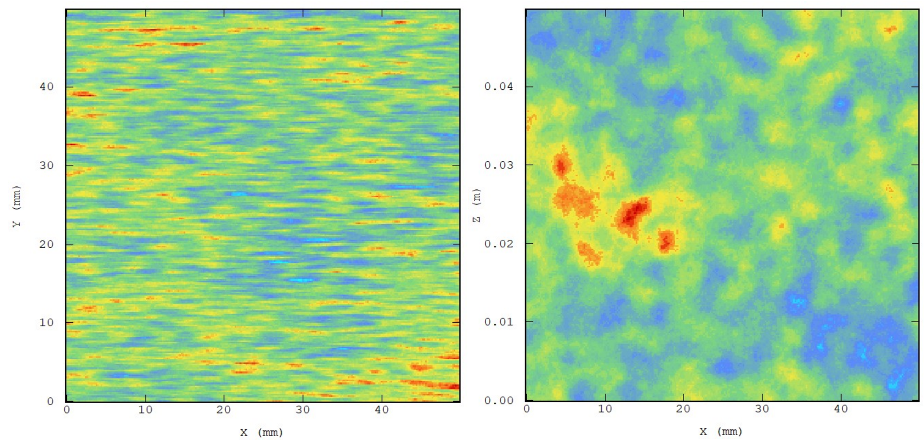

Figure 4: **Example of simulated structure of local segregation. Colour represents a normalized scale of grey level (similar to macrographs). Left section through a plane normal to R1 or R2 – Right Section to a plane normal to S**