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DETERMINATION OF THE REPRESENTATIVE VOLUME ELEMENT OF DUAL-PHASE STEELS BY 3D TOMOGRAPHY

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ABSTRACT
Dual phase steels are low carbon steels which are thermo-mechanically processed to getting better formability and toughness than ferrite-perlite steels with similar tensile strength. The microstructure of these steels consisting of a ferrite matrix with hard martensitic/ bainitic second phase. The concept of representative volume element (RVE) is critical to understand and predict the behavior of effective parameters of steels. The RVE is considered to be a partial volume of the material, which is statistically homogeneous from the macroscopic point of view. In this paper determination of the representative volume of two dual phase steels (one with a martensitic and the second with a bainitic) is presented. Multiple samples are excised from the total volume of tomography and different parameters are observed to get the smallest RVE with stabile parameters. Results show that size of reduced volume has an influence on the parameterstability, while position of the observed reduced volume has not.

1. INTRODUCTION

DP steels are developed in the mid-seventies in order to satisfy needs of increasing the developing automobile industry. The main driving forces are the reduction of weight as well as an increasing stability and crash safety. Today, in material engineering using of the lightweight components is a main requirement. Due to the economic and ecological considerations, the weight of the structure should be reduced, while at the same time, strength of the structure is necessarily to increase, [1,2].These steels show high ultimate tensile strength (UTS) combined with low initial yield stress, high early-stage strain hardening, and macroscopically homogeneous plastic flow that make them ideal for using in automotive-related sheet-forming operations, [2,3]. One of the most important characteristics of DP steel are high strength and good toughness in the same time, [4].

For accurately describing the microstructure developing of new methods of 3D analysis isnecessary. Many parameters can be gained from 2D images by using stereology [5], but2D analysis does not provide accurate information about key parameters such as particle number per volume, connectivity, size distributions, and actual particle shape. Even basic characteristics, such as the number of particles, average size and size distribution, so can only approximate heterogeneous microstructures cannot be described, [6].

In order to obtain a representative result with respect to the overall material behavior, the considered sample must be a representative volume element (RVE). The RVE is considered to be a partial volume of the material, which is statistically homogeneous from the macroscopic point of view [7].

2.EXPERIMENTAL PART

2.1 Serial sectional tomography

Tomography and 3D data are very important to gain new insights into the real microstructure with information of shape, distribution and connectivity of different phases.This information will help to understand the correlations of parameters across all scales and dimensions.

The whole process of serial sectioning is composed of some steps that are repeating such as polishing, etching and collecting 2D images until the required depth is achieved. For the reconstruction into a virtual 3D structure images have to be aligned and converted to binary images. On that way 3D image stacksare obtain and then by using 3D reconstruction different parameters (e.g. the connectivity of the phase, number of particles etc.) could be measured. The process has been explained in details by Vardo et al. [8].

2.2 Representative volume element (RVE) of tomography

In this paper two tomographies of steels with a ferritic matrix and a martensitic or a bainitic second phaseare obtained. The total volume for the tomography with martensitic second phase is 300 x 334 x 125 μm^3 while the bainitic tomography had a total volume of 296 x 386 x125 μm^3. For the determination of the morphological parametersRVE multiple samples of different volumes from the total tomographies are excised.The 3D parameters that are used to determine theRVE are: Volume density, Surface and Euler densityof the second phase objects.

Volume is the quantity of three-dimensional space enclosed by some closed boundary while the surface area of the solid objects is a measure of the total area that the surface of an object occupies.Volume density is the surface occupied by the second phase.Surface density means surface area per unit volume. Also, the specific surface (surface density) is inversely proportional to the harmonic mean of the volume-weighted distribution, also called “natural” mean or Sauter mean (mean volume-to surface particle size), [9,10].The density of the Euler number is the expected number of objects in a unit window.The density of the Euler number is better matched by models with circular cross sections, [10,11].

3. RESULTS AND DISSCUSION

3.1 RVE of the martensitic tomography

In Figure 1 different volumes of martensitic tomography are presented which are taken into consideration for the RVE. The total volume is divided in 5 different ways, every time the reduced volume is smaller than one before.The areas of the martensite second phase appear white while the surrounding ferrite matrix is displayed as black.

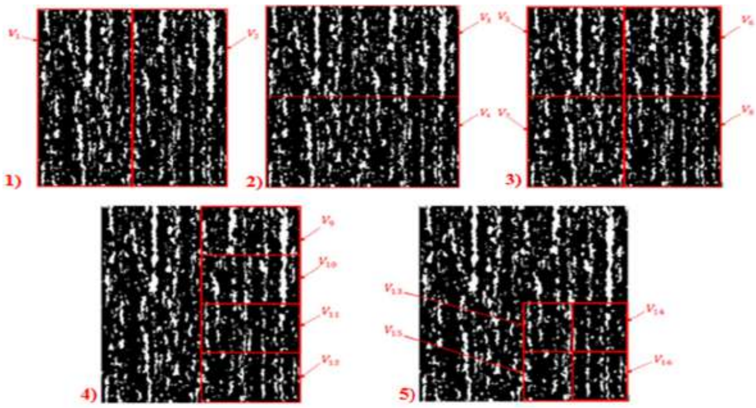

Figure 1. Schematic representation of the position and size of the reduced volumes for the martensitic tomography

Table 1. Analyses of the structural parameters: Volume density, Surface density and Euler density for different volumes of the martensitic tomography.

Way of reducing	**Position**	**Volume size (μm^3)**	**Volume density**	**Surface density**	**Euler density**
	Total volume				
	V	300x334x125	0.1783	231900	-1.53E+15
Figure 1.1)	Reduced volume (1)				
	V_1	150x334x125	0.1730	228456	-1.48E+15
	V_2	150x334x125	0.1839	235183	-1.59E+15
Figure 1.2)	Reduced volume (2)				
	V_3	300x167x125	0.1843	235898	-1.45E+15
	V_4	300x167x125	0.1724	227648	-1.61E+15
Figure 1.3)	Reduced volume (3)				
	V_5	150x167x125	0.1797	232341	-1.38E+15
	V_6	150x167x125	0.1894	239254	-1.53E+15
	V_7	150x167x125	0.1665	224310	-1.57E+15
	V_8	150x167x125	0.1785	230863	-1.65E+15
Figure 1.4)	Reduced volume (4)				
	V_9	150x84x125	0.1882	241147	-1.42E+15
	V_{10}	150x84x125	0.1906	236748	-1.64E+15
	V_{11}	150x84x125	0.1805	231358	-1.65E+15
	V_{12}	150x84x125	0.1765	229742	-1.65E+15
Figure 1.5)	Reduced volume (5)				
	V_{13}	75x84x125	0.2058	255004	-2.01E+15
	V_{14}	75x84x125	0.1551	206273	-1.23E+15
	V_{15}	75x84x125	0.1868	241972	-1.80E+15
	V_{16}	75x84x125	0.1663	216059	-1.47E+15

In order to test stability of values of the parameters of interest reduction of total volume V (300x334x125 μm^3) of specimen is performed sequentially. Sections arereduced and results are compared by each section to predict and avoid any variations of important parameters of tomography. For that purpose, mean value and standard deviation of each section (reduced volume) is calculated and compared.

Table 2. Mean value and standard deviation for each reduced volume

Position	**Volume density**	**Surface density**	**Euler density**
Mean value			
Reduced volume (1)	0.1785	231820	-1.53E+15
Reduced volume (2)	0.1783	231773	-1.53E+15
Reduced volume (3)	0.1785	231692	-1.53E+15
Reduced volume (4)	0.1840	234749	-1.59E+15
Reduced volume (5)	0.1785	229827	-1.63E+15
Standard deviation			
Reduced volume (1)	0.0077	4757	0.079E+15
Reduced volume (2)	0.0084	5834	0.110E+15
Reduced volume (3)	0.0094	6132	0.112E+15
Reduced volume (4)	0.0066	5212	0.114E+15
Reduced volume (5)	0.0224	22552	0.345E+15

After the first reducing of the volume (1), two equals vertical halves (V_1andV_2) with volume of 150x334x125 μm^{3}are obtained, the results shows high level of stability with the lowest standard deviation of Surface density and Euler density.

With the second reducing (2), two equals horizontal halves (V_3andV_4) are obtained. Standard deviation of the volume density is 9.09% higher than in the first reducing, 22.64% of the surface density and 38.71% higher of the Euler density.

After that the volume isdivided (3) on four equals' halves with the size of 150x167x125 μm^3 (from V_5 to V_8). As it expected the results are more various with the reducing of the volume, for this size of the volume, standard deviation of the volume density is 11.90% higher than in the second reducing, while surface density and Euler density are increased about 5.11% i.e. 1.82%.

In the fourth reducing (4) one of the volumes V_1 and V_2 could be chosen because the results are very close to each other. For this tomography volume V_2ischoose and divided on the four parts (V_9 to $V_{12}$with the size of 150x84x125μm^3. Values of the standard deviation in comparison with the first reducing: volume density is about 14.3% lower, surface density 9.56% higher and Euler density 43.76% higher.

In the last reducing (5) volume V_8isdivided in a new four equal parts $V_{13}$to $V_{16}$and the results show the biggest variations in comparison with the others and mean values of the all parameters are higher than in the total volume so this cannot be a RVE.

The smallest representative volume element for this tomography is obtained after reducing (4) with the volume size of 150x84x125 μm^3.

3.2 RVE of the bainitic tomography

For the bainitic tomography reducing of the total volume isdone in the same way as for the martensitic one, as can be seen in the Figure 2. Bainitic objects are shown in white, while ferrite matrix is black.

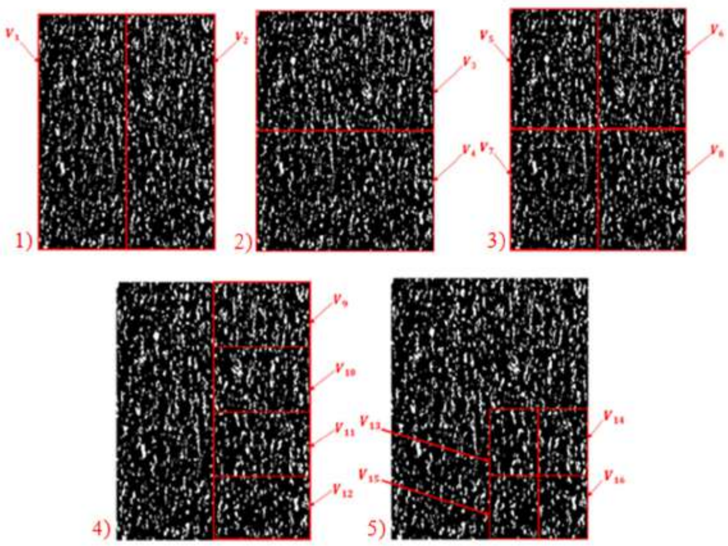

Figure 2. Schematic representation of the position and size of the reduced volumes for the bainitic tomography, which are cut out and compared for the determination of the RVE from the total tomography.

Table 3. Analyses of the structural parameters: Volume density, surface density and Euler density for different volumes of the bainitic tomography.

Way of	Position	Volume size	Volume	Surface	Euler

reducing		(μm^3)	density	density	density
	Total volume				
	V	296x386x125	0.1938	317954	-4.21E+15
Figure 2.1)	Reduced volume (1)				
	V_1	148x386x125	0.1872	310877	-4.22E+15
	V_2	148x386x125	0.2004	324477	-4.20E+15
Figure 2.2)	Reduced volume (2)				
	V_3	296x158x125	0.2046	326260	-4.41E+15
	V_4	296x158x125	0.1830	309213	-4.01E+15
Figure 2.3)	Reduced volume (3)				
	V_5	148x158x125	0.1968	318229	-4.34E+15
	V_6	148x158x125	0.2123	333740	-4.48E+15
	V_7	148x158x125	0.1775	303108	-4.11E+15
	V_8	148x158x125	0.1885	314761	-3.91E+15
Figure 2.4)	Reduced volume (4)				
	V_9	148x386x125	0.2172	332989	-4.43E+15
	V_{10}	148x386x125	0.2073	333580	-3.24E+15
	V_{11}	148x386x125	0.1928	315082	-4.01E+15
	V_{12}	148x386x125	0.1842	313586	-3.96E+15
Figure 2.5)	Reduced volume (5)				
	V_{13}	74x96x125	0.1941	323495	-4.11E+15
	V_{14}	74x96x125	0.1917	305576	-4.86E+15
	V_{15}	74x96x125	0.1868	315264	-3.84E+15
	V_{16}	74x96x125	0.1846	310643	-3.99E+15

Table 4. Mean value and standard deviation for each reduced volume

Position	Volume density	Surface density	Euler density
Mean value			
Reduced volume (1)	0.1938	317677	-4.21E+15
Reduced volume (2)	0.1938	317737	-4.21E+15
Reduced volume (3)	0.1938	317460	-4.21E+15
Reduced volume (4)	0.2004	323809	-3.91E+15
Reduced volume (5)	0.1885	313745	-4.20E+15
Standard deviation			
Reduced volume (1)	0.0093	9617	0.014E+15
Reduced volume (2)	0.0153	12054	0.283E+15
Reduced volume (3)	0.0147	12635	0.252E+15
Reduced volume (4)	0.0147	10961	0.494E+15
Reduced volume (5)	0.0051	7610	0.454E+15

The values of the standard deviation after the second reducing (2) show increasing for all parameters; about 64.52% for the volume density, 25.34% for the surface density and the Euler number is 20 times higher as for the reducing (1).

With the next reducing (3), values for the standard deviation of the all parameters are still higher than in the first (1); volume density 58.06%, surface density 31.38% and Euler density 18 times.

In the fourth reducing (4), value for the volume density is the same as in the reducing 3, while surface density shows increasing in comparison with the reducing (1) but on the other hand decreasing in comparison with the reducing (2) and (3). The standard deviation of the Euler density in this reducing has the biggest value in the whole tomography, about 35 times higher than for the first reducing (1).

Values of the standard deviation of the volume and surface density after reducing (5) show the lowest values of the all reducing. In comparison with the reducing 1, 45.16% and 20.87% lower while Euler density is significantly increased, about 32 times.

As it can be seen from the Table 4 the lowest values of the deviation are in the reducing 5 for the volume and surface density so that is the smallest representative volume for this tomography.

For the bainitic tomography RVE is smaller in comparison with the martensitic one. This is connected with the size of the particles, the smaller the particles are the smaller RVE is required. The mean values of all parameters are increasing with the decreasing size of the particles, as can be seen in Table 2 and Table 4. If the RVE for the both tomographies are compared, the results show higher mean values for the bainitic tomography, the volume density about 2.45%, the surface density is significantly higher about 33.5% and Euler density more than double.

4. CONCLUSION

For the sizeof therepresentative volume element the reduced volume has an influence in the variation of the values of volume, surface and Euler density, while position of that reduced volume in the tomography is not important. With volume reduction there are variations in parameter stability.

For the martensitic tomography representative volume element is 150x167x125μm^3, while for the bainitic tomography is 74x96x125μm^3. Bainitic second phase objects are smaller than martensiticonesas it can be seen in the Figure 1 and 2, therefore a smaller representative volume element is needed.

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