

1 *Review*

2 Latest developments in industrial Hybrid Machine 3 Tools that combine additive and subtractive 4 operations

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11

12 **Abstract:** Hybrid machine tools combining additive and subtractive processes have arisen as a
13 solution to the increasing manufacture requirements, boosting the potentials of both technologies,
14 while compensating and minimizing their limitations. Nevertheless, the idea of hybrid machines is
15 relatively new and there is a notable lack of knowledge in the field. Therefore, in the present paper,
16 an insight into the advancements of hybrid machines is given, identifying their real capabilities,
17 together with the latest developments from an industrial context. In addition, the current situation
18 and future perspectives of hybrid machines from the point of view of process planning, monitoring
19 and inspection are discussed. Finally, the challenges that must be overcome and the opportunities
20 that the hybrid machines will provide in the forthcoming years are presented.

21 **Keywords:** hybrid machines; hybrid manufacturing; additive manufacturing; subtractive
22 manufacturing; Directed Energy Deposition; Powder Bed Fusion
23

24 1. Introduction

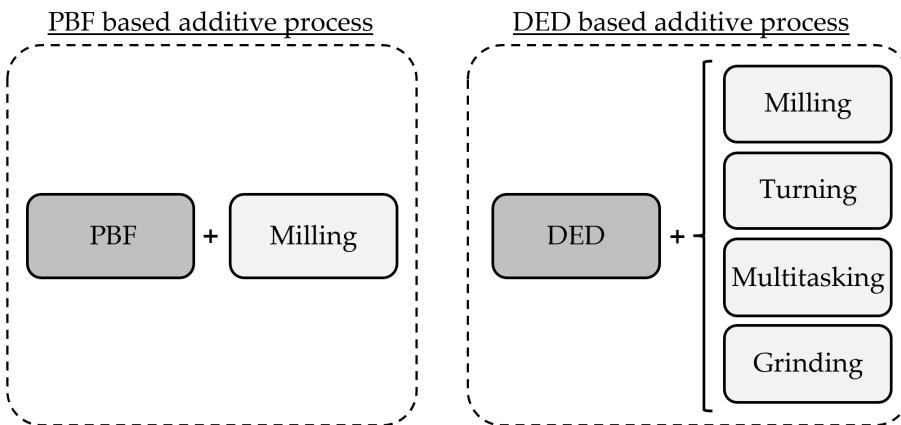
25 Manufacturing industries demand efficient processes that provide a reduction in manufacturing
26 costs and required time in order to gain competitiveness while increasing quality standards are to be
27 met. Thus, hybrid-manufacturing systems are becoming an industrial solution for the manufacture
28 and repair of high complexity parts aimed at various sectors [1]. The objective of developing hybrid
29 processes is to enhance their individual advantages while minimizing their limitations [2]. Therefore,
30 they enable to manufacture components that are not cost-effective or even impossible to manufacture
31 by a single process [3].

32 The concept of hybrid machines that combine various processes is not new. Already in the year
33 2011, Nassehi proposed a technology-based classification for the different processes that could be
34 integrated into a hybrid machine [4]. These processes are joining, dividing, subtractive,
35 transformative and additive. Nevertheless, due to their irruption, the present article focusses on
36 hybrid processes that combine subtractive and additive technologies.

37 In view of the market possibilities ahead, many machine tool builders have opted for this
38 solution and started to develop different hybrid machines that combine additive and subtractive
39 operations. Despite the numerous benefits of additive manufacturing, the resulting parts usually
40 require additional machining operations, regardless the additive approach [5]. This way, hybrid
41 machines have allowed overcoming the main drawbacks associated with additive manufacturing,
42 such as low accuracy and high surface roughness [6]. The combination of both technologies in a single
43 machine is therefore advantageous, as it enables to build ready to use products within an all in one
44 hybrid machine [6, 7], what maximizes the strong points of each technology [8]. This way, complex

45 components that are originally not possible to be machined due to accessibility constraints, are now
46 approachable [9].

47 The ISO/ASTM 52900 International Standard Terminology for Additive Manufacturing
48 Technologies defines additive manufacturing as the “process of joining materials to make parts from
49 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative
50 manufacturing methodologies” [10]. Among the different metal additive manufacturing technologies
51 available, the industry has predominantly opted for Powder Bed Fusion (PBF) and Directed Energy
52 Deposition (DED) processes [8]. Almost any weldable metal can be processed with any of these two
53 techniques. Nevertheless, the vast majority of hybrid systems integrate Laser Metal Deposition
54 (LMD), which is a DED technology that is faster than Selective Laser Melting (SLM), a PBF process,
55 and does not need any process chamber nor supporting structures [11, 12]. For instance, in LMD
56 typical deposition rate values of $5\text{-}30 \text{ g}\cdot\text{min}^{-1}$ are obtained, whereas the SLM process presents typical
57 values of $2\text{-}3 \text{ g}\cdot\text{min}^{-1}$ [13]. In addition, this approach is adaptable to existing conventional machine
58 tools. Hence, hybrid machines give rise to new opportunities in the manufacturing of high-added-
59 value parts, enabling the high-efficiency production of near net shape geometries, as well as the repair
60 and coating of existing components [14]. Besides, the capability to switch between laser and
61 machining operations during the manufacturing process enables finishing by machining regions that
62 are not reachable once the part is finished. In Figure 1, the main additive and subtractive process
63 combinations are shown. They are divided into two groups according to the additive approach in
64 which they are based on. It is noteworthy mentioning that while PBF based processes are mainly
65 directed to produce complex whole parts, DED processes are more focused on the generation of
66 coatings. That is why the latter can be combined with a wider range of subtractive processes.

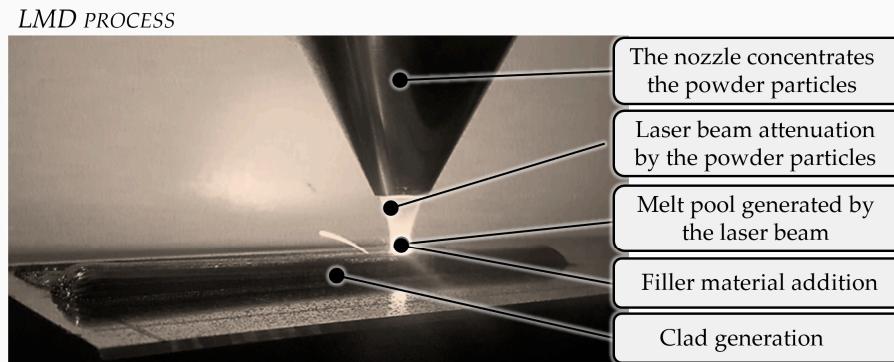


67

68 **Figure 1.** Different process combination in existing hybrid machines.

69 The combination of additive and subtractive processes in a single hybrid machine is especially
70 well suited for the manufacture of low machinability materials, such as heat resistant alloys and high
71 hardness materials, which are widely used in various industries, including aerospace & defense,
72 automotive, medical and oil & gas, among others [11]. In fact, this hybrid manufacturing approach
73 has already been used for remanufacturing existing high-added-value components, such as turbine
74 blades [15], integrally bladed rotors [16], gas turbine burner tips [17] or dies & molds [18].
75 Nevertheless, the full integration of both processes is a complex task that must still overcome many
76 difficulties.

77 The present work aims to provide insight into the latest developments in industrial hybrid
78 machine tools combining additive and subtractive operations. To that end, the current situation of
79 this technology is addressed, covering issues such as the potentials and limitations of hybrid
80 manufacturing, machine configuration and its presence in the international market from an industrial
81 point of view. Finally, challenges and opportunities are identified, concluding with the global outlook
82 of this manufacturing approach.

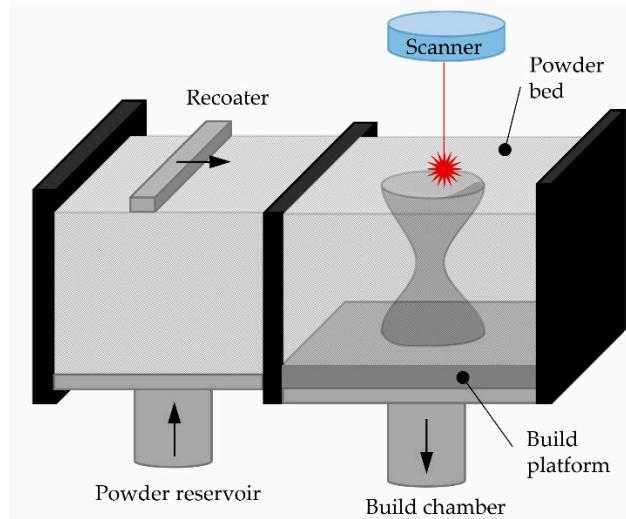
83 **2. Basis of the metal additive processes**84 Despite different technologies can be distinguished, most hybrid machines use DED as the
85 additive approach. This decision is grounded on the higher deposition rate of the DED processes
86 compared with PBF, together with its capability to add material over a freeform surface.87 *2.1. Fundamentals of the DED process*88 The ISO/ASTM 52900 International Standard Terminology for Additive Manufacturing
89 Technologies defines DED processes as “additive manufacturing processes in which focused thermal
90 energy (e.g. laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being
91 deposited” [10]. Among the different DED processes, one of the most broadly used is the Laser Metal
92 Deposition (LMD).93 Laser Metal Deposition or LMD is probably the most common DED process and it is usually
94 applied to build up fully dense coatings and functional metal parts [19]. In this process, the laser
95 beam generates a melt pool on the surface of the substrate; see Figure 2, while filler material is injected
96 simultaneously through a nozzle, which is also responsible for generating a protective atmosphere
97 that avoids material oxidation [20]. Filler material, supplied in the form of powder or wire [21] is
98 molten by the laser beam and bonded to the substrate, forming clads and subsequent layers until the
99 required geometry is obtained [22].101 **Figure 2.** Basis of the LMD process.102 The total amount of energy introduced by the LMD technology into the substrate material is
103 very low when compared to other conventional metal joining techniques, such as arc welding or
104 plasma spraying, what leads to minimum distortion of the workpiece [23]. This creates a fine
105 microstructure, with low levels of dilution between layers and low distortion [18]. All these
106 characteristics give rise to final parts with good mechanical properties and minimal imperfections.107 A wide variety of materials common in several industries have been proven adequate for
108 processing via LMD until now and several authors have worked on the experimental determination
109 of the optimal process parameters for the different materials. Some of them are tool steels [24],
110 stainless steels [25], nickel alloys [26], titanium alloys [27] and copper alloys [28]. In addition, LMD
111 is also suitable for adapting the material properties of certain regions of the part to its final
112 requirements and processing Functionally Graded Materials [29, 30]. Besides, LMD enables to
113 produce near-net-shape parts, what reduces the material wastage and results in a cleaner and
114 environmentally friendlier process [31]. For instance, typical buy-to-fly material ratios of 4:1 (input
115 material to final component) are common in traditional 5-axis milling processes, with some
116 components having a ratio as high as 20:1 [32]. Nevertheless, LMD is capable of improving these buy-
117 to-fly ratios up to values below 1.5:1 [33].118 This additive manufacturing process is proved to be effective in the remanufacturing, coating
119 and repair of existing parts [34], as well as to open new possibilities in the design of innovative
120 geometries [35, 36]. For instance, LMD is used for the manufacture and refurbishment applications
121 of critical aerospace engine components [37, 38], dies and molds [39] and coatings [40], among others.

122 However, LMD technology has also limiting factors that make the post-processing of the
123 manufactured parts necessary in order to attain the required final properties. Some examples of the
124 process limitations are the relatively low accuracy of the parts manufactured via LMD and the fact
125 that the resultant surface roughness does not usually match the final requirements [8]. In addition,
126 the anisotropic behavior of the material properties and the generation of residual stresses can lead to
127 geometrical distortions and even the cracking of the material [41]. Consequently, continuous
128 corrective measurements during the LMD process are necessary in order to manufacture near-net-
129 shape functional parts with close tolerances and acceptable residual stress [42].

130 When higher deposition rates are to be achieved, the Wire Arc Additive Manufacturing
131 (WAAM) process is gaining a wider acceptance in the industrial manufacturing sector. This process
132 is a wire-based DED technique that uses an arc-based energy source, which melts the substrate, while
133 wire is used as feedstock material [43]. The components manufactured by this technique are built
134 layer by layer, thus being the deposition procedure similar to that of LMD [44]. Nevertheless, WAAM
135 presents some advantages such as high deposition rates (up to $10 \text{ kg}\cdot\text{h}^{-1}$), low equipment cost and
136 high material utilization. However, high levels of heat input are also inherent to this process, hence
137 inducing residual stresses and high distortion in the built components [45]. As a result, part accuracy
138 and surface finish are lower than in other additive approaches, and a more complex post-processing,
139 usually carried out by subtractive operations, is required. The variety of materials processed by
140 WAAM ranges from nickel alloys and steels to titanium or aluminum [46]. Its main application field
141 is the manufacture of medium-large size parts of medium geometrical complexity with high
142 mechanical requirements, for instance, aircraft structural components. [47].

143 2.2. Fundamentals of the PBF process

144 Powder Bed Fusion (PBF) processes are based on the selective melting of determined regions of
145 a pre-deposited powder bed by one or more thermal sources (typically lasers), thus generating a thin
146 layer of material. In order to guarantee a uniform distribution of the powder a levelling system or
147 recoater blade is used. This process is repeated layer by layer until the desired solid is built (see
148 Figure 3). Once the process is completed and the part finished, the metal powder that has not been
149 melted can be sieved and reused [48].



150
151 Figure 3. Basis of the PBF processes.

152 These processes are performed on a build platform inside an enclosed build chamber, which in
153 the case of SLM is filled with inert gas, and often require support structures in order to improve heat
154 dissipation and keep the part from excessive warping [49]. As a result, both the orientation of the part
155 together with the location of the supports are key factors when setting up a build. Additionally to
156 support structures, the pre-heating of the build platform can also be used for reducing residual
157 stresses.

158 Due to the nature of PBF technologies, a broad range of materials, including metals, ceramics,
 159 polymers and composites can be processed, where the main application is the manufacture of full 3D
 160 parts with high complexity geometries. Besides, a good accuracy and resolution are attained for
 161 metals. For those reasons, metal PBF processes are becoming increasingly popular for aerospace and
 162 biomedical applications, due to their ability to fabricate complex geometries with a wide range of
 163 materials and their excellent properties compared to traditional metal manufacturing techniques [50].
 164 Some examples of the application of PBF processes for the production of functional parts are dental
 165 and bone implants [51, 52], airfoils or turbine blades with embedded cooling channels [53], thus being
 166 able to give service to the aerospace, energy and medical industries, among others.

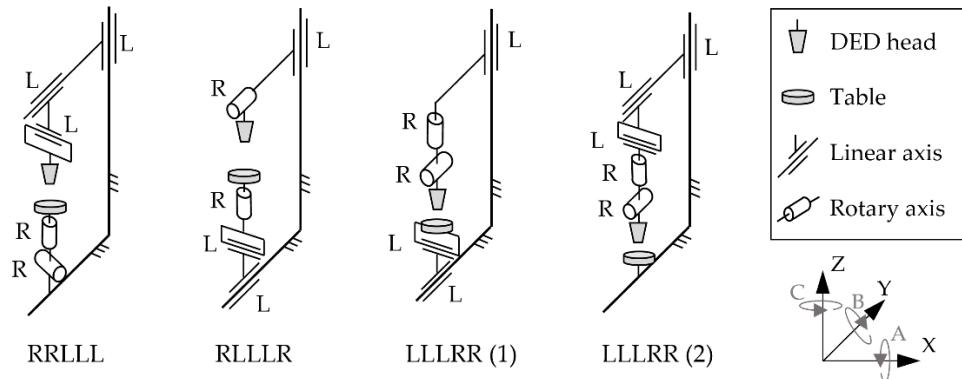
167 Compared to DED technologies, PBF processes have a relatively slow build rate, but higher
 168 complexity and better surface finish can be achieved. However, the size of the build chamber remains
 169 as a limitation on the size of the part to be manufactured. In addition, when the PBF manufacturing
 170 process is finished, the obtained part must be post processed in order to be separated from the build
 171 platform inherent to this technique and remove the supports [54].

172 3. Configuration of hybrid machines

173 As stated in the introduction, hybrid-manufacturing systems are becoming an industrial
 174 solution for the production of high complexity parts. In this section, the particularities in terms of
 175 configuration as a result of the integration of both additive and subtractive processes in a single
 176 platform are addressed.

177 3.1. Kinematic configuration

178 Aiming at the manufacturing of high-complexity parts, the kinematics of hybrid machines plays
 179 an important role in both the accessibility during the process and the resulting accuracy. In Figure 4,
 180 the kinematic chains usually employed in hybrid machines are shown. From left to right they are
 181 classified according to their suitability for the manufacture of bigger and therefore, heavier parts.
 182 Despite 3-axis machines can be also used for hybrid machines, DED processes usually require the
 183 deposition of the material normal to the substrate. On the other hand, DED processes use to be
 184 applied to very complex shape parts. Thus, most of the hybrid machines that combine additive and
 185 subtractive processes are based on 5-axis machine configurations, on which the present kinematic
 186 study is focused.



187
 188 **Figure 4.** Most common kinematic schemes of hybrid machines.

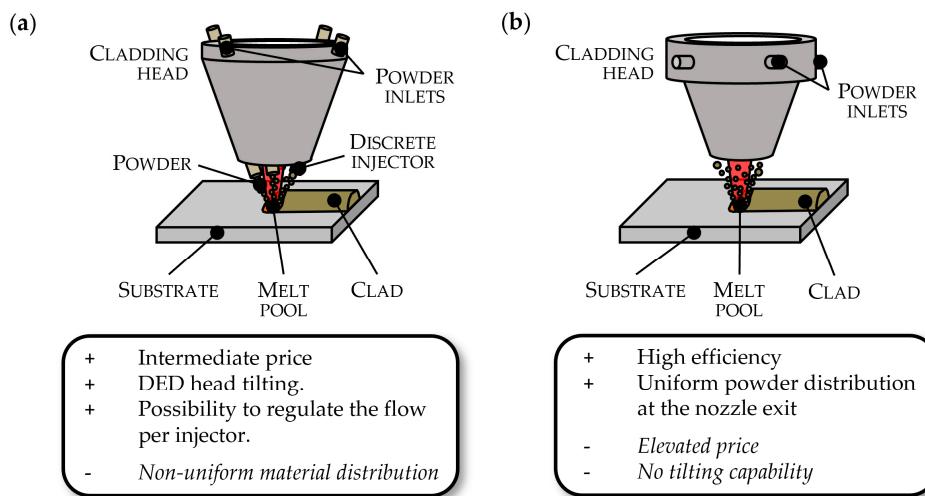
189 On the one hand, most hybrid machines are currently based on an RLLLR kinematic chain,
 190 where the DED head includes a tilting movement (usually B-axis) and the table includes a rotary table
 191 or a universal clamping system (A or C-axis). These types of machines offer a high flexibility together
 192 with an elevated stiffness. Moreover, most machine builders have already developed multitasking
 193 machines combining turning and milling, where the RLLLR is the most widely used kinematic chain.
 194 Therefore, the development of a 5-axis hybrid machine does not imply much design change from the
 195 point of view of kinematics, despite many changes are required in terms of safety and machine
 196 protection.

197 On the other hand, if the machine is focused on the production of small and complex parts, the
 198 use of tilting-table machines, RRLLL kinematic chain, is extended. On the contrary, the biggest parts
 199 are manufactured in LLLRR(2) type machines, where the part to be manufactured is fixed and all
 200 moving axes are situated in the DED head.

201 *3.2. Nozzles and strategy restrictions*

202 In order to obtain a stable process, simultaneously to the generation of the melt pool on the
 203 surface of the substrate, filler material needs to be directed and injected using a specific nozzle. There
 204 are different types of nozzles for powder-based DED processes and based on their geometry and
 205 depending on the powder injection system, three nozzle types can be distinguished: off-axis, coaxial
 206 discrete and coaxial continuous [55]. The design of the nozzle is a key factor that has a direct influence
 207 on the powder pass distribution at the nozzle exit and therefore, determines its efficiency. In addition,
 208 the design type also determines the kind of application of the nozzle, restricting the operations in
 209 which it is suitable: off-axis nozzles are usually employed for coatings, while coaxial nozzles are used
 210 for building 3D parts.

211 The off-axis nozzles are the simplest and most economical ones, where a single powder stream
 212 is fed laterally into the laser beam. However, as their powder feed is dependent of the direction, their
 213 use is restricted to a unidirectional deposition strategy, mainly to the coating of rotary parts, being
 214 unable to build 3D parts. Therefore, their use in hybrid machines is residual.



215

216 Figure 5. Different nozzles used in powder-based DED: (a) Discrete and (b) Continuous coaxial nozzles [56].

217 As an evolution of the off-axis, coaxial discrete nozzles have been developed (see Figure 5(a)),
 218 which enable multidirectional deposition at an intermediate price. Their working principle is based
 219 on a number of discrete injectors that are positioned around the rotary axis of the nozzle and powder
 220 particles are fed coaxially to the laser beam. Depending on the design, three or four injectors may be
 221 positioned, whose powder flow can be regulated independently. However, and due to its working
 222 principle, the powder distribution obtained is not uniform. The configuration of the coaxial discrete
 223 nozzles enables the tilting of the DED head up to 180° and therefore 5-axis deposition [57].

224 Lastly, coaxial continuous nozzles have also arisen (see Figure 5(b)), generating an axisymmetric
 225 flow of powder at the nozzle exit that encloses the laser beam, thus being able to build 3D parts. In
 226 this case, a higher efficiency of the nozzle can be achieved, as the diameter of the powder stream can
 227 be adapted to the size of the laser beam on the workpiece [58]. In addition, the powder distribution
 228 is ensured to be uniform and homogeneous at the nozzle exit. However, due to their complexity,
 229 these kinds of nozzles are expensive. Besides, their tilting is restricted due to the effect of gravity on
 230 the powder cone. Experiments show that this system can work satisfactorily with a maximum tilt
 231 angle of 20° [57].

232 *3.3. Other features*

233 The introduction of powder particles in the working envelope of the hybrid machine in order to
 234 perform additive operations forces to make some considerations in order to preserve the integrity of
 235 the moving elements. Thus, machine tool builders have started to take measures to address this issue.
 236 For instance, some manufacturers (e.g. Mitsui Seiki, Okuma) have incorporated the same features as
 237 in their machining centers aimed at the machining of graphite, during which graphite dust is
 238 generated. That is, the machines include a fully enclosed guard that completely seals powder particles
 239 inside and then extracts them by means of an exhaust system. In addition, kinematic protections are
 240 also implemented in order to protect the moving elements from metal powder [59, 60]. Furthermore,
 241 another kind of safeguard to be taken is that against sparks due to static discharges.

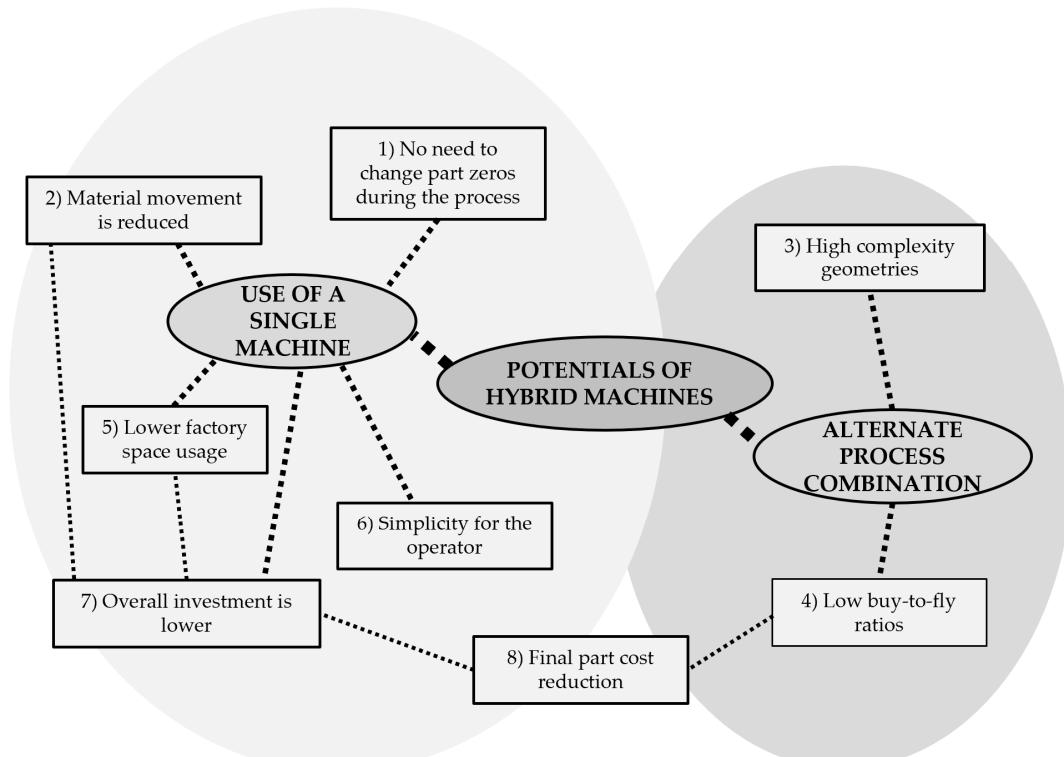
242 The combination of additive and subtractive technologies has also certain implications to be
 243 considered so that one process does not affect the other negatively. One example of it is the cutting
 244 fluid – laser tandem. In order to remove the excessive cutting fluid from the part to be processed
 245 additively, some manufacturers are opting for blowing it off the part [61]. However, this is not an
 246 advisable practice when metal powder is present, as it poses fire and explosion risks [62].

247 **4. Study of the real capabilities of hybrid machines**

248 The combination of additive and subtractive technologies in a single hybrid machine brings
 249 unquestionable advantages for the production of complex parts. However, not only are there positive
 250 aspects. Hence, in this section a critical analysis of the real capabilities of hybrid machines is
 251 performed, including their potentials, as well as the challenges still to be faced.

252 *4.1. Potentials of hybrid machines*

253 The development of hybrid machines has enabled to unite the advantages of both processes as
 254 using a single machine for the whole manufacture of metallic parts with the subsequent benefits that
 255 it brings (pre and post process operations that require other machines or working stations might be
 256 still necessary: heat treatments, painting operations, ...). The most relevant strong points derived
 257 from the use of hybrid machines are presented in Figure 6 and expanded upon in the subsequent list.



258

259

Figure 6. Potentials of the hybrid machines.

260 1. There is no need to change part zeros during the manufacturing process. A single setup is used
261 for both additive and subtractive operations [63]. Therefore, the part-positioning error is
262 minimized, what results in a higher final accuracy. Furthermore, as there is only the need for a
263 single zero-setup per part or set of parts, non-productive time due to zero making is reduced to
264 minimum values.

265 2. Material movement inside the factory is reduced. Hybrid machines enable to manufacture whole
266 parts in the same machine, without the necessity to move the part to other machines for finishing
267 operations [64]. Hence, intermediate warehouses are eliminated from the factory, what results in
268 a better use of the available space. Besides, as the movement of the material is minimized, on the
269 one hand, the workload of the equipment for material handling is reduced and, on the other
270 hand, the chances for collisions and accidents are lowered, what results in an increase of the
271 employees' safety.

272 3. Enables the manufacture of higher complexity geometries. The hybrid machine can switch
273 between additive and machining operations seamlessly during the manufacture of a single part
274 [65]. Therefore, it is feasible to machine areas that are no longer accessible once the part is
275 finished. This results in a higher freedom and flexibility when designing an optimum geometry
276 of the part. Besides, this point is directly related with the previously introduced issues 1 and 2,
277 because when the manufacturing process switches between additive and subtractive operations,
278 there is no material movement inside the factory, nor precision lost due to zero changes between
279 different manufacturing platforms.

280 4. Low buy-to-fly ratios. The possibility to generate near-net-shape components using additive
281 manufacturing results in a reduction of material waste, as well as the economic costs related to
282 the material recycle and waste treatment. Buy-to-fly ratios as low as 1.5:1 are achieved thanks to
283 hybrid machines [32]. Consequently, the ecological footprint resulting from the process is
284 reduced. Combining additive and subtractive operations enables to take advantage of the
285 potential of both processes and therefore, material-efficiencies up to 97% can be achieved [66, 67].

286 5. Lower factory space is used. Thanks to the use of hybrid machines, as additive and subtractive
287 operations can be carried out within the same machine, the number of required machines for the
288 manufacture of a certain part is reduced. Therefore, also is reduced the occupied space in the
289 workshop.

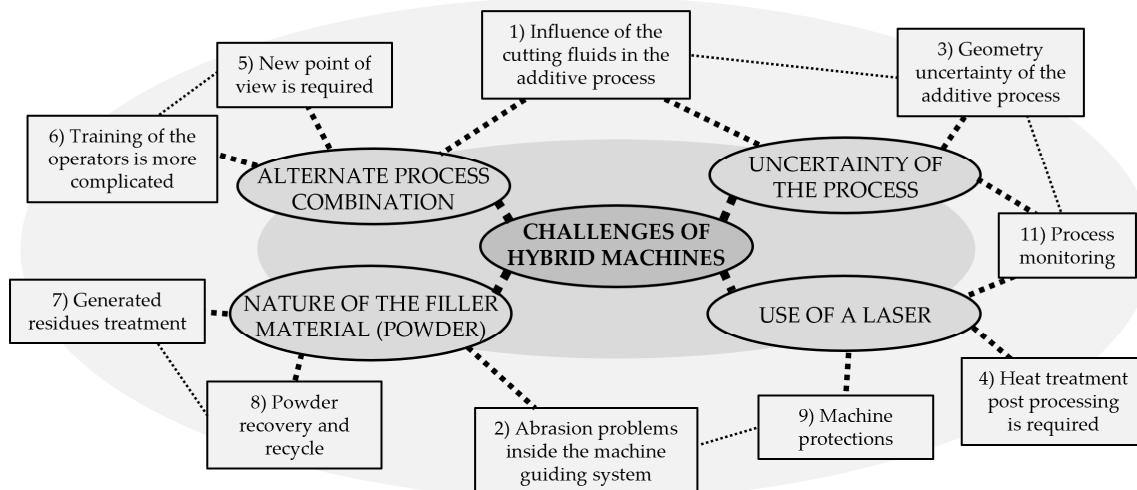
290 6. Simplicity for the operator. The integration of both processes in a single machine under a unique
291 interface involves that the operator must only deal with one working station, what eases both the
292 training as well as the daily work.

293 7. The overall investment is lower. Hybrid machines are more expensive than simple additive or
294 milling machines. However, the integration of both technologies in a hybrid machine involves
295 sharing common elements (e.g. guiding systems, machine tool structure, CNC control, user
296 interface). Hence, the total investment required for the acquisition of a hybrid platform is
297 considerably lower than buying two separate machines.

298 8. Reduction of the costs of the final part. Additive manufacturing enables to realize high
299 performance coatings over ordinary or "cheap" materials, thus achieving a final part with
300 enhanced properties, but at a cheaper cost.

301 4.2. *Challenges of hybrid machines*

302 Despite the numerous potentials of the hybrid machines, many issues still need to be solved
303 when combining additive and subtractive processes. In Figure 7 the most relevant challenges to be
304 faced before their complete implantation are shown and their connections are highlighted.



305

306

Figure 7. Challenges of hybrid machines.

307 1. **Influence of the cutting fluids in the additive process.** The remains of the cutting fluids from the
 308 machining process can influence the subsequent additive process [68]. This issue has a double
 309 effect. On the one hand, powder particles do mix with the fluid and generate a moisture that
 310 influences directly the laser beam absorptivity and the dilution of the filler material within the
 311 substrate. On the other hand, the cutting fluid vaporizes during the additive process and results
 312 in porosity increase, as well as possible damage to the optical systems due to the contamination
 313 of the lenses [69, 70].
 314 Problems with cutting fluids are even more critical when SLM and milling are combined. In this
 315 case, no cutting fluids can be used in the subtractive operation, what results in lower feed rate,
 316 lower plunging depths, higher tool wear, etc.

317 2. **Abrasion problems inside the guiding system of the machine.** Hybrid machines require a special
 318 system that protects the guiding system from the powder used in the additive operation [59, 60].
 319 The powder particles used in DED and PBF processes have a diameter ranging 45-150 μm and
 320 10-40 μm , respectively. Therefore, if the machine is not properly sealed, powder particles might
 321 intrude and interfere with the smooth movement of the guiding system, as well as with the
 322 encoders used for determining the position in the machine.

323 3. **Geometry uncertainty in the additive process.** Due to the uncertainty that additive
 324 manufacturing suffers as a consequence of the state of the art and lack of maturity of the
 325 technology, the additive stage is the weakest link within the hybrid machines. For example, it is
 326 well known that additive manufacturing can grow complex internal features, but there is a lack
 327 of knowledge regarding how those features should be inspected [71].
 328 With regard to the accuracy of the additive process, especially in DED operations, it is lower than
 329 that of machining. In Table 1, a comparison between PBF and DED technologies dimensional
 330 accuracy and surface roughness is presented [72]. As it can be seen, DED is a less accurate process
 331 than PBF. However, in both cases, a post-processing stage is necessary depending on the final
 332 requirements of the part.

333

Table 1. Comparison between PBF and DED technologies. [72]

Technology	Dimensional accuracy [mm]	Surface roughness [μm]	Ref.
PBF	± 0.05	9-16	[73, 74]
DED	± 0.13	≈ 40	[75, 76]

334
335
336

The material deposition rate in the additive process is extremely sensitive to the feed rate of the machine, the volume of the substrate, the geometry of the region where the material is being

337 deposited, the surface finish, etc. what may generate differences between the originally designed
338 and really manufactured part [77]. Besides, the internal stresses generated during the additive
339 stage due to the thermal nature of the process may generate considerable geometrical distortions.
340 Therefore, in the subsequent machining operation, the tool may encounter material over-
341 accumulations and different geometries from those expected, what may lead to the breakage of
342 the cutting tool.

343 4. The requirement of a post-processing heat treatment. During the additive process, the material
344 is subjected to heating and cooling thermal cycles, what leads to the generation of residual
345 stresses that might be released during the subsequent machining operations. This results in
346 distortions of the part geometry and hence, the machining tool may encounter different plunging
347 depths to those programmed [78]. Besides, the mechanical properties of the deposited material,
348 for instance ductility, are very sensitive to the presence of internal defects and porosity [79].
349 In order to reduce internal stresses and solve these issues, additively manufactured parts usually
350 require a post-processing heat treatment [80]. For example, Kobryn and Semiating studied the
351 influence of a post-processing stage on a Ti-6Al4V part produced by Laser Engineered Net
352 Shaping (LENS) and concluded that a Hot Isostatic Pressing (HIP) operation can increase
353 ductility from 0.8% to values of almost 12% [81]. Besides, authors like Åsberg et al. studied the
354 influence of HIP on the yield strength of an AISI H13 tool steel and a 30% improvement was
355 obtained with regard to the as-deposited material, reaching an average value of 1502 MPa [82].
356 Therefore, in case the hybrid machine is not prepared for providing the required heat treatment,
357 material movement to an external furnace is mandatory, what eliminates one of the main
358 advantages of using a hybrid machine.

359 5. Necessity of a paradigm shift. Design engineers need to learn not only each process
360 independently (additive and subtractive) but also the possibilities that arose thanks to their
361 combination, what may result in a change of the whole conception of designing parts. For
362 instance, Salonitis and Zarban proposed a methodology for redesigning the geometry of a part
363 to be additively manufactured based on a Multi-Criteria Decision Analysis (MCDA) for assisting
364 in decision-making [83]. However, there is no standard methodology or process planning aimed
365 at hybrid machines.

366 Besides, Hällgren et al. stated that additive manufacturing could be approached from two points
367 of view: design driven and process driven [84]. The first one focusses on improving the geometry
368 of the manufactured part, but without considering the optimization of the manufacturing process
369 itself, whereas the second one works the other way. However, if satisfying results are to be
370 obtained and the full potential of hybrid manufacturing is to be exploited, a new point of view
371 that combines both ideas is required.

372 6. Training of operators is more complicated. Operators require a wider background knowledge to
373 master in both processes; hence, this is directly translated into a longer training period. Moreover,
374 due to the extensive freedom of additive manufacturing, hybrid machines usually require the use
375 of computational frameworks in order to optimize both processes [85]. Besides, operators must
376 be trained in safety issues, especially with regard to the powder handling and lasers operating
377 [86].

378 7. Generated residues treatment. Thanks to the capability of the additive manufacturing to generate
379 near-net-shape geometries, hybrid machines reduce the generated amount of waste material as
380 much as the 90% [87]. However, their treatment may result far more complicated from a logistical
381 point of view and economically expensive. Special attention must be paid to powder handling,
382 recycling of the liquid wastes (e.g. lubrication oils used for the movement of the axes, cutting
383 fluids employed in machining). Depending on the composition of the used powder particles, the
384 residues are extremely hazardous to human health. Especially powder with high content of nickel
385 or cobalt are carcinogenic to our health. All this obliges the company to install special protective
386 measures, as well as a proper protocol for treating the residues [88]. Moreover, despite the latest
387 advances, there is a lack of knowledge and studies related to the toxicity and harmful effects
388 related to the powder particles [89].

389 8. Powder recovery and recycle. In laser metal additive processes, only a fraction of the fed powder
390 is melted by the laser and added to the substrate, whereas the rest of the powder is lost. Industrial
391 powder based DED systems have an efficiency ranging between 5 and 70% [90], whereas in wire-
392 based DED and PBF much higher efficiency values are obtained, reaching values of almost 100%.
393 However, this powder has interacted with the laser beam and consequently, the shape and
394 composition of the particles may have changed, what is detrimental for its reutilization. Carroll
395 et al. concluded that the reused powder reduces the hardness of the deposited material and
396 increases the surface roughness [90]. Besides, it may have contacted with substances such as oil,
397 dust, other composition powders, etc. affecting negatively to the process. In order to highlight
398 the discrepancies between the different authors and the existing uncertainty in this field, some
399 authors conclude that Inconel 718 DED powder can be reused twice [91], whereas others increase
400 this number up to 10 reuses without major changes in the results for the Inconel 625 DED [90].
401 9. Machine protections. Besides protecting the machine operator from collisions, the fairing of the
402 hybrid machines needs to be capable of retaining the high-intensity light generated by the laser
403 inside the machine and able to withstand the heat generated during the additive process.
404 Reflections of the laser beam when highly reflective materials are being processed (e.g.
405 aluminum, copper) may result in the melting of specific areas of the fairing or other sensitive
406 elements and therefore, proper protections must be arranged.

407 5. Latest developments from an industrial perspective

408 Despite the potential of additive manufacturing on its own, it also has some limitations to its
409 application, such as accessing difficult to reach areas inside complex parts. This issue is one of the
410 main reasons why many machine tool builders have opted for offering hybrid systems that combine
411 additive and subtractive processes.

412 In this section, the latest hybrid machines developed by the market leading machine tool
413 builders are detailed with the aim of providing readers a broad vision of the market situation and the
414 latest launches. They are grouped into two categories, depending on the additive approach, DED or
415 PBF, employed.

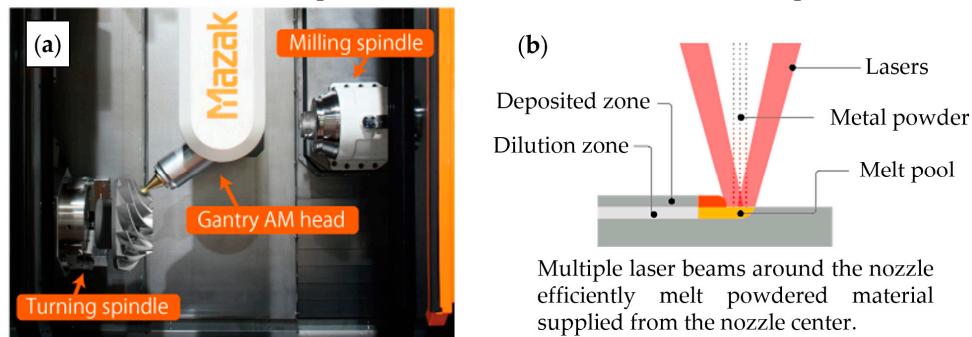
416 5.1. DED based hybrid machines

417 Many machine tool builders are successfully operating in the market of additive manufacturing
418 using both DED and PBF technologies. However, when it comes to hybrid systems, the available offer
419 of machines based on DED technology is noticeably wider than those integrating PBF processes.
420 Some of the underlying reasons for such situation are the much higher deposition rate that DED
421 offers, as well as the possibility of adding material on existing parts. Moreover, thanks to the
422 feasibility of depositing material while the five-axis of the machine are simultaneously interpolated,
423 complex geometries can be built without any support structure.

424 One of the companies that has strongly invested in hybrid machines integrating DED processes
425 rather than PBF is the German-Japanese DMG MORI, who aims to gain access to the aerospace,
426 energy, and die and mold industries with the help of LASERTEC 3D hybrid series. To that end, they
427 already count with two different hybrid solutions: **LASERTEC 65 3D hybrid** and **LASERTEC 4300**
428 **3D hybrid**, launched in 2014 and 2016, respectively. The first one, based on an RRLLL kinematic
429 chain, includes a tilting table and combines the flexibility of LMD with the precision of five-axis
430 milling [92]. Alternatively, the second one includes a B-axis tilting movement in the head and an
431 RLLLR kinematic chain, integrating six-axis LMD and five-axis turning/milling operations. In
432 addition, this machine is equipped with up to five nozzles of different sizes and an automatic laser
433 head changer [93]. Both machines are provided with process monitoring and control devices, such as
434 real-time temperature and melt pool size measurement that enables automatic laser power
435 regulation.

436 Based on its extensive expertise in building multitasking machine centers, the Japanese Mazak
437 has also made inroads into the hybrid machine's market with five DED based hybrid machines. The
438 **INTEGREX i-400AM** [94], launched in 2014, combines 5-axis machining and LMD under a RLLLR

439 kinematic configuration. The machine can switch between two different laser processing heads that
 440 are loaded into the milling spindle by a standard tool changer, aiming high speed or high accuracy
 441 deposition and enabling the adjustment of the deposited clad size depending on the process
 442 requirements and employed material. Two years later, in 2016, the **VC-500 AM** hybrid multitasking
 443 machine was presented [95]. This machine, which is only available in the US market, features 5-axis
 444 milling and LMD additive technology. Alike the **INTEGREX i-400AM**, the **VC-500 AM** is based on an
 445 RRLLL kinematic chain, which includes a tilting-table, A and C axis, and the translation movements
 446 are situated in the LMD head. Besides, the machine is provided with the **Mazak MAZATROL SmoothX**
 447 CNC technology [96], which eases the generation of programs for complex parts manufacturing. In
 448 the same year, 2016, the **INTEGREX i-200S AM** was introduced at JIMTOF 2016 [97]. This hybrid
 449 machine tool uses an RLLLR kinematic chain, including two turning spindles, a milling spindle and
 450 a Gantry AM head (Figure 8(a)), and integrates Multi-Laser Metal Deposition with milling/turning.
 451 Multi-Laser Metal Deposition is a process in which multiple laser beams are used to melt metal
 452 powder fed through the center of a laser head, attaining a stable metal powder flow even when tilting
 453 the laser head and a very high accuracy (Figure 8(b)). The evolution of this machine, the **INTEGREX**
 454 **i-300S AM**, was also launched and presented at the Machine Tool World Exposition (EMO) 2017.



455

456 **Figure 8.** (a) Gantry AM head used in the INTEGREX i-200S; (b) Multi-Laser Deposition process.
 457 [98]

458 The **VARIAXIS j-600/5X AM** [99], launched in 2016, is based on a vertical 5-axis machining
 459 center combined with WAAM. This machine is based on an RRLLL kinematic chain, where a tilting
 460 table is used while the additive manufacturing head includes the linear movements.

461 Another company that has also broken into the hybrid market is the Japanese Okuma, who since
 462 2016 includes the LASER EX series within its portfolio. These machine series, developed in
 463 collaboration with TRUMPF, combine subtractive and additive functionalities, hardening and
 464 coating in a single platform. On the one hand, the **MU-V LASER EX** [100] machines are 5-axis vertical
 465 machining centers provided with laser processing capabilities. All MU-V machines are based on an
 466 RRLLL kinematic chain, where the tilting table includes the X linear axis and the Y and Z are included
 467 in the DED/milling head. On the other hand, the **MULTUS U LASER EX** [101] series are based on a
 468 5-axis horizontal multitasking machine. However, unlike the vertical centers, these horizontal centers
 469 include an RLLLR kinematic chain, together with a B-axis tilting head.

470 The worldwide manufacturer WFL, who concentrates uniquely on the production of
 471 multifunctional complete machining centers, has integrated laser based additive technologies into a
 472 MILLTURN multi-task machining center. This way, fully integrated laser solutions like laser
 473 cladding, laser welding and laser hardening are possible on the **M80 MILLTURN** [102], which is also
 474 provided with turning, boring and milling functionalities. The machine's kinematic chain is based on
 475 an RLLLR configuration, where the DED/milling head includes a B-axis tilting movement.

476 The Basque machine tool builder Ibarmia has also decided to start incorporating laser cladding
 477 functionalities in its 5-axis multitasking machines, giving rise to the **ADD+PROCESS** series and the
 478 **ZVH 45/L1600 ADD+PROCESS** machine. This machine is based on a moving column architecture
 479 with a B axis tilting head, RLLLR kinematic chain, and combines DED with precision milling and
 480 turning. Besides, the laser spot size can be modified in order to attain high productivity or fine
 481 geometries by DED [103].

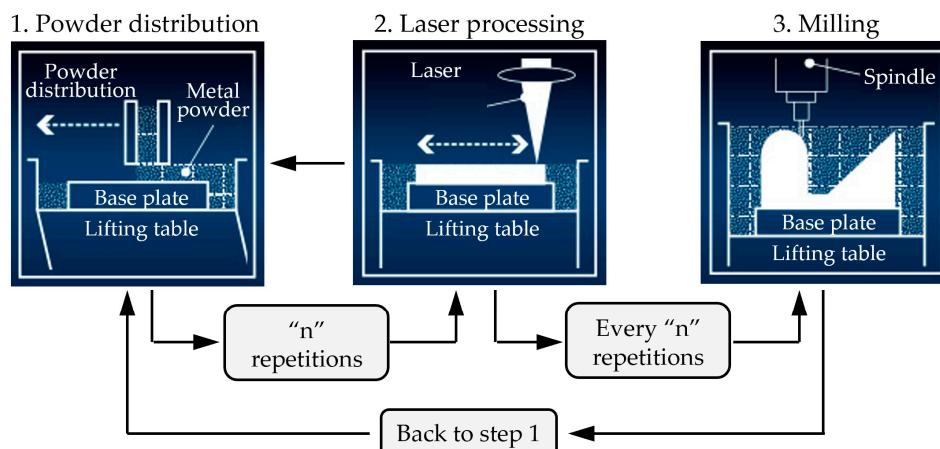
482 Mitsui Seiki also launched in 2016 the hybrid machine **Vertex 55X-H**, which integrates a
 483 spindle-adapted laser DED system into a traditional high precision machine tool [104]. The machine
 484 is based on an RRLLL kinematic chain with a tilting table and a gantry-type structure. Especially
 485 notable are the measures this company has taken in order to face the problems arisen due to the
 486 combination of additive and subtractive operations. On the one hand, the machine includes an air
 487 blow-off operation that removes much of the volume of coolant still on the part followed by a laser
 488 cleaning stage (with the laser defocused) prior to the additive operation [60]. On the other hand, in
 489 order to avoid problems in the bearings and axis guiding systems, the machine has guarding and
 490 other kinematic protections that the company has adapted from other milling machines that are
 491 especially designed for working with graphite.

492 Despite traditionally integrating machining operations, the hybrid manufacturing and hybrid
 493 machine tool concept are also open to other alternatives. One example of it is the **millGrind** hybrid
 494 machine developed by Elb-Schliff WZM GmbH, which combines DED and grinding technologies,
 495 offering, according to the company, a 0.1 μm accuracy [105].

496 *5.2. PBF based hybrid machines*

497 Despite most of the manufacturers opting for DED based hybrid machines, there are also PBF
 498 based alternatives that are worth mentioning. For instance, Sodick, a Japanese company focused on
 499 the manufacturing of Electrical Discharge Machining (EDM) and High speed milling center
 500 machines, has developed the new OPM series, comprised by **OPM250L** [106] and **OPM350L** [107]
 501 and performing both SLM and high-speed milling. Each layer is milled as soon as it is built so that a
 502 high-quality accuracy and precision are attained, even on cavities or inner features that are not
 503 reachable once the part is finished. Therefore, these hybrid machines are specially designed for the
 504 manufacture of mold cooling channels.

505 Meanwhile, the high-speed machining centers manufacturer Matsuura has developed since the
 506 year 2003 Metal Laser Sintering Hybrid Milling Machines under the name LUMEX Series [108]. This
 507 series consists of two different machines that differ in the size of their working area, **Lumex Avance**
 508 **25** [109] and **Lumex Avance 60** [110]. In both models, an Ytterbium fiber laser is installed and the
 509 milling operation is performed by default after every 10 layers are processed, as seen in Figure 9.



510

511 **Figure 9.** Additive and subtractive operation combination on which the Matsuura hybrid machines
 512 are based. [111]

513 Finally yet importantly, GF Machining Solutions has collaborated with different additive
 514 manufacturers and now is developing joint solutions with the US company 3D Systems in order to
 515 develop the **DMP Factory 500** [112, 113]. The machine is grounded on a Direct Metal Printing based
 516 additive manufacturing platform, to which a **System3R tooling system** (see Figure 10) has been
 517 incorporated [114]. This tooling system enables to switch the part between the different additive and
 518 subtractive machines.



519

520 **Figure 10.** 3R tooling system used for keeping a fixed reference during the whole process [112].

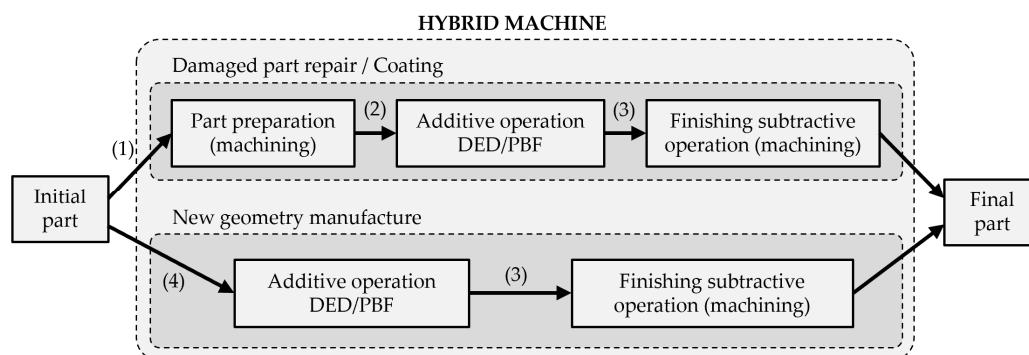
521 Therefore, the proposal of GF and 3D Systems is not a hybrid machine itself, but an especial
 522 tooling system that is claimed to reduce the setup time to a few minutes, as well as to guarantee the
 523 precision and accuracy during the entire manufacturing process chain. This way, they compare their
 524 process to that performed in a hybrid machine.

525 **6. Current situation and future perspectives**

526 The development of hybrid machines combining additive and subtractive processes opens doors
 527 to a new concept in terms of both design and manufacturing, enabling the consecution of new
 528 components previously beyond reach. Nevertheless, the consideration of both technologies in holistic
 529 terms is a pressing need in order to perform their full integration within a single platform as a
 530 comprehensive manufacturing approach. This necessity gives rise to a new vision of the process,
 531 conscious of the requirements and restrictions of each technology and leveraging their potentials. In
 532 order to grasp its importance, the most relevant advances made in this direction are addressed in
 533 terms of process planning, monitoring and inspection, and CAM (Computer-Aided Manufacturing)
 534 software developments.

535 **6.1. Process planning**

536 An integral view of hybrid processes combining additive and subtractive operations is required
 537 in order to optimize the interaction of both technologies during the production of a component.
 538 Hybrid manufacturing is especially interesting for the manufacture and repair of high-added-value
 539 parts. Depending on whether a new geometry is to be manufactured or a damaged part needs to be
 540 repaired, a different approach is adopted, as shown in Figure 11. The manufacture of a new geometry
 541 starts with the addition of material followed by a finishing operation, usually by machining, so that
 542 the requirements of the final part are met. By contrast, the process sequence required in a repair or
 543 coating context may involve the intercalation of additive and subtractive operations. In this case, the
 544 interaction between both processes becomes especially important.



545

546 **Figure 11.** Process interactions within a hybrid machine.

547 Nevertheless, some considerations to be taken are represented in the figure. On the one hand,
548 when reincarnating a component, (1) the initial part needs to be measured and characterized before
549 any operation is performed. Then, (2) an intermediate cleaning stage between the subtractive and
550 additive operations is required in order to remove the cutting fluid remnants from the area to be
551 additively processed. In addition, after performing any additive approach, (3) the resulting
552 component needs to be measured so that the outcome of the additive operation is checked, and the
553 subsequent machining tool paths are defined. On the other hand, when a new geometry is to be built,
554 (4) the initial part or substrate needs to be inspected and subsequently clean in order to ensure a good
555 quality of the deposited material. Similarly to the previous case, the dimensional characterization of
556 the additively built-up part (3) is crucial in order to proceed with the finishing operation.

557 So far, few researchers have focused their efforts on process planning for combined additive and
558 subtractive manufacturing technologies. Ren et al. [18] defined a process planning procedure for
559 repairing dies by DED and machining. For that purpose, authors identified the following sequence
560 of operations: (1) determining the features to be repaired, (2) machining the damaged features, (3)
561 additive operation to repair the feature and (4) finishing of the deposited material by machining. On
562 the other hand, Kerbrat et al. [115] proposed a methodology based on manufacturability indexes for
563 identifying features susceptible to be manufactured by additive processes during the product design
564 stage. Besides, Le et al. [116, 117] generated a manufacturing process sequence aimed at reincarnating
565 end of life (EoL) or existing components into final parts with new functionalities. In a first step,
566 authors identified machining and additive manufacturing features by comparing the CAD
567 (Computer-Aided Design) models of the existing and the objective geometries and considering the
568 restrictions of each technology. Then, the process plan is designed by respecting relationships
569 between features, rules based on manufacturing precedence constraints and tool accessibility. More
570 recently, Behandish et al. [118] developed an early approach for automatic evaluation of
571 manufacturability and generation of process plans for hybrid manufacturing via computer-aided
572 process planning.

573 6.2. Monitoring and inspection

574 The implementation of in situ monitoring and inspection systems enables obtaining immediate
575 information from the manufacturing process and an early detection of defects or anomalies. This way,
576 the quality of both, final part and process is enhanced, while the number of rejections and scrap is
577 reduced. To that end, process parameters need to be controlled instantaneously depending on
578 external variables and many authors have focused their efforts on monitoring the process during the
579 last decade [119-122].

580 As far as DED processes are concerned, temperature monitoring is of major importance, as the
581 melt pool temperature is a relevant parameter that affects both the metallurgical quality and
582 geometry accuracy of the manufactured component [123]. In addition, the height of the layers
583 deposited by this technique does not keep constant throughout the process, what makes the
584 subsequent inspection of the produced part crucial. Literature shows that researchers have made
585 effort in monitoring the size and temperature of the melt pool. For instance, some authors suggest
586 the integration of imaging sensors into the nozzle aiming to control the width of the melt pool and,
587 consequently, the quality of the deposition [124, 125]. Hofman et al. developed feedback control
588 algorithms that enable to adjust process parameters in situ in order to control the melt pool size [126]
589 and measure the clad height in real time [127, 128]. Besides, aiming to control the microstructure of
590 the deposited material, Farshidianfar et al. processed thermal information in real time [129]. Aware
591 of the growing interest aroused by monitoring and control, Siemens is currently looking for
592 cooperation with additive manufacturing OEMs to develop and implement process monitoring into
593 different additive manufacturing processes. [123].

594 Moreover, due to the relatively low dimensional accuracy of the additive processes and the
595 uncertainty related with them, in many cases, it is necessary to measure the additively manufactured
596 part before the subtractive stage. For instance, Campbell et al. implemented a 3D visualization
597 algorithm based on AutoCAD software that enables to evaluate the surface roughness, compare the

598 geometry with the theoretical and detect any potential problematic area [130]. Besides, many times
599 the geometry of the substrate must be accurately defined before determining the DED strategies for
600 the additive process [131]. In this direction, Liu et al. developed a set of algorithms and numerical
601 methods to generate the most suitable tool paths and enable the DED process automation. If the
602 distance between the nozzle and the substrate departs from its optimal value, the powder-laser
603 interaction is altered, resulting in process growth variations and, consequently, reduced deposition
604 quality and geometrical inaccuracies [132, 133].

605 In addition, Siemens has also made inroads into part inspection by integrating computer aided
606 inspection tools in NX environment. This way, the software enables to validate the quality of printed
607 parts by Coordinate Measuring Machine (CMM) inspection programming together with the
608 visualization and analysis of the data so that both theoretical CAD and real geometries can be easily
609 compared [134].

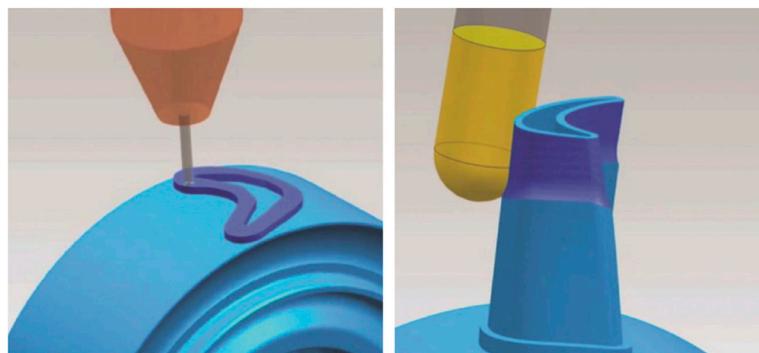
610 6.2. CAM software developments

611 In metal additive manufacturing, built parts are usually finished by means of subtractive
612 technologies. However, the combination of both processes in a unified software solution allowing a
613 holistic process planning remains today as a challenge and thus matter of research.

614 As far as the additive operation is concerned and regarding the LMD process, which is the most
615 extended technology in hybrid machines, the main applications are focused on the generation of
616 coatings and the repair of high-added-value components. However, the fact that the manufactured
617 parts may have complex geometries and the LMD process orientation must be kept normal to the
618 substrate obliges to interpolate the five axes of the machine simultaneously in order to obtain the
619 desired part.

620 The trajectory generation for the subtractive processes is relatively well solved because it is
621 mainly a geometric problem. However, the additive process is more sensitive and the resulting
622 geometry depends on much more factors, such as the size of the part, the duration of the additive
623 operation, the complexity of the trajectory to be followed, etc.

624 In order to solve this issue, the Fraunhofer Institute for Laser Technology (ILT) has developed a
625 tool called LaCam3D that enables both programmers and end-users to generate tool paths and
626 translate them into the CNC machine code. Furthermore, it allows to simulate the process and look
627 for possible collisions [135]. In addition, some researchers are also working on the development of
628 Application Programming Interfaces (APIs) implemented on commercial software, aiming to offer
629 full solutions for hybrid processes [136]. Siemens is also collaborating with DMG Mori [137] on the
630 development of the PLM software *NX Hybrid Additive Manufacturing*, having both additive and
631 subtractive manufacturing functions in a single software. Despite this software is not commercially
632 available yet, further details can be found on their webpage [138]. As it can be seen in Figure 12, the
633 in-process workpiece designed in the NX CAD module can undergo both additive and subtractive
634 operation in any order.



635

636 Figure 12. In-process workpiece and verification work for both additive and subtractive modes [137].

637 This is the first commercial solution that allows CAD/CAM additive operations and was
638 presented in Milan at the EMO in 2015. The developed *NX Hybrid Additive Manufacturing* module is
639 currently specifically configured for the Lasertec 65 3D from DMG Mori and the Siemens Sinumerik
640 840D CNC control system.

641 **7. Conclusions**

642 There is no doubt that additive manufacturing technologies are changing the paradigm of
643 production. However, the mindset of designers and engineers must be changed in order to fully
644 understand and therefore utilize additive manufacturing technologies. Their combination with
645 subtractive operations helps to overcome the low accuracy, precision and high roughness usually
646 related to additive manufacturing, hence enabling the production of components previously
647 unattainable. Nevertheless, the integration of additive and subtractive operations into a single
648 machine, although the latter being a mature technology, is certainly not without its challenges.

649 On the one hand, the main benefit of hybrid machines can be outlined as a more efficient use of
650 the available resources, resulting in the shortening of the process chains, with the subsequent time
651 and economic savings it involves. At the technical level, hybrid machines open the possibility of
652 manufacturing higher-complexity components, thus enabling the consecution of more flexible new
653 designs with enhanced characteristics. On the other hand, the vast majority of challenges that hybrid
654 machines must still face come from the additive side and its lack of maturity. In this direction, the
655 industrial sector has already started to make some considerations when building these new machine
656 tools so that issues such as safety of the user, guarding of the machine or residues treatment, among
657 others, are addressed. However, and from a technical point of view, there is still work to be done
658 with regard to understanding additive technologies and their interaction with subtractive processes.
659 For instance, the combination of thermomechanical models with CAD/CAM software is of great
660 importance in order to be able to design adequate building strategies and guarantee there is no
661 excessive deviation between the projected and the actual part. In addition, there is still a lack of
662 agreement on some aspects, such as the best means to eliminate metal powder or cutting fluid from
663 the working environment. In this regard and on the basis of experience, authors believe that the best
664 way to proceed would be a combination of powder blowing and laser cleaning prior to the additive
665 process. Moreover, and despite the fact that machine tool mechatronics and process integration is
666 near to be solved, there are still key aspects that need to be improved such as programming tools,
667 process monitoring, powder recovery, etc.

668 Process planning for hybrid solutions is a major outstanding issue, where substantial progress
669 needs to be made. The main challenge is now the development of a software tool that allows the
670 design of an optimized process plan comprised of enhanced additive and subtractive operations that
671 can be applied alternately. This task requires an in-depth knowledge of both technologies, as well as
672 the consideration of part inspection as a built-in functionality able to update the manufacturing
673 strategies in process. Decision planning is another issue to be faced in order to discern whether a
674 feature should be manufactured subtractive or additively. This way, a more efficient use of machine,
675 materials and resources might be attained.

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677 prepared and wrote the original draft, Jose Exequiel Ruiz helped with the literature survey, Eneko Ukar and
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