NUMERICAL MODELING AND ANALYSIS OF MICROSTRUCTURE EVOLUTION IN MULTI-MATERIAL CO-EXTRUSION OF BIMETALLIC Ti6Al4V-AZ31B BILLETS

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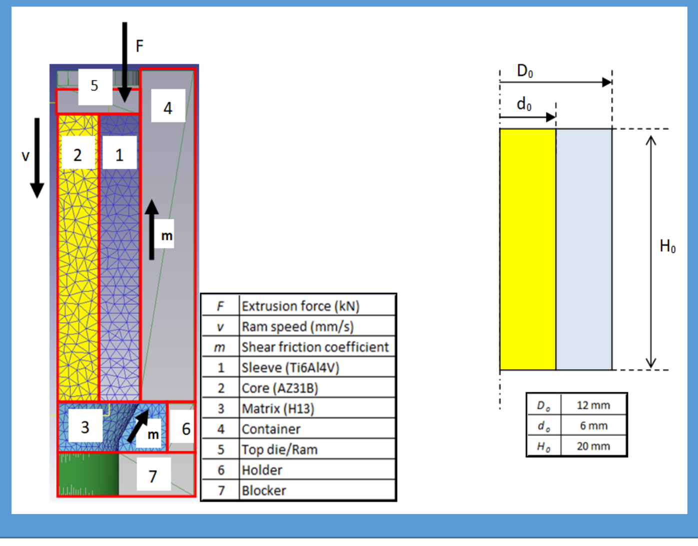
ABSTRACT

The target of this investigation is to model and analyze the effect of the multi-material co-extrusion process parameters on microstructure in bimetallic Ti6Al4V-AZ31B billets. Johnson-Mehl-Avrami-Kolmogorov (JMAK) equations have been implemented in the Finite Element (FE) model in DEFORM3D© to simulate dynamic recrystallization and predict the final grain size. This study used the following co-extrusion parameters to evaluate their influence on the final average grain size of the manufactured part: temperature, ram speed, extrusion ratio, die semi-angle and shape factor (relation between core diameter and billet height).



FINITE ELEMENT MODELING

JMAK dynamic recrystallization model equations:

$$\varepsilon_p = a_1 \cdot d_{g_0}^{n_1} \cdot \dot{\varepsilon}^{m_1} \cdot exp\left(\frac{Q_1}{R \cdot T}\right) + C_1$$

$$\varepsilon_c = a_2 \cdot \varepsilon_c$$

$$X_{drex} = 1 - exp\left[-\beta_d \cdot \left(\frac{\varepsilon - a_{10} \cdot \varepsilon_p}{\varepsilon_{0.5}}\right)^{K_d}\right]$$

$$\varepsilon_{0.5} = a_5 \cdot d_{g_0}^{h_5} \cdot \varepsilon^{n_5} \cdot \dot{\varepsilon}^{m_5} \cdot exp\left(\frac{Q_5}{R \cdot T}\right) + C_5$$

$$d_{drex} = a_8 \cdot d_{g_0}^{h_8} \cdot \varepsilon^{n_8} \cdot \dot{\varepsilon}^{m_8} \cdot exp\left(\frac{Q_8}{R \cdot T}\right) + C_8$$

$$d_g = d_{g_0} \cdot (1 - X_{drex}) + d_{rex} \cdot X_{drex}$$

Simulation process parameters:

Parameter	Value
Number of elements	7000
Mesh density type	Relative
Target volume	Active in FEM + meshing
Simulation type	Lagrangian incremental
Step increment control (mm/step)	Constant = 0.06
Interference depth	Relative = 0.7
Heat transfer coefficient between matrix and ring (N·°C⁻¹·s⁻¹·mm⁻¹)	11
Heat transfer coefficient between ring and core (N·°C⁻¹·s⁻¹·mm⁻¹)	11
Heat transfer coefficient between billet and air (N·°C⁻¹·s⁻¹·mm⁻¹)	0.02
Heat transfer coefficient between billet and tooling (N·°C⁻¹·s⁻¹·mm⁻¹)	5
Friction type	Shear

Avrami coefficients:

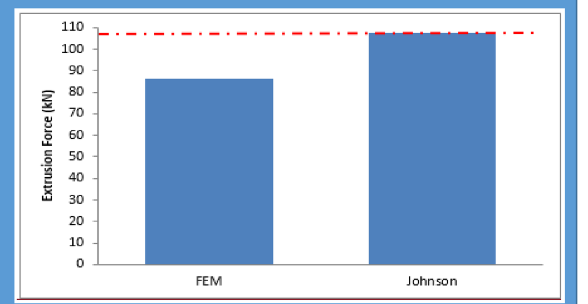
Ti6Al4V

Peak strain	a_1	n_1	m_1	Q_1	C_1	a_2			
	0.0064	0	0.0801	30579	0	0.8			
Drex Kinematics	a_5	h_5	n_5	m_5	Q_5	C_5	B_d	K_d	a_{10}
	0.022	0	0	0.11146	26430	0	0.9339	0.5994	0.0311
Drex grain size	a_8	h_8	n_8	m_8	Q_8	C_8			
	1280	0	0	-0.088	-36848	0			

AZ31B

Peak strain	a_1	n_1	m_1	Q_1	C_1	a_2			
	$2.6e^{-5}$	0	0.31	42820	0	0.8			
Drex Kinematics	a_5	h_5	n_5	m_5	Q_5	C_5	B_d	K_d	a_{10}
	0.1336	0	0	0.0406	5608.078	0	0.209	1.06	0
Drex grain size	a_8	h_8	n_8	m_8	Q_8	C_8			
	173.83	0	0	-0.1	-13813	0			

FEM model validation by semi-empirical model of Johnson.



METHODOLOGY

Co-extrusion parameters:

Process parameters	Tooling parameters	Geometrical parameters
Temperature (° C)	Extrusion ratio (A_0/A_f)	Billet height (mm)
Ram speed (mm/s)	Die semi-angle (°)	Core diameter (mm)
-	Shear friction factor	-

DOE (Design Of Experiments):

	Temperature (° C)	Ram speed (mm/s)	Extrusion ratio (A_0/A_f)	Die semi-angle (°)	Friction	Billet height (mm)	Core diameter (mm)
Baseline	350	2	1.78	30	0.1	20	6

Extrusion Parameters	Level			
	1	2	3	4
Temperature (°C)	300	350	400	450
Ram speed (mm/s)	1	2	3	4
Extrusion ratio	1.44	1.78	2.25	-
Die semi-angle (°)	15	30	45	60
Friction	0.05	0.1	0.3	0.5
Billet height (mm)	15	20	25	30
Core diameter (mm)	4	6	8	10

CONCLUSIONS

Microstructure is not uniform in the ring, with a large difference between inner and outer area. Nor does the evolution of this microstructure occur in the same way in the inner and outer areas.

As a general rule, the core presents a smaller grain reduction than the ring. In addition, this reduction is mainly located in the bottom part of the core where the permanent regime of the co-extrusion process is not yet achieved, corresponding to the initial stage of the transitory.

Ram speed and friction have barely effect on core microstructure.

Temperature values lower than 30 º C produces no crystallization on the ring.

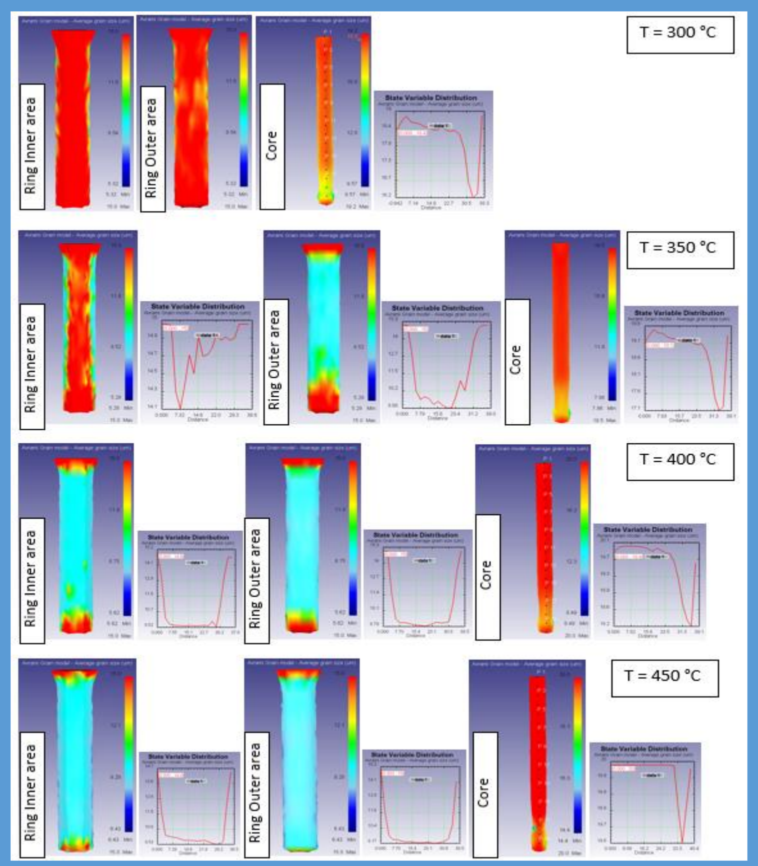
Die semi-angle is the most influential parameter on microstructure evolution of both ring and core.

High values of billet height and low values of core diameter produce the smallest average grain size in the final part.

Finally, this report proves that microstructure of a manufactured part can be controlled and customized during a multi-material co-extrusion process

RESULTS AND DISCUSSION

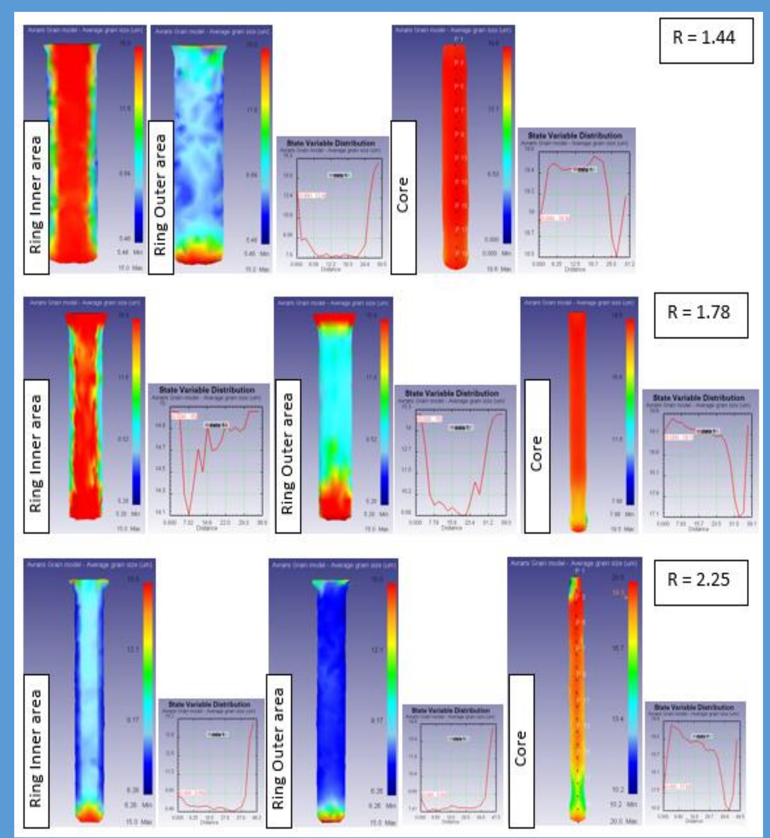
TEMPERATURE



The increase of the temperature produces a fine-grained microstructure in the ring, while in the core the effect of the temperature is the opposite, obtaining a coarse-grain microstructure at high temperatures.

Temperatures values below 300 º C produce no effect in the ring microstructure.

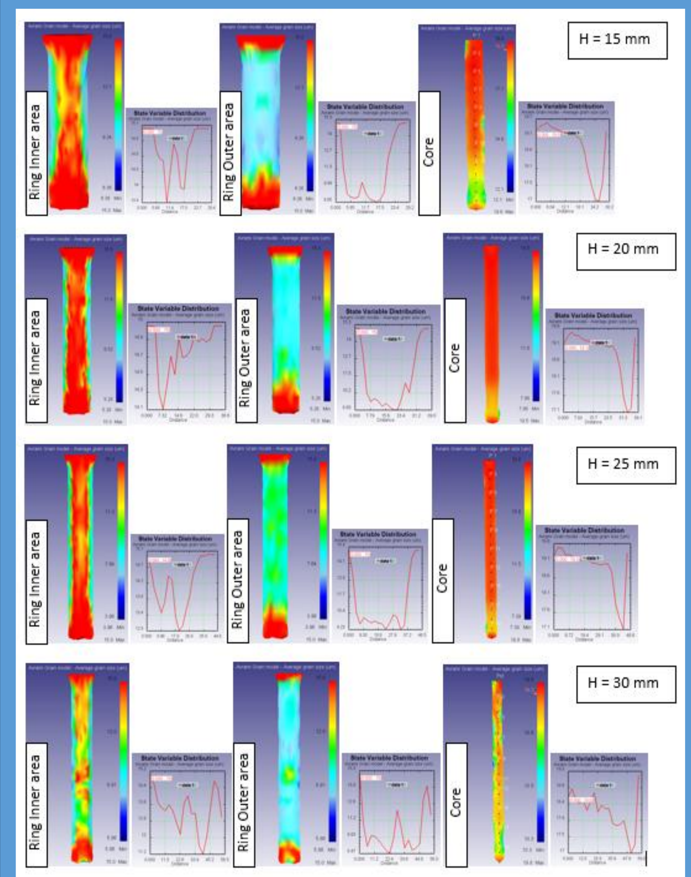
EXTRUSION RATIO



This parameter mainly affects the inner area of the ring. For low extrusion ratio values there is hardly any recrystallization while for 2.25 extrusion ratio values the final average grain size is reduced to 8 µm.

Core microstructure experiments a reduction on the average grain size with increasing of the extrusion ratio values.

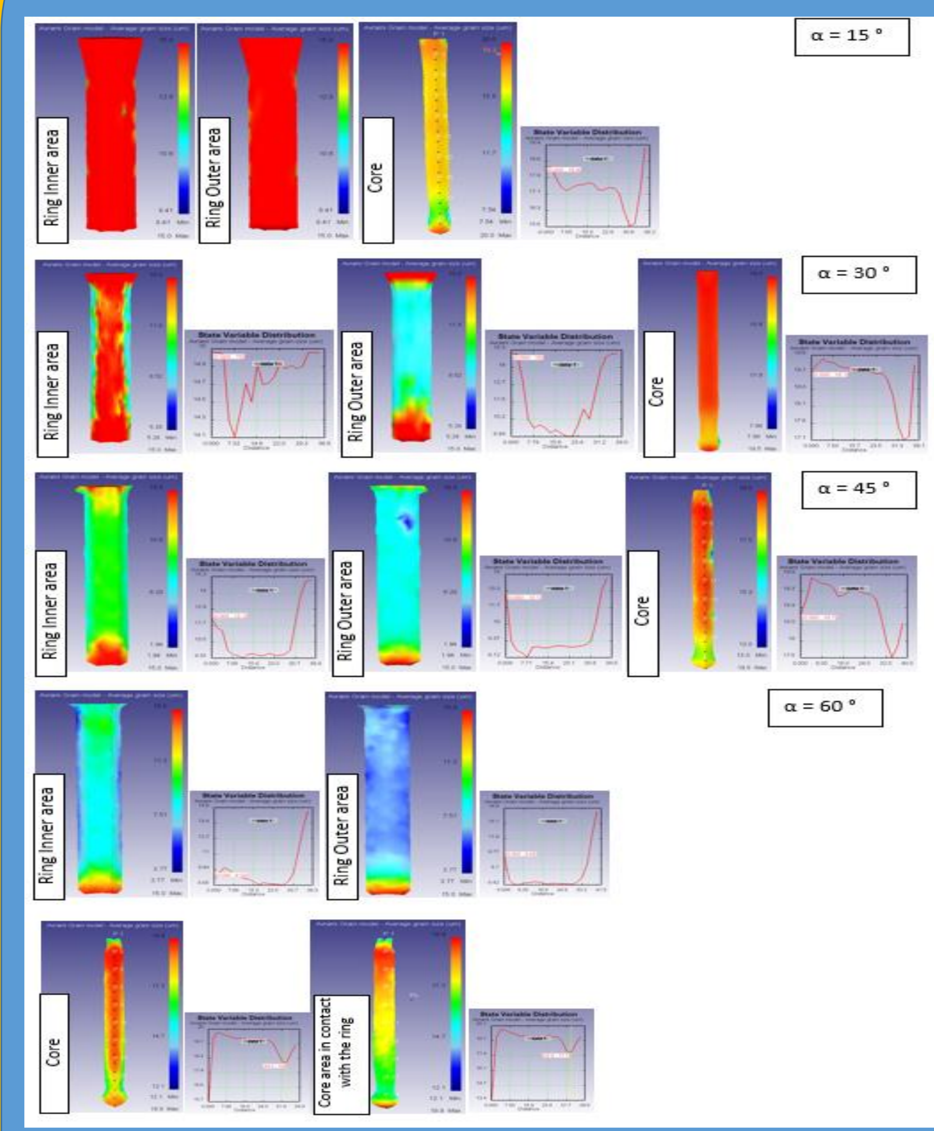
BILLET HEIGHT



Core microstructure only undergoes changes for billet height values from 30 mm.

As the billet height increases a fine-grain microstructure is obtained in the ring. These changes in the grain size are no uniform through the ring, with large differences between inner and outer areas

DIE SEMI-ANGLE

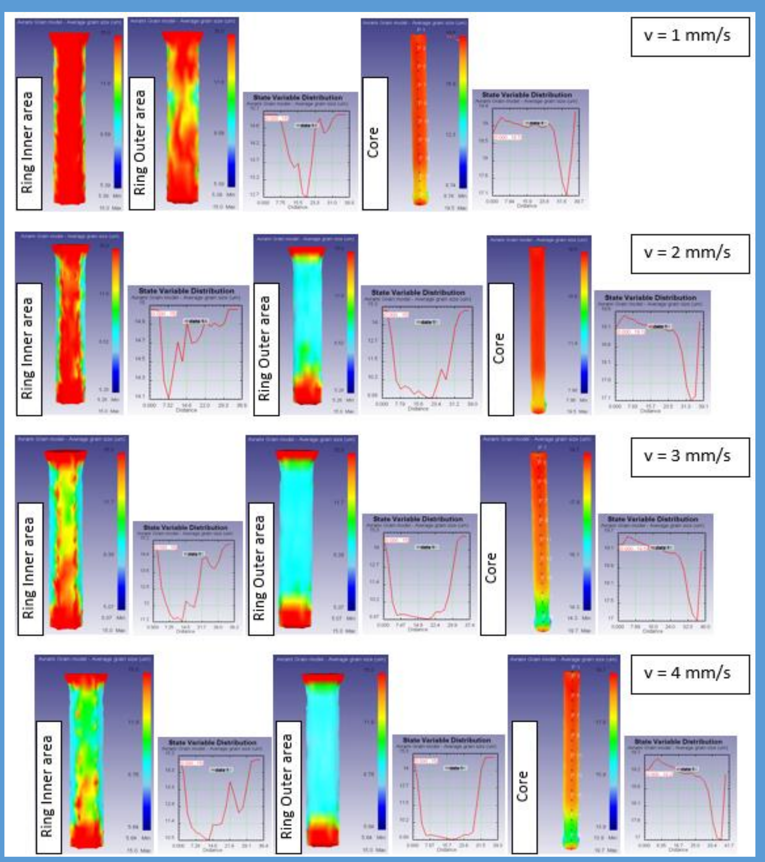


Die semi-angle is the most influential parameter on microstructure evolution.

For low values of die semi-angle, such as 15 º, the microstructure of the ring does not present any change neither in the inner or outer areas. Nevertheless for 60 º values of die semi-angle, the inner area of the ring reaches an average grain size of 8.65 µm and the outer area reduces its average grain size to 6.42 µm.

Core average grain size increases with increase of the die semi-angle values.

RAM SPEED

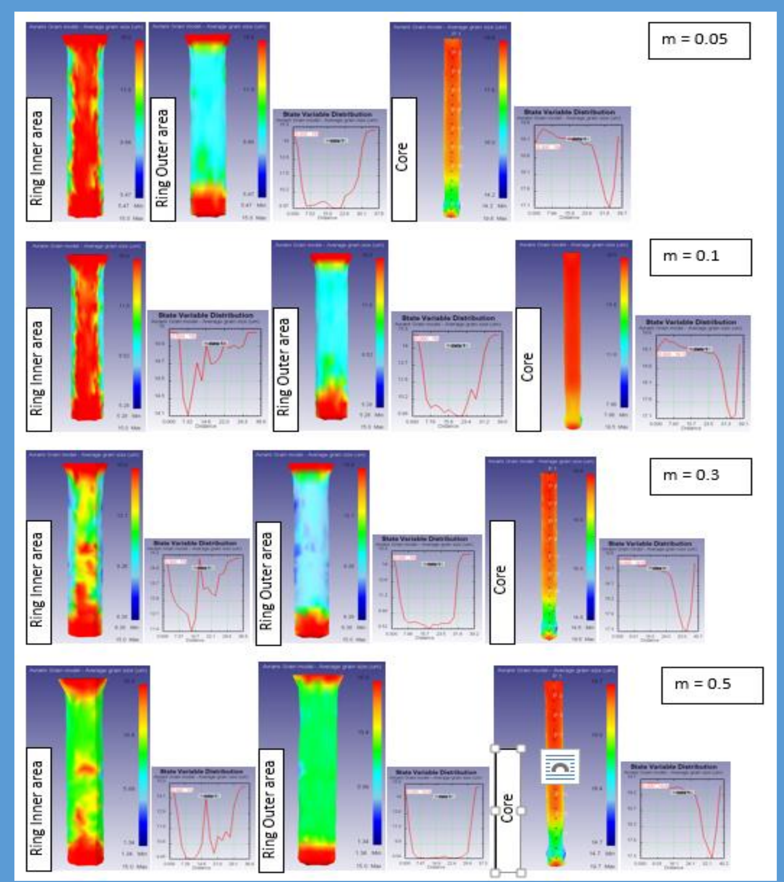


High values of ram speed produces a fine-grain size microstructure.

Core microstructure does not present relevant changes with the variation of the ram speed.

The decrease in the average grain size with the increase of the ram speed is not uniform in the ring, reaching the outer area the maximum grain size reduction for 3 mm/s ram speed.

FRICTION

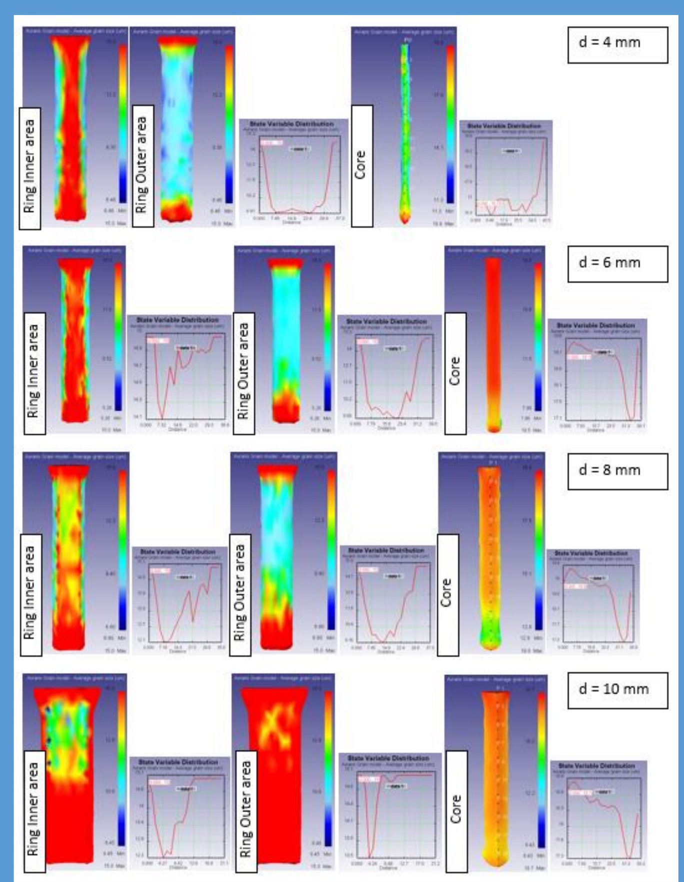


Friction only has an effect in the ring microstructure.

There is a non-homogenous distribution of the grain size between inner and outer area of the ring for low friction values.

The increases of the friction mainly affects the inner area of the ring keeping the outer area with hardly any changes.

CORE DIAMETER



The inner and outer areas of the ring have opposite behaviors. While in the inner area the average grain size distribution decreases as the internal diameter of the ring increases, the outer area shows a coarse-grain microstructure.

Core reaches the minimum grain size values for 4 mm values diameter