



Microstructural and hardness characterization of stainless steel 316-Inconel 718 multimaterial developed by wire-based Directed Energy Deposition

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Abstract

The combination of different material properties to face severe conditions has been always demanded by different industrial sectors. Traditionally, this has been achieved by conventional manufacturing of multiple materials with several steps and joining processes. However, manufacturing the entire component within the same process by additive manufacturing and the combination of two different materials is presented as a potential via to explore. In this study, three IN718/SS316 multimaterial samples were designed and successfully manufactured by a novel multilaser head deposition, wire-based Directed Energy Deposition (DED-wire) technology. Multimaterial-sandwich design strategies composed of two, three and four layers per material led to S1, S2, and S3 samples, respectively. In all of them, the direct transition between materials was applied. The cross-section of the three multimaterial samples was analyzed by optical microscopy to verify the influence of the number of the material layer on the defect appearance like porosity, cracks or lack-of-fusion. Evolution of the hardness property across the XZ direction of the three samples was assessed, and the microstructure of the IN718 region, IN718/SS316 interphase and SS316 region was evaluated across the XZ build direction (multimaterial gradient) and in the XY direction (single layer of SS316 or IN718). It was found that the multimaterial-sandwich design strategy of four layers per material employed for processing sample S3 led to IN718/SS316 interphases without the presence of relevant defects. The sample processed with two layers per material (S1) presented a similar crack pattern at each IN718-SS316 interface, but only very small and isolated pores were identified in S2 and S3 samples. A Microstructure composed of very fine grains together with a smooth transition zone was generated in a sample processed by S3. The three multimaterial samples resulted in a gradient of the hardness properties, decreasing the average hardness value from IN718 region, IN718/SS316 interphase to the SS316 region. S3 showed the hardness profile with the highest: IN718 region (55 ± 6 HRC), IN718/SS316 interphase (34 ± 1 HRC) and SS316 region (9 ± 2 HRC), where the value of IN718 is significantly higher compared to that of the conventional IN718 material (47 HRC).

Keywords Multimaterial · Additive manufacturing (AM) · Directed Energy Deposition (DED) · Wire-based · IN718/SS316 · Microstructure · Hardness

1 Introduction

Multimaterial combinations are widely present in our daily life, and most of them are nature-inspired multimaterial structures. Design and innovative processing methods for

optimized multimaterial are being investigated by selecting application-specific combinations of compositional structures of two materials [1].

SS316/IN718 was selected for this study due to their useful combination properties for both strength and corrosion resistance at elevated temperature. With this IN718/SS316 multimaterial, high wear and corrosion resistance at high temperature will be provided by IN718 when required, whereas weight and cost reduction will be locally achieved by applying SS316 material. Gas turbine components, high-end automobile engine valve stems or coatings are different

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applications where such material properties combination is highly interesting [2].

The stainless steel (SS316L)-nickel-based superalloy Inconel 718 (IN718) multimaterial has increased its attraction to be investigated together in multimaterial structures due to their different properties in the same manufacturing process [3]. Weldability between both materials is considered a relevant issue in this kind of AM processing to avoid cracks and porosity in the resulting multimaterial. Chemical compatibility and metal welding between both materials are classified satisfactory. IN718 presents good weldability, and porosity tends to easily escape from the melt pool because of the long solidification time [4]. However, the common problems of processing dissimilar materials with different physico-chemical properties must be addressed in all fusion processes.

Different fusion welding processes by applying heat with or without pressure or filler materials are usually found among the most common conventional methods for joining similar or dissimilar metals. This is the conventional route for manufacturing a part composed of different metallic materials. However, in order to avoid or minimize the crack formation or embrittlement, these conventional joining processes employ intermediate layers for separating two dissimilar metals or high energy sources. Nevertheless, some innovative joining processes like Friction Stir Welding (FSW) are also alternative joining methods for welding dissimilar materials in the solid state by severe plastic deformation using a harder tool. In this way, mechanical bonding occurs between both metallic alloys to join without an energy source or melting steps [5].

However, metallic multimaterial manufacturing can be suitably performed with some additive manufacturing (AM) processes in which different metallic materials are able to be melted through a controlled electron or laser beam energy source. Therefore, in addition to the advantages of multimaterials, the fact of manufacturing them by AM results in merits like the following: (i) developing metallic multimaterials as a single-step process without the necessity of joining post-processing methods; (ii) enabling design freedom for customization; (iii) cost-effective and environmental-friendly manufacturing solutions with a reduced amount of raw material and material waste as well as reduced production costs saving energy, time, and steps [6].

Laser Metal Deposition (LMD) is a laser-based Directed Energy Deposition (DED) process in which a nozzle mounted on a multi-axis arm deposits molten material in powder or wire format layer by layer onto a build plate at a specific angle [6]. The energy source can be a laser, electron beam or plasma arc, and it is used to create beads, tracks, and layers of solid materials upon solidification of the melt pool on the substrate [7].

On one hand, currently, the majority of valuable researches found in processing IN718 and SS316 single materials focus on powder bed fusion (PBF) and powder-based DED technologies [8–10]. These AM technologies have great relevance in terms of complex geometries, good precision and surface quality. However, they are associated with high equipment costs, lower deposition rates, and some limitations in manufacturing large parts compared to the AM technologies which use wire metals like Wire and Arc Additive Manufacturing (WAAM), widely recognized by manufacturing large industrial components, as discussed elsewhere [11–13]. But applications of WAAM in multimaterial processing have not yet been found in the literature, probably due to the difficulty of allocating two or more wire metallic materials in this kind of equipment. One research study found investigates the mechanical and microstructural characterization of functionally graded Inconel 825-SS316L fabricated using wire arc additive manufacturing but using powder feedstock [5].

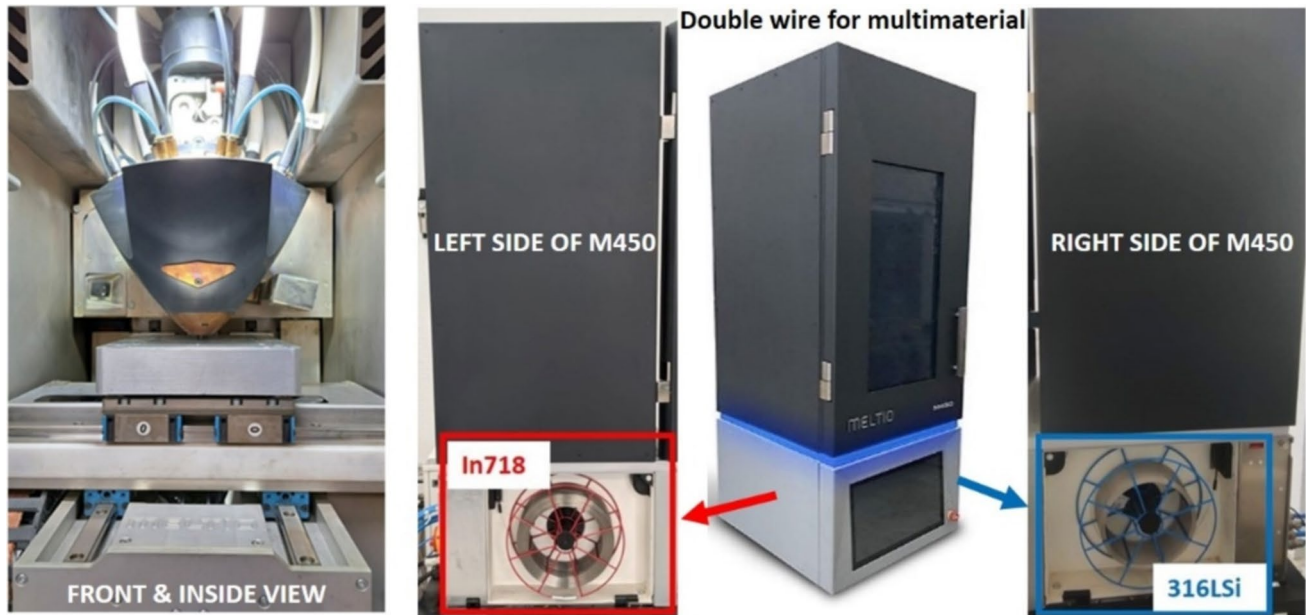
On the other side, DED processing with powder feedstock is commonly used for functional graded materials (FGM) due to its high flexibility in multimaterial composition, gradients and variation [7]. Bimetal, FGM and hybrid material multimaterial strategies have been used with DED-powder to process Ti6Al4V-SS304L multimaterial, Ti6Al4V-SS316 or Ti6Al4V-Invar different combinations [4]. Stainless steel 420-IN718 multimaterial structures were also manufactured by DED-powder and microstructural characterized as reported [14].

In the case of DED-wire, very few publications have been found in literature for processing single materials like stainless steel [15], titanium alloy [16], copper alloys [17, 18], aluminium–silicon alloy [19], aluminium alloy [20] or Inconel 718 alloy [21]. However, Stainless Steel-Inconel multimaterial processing by DED-wire has not been found in literature. Therefore, exploring the IN718/SS316 multimaterial manufacturing via wire-based DED processing in this research will contribute to widening the state-of-the-art with innovative knowledge.

In this work, three IN718/SS316 multimaterial samples were designed and successfully manufactured by wire-based DED technology through multimaterial-sandwich design strategies. Gradients composed of two, three, and four layers per material were designed for samples S1, S2 and S3, respectively. Direct transitions between materials were applied in all samples. Cross-sections, microstructure in both build directions and hardness properties were evaluated in the different regions (IN718 segments, IN718/SS316 interphases and SS316 segments) to compare the material behaviour of the three multimaterial strategies employed. The effect of a number of layers per material on the interphases and adjacent layers is studied to better understand the

Table 1 Chemical composition of the starting wire SS316 and IN718 materials for the DED processing

Material	Chemical composition (wt. %)											
	C	Mn	Si	Ni	Cr	Mo	Cu	Ferrite	Fe	Ti	Al	Nb+Ta
SS316L	0.01	1.8	0.9	12.2	18.4	2.6	0.12	7	Bal	–	–	–
IN718	0.05	0.2	0.2	Bal	19	3	–	–	20	0.9	0.5	5.2

**Fig. 1** Multi-laser deposition head system (M450, Meltio) double wire DED technology used for the additive manufacturing of the SS316/IN718 multimaterial

service life of a part additively manufactured in this multimaterial by wire-based DED technology.

2 Experimental procedure

Wire metals of low-carbon stainless steel 316L (SS316) and nickel-based superalloy Inconel 718 (IN718) were employed to process the SS316/IN718 multimaterial. The stainless steel SS316L is a standard low-carbon austenitic steel containing molybdenum, which makes excellent durability, biocompatibility and corrosion resistance, particularly against pitting and crevice corrosion in chloride environments [5]. The IN718 superalloy is a high-strength alloy widely used in high-temperature applications due to its good mechanical properties and excellent corrosion resistance. Both materials were employed in 1-mm-diameter wire for manufacturing the SS316/IN718. The chemical composition of the starting SS316 stainless steel and IN718 nickel-based superalloy wires are listed in Table 1. MELTIO was the supplier for both materials as well as the manufacturer of the double wire-based DED technology used in this research.

Table 2 DED-wire process parameters for SS316/IN718 multimaterial manufacturing

Material	DED process parameters for SS316/IN718 multimaterial				
	Print speed (mm/min)	Layer height (mm)	Laser power (W)	Track spacing (mm)	Gas flow (L/min)
SS316	600	1	1100	1	10
IN718	450	1	1100	1	10

The multimaterial SS316/IN718 was processed using the innovative Meltio M450 Directed Energy Deposition (DED) technology. This additive manufacturing technology is equipped with a multi-laser deposition head system capable of processing two different wires simultaneously (Fig. 1).

The Laser DED additive manufacturing system, equipped with a 1.2 kW Multilaser system composed of 6 (200 W) fibre-coupled diode lasers of 976 nm wavelength, was used to manufacture the samples. Argon with a purity higher than 99.996 % was used as shielding gas during the whole 3D processing. The process parameter combination employed

in this research for both materials is summarized in Table 2. Process parameters have been those recommended by the M450 provider reported in their material datasheet and available on their website.

The multimaterial strategy sandwich SS316/IN718 for manufacturing small cubes of 25 mm wide and 25 mm tall designed by three different strategies are schematically represented in Fig. 2, using S1 (two layers multimaterial strategy), S2 (three layers multimaterial strategy) and S3 (four layers multimaterial strategy). All of them are composed of SS316 and IN718 direct transition material gradients, represented in grey and blue colour, respectively.

The microstructural analysis was carried out by optical microscopy (AxioLab A1 equipped with an AxioCam ERc, Carl Zeiss ICS and ZeissCore software) after cross-sectioning and surface preparation by standard metallographic techniques to evaluate the density level of the different materials processed. The surface of the specimens was ground successively from 600 to 4000 grit with SiC papers, followed by polishing with 1 µm diamond suspension and finally with colloidal silica suspension. The as-polished samples were chemically etched for a few seconds to reveal the microstructures by using a solution of Vilella and HCl for the stainless-steel segments and a diluted solution of FeCl₃ for the Inconel regions. Multimaterial densification and defects were evaluated along the cross-section of the three samples. Then, the microstructure of the sample showing the highest density was studied in two different areas (middle and upper regions).

Finally, hardness Rockwell C was measured at different points of the cross-sections in SS316, IN718 and SS316/IN718 regions. Five measurements were performed in each of the three regions of the three samples for reliability purposes. Results were represented as the average value with the standard deviation. Hardness measurements were performed by a Wilson Rockwell C hardness tester where a loading force of 150 kg and 15 s indentation time were effective for achieving accurate measurements for the SS316 and IN718 segments as well as SS316/IN718 interphases.

3 Results and discussion

3.1 Production of the multimaterial specimens

The three SS316/IN718 multimaterial sandwich specimens designed and placed are shown in Fig. 3. This multimaterial design can be applicable to bimetallic structures where dual functionalities are required. Three different material gradients were created where the material layer disposition was different. Two, three and four layers per material have been considered the three different multimaterial strategies S1, S2 and S3, respectively. The process parameters for the manufacturing and the detailed multimaterial strategies are described in Table 2 and Fig. 2, respectively.

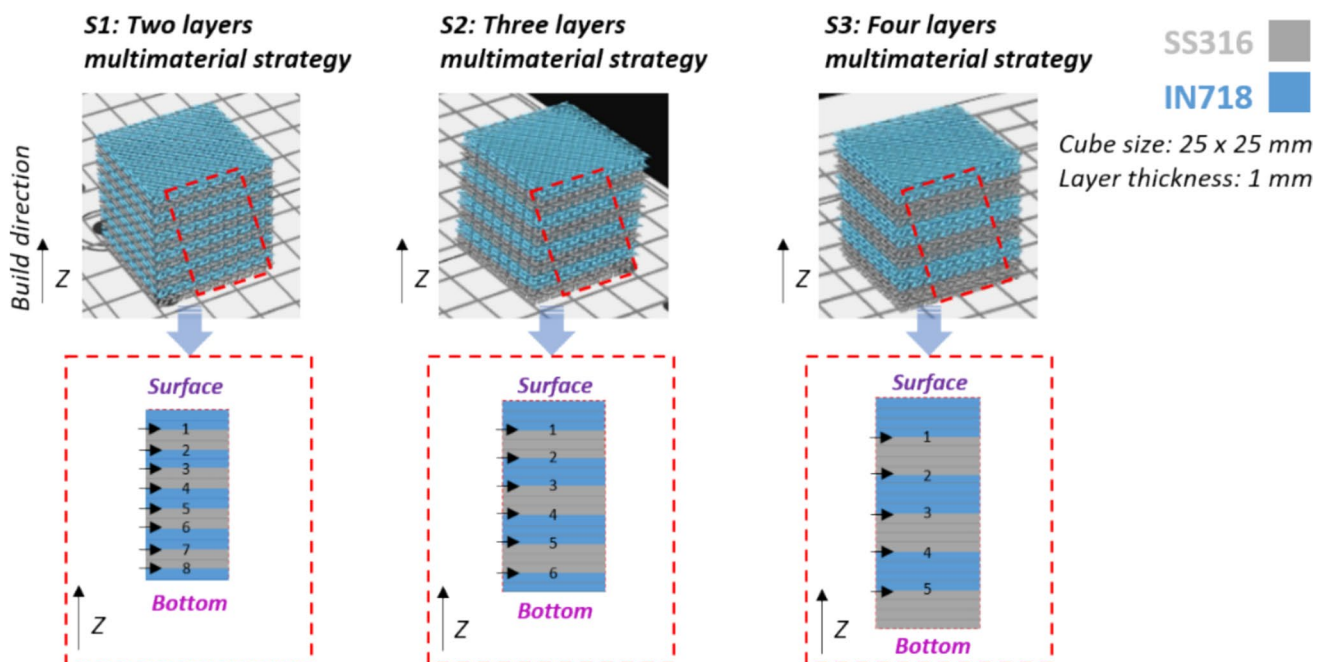


Fig. 2 Multimaterial strategy sandwich design for SS316/IN718 additive manufacturing by DED-wire: S1 (two layers); S2 (three layers) and S3 (four layers). Detailed views of the three different gradients created

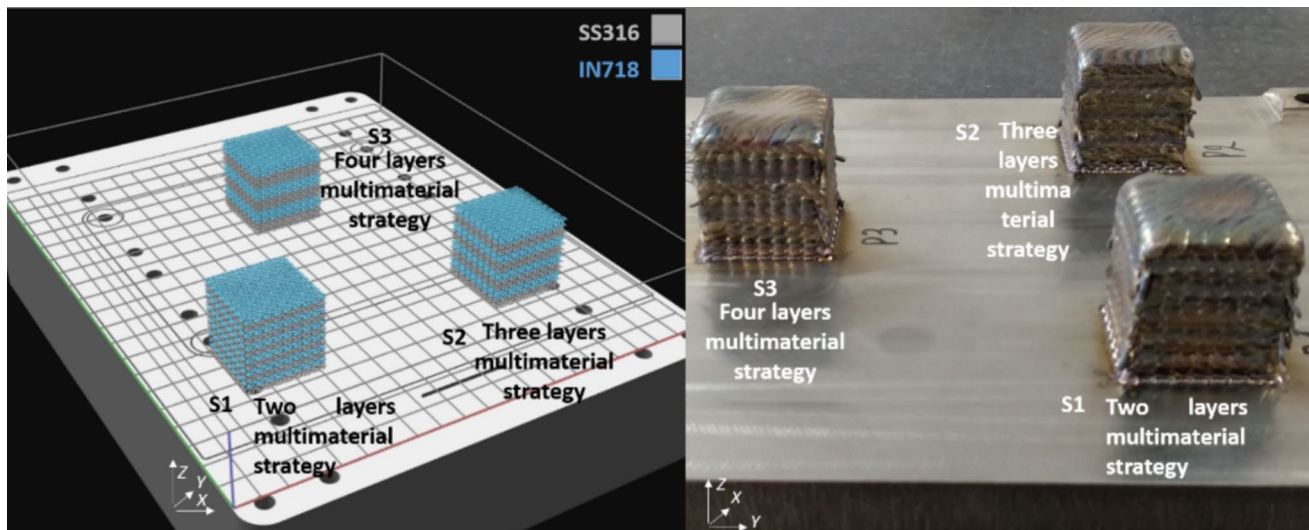


Fig. 3 Design and manufacturing of the three SS316/IN718 multimaterial sandwich strategies by DED-wire technology: S1 (two layers multimaterial strategy); S2 (three layers multimaterial strategy); and S3 (four layers multimaterial strategy)

3.2 Cross-section of the multimaterial specimens

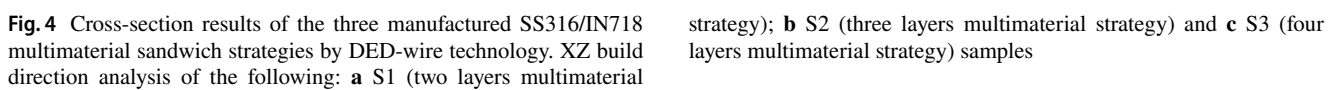
First, Fig. 4 shows the cross-section of the additive manufactured samples processed by DED technology along with the design considered for each multimaterial strategy. In Fig. 4a, the multimaterial sandwich strategy considered (S1) is composed of two IN718 layers and two SS316 layers, consecutively, from the bottom to the surface with eight IN718/SS316 interphases. Secondly, in Fig. 4b, the multimaterial sandwich strategy considered (S2) was composed of three IN718 layers and three SS316 layers, consecutively, with six IN718/SS316 interphases. Finally, strategy S3 composed of four consecutive layers of each material (five IN718/SS316 interphases) is represented in Fig. 4c.

In the S1 strategy (Fig. 4a), some lack-of-fusion and crack defects were found repeatably at the interphase. It can be pointed out that all of them were originated at the border of the IN718 layer, and they were propagated to the SS316 layer. The irregular lack-of-fusion defects are usually attributed to an insufficient heat input. Cracks could indicate the presence of a second phase enriched in Nb and Mo, as it was reported by [22]. Supercooling, thermal and residual stress concentration as well as the CTE difference between dissimilar materials could also affect to crack formation. It seems that it can be controlled by applying more layers per material as in the case of S2 and S3 samples where only some isolated pores were identified in Fig. 4b (S2) and Fig. 4c (S3). This behaviour can be correlated with the thermal responses of the three multimaterial strategies employed. In the case of the samples manufactured with S2 and S3 strategies, three and four material layers, respectively, are deposited and melted of each SS316 and IN718 material.

In contrast, the gradient generated in the sample manufactured with the S1 multimaterial strategy is composed of two consecutive layers of both alloys. This seems to have a major impact on the thermal gradient response between layers. Therefore, although 2 layers per material transition could be built, the thermal and residual stresses formed in the previous interphase region could affect the subsequent layer through close contact during the change of material. Within the three different strategies employed, it has been proved that in this study, thermal and residual stresses can be controlled with two things: first, using the selected process parameters, and second, depositing more than two layers per material. Furthermore, the pores and cracks induced during the cooling of the IN718 layer can propagate at the IN718/SS316 interphase and move into the nearby SS316 layer with no defects. This was also evidenced by other authors where similar defects were found in functionally graded materials with 3–4 layers and even 1 layer per compositional transition manufactured by DED technology [2].

3.3 Microstructure

Microstructural examination of the DED specimen manufactured through S3 condition (four layers per material) was observed along the cross-section in two different areas, at the middle region of the sample (Fig. 5a) and at the upper area of the sample (Fig. 5b) with the aim to observe any difference between different regions. A microstructural gradient was obtained throughout the sample in both areas analyzed, where IN718 segment, IN718/SS316 interphase and SS316 segment are represented from left to right.



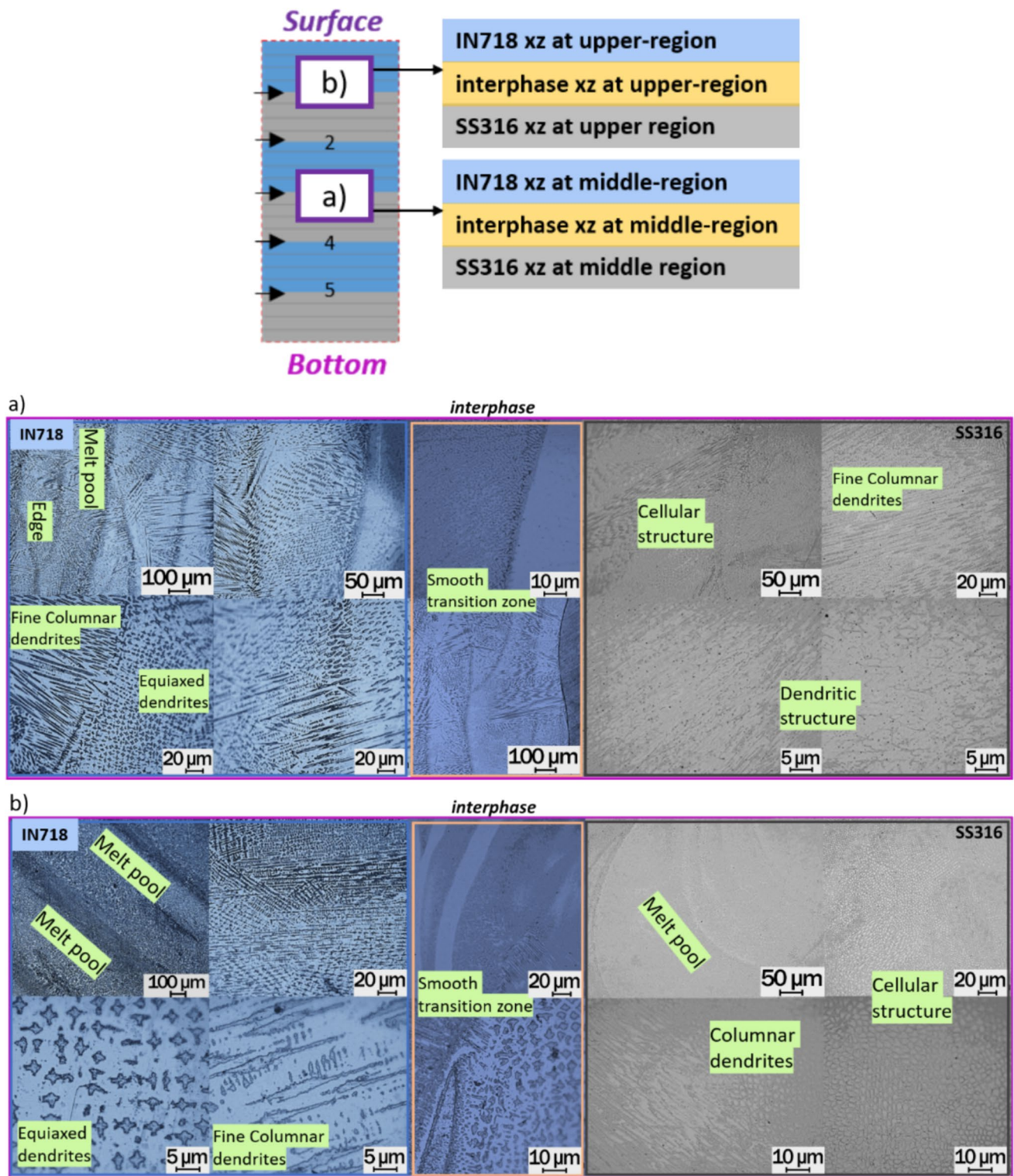


Fig. 5 Microstructure results of the manufactured SS316/IN718 multimaterial (S3) sample employing direct transition by DED-wire technology. XZ plane of the IN718 region, SS316/IN718 interphase and SS316 regions found at **a** middle region and **b** upper area

First, in Fig. 5a, deep melt pool signs were observed at low magnification as a consequence of high thermal gradients which caused different grain growth directions

in the IN718 segment. It is known that the dimensions of the melt pool are associated with thermal conductivity, thermal diffusivity, cooling rate and solidification front

velocity as described in another study [22]. Thermal gradients originated a microstructure partially formed by columnar and equiaxed dendrites as it was observed at higher magnifications. Then, a smooth transition zone was identified at the IN718/SS316 interphase, meaning a successful union of both dissimilar materials by a good combination of DED process parameters between them. At the SS316 segment, the main microstructure features found were austenite and ferrite composed of a mix of cellular and dendritic structures, showing an important region of columnar dendrites. This type of microstructure is usually attributed to the additive manufacturing process itself since they are not continuous processes. Each layer is solidified during its material layer deposition, but also experiences partial melting and solidification steps with the subsequent layer deposition as it was reported in other research [23].

The microstructure size of SS316 and IN718 materials is one of the main differences between the processing by AM and conventional methods. A very fine microstructure was obtained in both the IN718 and SS316 segments. The possibility to control cooling rates during and after solidification in AM by the process parameters allows to control microstructures at a fine scale impossible in conventional methods [24].

The grains observed in the stainless-steel regions (Fig. 5a) presented an average grain size between 5 μm (equiaxed grains) and 20 μm (columnar and elongated grains). Coarser microstructure with grain sizes between 30 and 50 μm was reported for the same conventional materials by other authors [14]. In a similar study, same was also found in the Laser Powder Bed Fusion (L-PBF) processing of the 316L-CuSn10 composition where the finest crystal grains were found at the 316L microstructure, whereas CuSn10 tended to be the coarsest [25].

Regarding the microstructure obtained at the surface or upper area (Fig. 5b), it was very similar to that obtained for the IN718 segment in the previous region (middle area). A great proportion of localized columnar structure was seen in IN718 at lower augments when fabricated using laser-DED with mixed regions of equiaxed grains. The reason for partial mixing could be related to the lower heat input of the DED processing together with a faster cooling rate which provides less time for the diffusion of elements like Mo and Cr to both sides [5]. A coarser microstructure is reported for conventional IN718 made via multiple isothermal forging (MIF) with a grain size of around 200 μm compared to finer grains in samples manufactured by L-PBF [26]. The same authors also showed that IN718 AM samples had slight hardness even at different temperatures compared to the conventional material. This could indicate that increased hardness values in the IN718 regions and interphases could be also expected for samples manufactured in this research.

In the transition IN718/SS316, a transition in microstructure was also revealed from equiaxed dendrites to more elongated dendrites, but in both cases with very fine microstructure, and free from defects like cracks, lack-of-fusion or delamination. Some remelting marks between consecutive layers were found within the transition area in the upper area, which can be associated with the partial remelt of the previous processed layer. Generally, in wire-based additive manufacturing processes, the high heat input of the process results in relatively large remelting on the pre-existing layers [27].

In the case of the SS316 segment, an important difference was observed between the surface (upper area) and the middle area. SS316 upper region appeared to show finer grains composed of a cellular structure with very well-defined and small grain sizes (3–5 μm) compared to the microstructure shown in the middle region of the sample. This could be explained due to the solidification rate achieved at the latest layers (upper area, surface) since no partial remelting is happening on subsequent layers as occurs at the middle region. In both areas examined, no compositional segregation was identified by optical microscopy, which could lead to cracks at the IN718/SS316 interphase.

Additionally, the microstructure in the XY plane of the S3 sample has been also studied in two single different SS316 and IN718 layers. Figures 6a and b reveal the microstructure found in two SS316 layers where very fine columnar and equiaxed dendrites were grown from the melt pool signs. Cellular and columnar austenite grains were partially mixed. Figures 6c and d pointed out the microstructure of two different IN718 layers. Signs of melt pools and transition layers were found parallel to the build direction. Very fine columnar grains showed an average grain size of 30 μm length and 2–3 μm wide, while equiaxed grains were mostly around 5 μm . Fine grain sizes are in agreement with the reported for IN718/SS316 FGM samples manufactured by DED powder [22].

3.4 Hardness

Figure 7 shows the average Rockwell C hardness values obtained along the cross-section of the three AM SS316/IN718 samples developed in this study. The indentation measurements can also be seen together with its corresponding material marked in blue (IN718), grey (SS316) or dark blue color (IN718/SS316 interphase).

Overall, the three multimaterial strategies presented a similar hardness tendency between their different material regions. The hardness of the IN718 segments was higher in all cases followed by the IN718/SS316 regions and SS316 segments. This led to a hardness transition in all samples as expected from the cross-section evaluation. The IN718 / IN718/SS316 / SS316 hardness transition gradient found for

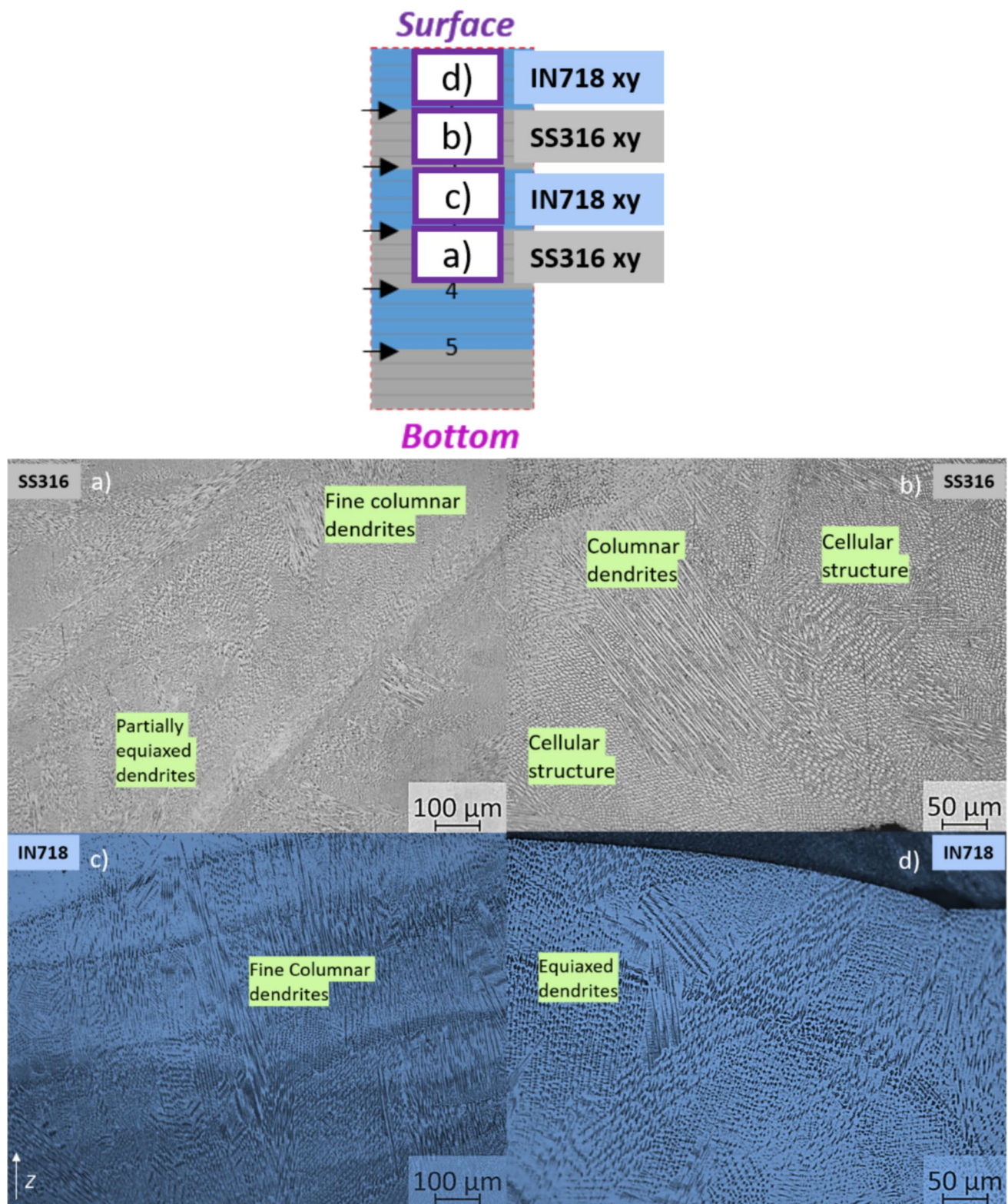


Fig. 6 Microstructure results of the manufactured SS316/IN718 multimaterial (S3) sample employing direct transition by DED-wire technology. XY plane of SS316 layer (a, b) and IN718 layer (c, d)

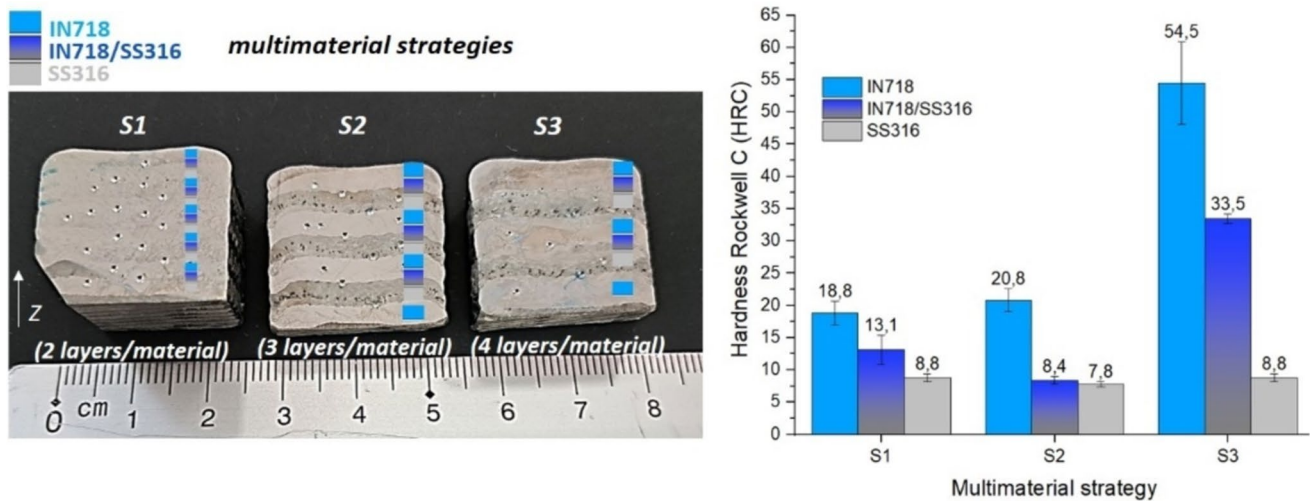


Fig. 7 Rockwell C hardness results of the three SS316/IN718 multimaterial sandwich strategies additively manufactured via DED technology. Measurements were performed in the cross-section of **a** S1

(two layers multimaterial strategy); **b** S2 (three layers multimaterial strategy); and **c** S3 (four layers multimaterial strategy) samples

S1, S2 and S3 was the following: (19 / 13 / 9 HRC), (21 / 8 / 8 HRC) and (55 / 34 / 9 HRC), respectively.

Hardness values in the SS316 segments resulted quite stable around 8–9 HRC in the three samples, whereas they increased from S1 to S3 in IN718 segments and IN718/SS316. In fact, this hardness increase is significantly high in S3, reaching values of 55 HRC and 34 HRC for IN718 segments and IN718/SS316 regions, respectively.

These values are correlated with those obtained from the cross-section evaluation, where although the three strategies can be successfully manufactured; S1 (two layers per material) led to more cracks due to a higher concentration of thermal and residual stresses between layers. Nevertheless, S2 (three layers per material) and S3 (four layers per material) samples did not show defects between subsequent layers. Thus, from the hardness point of view, S3 is the multimaterial strategy which offers the transition hardness with the highest values accompanied with very good microstructure properties. It would be worth it to highlight that hardness in IN718 regions (55 ± 6 HRC) and IN718/SS316 interphases (34 ± 1 HRC) are significantly higher compared to results reported for conventional IN718 alloy (28 HRC) and IN718/SS420 mixtures (15–18 HRC) as well as for IN718-DED (33 HRC) [14, 23].

A consistent behaviour of adjacent layers in dissimilar structures is considered of high relevance due to the fact that it can significantly affect the improving service life and prevent the premature failure of multimaterial parts [11]. Therefore, the low deviation hardness value achieved in S3 can be related to a great consistency between interfaces, which it could also result in a gradient of mechanical properties. It has been shown that a specific heat treatment of

solution plus aging-2 steps increases the IN718 mechanical properties. This heat treatment has been identified and studied in a previous work with IN718 samples manufactured throughout same DED technology as the one employed in this study. Enhanced mechanical behavior of up to 55 % in the yield strength from 660 to 1025 MPa was previously demonstrated for IN718 samples processed by DED technology [28]. Thus, the same heat treatment could be conducted in the samples developed in this research to study the effect on hardness properties and gradient transition.

4 Conclusions

In this study, the additive manufacturing wire-based DED process was used to manufacture SS316-IN718 multimaterial samples by different multimaterial sandwich strategies. Samples were composed of two, three or four layers per material: S1, S2 and S3 samples, respectively. In all of them, direct transition between SS316 and IN718 materials was applied. The influence of the number of material layer on porosity, lack-of-fusion, crack defects formation and hardness property were studied and discussed.

The results showed that although the three strategies employed led to the SS316/IN718 multimaterial processing, the sample processed with a gradient composed of two layers per material (S1) presented relevant defects of cracks as a consequence of a higher concentration of thermal and residual stresses between adjacent layers. This was evidenced due to the similar crack pattern found at each IN718-SS316 interface. However, only very small and isolated pores were

identified in S2 and S3 samples manufactured with three and four layers per material, respectively.

The microstructure of the validated sample (S3) was also presented across the multimaterial gradient (XZ build direction) and in single layers of SS316 and IN718 (corresponding to XY plane). Results showed a microstructure composed of very fine grains together with a smooth transition zone in both analyzed areas, middle region and upper area. A partial microstructure with a mean grain size between 5 (equiaxed grains) and 20 μm (columnar and elongated grains) was achieved in the IN718 regions, whereas austenitic phase composed of a mix of cellular and dendritic structures was found at SS316 regions. A transition in microstructure from equiaxed dendrites to more elongated ones, with very fine microstructure, and free from defects like cracks, lack-of-fusion or delamination was revealed in the IN718/SS316 interfaces.

Additionally, it was found that the three multimaterial samples resulted in a gradient of the hardness properties. The average hardness value decreased from the IN718 region, IN718/SS316 interphase to the 3316 region in all of the samples. Multimaterial sample developed through four layers per material showed the highest hardness profile: IN718 region (55 ± 6 HRC), IN718/SS316 interphase (34 ± 1 HRC) and SS316 region (9 ± 2 HRC). These hardness values of IN718 region and IN718/SS316 interphase are higher than others reported in similar compositions developed by different AM technologies, and significantly higher compared to that of the conventional IN718 material (47 HRC).

This study provides a practical approach in the manufacturing of multimaterial samples with a sandwich gradient composed of different numbers of layers per material by controlling the effect of the layer number of the same material on the presence of defects, microstructure and hardness properties. A multilaser head wire-based Directed Energy Deposition has been selected as the innovative AM technology for this research to contribute to widening the state-of-the-art of the multimaterial processing by DED-wire. Comparison of hardness evolution along the build direction of samples processed with 2, 3 or 4 layers per material could give helpful information about the possible service life of a multimaterial part built with this kind of sandwich strategy. Further investigations about chemical composition and mechanical testing will be also conducted to better understand the behaviour of these multimaterial samples.

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Author contribution Julia Ureña: main project researcher; conceptualization; data curation; formal analysis; investigation; methodology; roles/writing—original draft; writing—review and editing. Marta Álvarez-Leal: investigation; roles/writing—review and editing.

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Data availability The data of the results are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate All authors agreed to participate in this manuscript.

Consent for publication All authors agreed to submit the manuscript.

Conflict of interest The authors declare no competing interests.

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