Nuclear Materials and Energy 30 (2022) 101149

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Evaluation of metal additive manufacturing for high-field modular-stellarator radial plates and conductors

V. Queral [a,*], E. Rincón [a], S. Cabrera [a], A. Lumsdaine [b]

[a] Laboratorio Nacional de Fusión, CIEMAT, 28040 Madrid, Spain
[b] Oak Ridge National Laboratory (ORNL), Oak Ridge, TN 37831, USA

ARTICLE INFO

Keywords:
Radial plates
Modular coils
Additive manufacturing
Metal
Stellarator

ABSTRACT

The utilization of metal additively manufactured radial plates and conductors for high-field modular-stellarator coils is assessed, particularly, for resistive coils having turns of variable cross-section (additively manufactured aluminium or copper turns). This concept of radial plates might also be applicable to superconducting wire and resistive conductors of constant cross-section.

Modular coils and their winding packs for (high-field) stellarators require high precision, durability under high internal Lorentz forces and thermal stresses, stiffness and strength, in rather contorted components. Radial plates have been utilized in tokamaks (i.e. ITER) and are proposed for tokamak and stellarator reactors (i.e. FFHR), particularly when the high Lorentz forces may compromise the mechanical integrity of the insulation and winding pack. Radial plates for tokamaks have been produced by milling steel plate, and welding different segments if the size requires it. However, the contorted shape of stellarator modular coils makes the manufacturing of radial plates more challenging. This suggests the possible use of additive manufacturing, which is particularly appropriate for short series of geometrically complex parts.

In relation to those matters, this work investigates whether metal additive manufacturing of contorted radial plates and metallic conductor turns (windings, to be introduced in the radial plates) of variable cross-section and proper insulation, may be satisfactory for small or middle size high-field stellarators. The emphasis is placed on the accuracy, mechanical properties and cost of those parts. The feasibility, advantages and weakness of the additive manufacturing process and the assembling procedure are tested and studied. With the present commercial metal 3D printers, metal additively manufactured radial plates will require final milling to achieve enough accuracy. Coil casings appear feasible without final milling, and windings of variable cross-section, produced from brazing modified flexible copper wire, are promising.

Introduction

Coils for high magnetic field fusion devices withstand high Lorentz forces which generally implies high stresses in: **i)** the support structures (coil monolithic supports, central ring structures, coils casings and inter-coil structures) [1], e.g. ARIES-CS ($B_0 \sim= 6$ T) [2], i-ASTER ($B_0 \sim= 10$ T) [3], and lower fields in W7-X ($B_0 < 3$ T) [4,5], and **ii)** the winding pack located inside the coil casing or monolithic support [6].

In the winding pack (Case 'ii'), the accurate and long-term positioning of the conductor turns, the stresses in the insulation material and the integrity of all the coil elements are critical issues for (relatively) high-field fusion devices [2,7,8]. Concerning these issues, radial plates are strong metallic structures which individually sustain each conductor-turn and insulation for each double-pancake, aimed at alleviate those issues. Thus, radial plates have been proposed for stellarators (i.e. for the FFHR heliotron power plant [9]), and designed, tested and satisfactorily produced for the ITER tokamak TF coils [10,11]. Nevertheless, radial plates have been barely produced and tested for modular stellarators. Certainly, an alternative without utilizing radial plates was proposed for relatively high-field in ARIES-CS ($B_0 \sim= 6$ T), which plans robotic systems to place the superconducting turns inside grooves in an additively manufactured monolithic frame [12]. However, this option has not been tested or implemented yet. In any case, radial plates might be necessary for modular stellarators when surpassing certain magnetic field in the winding pack, given a particular conductor/insulation, geometrical disposition and direction of forces.

* Corresponding author.
E-mail address: vicentemanuel.queral@ciemat.es (V. Queral).

https://doi.org/10.1016/j.nme.2022.101149
Received 27 October 2021; Received in revised form 16 February 2022; Accepted 18 February 2022
Available online 22 February 2022

The fabrication and assembly of radial plates and their conductors is complex even for planar coils, i.e. ITER [13], requiring precision of the grooves better than 0.01% with respect the larger dimension [14]. The fabrication and process appear even more difficult or expensive for stellarator modular coils, due to the contorted shape of these coils. In relation to this difficulty in stellarators, additive manufacturing (AM) might facilitate the manufacture, since it is particularly appropriate for short series of geometrically complex parts, though achieving the required tolerances could be difficult. The production of radial plates for tokamaks by Hot Isostatic Pressing (HIP) was proposed and tested, [14,15]. Each radial plate in ITER is fabricated from several sectors of milled steel plate, subsequently welded and final milling, [10,11].

Additively manufactured plastic frames reinforced with carbon-fibre composites might be appropriate to fabricate coil supports and coil casings [16]. Nevertheless, this method is uncertain to fabricate radial plates, due to practical fabrication difficulties, the anisotropic behaviour of composites and the varied principal directions of the mechanical stresses in the winding pack, as deduced from Ref. [16].

Certainly, metal additive manufacturing of radial plates appears a possible alternative, and thus, it deserves further study, in spite of the current limitations of metal additive manufacturing.

In a simplified manner, metal additive manufacturing could be classified in two categories [17,18]: **1.** Binder methods: Metal powder is selectively bound by an injected binder (usually called '*binder jetting*'), similarly to an ink-jet printer, or bound by a binder mixed with the metal powder and fused by a laser, part subsequently either infused with another metal alloy (usually bronze) or directly sintered by heat, **2.** Direct metal melting: Metallic powder is selectively fully melted and welded together. Currently, melting is mostly produced by powerful lasers (SLM, Selective Laser Melting), but usually by electron beams (EBM, Electron Beam Melting) for reflective and high thermal-conductive metals (i.e. pure Cu). Both categories are tested and analysed in this work.

Further information on AM manufacturing, in general and for stellarators, can be obtained from Refs. [17,18,19].

The main limitations of current metal commercial AM printers for fusion parts might be:

- Still limited accuracy: i.e. commercial metal printers are generally less dimensionally accurate than Stereolithography printers for plastics, which is a non-thermal resin additively manufacturing technique, [20].
- Relatively small commercial SLM metal printers: The larger dimension is about 1–2 m length. However, one EBM commercial printer (EBAM 300 from Sciaky) reaches 6 m part length, at expense of larger voxel size and shape limitations for the part. Unique laboratory printers can also reach several metres, i.e. metal printers in the Manufacturing Development Facility, ORNL (USA).
- The diversity of common commercial alloys, in particular steels, and heat treatments offered is still limited. Common commercial 3D-printed steels are AISI 316L/1.4404, maraging steel 18Ni-300/1.2709, and Inconel.
- The economic competitiveness in relation to other fabrication techniques (e.g. metal casting/machining or HIP) for large and accurate radial plates or coil supports is still dubious.

This work sheds further light on some of such uncertainties.

The methods are briefly described in Section 2, Section 3 reports the tests performed on AM radial plates, Section 4 evaluates AM and other methods for variable cross-section windings, and Section 5 offers a general discussion.

Methods

The main objective of the work is to obtain first insight on the feasibility and issues of metal additive manufacturing for radial plates

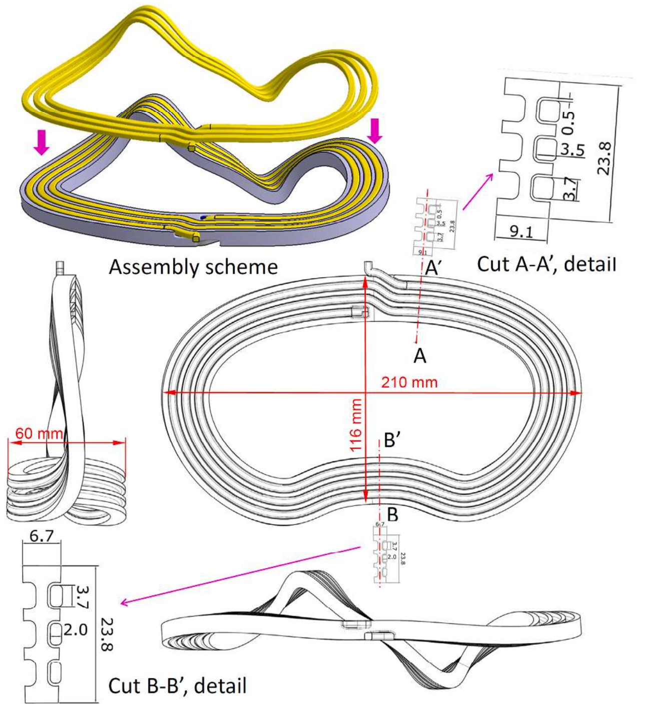

Fig. 1. Model, assembly and dimensions of the assayed 3D-printed parts. Dimensions in mm.

and conductors (turns in windings) in stellarators, including accuracy, strength of available materials and approximate cost. For that, tests of additive manufacturing of small radial plates and turns fabricated in different materials are performed. Also, the feasibility of a possible application to i-ASTER is sometimes assessed, although the tests are produced in small parts. Concerning accuracy, commercial additive manufacturing with the maximum precision is sought to try to avoid final milling of the part to achieve the necessary accuracy.

Only few particular assays of AM parts for stellarators are produced. Thus, wide generalisations cannot be made from the results since much more assays would be required.

Only commercial suppliers working at standard industrial qualities have been considered. Higher accuracies and performance may be achieved in laboratory-like printing facilities.

The mechanical properties of the material are obtained from the supplier and from bibliography. The dimensional accuracy of each part is obtained from measurements on the received parts, and it is compared with the information from the supplier or bibliography. The approximate cost of each manufacturing method is indicated as a range or as an average from different suppliers. Properties and cost are usually rounded for easier understanding.

The produced radial plates (two parts) correspond to a scaled down coil located at the high-field region (bean shape) of i-ASTER [3]. i-ASTER is a conceptual design of an experimental high-field ignition stellarator based on the quasi-isodynamic QIPCC3 magnetic configuration [21]. One of the parts is a section of radial plate, to decrease production cost but still studying the performance. Three different windings of variable cross section have been produced and analysed. Their size matches the radial plates, aiming at the introduction in the grooves.

Following, modular stellarators are meant even if 'modular' is usually omitted. Despite that, some of the techniques may be applied to torsatrons/heliotrons or other types of stellarators.

The term 'high magnetic field' is relative and, in stellarators, it might mean $B_0 \sim> 5$ T, much higher than the field in W7-X and LHD. Also, it may mean $B_0 \sim> 10$ T when comparing with high-field tokamaks (i.e. Alcator line).

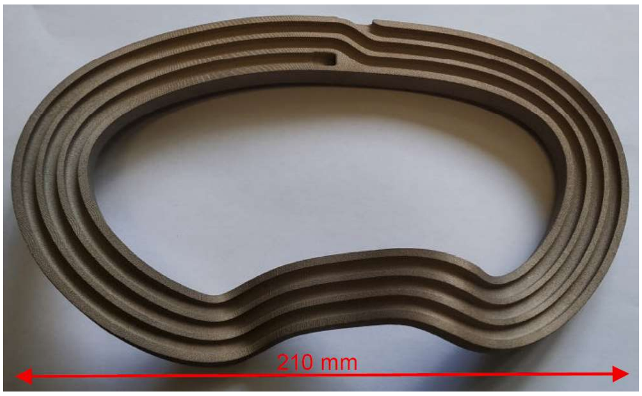

Fig. 2. Trial of stellarator radial plate made of steel-bronze.

The term 'support' or 'printing supports', when referring to the additive printing process, means the materials and structures printed below the part (or below/inside overhanging elements of the part) to enable printing and to keep the mechanical and dimensional stability during the process of printing. These 'supports' are removed (usually by the supplier) and are not visible in the pictures. Elements to keep the structural stability during transport and manipulation of the part are called 'reinforcements'. Reinforcements are removed when the structural stability of the part is not compromised any more (see the reinforcements in Figs. 5–7).

Different materials and additive manufacturing methods have been utilized for the fabrication, to compare properties and cost.

The model of radial plates and windings utilized in the next sections is shown in Fig. 1. Sections "Radial plate in steel infused with bronze" and "Winding made of SLM aluminium alloy" follow exactly this design while the other AM parts (Sections "Section of radial plate in SLM SS316" and "Winding made of EBM pure copper") have slight dimensional differences (~0.1–0.2 mm) for adaptation to the particular assay, 3D-printer and material.

Experiments on additively manufactured stellarator radial plates

The stellarator AM radial plate is a double pancake, alike the ITER radial plates. In this study, each radial plate is produced as a single 3D-printed part, due to the small size, while several sectors are utilized in ITER radial plates. However, welding 3D-printed sectors would be unavoidable for larger plates (>~1–2 m for present commercial printers). Each pancake is composed only by three turns. Certainly, limitations on the thickness of the walls and the expected low accuracy of the fabrication favour few turns for this first test.

Radial plate in steel infused with bronze

The radial plate (Fig. 2) is additively manufactured by bound particles of steel 420, subsequently infused with bronze (60% steel and 40% bronze). Bronze is made of Cu 90% and Sn 10%. The part was printed by the online company i-Materialise. Data in the next subsections comes

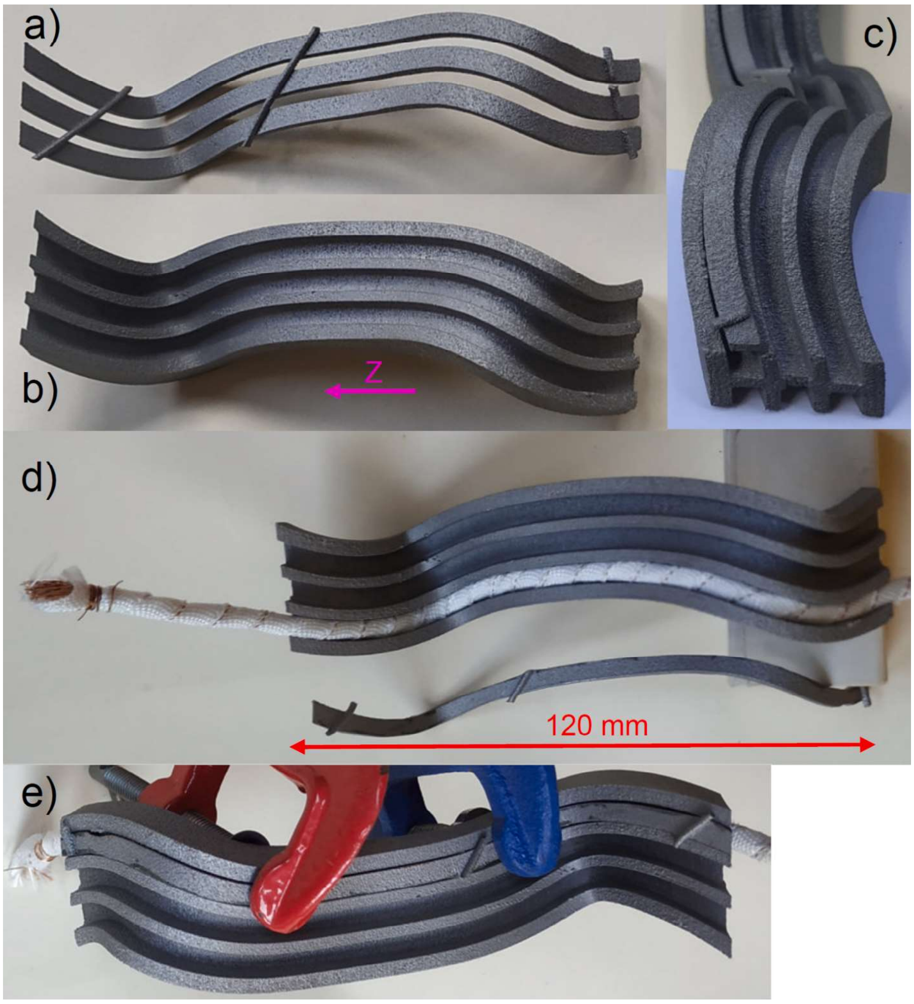

Fig. 3. Assessment of a section of stellarator radial plate and cover plates, made of 316L steel.

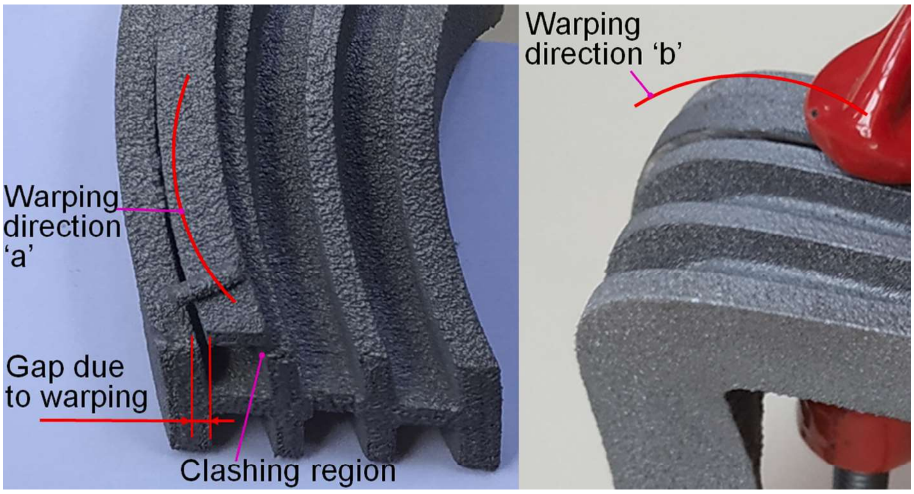

Fig. 4. Detail of the radial plate and cover plates (316L steel) showing consequences of warping.

from the particular dimensions and cost of the part, and from Refs. [22,23].

Mechanical and other properties of the material: S_y ~ 400 MPa, S_u ~ 500 MPa, E ~ 150 GPa, ρ = 7.9 gr/cm^3. The printing direction has little impact on properties. It is relatively strong but elongation at break is only 2.3% (7% in annealed condition). Melting point is 800–850 °C. It can be easily mechanised but welding has to be performed by silicone-bronze rods and TIG welding.

Accuracy: From the supplier, this infused steel-bronze can achieve ± 1% accuracy if pre-adjustment of dimensions is performed to compensate shrinkage. Maximum calliper-measured deviation on the large dimensions of the part (~111 mm and 213 mm) was 1.2%, being the part smaller than the nominal dimensions.

Cost: The volume of material in the part is ~ 60 cm^3 and the cost was slightly higher than 1000 € (year 2020), resulting ~ 20 €/cm^3 of printed material for this particular *box density* (~0.12 gr/cm^3). The *box density* is defined here as the ratio of mass of the part to the volume of the bounding box. The *bounding box* (b.b.) is the minimum cuboid externally enclosing the part, which also impacts on the price of the part. The bounding box is ~ 130x150x200 mm, resulting ~ 0.3 €/cm^3 of volume of bounding box.

Discussion: Complex shapes can be printed without the difficulty of removal of supports. Supports are required for certain printing methods when overhangs (i.e. top of arcs) may fall down and cannot be printed. This is an advantage for stellarator radial plates, which are non-planar contorted parts. Dimensional accuracy is considerably lower than for high quality SLM printing, about five times lower. Cost of steel/bronze parts is lower than SLM steel parts –roughly three times is estimated. However, the material is not properly steel but a composite of bronze matrix filled with steel powder filler. It cannot be welded as steel but as bronze.

Section of radial plate in SLM SS316

A section of the radial plate (Fig. 3-b), and cover plates (Fig. 3-a) was additively manufactured in stainless steel AISI 316L by the company Addimen Bizkaia S.L. (Spain), Fig 3. Cover plates were designed and printed with the same material. *Cover Plates*, following the ITER terminology, are slender metallic covers for each groove in the radial plate, to keep the conductor in the groove and close the groove. Three cover plates were jointly AM fabricated, for increased accuracy and cost reduction. Data in the next subsections comes from the particular dimensions and cost of the part, and from the Material Data Sheet from the supplier, [24].

Properties of the material: $S_{y\text{-vertical}}$ = 440±10 MPa, $S_{u\text{-horizontal}}$ = 662 MPa, $S_{u\text{-vertical}}$ ~ 574±10 MPa, $E_{vertical}$=134 GPa, ρ=8 gr/cm^3, relative density with respect the same forged metal ~99%. The printing direction has notable impact on the properties. The lower mechanical specification (vertical direction) should be used for simplified structural calculations. Elongation at break in vertical direction is 26 ±12%. This is roughly half of the elongation at break for a SS316 bar in annealed condition, but similar to the one for cold drawn condition. Recent SLM printers may obtain up to ~10% higher values than the indicated ones [24]. For comparison, for ITER SS316LN in annealed condition at Room Temperature, S_u = 660±10 MPa, S_y = 350 MPa, Elongation at break 52% [25].

Accuracy: From the supplier, the part was specified to fulfil 'mL' Class for tolerance DIN ISO 2768 for dimensions>6 mm (±0.2 mm for dimensions shorter than 6 mm). The longer dimension of the radial plate section is 120 mm which implies maximum ± 0.3 mm deviation. For the width of the part, ~30 mm, the maximum deviation specified is ± 0.2 mm. Deviations measured by calliper on the part resulted from 0.14% to 0.25% (0.15–0.3 mm) for dimensions ~ 100 mm, and 0.4% for dimension 24 mm. The accuracy of the part mostly fulfils the supplier specifications.

Concerning warping, warping of the cover plates was a concern due to their slender shape. In AM, warping is the curving and distortion of the printed part (or certain areas of the part) due to spatially variable heating and cooling (temperature gradients), which produces internal stresses and thus, deformations. Thin-walled and slender parts show higher warping [26], alike a thermometer bimetallic strip deflects due to small spatial differences in expansion/contraction. Warping also depends on the building orientation, being favourable vertical printing of a slender shape for low warping [26,27].

Certainly, deviations of ~ 0.5 mm have been observed in the printed cover plates (see Fig. 3-c and Fig. 4). Both directions 'a' and 'b' (relative to the cover plate axis, Fig. 4) were affected by warping. The 'a' warping direction hampered the introduction of the cover plate in the groove without mechanisation, due the existence of a clashing region (Fig. 4). Warping in 'b' direction did not hinder the introduction of the cover plate in the groove due to flexibility of the part in this direction. The cover plate was filed and it allowed the introduction and closure of the grove (Fig. 3-e). Still, warping required fasteners to keep the cover plate in position (Fig. 3-e).

Cost: The volume of material in the section of radial plate (cover not included) is ~ 23 cm^3, weight ~ 180 gr, and the price varied depending on the supplier, from ~ 700 to 1500 € (for the radial and cover plates together, year 2021). Considering 800 € for the section of radial plate alone, it results ~ 35 €/cm^3 or ~ 4 €/gr of printed material for this particular box density. The bounding box is ~ 90x70x110 mm, resulting

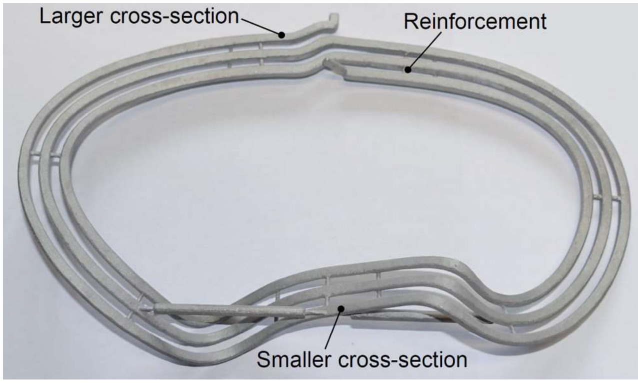

Fig. 5. Trial of 3-turns winding in SLM Aluminium alloy. The part is shown as-built, before removing the reinforcements.

~ 0.03 cm^3 of part/cm^3 of bounding box, ~0.27 gr/cm^3b.b and ~ 1 €/cm^3b.b.

Discussion: The linear dimensional deviations are small but still far from the ~ 0.01% required for the grooves in the radial plate (relative to the maximum dimension of the radial plate). Thus, final milling of the part is mandatory to achieve the required radial plate tolerances.

Nevertheless, the accuracy required for stellarator coil casings and supports (min ~ 0.1% [28]) is almost achieved.

The part, as suggested by the supplier, was located in the printer approximately having the Z direction (Fig. 3) aligned with the Z-(vertical) axis of the printer, for few printing supports and lower thermal distortion during printing. Complex shapes can be printed with SLS additive manufacturing, but some parts with many overhanging areas (angle ~>45° for SLM steel) would involve the removal of numerous printing supports. Certainly, the radial plate would require many supports if fully printed.

The mechanical properties of the 3D-printed steel are similar or superior to the cold-drawn condition of forged 316 steel. Nevertheless, elongation at break (~fragility) appears inferior for industrial AM. Also, this material and fabrication procedure is not normalised yet for safety-relevant nuclear components.

Evaluation of advanced and additive manufacturing of windings

Methods for windings

The windings for the i-ASTER application are resistive and have variable cross section along the poloidal direction (Fig. 5). The variable cross-section reduces the total electric power needed to feed the coils, given certain magnetic field [29]. The inboard space for the coils is limited in any stellarator, and particularly at the inboard curved areas in quasi-isodynamic stellarators. Indeed, if the (resistive) coil and windings would have constant cross section equal to the one at the inboard, the resistance per conductor turn would increase, and so the total electric power consumed (given a particular current and magnetic field). The reduction of coil power is decisive for i-ASTER, and for any resistive high-field experimental stellarator, since the electric power required for the coils is huge.

Thus, standard rigid or flexible copper/aluminium wire is not appropriate. Due to the contorted shape of the part, additive manufacturing, or perhaps metal casting from an additively manufactured pattern, may be satisfactory alternatives. Direct metal melting AM is selected for this work. The study of possible casting methods remains for a future work.

Current commercial Selective Laser Melting (SLM) presents issues for metals of high thermal conductivity and reflectivity, like high-purity aluminium and copper. Electron Beam Melting (EBM) manufacturing is industrially utilized to print pure Al and Cu. Both methods, SLM and EBM, are assayed next.

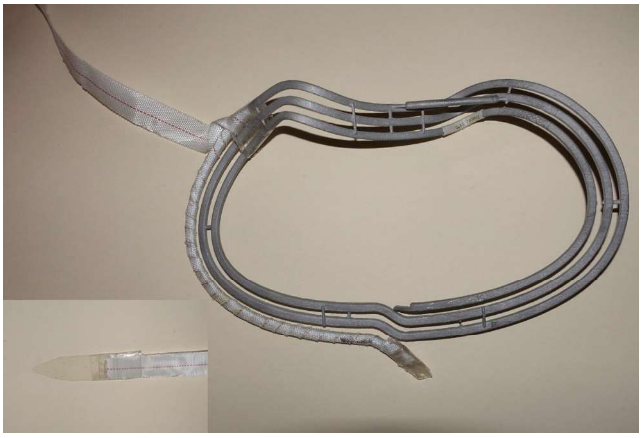

Fig. 6. Test of insulation on the SLM Al-Si winding. Needle-like end of insulation for faster winding (bottom left).

The windings are produced by additive manufacturing (SLM in Section “Winding made of SLM aluminium alloy”, EBM in Section “Winding made of EBM pure copper”) or by an innovative flexible copper wire (Section “Windings of variable-section flexible copper wire”). After producing the winding, the conductor is insulated by glass fibre tape.

Winding made of SLM aluminium alloy

A winding composed by three turns of variable cross- section for a single pancake (Fig. 5) were additively manufactured by SLM in AlSi10Mg (10% Si, 0.3% Mg, impurities, Al balance). The part was printed by the online company i-Materialise. Data in the next subsections comes mainly from the particular dimensions and cost of the part, and from [22,30].

Properties of the material: S_y = 180–220 MPa, S_u ~ 250–330 MPa, E = 50–70 GPa, ρ=~2.6 gr/cm^3, relative density with respect the same forged metal > 97%. Elongation at break 1–2 %. Higher elongation at break (>2%) and relative density (>99%) can be achieved by reducing the thickness of the printed layers (called ‘Performance Grade’ in [22]). Electrical resistivity of the 3D-printed Al alloy ranges from 6 × 10^{-8} Ω-m to 10^{-7} Ω-m depending on the condition (as-built, annealed or heat treated, and the direction with respect the printing [30]), which is 3 to 6 times higher than pure copper.

Accuracy: From data from the online supplier [22], the parts shall achieve ± 0.2% for proper designs, with a lower limit of ± 0.2 mm. For non-online fabricated parts in the same company, tolerances offered are Class DCTG 8 for dimensions 30 to 400 mm (±0.8 mm for 180 mm dimension, higher than ± 0.2%) under the casting standard DIN EN ISO 8062–3 (2008–9), but ± 0.2% was communicated achievable under proper design and care fabrication. The maximum linear deviation measured by calliper on the part resulted 0.4% (with respect the measured dimension), being the part larger than the nominal dimensions. Warping, as deviation from the surface containing the winding, is small and the winding can be accommodated to the radial plate due to the flexibility. Reinforcements as thin bars are defined among the turns of the winding in order to create a monolithic winding. Otherwise, the slender turns would unwind and deflect due to printing thermal stresses. The bars are thin, circular and few in number to be easily cut with a simple method (pliers) while enough to withstand the tensile stress in the bars from the unwinding tendency (low due to the slender conductors). Bars are mainly located near the two ends of the coil and at the weaker area of smaller cross-section of the conductors, see Fig. 5.

Cost: The volume of material in the part is ~ 18 cm^3, weight ~ 47 gr,

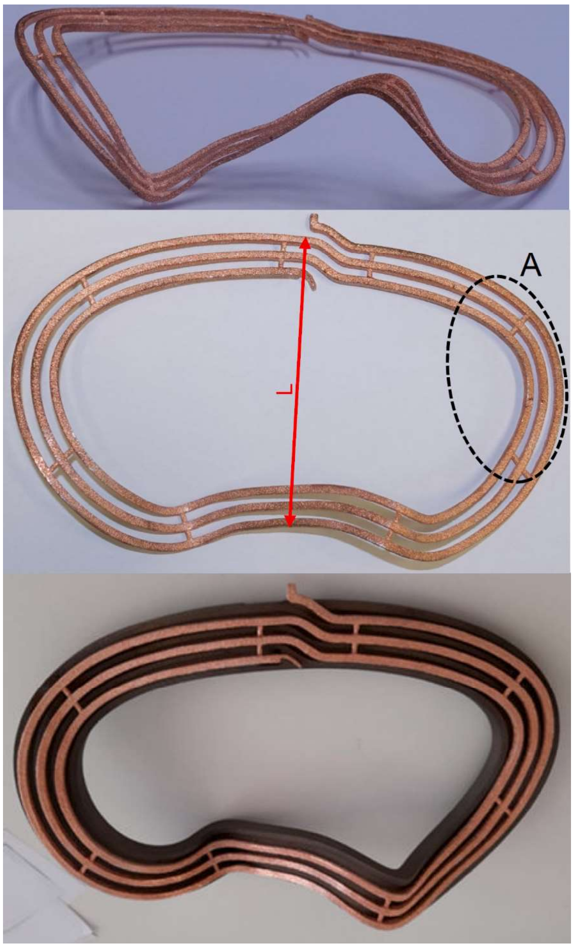

Fig. 7. Trial of 3-turns winding in EBM 99.95% pure copper. Winding on the radial plate (bottom).

and the cost ~ 800 € (year 2020), resulting ~ 50 €/cm^3 and 17€/gr of printed material for this particular low box density and low density material. The bounding box is ~ 125x130x180 mm, resulting ~ 0.006 cm^{3}of part/cm^{3}b.b, ~0.015 gr/cm^{3}b.b. and ~ 0.3 €/cm^{3}b.b.. A solid cube with the same weight (26 mm in side) would cost ~ 120 € for the same material and company (2.5 €/gr). This is about seven times less than the winding. Thus, the low box density is the main driver of the cost for the slender 3-turns winding.

Insulation: An insulation assay was produced with glass fibre tape 15 mm wide and 0.25 mm thick, Fig. 6. A needle-like tool helped passing the glass tape among the aluminium turns, since the spiralling shape of the turns hinders the common insulation process for straight wires. One third of a turn was wound in less than an hour. A flat spindle, alike the ones used in textile industry, might allow larger lengths of tape to be wound without interruption. Subsequently, resin impregnation would be produced similarly to the method utilized for the ITER TF coils [31,32]. Holes in the cover plates (not produced in the AM cover plates) allow the introduction of resin in the grooves for vacuum impregnation and extraction of trapped air. Each radial plate (a double pancake), whose winding turns are already wrapped with insulation tape (i.e. glass fibre, polyimide or combination), is introduced in a vacuum impregnation mould. Achieving full impregnation can be confirmed by non-destructive methods (i.e. measure of capacitance). In stellarators, the process is expected somewhat more difficult than in tokamaks due to the contorted radial/cover plates.

Discussion: Mechanical properties are rather similar to the ones for the same alloy in cast condition. Only elongation at break (3–5% for cast 360 series aluminium) is lower than equivalent cast parts, for the standard printing fabrication.

The electrical resistivity for annealed or heat treated turns would be appropriate for certain electrical applications. However, the conductivity appears too low for i-ASTER, which needs maximum conductivity to reduce the extreme electric power required to feed the coils, even for pure copper [29]. EBM (see Section "Winding made of EBM pure copper") of pure aluminium would be an alternative to SLM if higher conductivity of aluminium would be required.

Accuracy of the part is low for direct introduction of the turns in the radial plates. Moreover, final milling of AM windings may be difficult due to weakness of the part, the needed fixations for mechanisation, and the considerable excess of material required to allow a final milling. Fabrication of this type of component by milling from an aluminium plate would be also difficult and expensive due to the slender and weak part.

The combination of the accuracy achieved for the radial plate and for the turns would require wide space (tolerance) between the grooves and turns to allow assembly. For three turns per winding and ~ 180 mm of maximum dimension, 0.2% accuracy implies in the worst case (smaller radial plate and larger winding turns, or vice-versa) a deviation of ~ 1 mm (0.5 mm for the radial plate and 0.5 mm for the turns), which is excessive for the nominal width of the grooves (~4 mm).

Insulation was possible with reasonable working time, though the spiralling turns hinder automatic winding.

Specific cost is considerably high (~45 €/cm^3), mainly due to the low quantity of material in a large bounding box.

Winding made of EBM pure copper

The objective is to obtain a highly conductive winding with variable cross section of conductor and reasonable accuracy. A winding also composed by three turns for a single pancake (Fig. 7) was additively manufactured by Electron Beam Melting (EBM) in an ARCAM A2 System, in copper of purity 99.95%. The part was printed by the technological institute AIDIMME (Spain). Data in the next subsections comes mainly from the particular dimensions and cost of the part, the specifications of the supplier and from Ref. [33].

Properties of the material: The material is highly malleable and tensile strength is low, as it is for pure copper (S_y ~ 30 MPa). The mechanical properties have minor relevance here since the conductors are embedded and kept by the radial plates. ρ=~9 gr/cm^3, and relative densification ~ 99.9% [34] (~99.5% is reported in [33]). From the supplier, electrical conductivity of the material as printed is 97–101 % IACS (International Annealed Copper Standard). IACS in the range 96–100 % for EBM is indicated in Ref. [33].

Accuracy: The part is specified to achieve ± 0.4%, with a lower limit of ± 0.4 mm for dimensions lower than 100 mm. The maximum deviations measured by calliper in short dimensions (~5 mm) are ± 0.3 mm. Global deviations cannot be correctly measured by a calliper since the local deviations mask the measurements. Measurements with a coordinate measuring machine or laser scanning will be produced in a future work. Globally, the copper winding fits with the radial plate, with deviations of ~±0.5 mm. Deviation of 1 mm (1%) was observed for the dimension L (part smaller than model), which includes the short-dimension deviation. Deviation of ~ 2 mm is perceptible at the area 'A', Fig. 7. The narrow (~3 mm width) and long conductors tend to warp (increase of curvature of conductors at area 'A'), so, the introduction of more reinforcements in the design might improve the final accuracy. The strategy for reinforcements was the same as for the Al alloy winding, but the global distortion of the part was not properly avoided. Advanced thermo-mechanical calculations including the supplier printing parameters would be needed for a detailed calculation of the reinforcements. Warping as deviation from the surface containing the winding is of the order of ± 1 mm, which is acceptable for this application due to flexibility of the part.

Cost: The volume of material in the part is ~ 18 cm^3, weight 160 gr,

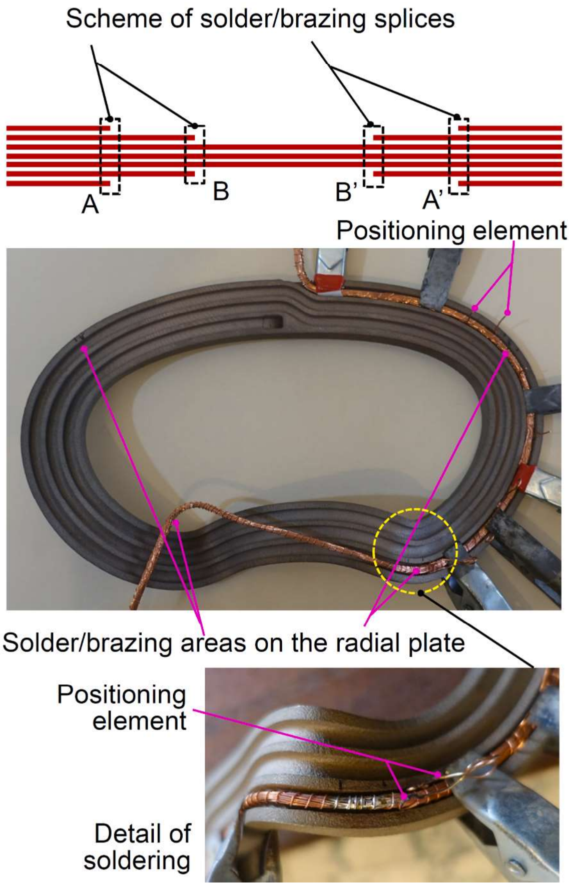

Fig. 8. Concept of modified flexible copper wire for variable cross-section, and actual implementation.

and the cost ~ 1500 – 3000 € (year 2021) depending on the supplier, resulting an order of magnitude of 100 €/cm^3, and 10 €/gr of printed material for this particular low bounding box density (~0.7 €/cm^{3}b.b., b.b. data as in Section "Winding made of SLM aluminium alloy").

Discussion: Conductivity of EBM of pure Cu is sufficient for demanding windings for fusion devices (i.e. i-ASTER). In contrast, conductivity of pure copper printed by SLM appears poor, 50 – 90 % IACS, depending on the case [33].

The same remarks on assembly tolerancing for the SLM winding (Section "Winding made of SLM aluminium alloy") are applicable for EBM.

Cost is deemed high for massive windings for high-field stellarators, like i-ASTER or smaller devices. However, the method appears satisfactory for complex but light windings. To alleviate the issue, several windings might be printed in the same batch, without much increasing the bounding box.

Windings of variable-section flexible copper wire

Present additive manufacturing of high conductivity windings (high purity Cu) resulted relatively expensive and slightly low accurate for stellarator coils. Thus, the concept of a modified flexible copper wire was concocted and tested, Fig. 8.

The variable cross section along the poloidal direction is discretised in a finite and reasonable number of section steps, four steps per turn in this test. For that, external and randomly chosen strands of the wire are cut at two points corresponding to a step. Subsequently, the area around the reduction of cross-section is soldered/brazed with high conductivity Ag, or lower conductivity Sn/Ag alloy. Sn-6%Ag solder alloy was used for the turn in Fig. 8. The capillarity of the strands distributes the molten solder inside the strands, forming long splices (1–2 cm of soldered length) which reduce the resistance among adjacent strands. This allows the flow of the electric current among contiguous strands at the cutting points, avoiding resistance due to oxidation or poor contact among strands. Long splices may only necessary if a low conductivity solder alloy, like Sn-6%Ag, is utilized.

Fig. 9. One turn of variable cross-section flexible copper wire after insulation, inside the groove of the radial plate.

The procedure for the production of one turn of variable cross-section flexible copper wire is:

- The radial plate acts as a mould for the accurate formation of each turn.
- A commercial copper conductor of constant cross section is located in the groove and the points of reduction of section are marked. This particular commercial conductor is formed by 72 strands.
- The copper strands are cut at the splice points A, B, A', B', Fig. 8 (four points in this test, two cuts per strand). 14 strands are cut at point A-A' and additionally 22 strands at point B-B' (36 strands remain from B to B'). The remaining strands are not cut at any point. The number of strands is approximately estimated from the variable cross-section windings in Section "Winding made of SLM aluminium alloy" and "Winding made of EBM pure copper".
- The strands are compressed by a wrapping thin copper filament. The conductor is re-located inside the groove.
- Positioning elements (Fig. 8) are used to accurately locate the conductor and achieve the correct radius of curvature at the solder/brazing areas.
- A pre-soldering is produced from the accessible side of the conductor. Subsequently, the conductor is extracted and soldered around the perimeter.
- The fibre-glass insulation is located after half of the turn is soldered, in order to avoid accumulation of small positioning deviations along the groove.
- The two remaining splices are soldered and the remaining insulation is installed.
- The final result for one turn before resin impregnation is shown in Fig. 9.

Discussion: The soldering appears uniform, deep in the strands and well wetted. The conductivity of the splices and the turns has not been measured. The production of the described process for one turn lasted 4 h.

Thus, currently, this fabrication method of variable cross-section copper wire might be more suitable than the previous AM methods if many turns are to be produced. This method avoids the accumulation of deviations among turns (the conductor is flexible and an excess/shortness in one turn can pass to the next, and the radial plate acts as a mould of the turns for improved matching), the issue of the need of higher relative accuracy when more turns per pancake are required, and

Table 1
Summary of main properties and results from AM parts and materials, and modified flexible Cu wire.

Trial	Accuracy	~ Sy (MPa)	Elong break	Cost (~€/cm^3)	Conductivity	Comment
Steel infused bronze	~1%	400	2%, up to 7%	~20		Capable of overhangs
SLM SS316	Up to 0.2%	440	25–35%	~35		
SLM Al-Si alloy	0.2–0.4%	~200	1–2% and slightly higher	~50*	3–6↓ than pure Cu	*Slender winding
EBM pure Cu	~0.5–1%	N/A	High, malleable Cu	~100*	97–101 %IA	*Slender winding
Modified flexible Cu wire	≡ to the radial plate	N/A	High, malleable Cu	~~40*	High	*Slender winding

facilitate insulation wrapping.

General discussion on the different methods

Accuracy resulted higher for SLM steel and Al alloy (up to 0.2%), while steel-bronze and EBM copper were less accurate (~0.5–1%). Final milling of AM parts will be currently necessary to fabricate radial plates for any AM method studied under industrial fabrication, since accuracy should be superior to 0.01%. Coil casings and coil supports may be fabricated without final milling. They would require ~ 0.1% accuracy among equal parts, and repetitively of parts produced in the same printer under the same conditions would allow achieving such accuracy. Complex shapes with important overhangs (i.e. several millimetres length for fabrication angle higher than ~ 45° for steel) can be AM produced without supports in steel-bronze, but SLM and EBM will require (many) supports. These supports have to be removed, and sometimes it is hardy feasible. Thus, the policy for printing supports has been the use of metal printing methods which do not require supports, or the minimization of their number when they are unavoidable, for which, slender parts are located preferably in vertical position.

Warping of the SLM steel cover plates resulted excessive due to the small tolerances required (~0.1 mm, ~ 0.1%) and due to the slender shape, which induce warping (see Section "Section of radial plate in SLM SS316"). Also, warping was relatively large for the Cu EBM winding, perhaps due to the combination of the EBM printing method, insufficient part reinforcements and recent start-up of the printer. In metal AM, the relative (in % of the part size) warping and accuracy depends weakly on the size of the part [26], for the same printing method and material. Also, the suppliers specified the achievable accuracy as a relative accuracy (%), or as DIN ISO 2768 (this gives slightly higher relative accuracy for larger parts). In contrast, warping is more problematic for amateur 3D printing of large parts in plastic (i.e. by Fused Deposition Modelling).

AM windings made of pure copper may accommodate to the grooves of the radial plates due to the malleability of pure Cu and the slender conductors. So, global warping of the part is largely irrelevant for EBM pure Cu. Still accumulation of deviations among turns is a concern. The fragility of SLM Al-Si alloy hinders accommodation in the grooves of the radial plate.

Most of the mechanical properties of AM are similar to the ones for the same material in cast or quenched condition. However, elongation at break requires particular attention since it tends to be lower. Also, the usually different properties of the printed material in the different directions has to be taken into account.

The range of industrial AM metals are still limited, but sufficient for many applications.

Cost per unit of volume of the component might seem high (i.e. 50 €/cm^3). Nevertheless, for example, milling cost for complex parts is also high. Thus, AM appears appropriate for the geometrically complex parts assayed.

Table 1 shows a summary of the main properties and results for the studied AM methods and materials.

Summary and conclusions

The utilization of metal AM radial plates and conductors for high-field modular-stellarator coils is assessed, particularly, for resistive coils having turns of variable cross-section. AM parts from commercial suppliers working at standard industrial qualities are produced and analysed. Currently, steel infused with bronze may be applicable to large stellarator parts requiring low accuracy (final milling required for high accuracy) and middle strength. SLM SS316 may be directly applicable to small or middle size stellarator parts (~1 m) requiring relatively high accuracy (up to 0.2%) and middle strength, being radial plates unfeasible without final milling. Few commercial printers allow metallic parts of some metres length. SLM of Al-Si alloy may be directly applicable to conductors and windings requiring moderate conductivity, accuracy (~0.3%) and strength (~200 MPa). EBM of pure Cu may be directly applicable to conductors and windings requiring maximum conductivity but low accuracy (~0.5%) and strength. The concept of windings of variable cross-section, produced from brazing modified flexible copper wire, appears more suitable than the previous AM methods if many turns per pancake are defined.

The generation of the grooves in the radial plates would require a final milling for any of the studied AM methods. In contrast, coil casings and coil supports require only slightly higher accuracy than the one achieved by current commercial SLM AM printers, opening the possibility to 3D-print such parts for small or middle size stellarators.

Further measurements of the parts by a coordinate measuring machine, and study of alternative casting systems based on AM will be produced in future works.

CRediT authorship contribution statement

V. Queral: Conceptualization, Investigation, Methodology, Data curation, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. **E. Rincón:** Conceptualization, Investigation, Supervision, Funding acquisition, Writing – review & editing. **S. Cabrera:** Investigation, Writing – review & editing, Funding acquisition. **A. Lumsdaine:** Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors are grateful to M. I. Mikhailov, J. Nührenberg, et al. [21] for supplying the QIPCC3 magnetic configuration, José Botija and Andres E. Jimenez (CIEMAT) for comments and assistance, information from J.R. Blasco et al. [34] (AIDIMME, Spain), and guidance from the companies involved in the manufacturing. This work has been funded by the Spanish 'Ministry of Science, Innovation and Universities' and the 'Fondo Europeo de Desarrollo Regional' (FEDER EU) under contract number RTI2018-098356-B-I00, project 'Study of additive and advanced

manufacturing for high magnetic field fusion devices of stellarator type'.

References

[1] P.H. Titus, Structural Design of High Field Tokamaks, Plasma Science and Fusion Center, Report PSFC/JA-03-9, Massachusetts Institute of Technology, Cambridge, MA (USA), April 2003.

[2] X.R. Wang, A.R. Raffray, L. Bromberg, J.H. Schultz, L.P. Ku, J.F. Lyon, S. Malang, L. Waganer, L. El-Guebaly, C. Martin, ARIES-CS magnet conductor and structure evaluation, Fusion Sci. Technol. 54 (3) (2008) 818–837.

[3] V. Queral, E. Rincon, S. Cabrera, A. Lumsdaine, F.A. Volpe, F. Tabares, High-Field Ignition-Capable Stellarator i-ASTER: Initial Structural Evaluation, IEEE Trans. Plasma Sci. 48 (6) (2020) 1842–1848.

[4] V. Bykov, F. Schauer, K. Egorov, P. van Eeten, C. Damiani, A. Dübner, M. Sochor, L. Sonnerup, A. Capriccioli, A. Tereshchenko, N. Jaksic, W. Dänner, M. Rumyancev, D. Zacharias, Structural analysis of W7-X: Main results and critical issues, Fusion Eng. Des. 82 (5-14) (2007) 1538–1548.

[5] V. Bykov, F. Schauer, K. Egorov, A. Tereshchenko, P. van Eeten, A. Dübner, M. Sochor, D. Zacharias, A. Dudek, W. Chen, P. Czarkowski, L. Sonnerup, J. Fellinger, D. Hathiramani, M.Y. Ye, W. Dänner, Structural analysis of W7-X: Overview, Fusion Eng. Des. 84 (2-6) (2009) 215–219.

[6] J. Zhu, V. Bykov, G. Ehrke, B. Mendelevitch, D. Naujoks, L. Wegener, H.-S. Bosch, Multiphysics analysis of W7-X control coils, Fusion Eng. Des. 146 (2019) 1369–1372.

[7] I.J. Zatz, J. Chrzanowski, B. Nelson, D. Williamson, P. Fabian, et al., Test program to determine the mechanical properties of the NCSX modular coils, IEEE, 20th IEEE/NPSS Symposium on Fusion Engineering (2003).

[8] N. Mitchell, The ITER magnet system: configuration and construction status, Fus. Eng. Des. 123 (2017) 17–25.

[9] S. Imagawa, et al., Concept of magnet systems for LHD-type reactor, Nucl. Fusion 49 (2009), 075017.

[10] H. Nakajima, K. Hamada, K. Okuno, K. Abe, T. Shimizu, H. Kakui, H. Yamaoka, N. Maruyama, T. Takayanagi, Development of optimum manufacturing technologies of radial plates for the ITER toroidal field coils, Fusion Eng. Des. 82 (5-14) (2007) 1473–1480.

[11] A. Bonito Oliva, Toward completion and delivery of the first EU ITER magnets, Presented on 25th September 2019 in Fusion for Energy, Barcelona, 2019.

[12] L.M. Waganer, K.T. Slattery, J.C. Waldrop, and Aries Team, ARIES-CS coil structure advanced fabrication approach, Fusion Sci. Technol. 54 (3) (2008) 878–889.

[13] N. Koizumi, T. Hemmi, K. Matsui, H. Nakajima, K. Okuno, K. Kuno, K. Nomoto, Critical issues for the manufacture of the ITER TF coil winding pack, Fusion Eng. Des. 84 (2-6) (2009) 210–214.

[14] H. Wu, H. Handroos, J.T. Lehtonen, P. Pale, M. Li, Manufacturing of the ITER TF coils radial plates by means of P/M HIP and a hybrid, Fus. Eng. Des. 86 (2011) 1369–1372.

[15] K. Takano, N. Koizumi, H. Masuo, Y. Natume, Development of manufacturing technology of radial plate in superconducting coil for fusion reactor by diffusion bonding by hot isostatic pressing, Weld. Int. 30 (3) (2016) 159–165.

[16] V. Queral, E. Rincon, A. Lumsdaine, S. Cabrera, D. Spong, Composites and additive manufacturing for high-field coil supports for stellarators, Fusion Eng. Des. 169 (2021), 112477.

[17] L. Bian, N. Shamsaei, J.M. Usher (Editors), Laser-Based Additive Manufacturing of Metal Parts: Modeling, Optimization, and Control of Mechanical Properties, CRC Press, ISBN: 978-1498739986, 2018.

[18] I. Gibson, D. W. Rosen, and B. Stucker, Additive Manufacturing Technologies, Ed. Springer, New York, NY (USA), ISBN 978-1-4419-1120-9, 2009.

[19] V. Queral, S. Cabrera, E. Rincon, V. Mirones, Prospects for Stellarators Based on Additive Manufacturing: Coil Frame Accuracy and Vacuum Vessels, IEEE Trans. Plasma Sci. 46 (5) (2018) 1173–1179.

[20] V. Queral, E. Rincón, V. Mirones, L. Rios, S. Cabrera, Dimensional accuracy of additively manufactured structures for modular coil windings of stellarators, Fusion Eng. Des. 124 (2017) 173–178.

[21] M.J. Mikhailov, W.A. Cooper, M.F. Heyn, M. Yu Isaev, V.N. Kalyuzhnyj, S. V. Kasilov, et al., Comparison of the properties of Quasi-isodynamic configurations for different number of periods, in Proc, in: of the 31st EPS Conf. on Plasma Phys, 2004, p. P-4.166..

[22] Company 'Materialise NV' (Belgium), https://i.materialise.com/en/3d-printing-materials/steel, accessed September 2021.

[23] ExOne^{TM},'420 Stainless Steel Infiltrated with Bronze', www.exone.com, accessed September 2021.

[24] 'Material data sheet SS 316L-0407' Version 05.2015, Renishaw plc. Received from the supplier of the part (See also www.renishaw.com/amdatasheets), 2015.

[25] Ji Hyun Kim, Jun Feng, Mechanical properties of modified SS316LN for jacket materials in superconducting fusion magnet, AIP Conf. Proc. 986 (2008) 92–99.

[26] X. Lu, M. Chiumenti, M. Cervera, H. Tan, X. Lin, S. Wang, Warpage Analysis and Control of Thin-Walled Structures Manufactured by Laser Powder Bed Fusion, Metals 11 (2021) 686 (16pp).

[27] D. Jafari, T.H.J. Vaneker, I. Gibson, Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts, Materials and Design 202 (2021) 109471 (50pp).

[28] A.F. Almagri, D.T. Anderson, S.F.B. Anderson, K.M. Likin, P.G. Matthews, T.L. Piccione, et al., Design and construction of HSX: a helically symmetric stellarator, J. Plasma Fusion Res. SERIES 1 (1998) 422–425.

[29] V. Queral, F.A. Volpe, D. Spong, S. Cabrera, F. Tabarés, Initial exploration of high-field pulsed stellarator approach to ignition experiments, Journal, Fusion Energy 37 (6) (2018) 275–290.

[30] C. Silbernagel, I. Ashcroft, P. Dickens, M. Galea, Electrical resistivity of additively manufactured AlSi10Mg for use in electric motors, Addit. Manuf. 21 (2018) 395–403.

[31] N. Koizumi, H. Kajitani, K. Matsui, T. Hemmi, M. Yamane, S. Ando, M. Nakamoto, K. Takano, Series production of ITER toroidal field coil double pancakes in Japan, Fusion Eng. Des. 124 (2017) 99–103.

[32] Neil Mitchell, Overcoming the Challenges of the ITER Magnets, Presentation 2LO3-01 in EUCAS 2017, Geneva (Switzerland), September 2017.

[33] Qi Jiang, et al., A Review on Additive Manufacturing of Pure Copper, Coatings (a MPDI journal) 11 (2021) 740 (30pp).

[34] L. Portolés, J.R. Blasco, M. Martínez, S. Sanjuan, Pure Copper processed by Electron Beam Melting (EBM) technology for industrial applications, Proceedings of the Euro PM2018 Congress, 14–18 October 2018, Bilbao, Spain, (2018) 1219–1224.